

# **FreeBSD Developers' Handbook**

**The FreeBSD Documentation Project**

## FreeBSD Developers' Handbook

by The FreeBSD Documentation Project

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# I. Basics



# Chapter 1 Introduction

*This chapter was written by Murray Stokely and Jeroen Ruigrok van der Werven.*

## 1.1 Developing on FreeBSD

So here we are. System all installed and you are ready to start programming. But where to start? What does FreeBSD provide? What can it do for me, as a programmer?

These are some questions which this chapter tries to answer. Of course, programming has different levels of proficiency like any other trade. For some it is a hobby, for others it is their profession. The information in this chapter might be more aimed towards the beginning programmer, but may also serve to be useful for the programmer taking her first steps on the FreeBSD platform.

## 1.2 The BSD Vision

To produce the best UNIX-like operating system package possible, with due respect to the original software tools ideology as well as usability, performance and stability.

## 1.3 Architectural Guidelines

Our ideology can be described by the following guidelines

- Do not add new functionality unless an implementor cannot complete a real application without it.
- It is as important to decide what a system is not as to decide what it is. Do not serve all the world's needs; rather, make the system extensible so that additional needs can be met in an upwardly compatible fashion.
- The only thing worse than generalizing from one example is generalizing from no examples at all.
- If a problem is not completely understood, it is probably best to provide no solution at all.
- If you can get 90 percent of the desired effect for 10 percent of the work, use the simpler solution.
- Isolate complexity as much as possible.
- Provide mechanism, rather than policy. In particular, place user interface policy in the client's hands.

From Scheifler & Gettys: "X Window System"

## 1.4 The Layout of `/usr/src`

The complete source code to FreeBSD is available from our public CVS repository. The source code is normally installed in `/usr/src` which contains the following subdirectories:

<b>Directory</b>	<b>Description</b>
<code>bin/</code>	Source for files in <code>/bin</code>
<code>contrib/</code>	Source for files from contributed software.
<code>crypto/</code>	Cryptographical sources
<code>etc/</code>	Source for files in <code>/etc</code>
<code>games/</code>	Source for files in <code>/usr/games</code>
<code>gnu/</code>	Utilities covered by the GNU Public License
<code>include/</code>	Source for files in <code>/usr/include</code>
<code>kerberosIV/</code>	Source for Kerberos version IV
<code>kerberos5/</code>	Source for Kerberos version 5
<code>lib/</code>	Source for files in <code>/usr/lib</code>
<code>libexec/</code>	Source for files in <code>/usr/libexec</code>
<code>release/</code>	Files required to produce a FreeBSD release
<code>sbin/</code>	Source for files in <code>/sbin</code>
<code>secure/</code>	FreeSec sources
<code>share/</code>	Source for files in <code>/usr/share</code>
<code>sys/</code>	Kernel source files
<code>tools/</code>	Tools used for maintenance and testing of FreeBSD
<code>usr.bin/</code>	Source for files in <code>/usr/bin</code>
<code>usr.sbin/</code>	Source for files in <code>/usr/sbin</code>

# Chapter 2 Programming Tools

*Written by James Raynard. Modifications for the Developer's Handbook by Murray Stokely.*

## 2.1 Synopsis

This chapter is an introduction to using some of the programming tools supplied with FreeBSD, although much of it will be applicable to many other versions of Unix. It does *not* attempt to describe coding in any detail. Most of the chapter assumes little or no previous programming knowledge, although it is hoped that most programmers will find something of value in it.

## 2.2 Introduction

FreeBSD offers an excellent development environment. Compilers for C, C++, and Fortran and an assembler come with the basic system, not to mention a Perl interpreter and classic Unix tools such as `sed` and `awk`. If that is not enough, there are many more compilers and interpreters in the Ports collection. FreeBSD is very compatible with standards such as POSIX and ANSI C, as well with its own BSD heritage, so it is possible to write applications that will compile and run with little or no modification on a wide range of platforms.

However, all this power can be rather overwhelming at first if you have never written programs on a Unix platform before. This document aims to help you get up and running, without getting too deeply into more advanced topics. The intention is that this document should give you enough of the basics to be able to make some sense of the documentation.

Most of the document requires little or no knowledge of programming, although it does assume a basic competence with using Unix and a willingness to learn!

## 2.3 Introduction to Programming

A program is a set of instructions that tell the computer to do various things; sometimes the instruction it has to perform depends on what happened when it performed a previous instruction. This section gives an overview of the two main ways in which you can give these instructions, or “commands” as they are usually called. One way uses an *interpreter*, the other a *compiler*. As human languages are too difficult for a computer to understand in an unambiguous way, commands are usually written in one or other languages specially designed for the purpose.

### 2.3.1 Interpreters

With an interpreter, the language comes as an environment, where you type in commands at a prompt and the environment executes them for you. For more complicated programs, you can type the commands into a file and get the interpreter to load the file and execute the commands in it. If anything goes wrong, many interpreters will drop you into a debugger to help you track down the problem.

The advantage of this is that you can see the results of your commands immediately, and mistakes can be corrected readily. The biggest disadvantage comes when you want to share your programs with someone. They must have the

same interpreter, or you must have some way of giving it to them, and they need to understand how to use it. Also users may not appreciate being thrown into a debugger if they press the wrong key! From a performance point of view, interpreters can use up a lot of memory, and generally do not generate code as efficiently as compilers.

In my opinion, interpreted languages are the best way to start if you have not done any programming before. This kind of environment is typically found with languages like Lisp, Smalltalk, Perl and Basic. It could also be argued that the Unix shell (`sh`, `csh`) is itself an interpreter, and many people do in fact write shell “scripts” to help with various “housekeeping” tasks on their machine. Indeed, part of the original Unix philosophy was to provide lots of small utility programs that could be linked together in shell scripts to perform useful tasks.

## 2.3.2 Interpreters available with FreeBSD

Here is a list of interpreters that are available as FreeBSD packages (<ftp://ftp.FreeBSD.org/pub/FreeBSD/ports/packages/>), with a brief discussion of some of the more popular interpreted languages.

To get one of these packages, all you need to do is to click on the hotlink for the package, then run

```
# pkg_add package name
```

as root. Obviously, you will need to have a fully functional FreeBSD 2.1.0 or later system for the package to work!

### BASIC

Short for Beginner’s All-purpose Symbolic Instruction Code. Developed in the 1950s for teaching University students to program and provided with every self-respecting personal computer in the 1980s, BASIC has been the first programming language for many programmers. It is also the foundation for Visual Basic.

The Bywater Basic Interpreter (<ftp://ftp.FreeBSD.org/pub/FreeBSD/ports/packages/Latest/bwbasic.tgz>) and the Phil Cockroft’s Basic Interpreter (<ftp://ftp.FreeBSD.org/pub/FreeBSD/ports/packages/Latest/pbasic.tgz>) (formerly Rabbit Basic) are available as FreeBSD packages (<ftp://ftp.FreeBSD.org/pub/FreeBSD/ports/packages/>).

### Lisp

A language that was developed in the late 1950s as an alternative to the “number-crunching” languages that were popular at the time. Instead of being based on numbers, Lisp is based on lists; in fact the name is short for “List Processing”. Very popular in AI (Artificial Intelligence) circles.

Lisp is an extremely powerful and sophisticated language, but can be rather large and unwieldy.

FreeBSD has GNU Common Lisp (<ftp://ftp.FreeBSD.org/pub/FreeBSD/ports/packages/gcl-2.0.tgz>) available as a package.

### Perl

Very popular with system administrators for writing scripts; also often used on World Wide Web servers for writing CGI scripts.

Perl is installed as `/usr/bin/perl` in the FreeBSD base system.

### Scheme

A dialect of Lisp that is rather more compact and cleaner than Common Lisp. Popular in Universities as it is simple enough to teach to undergraduates as a first language, while it has a high enough level of abstraction to be used in research work.

FreeBSD has packages of the Elk Scheme Interpreter (<ftp://ftp.FreeBSD.org/pub/FreeBSD/ports/packages/Latest/elk.tgz>), the MIT Scheme Interpreter (<ftp://ftp.FreeBSD.org/pub/FreeBSD/ports/packages/Latest/mit-scheme.tgz>) and the SCM Scheme Interpreter (<ftp://ftp.FreeBSD.org/pub/FreeBSD/ports/packages/Latest/scm.tgz>).

### Icon

The Icon Programming Language (<ftp://ftp.FreeBSD.org/pub/FreeBSD/ports/packages/Latest/icon.tgz>).

### Logo

Brian Harvey's LOGO Interpreter (<ftp://ftp.FreeBSD.org/pub/FreeBSD/ports/packages/Latest/ucblogo.tgz>).

### Python

The Python Object-Oriented Programming Language (<ftp://ftp.FreeBSD.org/pub/FreeBSD/ports/packages/Latest/python.tgz>)

## 2.3.3 Compilers

Compilers are rather different. First of all, you write your code in a file (or files) using an editor. You then run the compiler and see if it accepts your program. If it did not compile, grit your teeth and go back to the editor; if it did compile and gave you a program, you can run it either at a shell command prompt or in a debugger to see if it works properly.<sup>1</sup>

Obviously, this is not quite as direct as using an interpreter. However it allows you to do a lot of things which are very difficult or even impossible with an interpreter, such as writing code which interacts closely with the operating system—or even writing your own operating system! It is also useful if you need to write very efficient code, as the compiler can take its time and optimise the code, which would not be acceptable in an interpreter. And distributing a program written for a compiler is usually more straightforward than one written for an interpreter—you can just give them a copy of the executable, assuming they have the same operating system as you.

Compiled languages include Pascal, C and C++. C and C++ are rather unforgiving languages, and best suited to more experienced programmers; Pascal, on the other hand, was designed as an educational language, and is quite a good language to start with. FreeBSD does not include Pascal support in the base system, but the GNU Pascal Compiler (`gpc`) is available in the ports collection.

As the edit-compile-run-debug cycle is rather tedious when using separate programs, many commercial compiler makers have produced Integrated Development Environments (IDEs for short). FreeBSD does not include an IDE in the base system, but `devel/kdevelop` is available in the ports tree and many use **Emacs** for this purpose. Using **Emacs** as an IDE is discussed in Section 2.7.

## 2.4 Compiling with `cc`

This section deals only with the GNU compiler for C and C++, since that comes with the base FreeBSD system. It can be invoked by either `cc` or `gcc`. The details of producing a program with an interpreter vary considerably between interpreters, and are usually well covered in the documentation and on-line help for the interpreter.

Once you have written your masterpiece, the next step is to convert it into something that will (hopefully!) run on FreeBSD. This usually involves several steps, each of which is done by a separate program.

1. Pre-process your source code to remove comments and do other tricks like expanding macros in C.
2. Check the syntax of your code to see if you have obeyed the rules of the language. If you have not, it will complain!
3. Convert the source code into assembly language—this is very close to machine code, but still understandable by humans. Allegedly.<sup>2</sup>
4. Convert the assembly language into machine code—yep, we are talking bits and bytes, ones and zeros here.
5. Check that you have used things like functions and global variables in a consistent way. For example, if you have called a non-existent function, it will complain.
6. If you are trying to produce an executable from several source code files, work out how to fit them all together.
7. Work out how to produce something that the system's run-time loader will be able to load into memory and run.
8. Finally, write the executable on the filesystem.

The word *compiling* is often used to refer to just steps 1 to 4—the others are referred to as *linking*. Sometimes step 1 is referred to as *pre-processing* and steps 3-4 as *assembling*.

Fortunately, almost all this detail is hidden from you, as `cc` is a front end that manages calling all these programs with the right arguments for you; simply typing

```
% cc foobar.c
```

will cause `foobar.c` to be compiled by all the steps above. If you have more than one file to compile, just do something like

```
% cc foo.c bar.c
```

Note that the syntax checking is just that—checking the syntax. It will not check for any logical mistakes you may have made, like putting the program into an infinite loop, or using a bubble sort when you meant to use a binary sort.<sup>3</sup>

There are lots and lots of options for `cc`, which are all in the manual page. Here are a few of the most important ones, with examples of how to use them.

`-o filename`

The output name of the file. If you do not use this option, `cc` will produce an executable called `a.out`.<sup>4</sup>

```
% cc foobar.c          executable is a.out
% cc -o foobar foobar.c  executable is foobar
```

-c

Just compile the file, do not link it. Useful for toy programs where you just want to check the syntax, or if you are using a `Makefile`.

```
% cc -c foobar.c
```

This will produce an *object file* (not an executable) called `foobar.o`. This can be linked together with other object files into an executable.

-g

Create a debug version of the executable. This makes the compiler put information into the executable about which line of which source file corresponds to which function call. A debugger can use this information to show the source code as you step through the program, which is *very* useful; the disadvantage is that all this extra information makes the program much bigger. Normally, you compile with `-g` while you are developing a program and then compile a “release version” without `-g` when you are satisfied it works properly.

```
% cc -g foobar.c
```

This will produce a debug version of the program.<sup>5</sup>

-O

Create an optimised version of the executable. The compiler performs various clever tricks to try and produce an executable that runs faster than normal. You can add a number after the `-O` to specify a higher level of optimisation, but this often exposes bugs in the compiler’s optimiser. For instance, the version of `cc` that comes with the 2.1.0 release of FreeBSD is known to produce bad code with the `-O2` option in some circumstances.

Optimisation is usually only turned on when compiling a release version.

```
% cc -O -o foobar foobar.c
```

This will produce an optimised version of `foobar`.

The following three flags will force `cc` to check that your code complies to the relevant international standard, often referred to as the ANSI standard, though strictly speaking it is an ISO standard.

-Wall

Enable all the warnings which the authors of `cc` believe are worthwhile. Despite the name, it will not enable all the warnings `cc` is capable of.

-ansi

Turn off most, but not all, of the non-ANSI C features provided by `cc`. Despite the name, it does not guarantee strictly that your code will comply to the standard.

`-pedantic`

Turn off *all* `cc`'s non-ANSI C features.

Without these flags, `cc` will allow you to use some of its non-standard extensions to the standard. Some of these are very useful, but will not work with other compilers—in fact, one of the main aims of the standard is to allow people to write code that will work with any compiler on any system. This is known as *portable code*.

Generally, you should try to make your code as portable as possible, as otherwise you may have to completely rewrite the program later to get it to work somewhere else—and who knows what you may be using in a few years time?

```
% cc -Wall -ansi -pedantic -o foobar foobar.c
```

This will produce an executable `foobar` after checking `foobar.c` for standard compliance.

`-llibrary`

Specify a function library to be used during when linking.

The most common example of this is when compiling a program that uses some of the mathematical functions in C. Unlike most other platforms, these are in a separate library from the standard C one and you have to tell the compiler to add it.

The rule is that if the library is called `libsomething.a`, you give `cc` the argument `-lsomething`. For example, the math library is `libm.a`, so you give `cc` the argument `-lm`. A common “gotcha” with the math library is that it has to be the last library on the command line.

```
% cc -o foobar foobar.c -lm
```

This will link the math library functions into `foobar`.

If you are compiling C++ code, you need to add `-lg++`, or `-lstdc++` if you are using FreeBSD 2.2 or later, to the command line argument to link the C++ library functions. Alternatively, you can run `c++` instead of `cc`, which does this for you. `c++` can also be invoked as `g++` on FreeBSD.

```
% cc -o foobar foobar.cc -lg++      For FreeBSD 2.1.6 and earlier
% cc -o foobar foobar.cc -lstdc++   For FreeBSD 2.2 and later
% c++ -o foobar foobar.cc
```

Each of these will both produce an executable `foobar` from the C++ source file `foobar.cc`. Note that, on Unix systems, C++ source files traditionally end in `.C`, `.cxx` or `.cc`, rather than the MS-DOS style `.cpp` (which was already used for something else). `gcc` used to rely on this to work out what kind of compiler to use on the source file; however, this restriction no longer applies, so you may now call your C++ files `.cpp` with impunity!



## 2.4.1 Common `cc` Queries and Problems

1. I am trying to write a program which uses the `sin()` function and I get an error like this. What does it mean?

```
/var/tmp/cc0143941.o: Undefined symbol `sin' referenced from text segment
```

When using mathematical functions like `sin()`, you have to tell `cc` to link in the math library, like so:

```
% cc -o foobar foobar.c -lm
```

2. All right, I wrote this simple program to practice using `-lm`. All it does is raise 2.1 to the power of 6.

```
#include <stdio.h>

int main() {
    float f;

    f = pow(2.1, 6);
    printf("2.1 ^ 6 = %f\n", f);
    return 0;
}
```

and I compiled it as:

```
% cc temp.c -lm
```

like you said I should, but I get this when I run it:

```
% ./a.out
2.1 ^ 6 = 1023.000000
```

This is *not* the right answer! What is going on?

When the compiler sees you call a function, it checks if it has already seen a prototype for it. If it has not, it assumes the function returns an `int`, which is definitely not what you want here.

**3. So how do I fix this?**

The prototypes for the mathematical functions are in `math.h`. If you include this file, the compiler will be able to find the prototype and it will stop doing strange things to your calculation!

```
#include <math.h>
#include <stdio.h>

int main() {
    ...
}
```

After recompiling it as you did before, run it:

```
% ./a.out
2.1 ^ 6 = 85.766121
```

If you are using any of the mathematical functions, *always* include `math.h` and remember to link in the math library.

**4. I compiled a file called `foobar.c` and I cannot find an executable called `foobar`. Where's it gone?**

Remember, `cc` will call the executable `a.out` unless you tell it differently. Use the `-o filename` option:

```
% cc -o foobar foobar.c
```

**5. OK, I have an executable called `foobar`, I can see it when I run `ls`, but when I type in `foobar` at the command prompt it tells me there is no such file. Why can it not find it?**

Unlike MS-DOS, Unix does not look in the current directory when it is trying to find out which executable you want it to run, unless you tell it to. Either type `./foobar`, which means “run the file called `foobar` in the current directory”, or change your `PATH` environment variable so that it looks something like

```
bin:/usr/bin:/usr/local/bin:.
```

The dot at the end means “look in the current directory if it is not in any of the others”.

**6. I called my executable `test`, but nothing happens when I run it. What is going on?**

Most Unix systems have a program called `test` in `/usr/bin` and the shell is picking that one up before it gets to checking the current directory. Either type:

```
% ./test
```

or choose a better name for your program!

7. I compiled my program and it seemed to run all right at first, then there was an error and it said something about `core dumped`. What does that mean?

The name *core dump* dates back to the very early days of Unix, when the machines used core memory for storing data. Basically, if the program failed under certain conditions, the system would write the contents of core memory to disk in a file called `core`, which the programmer could then pore over to find out what went wrong.

8. Fascinating stuff, but what I am supposed to do now?

Use `gdb` to analyse the core (see Section 2.6).

9. When my program dumped core, it said something about a `segmentation fault`. What is that?

This basically means that your program tried to perform some sort of illegal operation on memory; Unix is designed to protect the operating system and other programs from rogue programs.

Common causes for this are:

- Trying to write to a NULL pointer, eg

```
char *foo = NULL;
strcpy(foo, "bang!");
```

- Using a pointer that has not been initialised, eg

```
char *foo;
strcpy(foo, "bang!");
```

The pointer will have some random value that, with luck, will point into an area of memory that is not available to your program and the kernel will kill your program before it can do any damage. If you are unlucky, it will point somewhere inside your own program and corrupt one of your data structures, causing the program to fail mysteriously.

- Trying to access past the end of an array, eg

```
int bar[20];
bar[27] = 6;
```

- Trying to store something in read-only memory, eg

```
char *foo = "My string";
strcpy(foo, "bang!");
```

Unix compilers often put string literals like `"My string"` into read-only areas of memory.

- Doing naughty things with `malloc()` and `free()`, eg

```
char bar[80];
free(bar);
```

or

```
char *foo = malloc(27);
free(foo);
free(foo);
```

Making one of these mistakes will not always lead to an error, but they are always bad practice. Some systems and compilers are more tolerant than others, which is why programs that ran well on one system can crash when you try them on another.

**10.** Sometimes when I get a core dump it says `bus error`. It says in my Unix book that this means a hardware problem, but the computer still seems to be working. Is this true?

No, fortunately not (unless of course you really do have a hardware problem. . .). This is usually another way of saying that you accessed memory in a way you should not have.

**11.** This dumping core business sounds as though it could be quite useful, if I can make it happen when I want to. Can I do this, or do I have to wait until there is an error?

Yes, just go to another console or xterm, do

```
% ps
```

to find out the process ID of your program, and do

```
% kill -ABRT pid
```

where `pid` is the process ID you looked up.

This is useful if your program has got stuck in an infinite loop, for instance. If your program happens to trap `SIGABRT`, there are several other signals which have a similar effect.

Alternatively, you can create a core dump from inside your program, by calling the `abort()` function. See the man page of `abort(3)` to learn more.

If you want to create a core dump from outside your program, but do not want the process to terminate, you can use the `gcore` program. See the man page of `gcore(1)` for more information.

## 2.5 Make

### 2.5.1 What is `make`?

When you are working on a simple program with only one or two source files, typing in

```
% cc file1.c file2.c
```

is not too bad, but it quickly becomes very tedious when there are several files—and it can take a while to compile, too.

One way to get around this is to use object files and only recompile the source file if the source code has changed. So we could have something like:

```
% cc file1.o file2.o ... file37.c ...
```

if we had changed `file37.c`, but not any of the others, since the last time we compiled. This may speed up the compilation quite a bit, but does not solve the typing problem.

Or we could write a shell script to solve the typing problem, but it would have to re-compile everything, making it very inefficient on a large project.

What happens if we have hundreds of source files lying about? What if we are working in a team with other people who forget to tell us when they have changed one of their source files that we use?

Perhaps we could put the two solutions together and write something like a shell script that would contain some kind of magic rule saying when a source file needs compiling. Now all we need now is a program that can understand these rules, as it is a bit too complicated for the shell.

This program is called `make`. It reads in a file, called a *makefile*, that tells it how different files depend on each other, and works out which files need to be re-compiled and which ones do not. For example, a rule could say something like “if `fromboz.o` is older than `fromboz.c`, that means someone must have changed `fromboz.c`, so it needs to be re-compiled.” The makefile also has rules telling `make` *how* to re-compile the source file, making it a much more powerful tool.

Makefiles are typically kept in the same directory as the source they apply to, and can be called `makefile`, `Makefile` or `MAKEFILE`. Most programmers use the name `Makefile`, as this puts it near the top of a directory listing, where it can easily be seen.<sup>6</sup>

### 2.5.2 Example of using `make`

Here is a very simple make file:

```
foo: foo.c
cc -o foo foo.c
```

It consists of two lines, a dependency line and a creation line.

The dependency line here consists of the name of the program (known as the *target*), followed by a colon, then whitespace, then the name of the source file. When `make` reads this line, it looks to see if `foo` exists; if it exists, it compares the time `foo` was last modified to the time `foo.c` was last modified. If `foo` does not exist, or is older than

`foo.c`, it then looks at the creation line to find out what to do. In other words, this is the rule for working out when `foo.c` needs to be re-compiled.

The creation line starts with a tab (press the **tab** key) and then the command you would type to create `foo` if you were doing it at a command prompt. If `foo` is out of date, or does not exist, `make` then executes this command to create it. In other words, this is the rule which tells `make` how to re-compile `foo.c`.

So, when you type **make**, it will make sure that `foo` is up to date with respect to your latest changes to `foo.c`. This principle can be extended to `Makefiles` with hundreds of targets—in fact, on FreeBSD, it is possible to compile the entire operating system just by typing **make world** in the appropriate directory!

Another useful property of `makefiles` is that the targets do not have to be programs. For instance, we could have a `make` file that looks like this:

```
foo: foo.c
    cc -o foo foo.c

install:
    cp foo /home/me
```

We can tell `make` which target we want to make by typing:

```
% make target
```

`make` will then only look at that target and ignore any others. For example, if we type **make foo** with the `makefile` above, `make` will ignore the `install` target.

If we just type **make** on its own, `make` will always look at the first target and then stop without looking at any others. So if we typed **make** here, it will just go to the `foo` target, re-compile `foo` if necessary, and then stop without going on to the `install` target.

Notice that the `install` target does not actually depend on anything! This means that the command on the following line is always executed when we try to make that target by typing **make install**. In this case, it will copy `foo` into the user's home directory. This is often used by application `makefiles`, so that the application can be installed in the correct directory when it has been correctly compiled.

This is a slightly confusing subject to try to explain. If you do not quite understand how `make` works, the best thing to do is to write a simple program like “hello world” and a `make` file like the one above and experiment. Then progress to using more than one source file, or having the source file include a header file. The `touch` command is very useful here—it changes the date on a file without you having to edit it.

### 2.5.3 Make and include-files

C code often starts with a list of files to include, for example `stdio.h`. Some of these files are system-include files, some of them are from the project you are now working on:

```
#include <stdio.h>
#include "foo.h"

int main(...
```

To make sure that this file is recompiled the moment `foo.h` is changed, you have to add it in your `Makefile`:

```
foo: foo.c foo.h
```

The moment your project is getting bigger and you have more and more own include-files to maintain, it will be a pain to keep track of all include files and the files which are depending on it. If you change an include-file but forget to recompile all the files which are depending on it, the results will be devastating. `gcc` has an option to analyze your files and to produce a list of include-files and their dependencies: `-MM`.

If you add this to your Makefile:

```
depend:
  gcc -E -MM *.c > .depend
```

and run **make depend**, the file `.depend` will appear with a list of object-files, C-files and the include-files:

```
foo.o: foo.c foo.h
```

If you change `foo.h`, next time you run `make` all files depending on `foo.h` will be recompiled.

Do not forget to run `make depend` each time you add an include-file to one of your files.

## 2.5.4 FreeBSD Makefiles

Makefiles can be rather complicated to write. Fortunately, BSD-based systems like FreeBSD come with some very powerful ones as part of the system. One very good example of this is the FreeBSD ports system. Here is the essential part of a typical ports Makefile:

```
MASTER_SITES= ftp://freefall.cdrom.com/pub/FreeBSD/LOCAL_PORTS/
DISTFILES=    scheme-microcode+dist-7.3-freebsd.tgz

.include <bsd.port.mk>
```

Now, if we go to the directory for this port and type **make**, the following happens:

1. A check is made to see if the source code for this port is already on the system.
2. If it is not, an FTP connection to the URL in `MASTER_SITES` is set up to download the source.
3. The checksum for the source is calculated and compared it with one for a known, good, copy of the source. This is to make sure that the source was not corrupted while in transit.
4. Any changes required to make the source work on FreeBSD are applied—this is known as *patching*.
5. Any special configuration needed for the source is done. (Many Unix program distributions try to work out which version of Unix they are being compiled on and which optional Unix features are present—this is where they are given the information in the FreeBSD ports scenario).
6. The source code for the program is compiled. In effect, we change to the directory where the source was unpacked and do `make`—the program's own make file has the necessary information to build the program.
7. We now have a compiled version of the program. If we wish, we can test it now; when we feel confident about the program, we can type **make install**. This will cause the program and any supporting files it needs to be copied into the correct location; an entry is also made into a package database, so that the port can easily be uninstalled later if we change our mind about it.

Now I think you will agree that is rather impressive for a four line script!

The secret lies in the last line, which tells `make` to look in the system makefile called `bsd.port.mk`. It is easy to overlook this line, but this is where all the clever stuff comes from—someone has written a makefile that tells `make` to do all the things above (plus a couple of other things I did not mention, including handling any errors that may occur) and anyone can get access to that just by putting a single line in their own make file!

If you want to have a look at these system makefiles, they are in `/usr/share/mk`, but it is probably best to wait until you have had a bit of practice with makefiles, as they are very complicated (and if you do look at them, make sure you have a flask of strong coffee handy!)

## 2.5.5 More advanced uses of `make`

`Make` is a very powerful tool, and can do much more than the simple example above shows. Unfortunately, there are several different versions of `make`, and they all differ considerably. The best way to learn what they can do is probably to read the documentation—hopefully this introduction will have given you a base from which you can do this.

The version of `make` that comes with FreeBSD is the **Berkeley make**; there is a tutorial for it in `/usr/share/doc/psd/12.make`. To view it, do

```
% zmore paper.ascii.gz
```

in that directory.

Many applications in the ports use **GNU make**, which has a very good set of “info” pages. If you have installed any of these ports, **GNU make** will automatically have been installed as `gmake`. It is also available as a port and package in its own right.

To view the info pages for **GNU make**, you will have to edit the `dir` file in the `/usr/local/info` directory to add an entry for it. This involves adding a line like

```
* Make: (make). The GNU Make utility.
```

to the file. Once you have done this, you can type `info` and then select `make` from the menu (or in **Emacs**, do `C-h i`).

## 2.6 Debugging

### 2.6.1 The Debugger

The debugger that comes with FreeBSD is called `gdb` (**GNU debugger**). You start it up by typing

```
% gdb progname
```

although most people prefer to run it inside **Emacs**. You can do this by:

```
M-x gdb RET progname RET
```



Using a debugger allows you to run the program under more controlled circumstances. Typically, you can step through the program a line at a time, inspect the value of variables, change them, tell the debugger to run up to a certain point and then stop, and so on. You can even attach to a program that is already running, or load a core file to investigate why the program crashed. It is even possible to debug the kernel, though that is a little trickier than the user applications we will be discussing in this section.

`gdb` has quite good on-line help, as well as a set of info pages, so this section will concentrate on a few of the basic commands.

Finally, if you find its text-based command-prompt style off-putting, there is a graphical front-end for it (`xxgdb` (`../../ports/devel.html`)) in the ports collection.

This section is intended to be an introduction to using `gdb` and does not cover specialised topics such as debugging the kernel.

## 2.6.2 Running a program in the debugger

You will need to have compiled the program with the `-g` option to get the most out of using `gdb`. It will work without, but you will only see the name of the function you are in, instead of the source code. If you see a line like:

```
... (no debugging symbols found) ...
```

when `gdb` starts up, you will know that the program was not compiled with the `-g` option.

At the `gdb` prompt, type **break main**. This will tell the debugger to skip over the preliminary set-up code in the program and start at the beginning of your code. Now type **run** to start the program—it will start at the beginning of the set-up code and then get stopped by the debugger when it calls `main()`. (If you have ever wondered where `main()` gets called from, now you know!).

You can now step through the program, a line at a time, by pressing `n`. If you get to a function call, you can step into it by pressing `s`. Once you are in a function call, you can return from stepping into a function call by pressing `f`. You can also use `up` and `down` to take a quick look at the caller.

Here is a simple example of how to spot a mistake in a program with `gdb`. This is our program (with a deliberate mistake):

```
#include <stdio.h>

int bazz(int anint);

main() {
    int i;

    printf("This is my program\n");
    bazz(i);
    return 0;
}

int bazz(int anint) {
    printf("You gave me %d\n", anint);
    return anint;
}
```

This program sets `i` to be 5 and passes it to a function `bazz()` which prints out the number we gave it.

When we compile and run the program we get

```
% cc -g -o temp temp.c
% ./temp
This is my program
anint = 4231
```

That was not what we expected! Time to see what is going on!

```
% gdb temp
GDB is free software and you are welcome to distribute copies of it
under certain conditions; type "show copying" to see the conditions.
There is absolutely no warranty for GDB; type "show warranty" for details.
GDB 4.13 (i386-unknown-freebsd), Copyright 1994 Free Software Foundation, Inc.
(gdb) break main Skip the set-up code
Breakpoint 1 at 0x160f: file temp.c, line 9. gdb puts breakpoint at main()
(gdb) run Run as far as main()
Starting program: /home/james/tmp/temp Program starts running

Breakpoint 1, main () at temp.c:9 gdb stops at main()
(gdb) n Go to next line
This is my program Program prints out
(gdb) s step into bazz()
bazz (anint=4231) at temp.c:17 gdb displays stack frame
(gdb)
```

Hang on a minute! How did `anint` get to be 4231? Did we not we set it to be 5 in `main()`? Let's move up to `main()` and have a look.

```
(gdb) up Move up call stack
#1 0x1625 in main () at temp.c:11 gdb displays stack frame
(gdb) p i Show us the value of i
$1 = 4231 gdb displays 4231
```

Oh dear! Looking at the code, we forgot to initialise `i`. We meant to put

```
...
main() {
    int i;

    i = 5;
    printf("This is my program\n");
    ...
```

but we left the `i=5;` line out. As we did not initialise `i`, it had whatever number happened to be in that area of memory when the program ran, which in this case happened to be 4231.

**Note:** `gdb` displays the stack frame every time we go into or out of a function, even if we are using `up` and `down` to move around the call stack. This shows the name of the function and the values of its arguments, which helps us keep track of where we are and what is going on. (The stack is a storage area where the program stores information about the arguments passed to functions and where to go when it returns from a function call).

## 2.6.3 Examining a core file

A core file is basically a file which contains the complete state of the process when it crashed. In “the good old days”, programmers had to print out hex listings of core files and sweat over machine code manuals, but now life is a bit easier. Incidentally, under FreeBSD and other 4.4BSD systems, a core file is called *progname.core* instead of just *core*, to make it clearer which program a core file belongs to.

To examine a core file, start up `gdb` in the usual way. Instead of typing `break` or `run`, type

```
(gdb) core progname.core
```

If you are not in the same directory as the core file, you will have to do `dir /path/to/core/file` first.

You should see something like this:

```
% gdb a.out
GDB is free software and you are welcome to distribute copies of it
under certain conditions; type "show copying" to see the conditions.
There is absolutely no warranty for GDB; type "show warranty" for details.
GDB 4.13 (i386-unknown-freebsd), Copyright 1994 Free Software Foundation, Inc.
(gdb) core a.out.core
Core was generated by `a.out`.
Program terminated with signal 11, Segmentation fault.
Cannot access memory at address 0x7020796d.
#0  0x164a in bazz (anint=0x5) at temp.c:17
(gdb)
```

In this case, the program was called `a.out`, so the core file is called `a.out.core`. We can see that the program crashed due to trying to access an area in memory that was not available to it in a function called `bazz`.

Sometimes it is useful to be able to see how a function was called, as the problem could have occurred a long way up the call stack in a complex program. The `bt` command causes `gdb` to print out a back-trace of the call stack:

```
(gdb) bt
#0  0x164a in bazz (anint=0x5) at temp.c:17
#1  0xefbfd888 in end ()
#2  0x162c in main () at temp.c:11
(gdb)
```

The `end()` function is called when a program crashes; in this case, the `bazz()` function was called from `main()`.

## 2.6.4 Attaching to a running program

One of the neatest features about `gdb` is that it can attach to a program that is already running. Of course, that assumes you have sufficient permissions to do so. A common problem is when you are stepping through a program that forks, and you want to trace the child, but the debugger will only let you trace the parent.

What you do is start up another `gdb`, use `ps` to find the process ID for the child, and do

```
(gdb) attach pid
```

in `gdb`, and then debug as usual.

“That is all very well,” you are probably thinking, “but by the time I have done that, the child process will be over the hill and far away”. Fear not, gentle reader, here is how to do it (courtesy of the `gdb` info pages):

```
...
if ((pid = fork()) < 0) /* _Always_ check this */
    error();
else if (pid == 0) { /* child */
    int PauseMode = 1;

    while (PauseMode)
        sleep(10); /* Wait until someone attaches to us */
    ...
} else { /* parent */
    ...
}
```

Now all you have to do is attach to the child, set `PauseMode` to 0, and wait for the `sleep()` call to return!

## 2.7 Using Emacs as a Development Environment

### 2.7.1 Emacs

Unfortunately, Unix systems do not come with the kind of everything-you-ever-wanted-and-lots-more-you-did-not-in-one-gigantic-package integrated development environments that other systems have.<sup>7</sup> However, it is possible to set up your own environment. It may not be as pretty, and it may not be quite as integrated, but you can set it up the way you want it. And it is free. And you have the source to it.

The key to it all is Emacs. Now there are some people who loathe it, but many who love it. If you are one of the former, I am afraid this section will hold little of interest to you. Also, you will need a fair amount of memory to run it—I would recommend 8MB in text mode and 16MB in X as the bare minimum to get reasonable performance.

Emacs is basically a highly customisable editor—indeed, it has been customised to the point where it is more like an operating system than an editor! Many developers and sysadmins do in fact spend practically all their time working inside Emacs, leaving it only to log out.

It is impossible even to summarise everything Emacs can do here, but here are some of the features of interest to developers:

- Very powerful editor, allowing search-and-replace on both strings and regular expressions (patterns), jumping to start/end of block expression, etc, etc.
- Pull-down menus and online help.
- Language-dependent syntax highlighting and indentation.
- Completely customisable.

- You can compile and debug programs within Emacs.
- On a compilation error, you can jump to the offending line of source code.
- Friendly-ish front-end to the `info` program used for reading GNU hypertext documentation, including the documentation on Emacs itself.
- Friendly front-end to `gdb`, allowing you to look at the source code as you step through your program.
- You can read Usenet news and mail while your program is compiling.

And doubtless many more that I have overlooked.

Emacs can be installed on FreeBSD using the Emacs port ([../ports/editors.html](http://ports/editors.html)).

Once it is installed, start it up and do **C-h t** to read an Emacs tutorial—that means hold down the **control** key, press **h**, let go of the **control** key, and then press **t**. (Alternatively, you can use the mouse to select Emacs Tutorial from the Help menu).

Although Emacs does have menus, it is well worth learning the key bindings, as it is much quicker when you are editing something to press a couple of keys than to try and find the mouse and then click on the right place. And, when you are talking to seasoned Emacs users, you will find they often casually throw around expressions like “`M-x replace-s RET foo RET bar RET`” so it is useful to know what they mean. And in any case, Emacs has far too many useful functions for them to all fit on the menu bars.

Fortunately, it is quite easy to pick up the key-bindings, as they are displayed next to the menu item. My advice is to use the menu item for, say, opening a file until you understand how it works and feel confident with it, then try doing `C-x C-f`. When you are happy with that, move on to another menu command.

If you can not remember what a particular combination of keys does, select **Describe Key** from the Help menu and type it in—Emacs will tell you what it does. You can also use the **Command Apropos** menu item to find out all the commands which contain a particular word in them, with the key binding next to it.

By the way, the expression above means hold down the Meta key, press `x`, release the Meta key, type `replace-s` (short for `replace-string`—another feature of Emacs is that you can abbreviate commands), press the return key, type `foo` (the string you want replaced), press the return key, type `bar` (the string you want to replace `foo` with) and press return again. Emacs will then do the search-and-replace operation you have just requested.

If you are wondering what on earth the Meta key is, it is a special key that many Unix workstations have. Unfortunately, PC's do not have one, so it is usually the **alt** key (or if you are unlucky, the escape key).

Oh, and to get out of Emacs, do `C-x C-c` (that means hold down the control key, press `x`, press `c` and release the control key). If you have any unsaved files open, Emacs will ask you if you want to save them. (Ignore the bit in the documentation where it says `C-z` is the usual way to leave Emacs—that leaves Emacs hanging around in the background, and is only really useful if you are on a system which does not have virtual terminals).

## 2.7.2 Configuring Emacs

Emacs does many wonderful things; some of them are built in, some of them need to be configured.

Instead of using a proprietary macro language for configuration, Emacs uses a version of Lisp specially adapted for editors, known as Emacs Lisp. This can be quite useful if you want to go on and learn something like Common Lisp, as it is considerably smaller than Common Lisp (although still quite big!).

The best way to learn Emacs Lisp is to download the Emacs Tutorial ([ftp://ftp.gnu.org/old-gnu/emacs/elisp-manual-19-2.4.tar.gz](http://ftp.gnu.org/old-gnu/emacs/elisp-manual-19-2.4.tar.gz))

However, there is no need to actually know any Lisp to get started with configuring Emacs, as I have included a sample `.emacs` file, which should be enough to get you started. Just copy it into your home directory and restart Emacs if it is already running; it will read the commands from the file and (hopefully) give you a useful basic setup.

### 2.7.3 A sample `.emacs` file

Unfortunately, there is far too much here to explain it in detail; however there are one or two points worth mentioning.

- Everything beginning with a `;` is a comment and is ignored by Emacs.
- In the first line, the `-- Emacs-Lisp --` is so that we can edit the `.emacs` file itself within Emacs and get all the fancy features for editing Emacs Lisp. Emacs usually tries to guess this based on the filename, and may not get it right for `.emacs`.
- The tab key is bound to an indentation function in some modes, so when you press the tab key, it will indent the current line of code. If you want to put a tab character in whatever you are writing, hold the control key down while you are pressing the tab key.
- This file supports syntax highlighting for C, C++, Perl, Lisp and Scheme, by guessing the language from the filename.
- Emacs already has a pre-defined function called `next-error`. In a compilation output window, this allows you to move from one compilation error to the next by doing `M-n`; we define a complementary function, `previous-error`, that allows you to go to a previous error by doing `M-p`. The nicest feature of all is that `C-c C-c` will open up the source file in which the error occurred and jump to the appropriate line.
- We enable Emacs's ability to act as a server, so that if you are doing something outside Emacs and you want to edit a file, you can just type in

```
% emacsclient filename
```

and then you can edit the file in your Emacs! <sup>8</sup>

#### Example 2-1. A sample `.emacs` file

```
;; --Emacs-Lisp--

;; This file is designed to be re-evald; use the variable first-time
;; to avoid any problems with this.
(defvar first-time t
  "Flag signifying this is the first time that .emacs has been evald")

;; Meta
(global-set-key "\M- " 'set-mark-command)
(global-set-key "\M-\C-h" 'backward-kill-word)
(global-set-key "\M-\C-r" 'query-replace)
(global-set-key "\M-r" 'replace-string)
(global-set-key "\M-g" 'goto-line)
(global-set-key "\M-h" 'help-command)
```

```

;; Function keys
(global-set-key [f1] 'manual-entry)
(global-set-key [f2] 'info)
(global-set-key [f3] 'repeat-complex-command)
(global-set-key [f4] 'advertised-undo)
(global-set-key [f5] 'eval-current-buffer)
(global-set-key [f6] 'buffer-menu)
(global-set-key [f7] 'other-window)
(global-set-key [f8] 'find-file)
(global-set-key [f9] 'save-buffer)
(global-set-key [f10] 'next-error)
(global-set-key [f11] 'compile)
(global-set-key [f12] 'grep)
(global-set-key [C-f1] 'compile)
(global-set-key [C-f2] 'grep)
(global-set-key [C-f3] 'next-error)
(global-set-key [C-f4] 'previous-error)
(global-set-key [C-f5] 'display-faces)
(global-set-key [C-f8] 'dired)
(global-set-key [C-f10] 'kill-compilation)

;; Keypad bindings
(global-set-key [up] "\C-p")
(global-set-key [down] "\C-n")
(global-set-key [left] "\C-b")
(global-set-key [right] "\C-f")
(global-set-key [home] "\C-a")
(global-set-key [end] "\C-e")
(global-set-key [prior] "\M-v")
(global-set-key [next] "\C-v")
(global-set-key [C-up] "\M-\C-b")
(global-set-key [C-down] "\M-\C-f")
(global-set-key [C-left] "\M-b")
(global-set-key [C-right] "\M-f")
(global-set-key [C-home] "\M-<")
(global-set-key [C-end] "\M->")
(global-set-key [C-prior] "\M-<")
(global-set-key [C-next] "\M->")

;; Mouse
(global-set-key [mouse-3] 'imenu)

;; Misc
(global-set-key [C-tab] "\C-q\t") ; Control tab quotes a tab.
(setq backup-by-copying-when-mismatch t)

;; Treat 'y' or <CR> as yes, 'n' as no.
(fset 'yes-or-no-p 'y-or-n-p)
(define-key query-replace-map [return] 'act)
(define-key query-replace-map [?\C-m] 'act)

;; Load packages

```

```

(require 'desktop)
(require 'tar-mode)

;; Pretty diff mode
(autoload 'ediff-buffers "ediff" "Intelligent Emacs interface to diff" t)
(autoload 'ediff-files "ediff" "Intelligent Emacs interface to diff" t)
(autoload 'ediff-files-remote "ediff"
  "Intelligent Emacs interface to diff")

(if first-time
  (setq auto-mode-alist
    (append '(("\\.cpp$" . c++-mode)
              ("\\.hpp$" . c++-mode)
              ("\\.lsp$" . lisp-mode)
              ("\\.scm$" . scheme-mode)
              ("\\.pl$" . perl-mode)
              ) auto-mode-alist)))

;; Auto font lock mode
(defvar font-lock-auto-mode-list
  (list 'c-mode 'c++-mode 'c++-c-mode 'emacs-lisp-mode 'lisp-mode 'perl-mode 'scheme-
mode)
  "List of modes to always start in font-lock-mode")

(defvar font-lock-mode-keyword-alist
  '((c++-c-mode . c-font-lock-keywords)
    (perl-mode . perl-font-lock-keywords))
  "Associations between modes and keywords")

(defun font-lock-auto-mode-select ()
  "Automatically select font-lock-mode if the current major mode is
in font-lock-auto-mode-list"
  (if (memq major-mode font-lock-auto-mode-list)
      (progn
        (font-lock-mode t))
      )
  )

(global-set-key [M-f1] 'font-lock-fontify-buffer)

;; New dabbrev stuff
(require 'new-dabbrev)
(setq dabbrev-always-check-other-buffers t)
(setq dabbrev-abbrev-char-regexp "\\sw\\|\\s_")
(add-hook 'emacs-lisp-mode-hook
  '(lambda ()
    (set (make-local-variable 'dabbrev-case-fold-search) nil)
    (set (make-local-variable 'dabbrev-case-replace) nil)))
(add-hook 'c-mode-hook
  '(lambda ()
    (set (make-local-variable 'dabbrev-case-fold-search) nil)
    (set (make-local-variable 'dabbrev-case-replace) nil)))
(add-hook 'text-mode-hook

```



```

(lambda ()
  (set (make-local-variable 'dabbrev-case-fold-search) t)
  (set (make-local-variable 'dabbrev-case-replace) t)))

;; C++ and C mode...
(defun my-c++-mode-hook ()
  (setq tab-width 4)
  (define-key c++-mode-map "\C-m" 'reindent-then-newline-and-indent)
  (define-key c++-mode-map "\C-ce" 'c-comment-edit)
  (setq c++-auto-hungry-initial-state 'none)
  (setq c++-delete-function 'backward-delete-char)
  (setq c++-tab-always-indent t)
  (setq c-indent-level 4)
  (setq c-continued-statement-offset 4)
  (setq c++-empty-arglist-indent 4))

(defun my-c-mode-hook ()
  (setq tab-width 4)
  (define-key c-mode-map "\C-m" 'reindent-then-newline-and-indent)
  (define-key c-mode-map "\C-ce" 'c-comment-edit)
  (setq c-auto-hungry-initial-state 'none)
  (setq c-delete-function 'backward-delete-char)
  (setq c-tab-always-indent t)
  ;; BSD-ish indentation style
  (setq c-indent-level 4)
  (setq c-continued-statement-offset 4)
  (setq c-brace-offset -4)
  (setq c-argdecl-indent 0)
  (setq c-label-offset -4))

;; Perl mode
(defun my-perl-mode-hook ()
  (setq tab-width 4)
  (define-key c++-mode-map "\C-m" 'reindent-then-newline-and-indent)
  (setq perl-indent-level 4)
  (setq perl-continued-statement-offset 4))

;; Scheme mode...
(defun my-scheme-mode-hook ()
  (define-key scheme-mode-map "\C-m" 'reindent-then-newline-and-indent))

;; Emacs-Lisp mode...
(defun my-lisp-mode-hook ()
  (define-key lisp-mode-map "\C-m" 'reindent-then-newline-and-indent)
  (define-key lisp-mode-map "\C-i" 'lisp-indent-line)
  (define-key lisp-mode-map "\C-j" 'eval-print-last-sexp))

;; Add all of the hooks...
(add-hook 'c++-mode-hook 'my-c++-mode-hook)
(add-hook 'c-mode-hook 'my-c-mode-hook)
(add-hook 'scheme-mode-hook 'my-scheme-mode-hook)
(add-hook 'emacs-lisp-mode-hook 'my-lisp-mode-hook)
(add-hook 'lisp-mode-hook 'my-lisp-mode-hook)

```

```

(add-hook 'perl-mode-hook 'my-perl-mode-hook)

;; Complement to next-error
(defun previous-error (n)
  "Visit previous compilation error message and corresponding source code."
  (interactive "p")
  (next-error (- n)))

;; Misc...
(transient-mark-mode 1)
(setq mark-even-if-inactive t)
(setq visible-bell nil)
(setq next-line-add-newlines nil)
(setq compile-command "make")
(setq suggest-key-bindings nil)
(put 'eval-expression 'disabled nil)
(put 'narrow-to-region 'disabled nil)
(put 'set-goal-column 'disabled nil)

;; Elisp archive searching
(autoload 'format-lisp-code-directory "lispdir" nil t)
(autoload 'lisp-dir-apropos "lispdir" nil t)
(autoload 'lisp-dir-retrieve "lispdir" nil t)
(autoload 'lisp-dir-verify "lispdir" nil t)

;; Font lock mode
(defun my-make-face (face colour &optional bold)
  "Create a face from a colour and optionally make it bold"
  (make-face face)
  (copy-face 'default face)
  (set-face-foreground face colour)
  (if bold (make-face-bold face))
  )

(if (eq window-system 'x)
    (progn
      (my-make-face 'blue "blue")
      (my-make-face 'red "red")
      (my-make-face 'green "dark green")
      (setq font-lock-comment-face 'blue)
      (setq font-lock-string-face 'bold)
      (setq font-lock-type-face 'bold)
      (setq font-lock-keyword-face 'bold)
      (setq font-lock-function-name-face 'red)
      (setq font-lock-doc-string-face 'green)
      (add-hook 'find-file-hooks 'font-lock-auto-mode-select)

      (setq baud-rate 1000000)
      (global-set-key "\C-cmm" 'menu-bar-mode)
      (global-set-key "\C-cms" 'scroll-bar-mode)
      (global-set-key [backspace] 'backward-delete-char)
      ; (global-set-key [delete] 'delete-char)
      (standard-display-european t)
    )
  )

```

```

    (load-library "iso-transl"))))

;; X11 or PC using direct screen writes
(if window-system
  (progn
    ;;      (global-set-key [M-f1] 'hilit-repaint-command)
    ;;      (global-set-key [M-f2] [?\C-u M-f1])
    (setq hilit-mode-enable-list
      '(not text-mode c-mode c++-mode emacs-lisp-mode lisp-mode
        scheme-mode)
      hilit-auto-highlight nil
      hilit-auto-rehighlight 'visible
      hilit-inhibit-hooks nil
      hilit-inhibit-rebinding t)
      (require 'hilit19)
      (require 'paren))
    (setq baud-rate 2400) ; For slow serial connections
  )

;; TTY type terminal
(if (and (not window-system)
  (not (equal system-type 'ms-dos)))
  (progn
    (if first-time
      (progn
        (keyboard-translate ?\C-h ?\C-?)
        (keyboard-translate ?\C-? ?\C-h))))))

;; Under UNIX
(if (not (equal system-type 'ms-dos))
  (progn
    (if first-time
      (server-start))))

;; Add any face changes here
(add-hook 'term-setup-hook 'my-term-setup-hook)
(defun my-term-setup-hook ()
  (if (eq window-system 'pc)
    (progn
      ;; (set-face-background 'default "red")
    )))

;; Restore the "desktop" - do this as late as possible
(if first-time
  (progn
    (desktop-load-default)
    (desktop-read)))

;; Indicate that this file has been read at least once
(setq first-time nil)

;; No need to debug anything now

```

```
(setq debug-on-error nil)

;; All done
(message "All done, %s%s" (user-login-name) ".")
```

## 2.7.4 Extending the Range of Languages Emacs Understands

Now, this is all very well if you only want to program in the languages already catered for in the `.emacs` file (C, C++, Perl, Lisp and Scheme), but what happens if a new language called “whizbang” comes out, full of exciting features?

The first thing to do is find out if whizbang comes with any files that tell Emacs about the language. These usually end in `.el`, short for “Emacs Lisp”. For example, if whizbang is a FreeBSD port, we can locate these files by doing

```
% find /usr/ports/lang/whizbang -name "*.el" -print
```

and install them by copying them into the Emacs site Lisp directory. On FreeBSD 2.1.0-RELEASE, this is `/usr/local/share/emacs/site-lisp`.

So for example, if the output from the `find` command was

```
/usr/ports/lang/whizbang/work/misc/whizbang.el
```

we would do

```
# cp /usr/ports/lang/whizbang/work/misc/whizbang.el /usr/local/share/emacs/site-lisp
```

Next, we need to decide what extension whizbang source files have. Let’s say for the sake of argument that they all end in `.wiz`. We need to add an entry to our `.emacs` file to make sure Emacs will be able to use the information in `whizbang.el`.

Find the `auto-mode-alist` entry in `.emacs` and add a line for whizbang, such as:

```
...
("\\.lsp$" . lisp-mode)
("\\.wiz$" . whizbang-mode)
("\\.scm$" . scheme-mode)
...
```

This means that Emacs will automatically go into `whizbang-mode` when you edit a file ending in `.wiz`.

Just below this, you will find the `font-lock-auto-mode-list` entry. Add `whizbang-mode` to it like so:

```
;; Auto font lock mode
(defvar font-lock-auto-mode-list
  (list 'c-mode 'c++-mode 'c++-c-mode 'emacs-lisp-mode 'whizbang-mode 'lisp-mode 'perl-
mode 'scheme-mode)
  "List of modes to always start in font-lock-mode")
```

This means that Emacs will always enable `font-lock-mode` (ie syntax highlighting) when editing a `.wiz` file.

And that is all that is needed. If there is anything else you want done automatically when you open up a `.wiz` file, you can add a `whizbang-mode` hook (see `my-scheme-mode-hook` for a simple example that adds `auto-indent`).

## 2.8 Further Reading

- Brian Harvey and Matthew Wright *Simply Scheme* MIT 1994. ISBN 0-262-08226-8
- Randall Schwartz *Learning Perl* O'Reilly 1993 ISBN 1-56592-042-2
- Patrick Henry Winston and Berthold Klaus Paul Horn *Lisp (3rd Edition)* Addison-Wesley 1989 ISBN 0-201-08319-1
- Brian W. Kernighan and Rob Pike *The Unix Programming Environment* Prentice-Hall 1984 ISBN 0-13-937681-X
- Brian W. Kernighan and Dennis M. Ritchie *The C Programming Language (2nd Edition)* Prentice-Hall 1988 ISBN 0-13-110362-8
- Bjarne Stroustrup *The C++ Programming Language* Addison-Wesley 1991 ISBN 0-201-53992-6
- W. Richard Stevens *Advanced Programming in the Unix Environment* Addison-Wesley 1992 ISBN 0-201-56317-7
- W. Richard Stevens *Unix Network Programming* Prentice-Hall 1990 ISBN 0-13-949876-1

## Notes

1. If you run it in the shell, you may get a core dump.
2. To be strictly accurate, `cc` converts the source code into its own, machine-independent *p-code* instead of assembly language at this stage.
3. In case you did not know, a binary sort is an efficient way of sorting things into order and a bubble sort is not.
4. The reasons for this are buried in the mists of history.
5. Note, we did not use the `-o` flag to specify the executable name, so we will get an executable called `a.out`. Producing a debug version called `foobar` is left as an exercise for the reader!
6. They do not use the `MAKEFILE` form as block capitals are often used for documentation files like `README`.
7. Some powerful, free IDEs now exist, such as `KDevelop` in the ports collection.
8. Many Emacs users set their `EDITOR` environment to `emacsclient` so this happens every time they need to edit a file.

# Chapter 3 Secure Programming

This chapter was written by Murray Stokely <murray@FreeBSD.org>.

## 3.1 Synopsis

This chapter describes some of the security issues that have plagued Unix programmers for decades and some of the new tools available to help programmers avoid writing exploitable code.

## 3.2 Secure Design Methodology

Writing secure applications takes a very scrutinous and pessimistic outlook on life. Applications should be run with the principle of “least privilege” so that no process is ever running with more than the bare minimum access that it needs to accomplish its function. Previously tested code should be reused whenever possible to avoid common mistakes that others may have already fixed.

One of the pitfalls of the Unix environment is how easy it is to make assumptions about the sanity of the environment. Applications should never trust user input (in all its forms), system resources, inter-process communication, or the timing of events. Unix processes do not execute synchronously so logical operations are rarely atomic.

## 3.3 Buffer Overflows

Buffer Overflows have been around since the very beginnings of the Von-Neuman 1 architecture. They first gained widespread notoriety in 1988 with the Morris Internet worm. Unfortunately, the same basic attack remains effective today. Of the 17 CERT security advisories of 1999, 10 of them were directly caused by buffer-overflow software bugs. By far the most common type of buffer overflow attack is based on corrupting the stack.

Most modern computer systems use a stack to pass arguments to procedures and to store local variables. A stack is a last in first out (LIFO) buffer in the high memory area of a process image. When a program invokes a function a new "stack frame" is created. This stack frame consists of the arguments passed to the function as well as a dynamic amount of local variable space. The "stack pointer" is a register that holds the current location of the top of the stack. Since this value is constantly changing as new values are pushed onto the top of the stack, many implementations also provide a "frame pointer" that is located near the beginning of a stack frame so that local variables can more easily be addressed relative to this value. 1 The return address for function calls is also stored on the stack, and this is the cause of stack-overflow exploits since overflowing a local variable in a function can overwrite the return address of that function, potentially allowing a malicious user to execute any code he or she wants.

Although stack-based attacks are by far the most common, it would also be possible to overrun the stack with a heap-based (malloc/free) attack.

The C programming language does not perform automatic bounds checking on arrays or pointers as many other languages do. In addition, the standard C library is filled with a handful of very dangerous functions.

<code>strcpy(char *dest, const char *src)</code>	May overflow the dest buffer
<code>strcat(char *dest, const char *src)</code>	May overflow the dest buffer

<code>getwd(char *buf)</code>	May overflow the buf buffer
<code>gets(char *s)</code>	May overflow the s buffer
<code>[v]scanf(const char *format, ...)</code>	May overflow its arguments.
<code>realpath(char *path, char resolved_path[])</code>	May overflow the path buffer
<code>[v]sprintf(char *str, const char *format, ...)</code>	May overflow the str buffer.

### 3.3.1 Example Buffer Overflow

The following example code contains a buffer overflow designed to overwrite the return address and skip the instruction immediately following the function call. (Inspired by 4)

```
#include <stdio.h>

void manipulate(char *buffer) {
    char newbuffer[80];
    strcpy(newbuffer,buffer);
}

int main() {
    char ch,buffer[4096];
    int i=0;

    while ((buffer[i++] = getchar()) != '\n') {};

    i=1;
    manipulate(buffer);
    i=2;
    printf("The value of i is : %d\n",i);
    return 0;
}
```

Let us examine what the memory image of this process would look like if we were to input 160 spaces into our little program before hitting return.

[XXX figure here!]

Obviously more malicious input can be devised to execute actual compiled instructions (such as `exec(/bin/sh)`).

### 3.3.2 Avoiding Buffer Overflows

The most straightforward solution to the problem of stack-overflows is to always use length restricted memory and string copy functions. `strncpy` and `strncat` are part of the standard C library. These functions accept a length value as a parameter which should be no larger than the size of the destination buffer. These functions will then copy up to 'length' bytes from the source to the destination. However there are a number of problems with these functions. Neither function guarantees NUL termination if the size of the input buffer is as large as the destination. The length parameter is also used inconsistently between `strncpy` and `strncat` so it is easy for programmers to get confused as to their proper usage. There is also a significant performance loss compared to `strcpy` when copying a short string into a large buffer since `strncpy` NUL fills up the size specified.

In OpenBSD, another memory copy implementation has been created to get around these problem. The `strncpy` and `strlcat` functions guarantee that they will always null terminate the destination string when given a non-zero length argument. For more information about these functions see 6. The OpenBSD `strncpy` and `strlcat` instructions have been in FreeBSD since 3.3.

### 3.3.2.1 Compiler based run-time bounds checking

Unfortunately there is still a very large assortment of code in public use which blindly copies memory around without using any of the bounded copy routines we just discussed. Fortunately, there is another solution. Several compiler add-ons and libraries exist to do Run-time bounds checking in C/C++.

StackGuard is one such add-on that is implemented as a small patch to the gcc code generator. From the StackGuard website (<http://immunix.org/stackguard.html>):

"StackGuard detects and defeats stack smashing attacks by protecting the return address on the stack from being altered. StackGuard places a "canary" word next to the return address when a function is called. If the canary word has been altered when the function returns, then a stack smashing attack has been attempted, and the program responds by emitting an intruder alert into syslog, and then halts."

"StackGuard is implemented as a small patch to the gcc code generator, specifically the `function_prolog()` and `function_epilog()` routines. `function_prolog()` has been enhanced to lay down canaries on the stack when functions start, and `function_epilog()` checks canary integrity when the function exits. Any attempt at corrupting the return address is thus detected before the function returns."

Recompiling your application with StackGuard is an effective means of stopping most buffer-overflow attacks, but it can still be compromised.

### 3.3.2.2 Library based run-time bounds checking

Compiler-based mechanisms are completely useless for binary-only software for which you cannot recompile. For these situations there are a number of libraries which re-implement the unsafe functions of the C-library (`strcpy`, `fscanf`, `getwd`, etc..) and ensure that these functions can never write past the stack pointer.

- `libsafe`
- `libverify`
- `libparnoia`

Unfortunately these library-based defenses have a number of shortcomings. These libraries only protect against a very small set of security related issues and they neglect to fix the actual problem. These defenses may fail if the application was compiled with `-fomit-frame-pointer`. Also, the `LD_PRELOAD` and `LD_LIBRARY_PATH` environment variables can be overwritten/unset by the user.



## 3.4 SetUID issues

There are at least 6 different IDs associated with any given process. Because of this you have to be very careful with the access that your process has at any given time. In particular, all seteuid applications should give up their privileges as soon as it is no longer required.

The real user ID can only be changed by a superuser process. The **login** program sets this when a user initially logs in and it is seldom changed.

The effective user ID is set by the `exec()` functions if a program has its seteuid bit set. An application can call `seteuid()` at any time to set the effective user ID to either the real user ID or the saved set-user-ID. When the effective user ID is set by `exec()` functions, the previous value is saved in the saved set-user-ID.

## 3.5 Limiting your program's environment

The traditional method of restricting a process is with the `chroot()` system call. This system call changes the root directory from which all other paths are referenced for a process and any child processes. For this call to succeed the process must have execute (search) permission on the directory being referenced. The new environment does not actually take effect until you `chdir()` into your new environment. It should also be noted that a process can easily break out of a chroot environment if it has root privilege. This could be accomplished by creating device nodes to read kernel memory, attaching a debugger to a process outside of the jail, or in many other creative ways.

The behavior of the `chroot()` system call can be controlled somewhat with the `kern.chroot_allow_open_directories` `sysctl` variable. When this value is set to 0, `chroot()` will fail with `EPERM` if there are any directories open. If set to the default value of 1, then `chroot()` will fail with `EPERM` if there are any directories open and the process is already subject to a `chroot()` call. For any other value, the check for open directories will be bypassed completely.

### 3.5.1 FreeBSD's jail functionality

The concept of a Jail extends upon the `chroot()` by limiting the powers of the superuser to create a true 'virtual server'. Once a prison is setup all network communication must take place through the specified IP address, and the power of "root privilege" in this jail is severely constrained.

While in a prison, any tests of superuser power within the kernel using the `suser()` call will fail. However, some calls to `suser()` have been changed to a new interface `suser_xxx()`. This function is responsible for recognizing or denying access to superuser power for imprisoned processes.

A superuser process within a jailed environment has the power to:

- Manipulate credential with `setuid`, `seteuid`, `setgid`, `setegid`, `setgroups`, `setreuid`, `setregid`, `setlogin`
- Set resource limits with `setrlimit`
- Modify some `sysctl` nodes (`kern.hostname`)
- `chroot()`
- Set flags on a vnode: `chflags`, `fchflags`
- Set attributes of a vnode such as file permission, owner, group, size, access time, and modification time.

- Bind to privileged ports in the Internet domain (ports < 1024)

`Jail` is a very useful tool for running applications in a secure environment but it does have some shortcomings. Currently, the IPC mechanisms have not been converted to the `suser_xxx` so applications such as MySQL cannot be run within a jail. Superuser access may have a very limited meaning within a jail, but there is no way to specify exactly what "very limited" means.

## 3.5.2 POSIX.1e Process Capabilities

Posix has released a working draft that adds event auditing, access control lists, fine grained privileges, information labeling, and mandatory access control.

This is a work in progress and is the focus of the TrustedBSD (<http://www.trustedbsd.org/>) project. Some of the initial work has been committed to FreeBSD-current (`cap_set_proc(3)`).

## 3.6 Trust

An application should never assume that anything about the users environment is sane. This includes (but is certainly not limited to): user input, signals, environment variables, resources, IPC, mmap, the filesystem working directory, file descriptors, the # of open files, etc.

You should never assume that you can catch all forms of invalid input that a user might supply. Instead, your application should use positive filtering to only allow a specific subset of inputs that you deem safe. Improper data validation has been the cause of many exploits, especially with CGI scripts on the world wide web. For filenames you need to be extra careful about paths (`"/"`, `"/"`), symbolic links, and shell escape characters.

Perl has a really cool feature called "Taint" mode which can be used to prevent scripts from using data derived outside the program in an unsafe way. This mode will check command line arguments, environment variables, locale information, the results of certain syscalls (`readdir()`, `readlink()`, `getpwxxx()`, and all file input).

## 3.7 Race Conditions

A race condition is anomalous behavior caused by the unexpected dependence on the relative timing of events. In other words, a programmer incorrectly assumed that a particular event would always happen before another.

Some of the common causes of race conditions are signals, access checks, and file opens. Signals are asynchronous events by nature so special care must be taken in dealing with them. Checking access with `access(2)` then `open(2)` is clearly non-atomic. Users can move files in between the two calls. Instead, privileged applications should `seteuid()` and then call `open()` directly. Along the same lines, an application should always set a proper `umask` before `open()` to obviate the need for spurious `chmod()` calls.

# Chapter 4 Localization and Internationalization

## - L10N and I18N

### 4.1 Programming I18N Compliant Applications

To make your application more useful for speakers of other languages, we hope that you will program I18N compliant. The GNU gcc compiler and GUI libraries like QT and GTK support I18N through special handling of strings. Making a program I18N compliant is very easy. It allows contributors to port your application to other languages quickly. Refer to the library specific I18N documentation for more details.

In contrast with common perception, I18N compliant code is easy to write. Usually, it only involves wrapping your strings with library specific functions. In addition, please be sure to allow for wide or multibyte character support.

#### 4.1.1 A Call to Unify the I18N Effort

It has come to our attention that the individual I18N/L10N efforts for each country has been repeating each others' efforts. Many of us have been reinventing the wheel repeatedly and inefficiently. We hope that the various major groups in I18N could congregate into a group effort similar to the Core Team's responsibility.

Currently, we hope that, when you write or port I18N programs, you would send it out to each country's related FreeBSD mailing list for testing. In the future, we hope to create applications that work in all the languages out-of-the-box without dirty hacks.

The FreeBSD internationalization mailing list <[freebsd-i18n@FreeBSD.org](mailto:freebsd-i18n@FreeBSD.org)> has been established. If you are an I18N/L10N developer, please send your comments, ideas, questions, and anything you deem related to it.

Michael C. Wu will be maintaining an I18N works in progress homepage at <http://www.FreeBSD.org/~keichii/i18n/index.html> Please also read the BSDCon2000 I18N paper and presentations by Clive Lin, Chia-Liang Kao, and Michael C. Wu at <http://www.FreeBSD.org/~keichii/papers/>

#### 4.1.2 Perl and Python

Perl and Python have I18N and wide character handling libraries. Please use them for I18N compliance.

In older FreeBSD versions, Perl may give warnings about not having a wide character locale installed on your system. You can set the environment variable LD\_PRELOAD to `/usr/lib/libxpg4.so` in your shell.

In sh-based shells:

```
LD_PRELOAD=/usr/lib/libxpg4.so
```

In C-based shells:

```
setenv LD_PRELOAD /usr/lib/libxpg4.so
```

# Chapter 5 Source Tree Guidelines and Policies

*Contributed by Poul-Henning Kamp <phk@FreeBSD.org>.*

This chapter documents various guidelines and policies in force for the FreeBSD source tree.

## 5.1 MAINTAINER on Makefiles

June 1996.

If a particular portion of the FreeBSD distribution is being maintained by a person or group of persons, they can communicate this fact to the world by adding a

```
MAINTAINER= email-addresses
```

line to the `Makefiles` covering this portion of the source tree.

The semantics of this are as follows:

The maintainer owns and is responsible for that code. This means that he is responsible for fixing bugs and answering problem reports pertaining to that piece of the code, and in the case of contributed software, for tracking new versions, as appropriate.

Changes to directories which have a maintainer defined shall be sent to the maintainer for review before being committed. Only if the maintainer does not respond for an unacceptable period of time, to several emails, will it be acceptable to commit changes without review by the maintainer. However, it is suggested that you try to have the changes reviewed by someone else if at all possible.

It is of course not acceptable to add a person or group as maintainer unless they agree to assume this duty. On the other hand it does not have to be a committer and it can easily be a group of people.

## 5.2 Contributed Software

*Contributed by Poul-Henning Kamp <phk@FreeBSD.org> and David O'Brien <obrien@FreeBSD.org>.*

June 1996.

Some parts of the FreeBSD distribution consist of software that is actively being maintained outside the FreeBSD project. For historical reasons, we call this *contributed* software. Some examples are perl, gcc and patch.

Over the last couple of years, various methods have been used in dealing with this type of software and all have some number of advantages and drawbacks. No clear winner has emerged.

Since this is the case, after some debate one of these methods has been selected as the “official” method and will be required for future imports of software of this kind. Furthermore, it is strongly suggested that existing contributed software converge on this model over time, as it has significant advantages over the old method, including the ability to easily obtain diffs relative to the “official” versions of the source by everyone (even without cvs access). This will make it significantly easier to return changes to the primary developers of the contributed software.

Ultimately, however, it comes down to the people actually doing the work. If using this model is particularly unsuited to the package being dealt with, exceptions to these rules may be granted only with the approval of the core team and

with the general consensus of the other developers. The ability to maintain the package in the future will be a key issue in the decisions.

**Note:** Because of some unfortunate design limitations with the RCS file format and CVS's use of vendor branches, minor, trivial and/or cosmetic changes are *strongly discouraged* on files that are still tracking the vendor branch. "Spelling fixes" are explicitly included here under the "cosmetic" category and are to be avoided for files with revision 1.1.x.x. The repository bloat impact from a single character change can be rather dramatic.

The **Tcl** embedded programming language will be used as example of how this model works:

`src/contrib/tcl` contains the source as distributed by the maintainers of this package. Parts that are entirely not applicable for FreeBSD can be removed. In the case of Tcl, the `mac`, `win` and `compat` subdirectories were eliminated before the import.

`src/lib/libtcl` contains only a "bmake style" Makefile that uses the standard `bsd.lib.mk` makefile rules to produce the library and install the documentation.

`src/usr.bin/tclsh` contains only a bmake style Makefile which will produce and install the `tclsh` program and its associated man-pages using the standard `bsd.prog.mk` rules.

`src/tools/tools/tcl_bmake` contains a couple of shell-scripts that can be of help when the tcl software needs updating. These are not part of the built or installed software.

The important thing here is that the `src/contrib/tcl` directory is created according to the rules: it is supposed to contain the sources as distributed (on a proper CVS vendor-branch and without RCS keyword expansion) with as few FreeBSD-specific changes as possible. The 'easy-import' tool on freefall will assist in doing the import, but if there are any doubts on how to go about it, it is imperative that you ask first and not blunder ahead and hope it "works out". CVS is not forgiving of import accidents and a fair amount of effort is required to back out major mistakes.

Because of the previously mentioned design limitations with CVS's vendor branches, it is required that "official" patches from the vendor be applied to the original distributed sources and the result re-imported onto the vendor branch again. Official patches should never be patched into the FreeBSD checked out version and "committed", as this destroys the vendor branch coherency and makes importing future versions rather difficult as there will be conflicts.

Since many packages contain files that are meant for compatibility with other architectures and environments that FreeBSD, it is permissible to remove parts of the distribution tree that are of no interest to FreeBSD in order to save space. Files containing copyright notices and release-note kind of information applicable to the remaining files shall *not* be removed.

If it seems easier, the bmake Makefiles can be produced from the dist tree automatically by some utility, something which would hopefully make it even easier to upgrade to a new version. If this is done, be sure to check in such utilities (as necessary) in the `src/tools` directory along with the port itself so that it is available to future maintainers.

In the `src/contrib/tcl` level directory, a file called `FREEBSD-upgrade` should be added and it should state things like:

- Which files have been left out.
- Where the original distribution was obtained from and/or the official master site.
- Where to send patches back to the original authors.

- Perhaps an overview of the FreeBSD-specific changes that have been made.

However, please do not import `FREEBSD-upgrade` with the contributed source. Rather you should `cvcs add FREEBSD-upgrade ; cvcs ci` after the initial import. Example wording from `src/contrib/cpio` is below:

```
This directory contains virgin sources of the original distribution files
on a "vendor" branch. Do not, under any circumstances, attempt to upgrade
the files in this directory via patches and a cvs commit. New versions or
official-patch versions must be imported. Please remember to import with
"-ko" to prevent CVS from corrupting any vendor RCS Ids.
```

For the import of GNU cpio 2.4.2, the following files were removed:

```
INSTALL          cpio.info      mkdir.c
Makefile.in     cpio.texi     mkinstalldirs
```

To upgrade to a newer version of cpio, when it is available:

1. Unpack the new version into an empty directory.  
[Do not make ANY changes to the files.]
2. Remove the files listed above and any others that don't apply to FreeBSD.
3. Use the command:  

```
cvcs import -ko -m 'Virgin import of GNU cpio v<version>' \
src/contrib/cpio GNU cpio_<version>
```

For example, to do the import of version 2.4.2, I typed:

```
cvcs import -ko -m 'Virgin import of GNU v2.4.2' \
src/contrib/cpio GNU cpio_2_4_2
```

4. Follow the instructions printed out in step 3 to resolve any conflicts between local FreeBSD changes and the newer version.

Do not, under any circumstances, deviate from this procedure.

To make local changes to cpio, simply patch and commit to the main branch (aka HEAD). Never make local changes on the GNU branch.

All local changes should be submitted to "cpio@gnu.ai.mit.edu" for inclusion in the next vendor release.

obrien@FreeBSD.org - 30 March 1997

## 5.3 Encumbered Files

It might occasionally be necessary to include an encumbered file in the FreeBSD source tree. For example, if a device requires a small piece of binary code to be loaded to it before the device will operate, and we do not have the source to that code, then the binary file is said to be encumbered. The following policies apply to including encumbered files in the FreeBSD source tree.

1. Any file which is interpreted or executed by the system CPU(s) and not in source format is encumbered.
2. Any file with a license more restrictive than BSD or GNU is encumbered.
3. A file which contains downloadable binary data for use by the hardware is not encumbered, unless (1) or (2) apply to it. It must be stored in an architecture neutral ASCII format (file2c or uuencoding is recommended).
4. Any encumbered file requires specific approval from the Core team ([../articles/contributors/staff-core.html](http://../articles/contributors/staff-core.html)) before it is added to the CVS repository.
5. Encumbered files go in `src/contrib` or `src/sys/contrib`.
6. The entire module should be kept together. There is no point in splitting it, unless there is code-sharing with non-encumbered code.
7. Object files are named `arch/filename.o.uu`.
8. Kernel files:
  - a. Should always be referenced in `conf/files.*` (for build simplicity).
  - b. Should always be in `LINT`, but the Core team ([../articles/contributors/staff-core.html](http://../articles/contributors/staff-core.html)) decides per case if it should be commented out or not. The Core team ([../articles/contributors/staff-core.html](http://../articles/contributors/staff-core.html)) can, of course, change their minds later on.
  - c. The *Release Engineer* decides whether or not it goes in to the release.
9. User-land files:
  - a.

The Core team ([../articles/contributors/staff-core.html](http://../articles/contributors/staff-core.html)) decides if the code should be part of `make world`.
  - b.

The Release Engineer ([../articles/contributors/staff-who.html](http://../articles/contributors/staff-who.html)) decides if it goes in to the release.

## 5.4 Shared Libraries

*Contributed by Satoshi Asami <[asami@FreeBSD.org](mailto:asami@FreeBSD.org)>, Peter Wemm <[peter@FreeBSD.org](mailto:peter@FreeBSD.org)>, and David O'Brien <[obrien@FreeBSD.org](mailto:obrien@FreeBSD.org)> 9 December 1996.*

If you are adding shared library support to a port or other piece of software that does not have one, the version numbers should follow these rules. Generally, the resulting numbers will have nothing to do with the release version of the software.

The three principles of shared library building are:

- Start from 1.0
- If there is a change that is backwards compatible, bump minor number (note that ELF systems ignore the minor number)

- If there is an incompatible change, bump major number

For instance, added functions and bugfixes result in the minor version number being bumped, while deleted functions, changed function call syntax, etc. will force the major version number to change.

Stick to version numbers of the form major.minor ( $x.y$ ). Our a.out dynamic linker does not handle version numbers of the form  $x.y.z$  well. Any version number after the  $y$  (i.e. the third digit) is totally ignored when comparing shared lib version numbers to decide which library to link with. Given two shared libraries that differ only in the “micro” revision, `ld.so` will link with the higher one. That is, if you link with `libfoo.so.3.3.3`, the linker only records `3.3` in the headers, and will link with anything starting with `libfoo.so.3.(anything >= 3).(highest available)`.

**Note:** `ld.so` will always use the highest “minor” revision. For instance, it will use `libc.so.2.2` in preference to `libc.so.2.0`, even if the program was initially linked with `libc.so.2.0`.

In addition, our ELF dynamic linker does not handle minor version numbers at all. However, one should still specify a major and minor version number as our `Makefiles` “do the right thing” based on the type of system.

For non-port libraries, it is also our policy to change the shared library version number only once between releases. In addition, it is our policy to change the major shared library version number only once between major OS releases (i.e. from 3.0 to 4.0). When you make a change to a system library that requires the version number to be bumped, check the `Makefile`’s commit logs. It is the responsibility of the committer to ensure that the first such change since the release will result in the shared library version number in the `Makefile` to be updated, and any subsequent changes will not.



## **II. Interprocess Communication**

# Chapter 6 \* Signals

Signals, pipes, semaphores, message queues, shared memory, ports, sockets, doors

# Chapter 7 Sockets

*This chapter was written by G. Adam Stanislav <adam@whizkidtech.net>*

## 7.1 Synopsis

BSD sockets take interprocess communications to a new level. It is no longer necessary for the communicating processes to run on the same machine. They still *can*, but they do not have to.

Not only do these processes not have to run on the same machine, they do not have to run under the same operating system. Thanks to BSD sockets, your FreeBSD software can smoothly cooperate with a program running on a Macintosh, another one running on a Sun workstation, yet another one running under Windows 2000, all connected with an Ethernet-based local area network.

But your software can equally well cooperate with processes running in another building, or on another continent, inside a submarine, or a space shuttle.

It can also cooperate with processes that are not part of a computer (at least not in the strict sense of the word), but of such devices as printers, digital cameras, medical equipment. Just about anything capable of digital communications.

## 7.2 Networking and Diversity

We have already hinted on the *diversity* of networking. Many different systems have to talk to each other. And they have to speak the same language. They also have to *understand* the same language the same way.

People often think that *body language* is universal. But it is not. Back in my early teens, my father took me to Bulgaria. We were sitting at a table in a park in Sofia, when a vendor approached us trying to sell us some roasted almonds.

I had not learned much Bulgarian by then, so, instead of saying no, I shook my head from side to side, the “universal” body language for *no*. The vendor quickly started serving us some almonds.

I then remembered I had been told that in Bulgaria shaking your head sideways meant *yes*. Quickly, I started nodding my head up and down. The vendor noticed, took his almonds, and walked away. To an uninformed observer, I did not change the body language: I continued using the language of shaking and nodding my head. What changed was the *meaning* of the body language. At first, the vendor and I interpreted the same language as having completely different meaning. I had to adjust my own interpretation of that language so the vendor would understand.

It is the same with computers: The same symbols may have different, even outright opposite meaning. Therefore, for two computers to understand each other, they must not only agree on the same *language*, but on the same *interpretation* of the language.

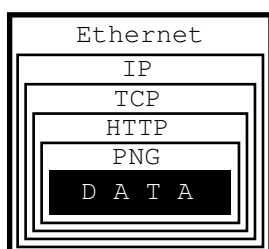
## 7.3 Protocols

While various programming languages tend to have complex syntax and use a number of multi-letter reserved words (which makes them easy for the human programmer to understand), the languages of data communications tend to be very terse. Instead of multi-byte words, they often use individual *bits*. There is a very convincing reason for it: While

data travels *inside* your computer at speeds approaching the speed of light, it often travels considerably slower between two computers.

Because the languages used in data communications are so terse, we usually refer to them as *protocols* rather than languages.

As data travels from one computer to another, it always uses more than one protocol. These protocols are *layered*. The data can be compared to the inside of an onion: You have to peel off several layers of “skin” to get to the data. This is best illustrated with a picture:



In this example, we are trying to get an image from a web page we are connected to via an Ethernet.

The image consists of raw data, which is simply a sequence of RGB values that our software can process, i.e., convert into an image and display on our monitor.

Alas, our software has no way of knowing how the raw data is organized: Is it a sequence of RGB values, or a sequence of grayscale intensities, or perhaps of CMYK encoded colors? Is the data represented by 8-bit quanta, or are they 16 bits in size, or perhaps 4 bits? How many rows and columns does the image consist of? Should certain pixels be transparent?

I think you get the picture...

To inform our software how to handle the raw data, it is encoded as a PNG file. It could be a GIF, or a JPEG, but it is a PNG.

And PNG is a protocol.

At this point, I can hear some of you yelling, “No, it is not! It is a file format!”

Well, of course it is a file format. But from the perspective of data communications, a file format is a protocol: The file structure is a *language*, a terse one at that, communicating to our *process* how the data is organized. Ergo, it is a *protocol*.

Alas, if all we received was the PNG file, our software would be facing a serious problem: How is it supposed to know the data is representing an image, as opposed to some text, or perhaps a sound, or what not? Secondly, how is it supposed to know the image is in the PNG format as opposed to GIF, or JPEG, or some other image format?

To obtain that information, we are using another protocol: HTTP. This protocol can tell us exactly that the data represents an image, and that it uses the PNG protocol. It can also tell us some other things, but let us stay focused on protocol layers here.

So, now we have some data wrapped in the PNG protocol, wrapped in the HTTP protocol. How did we get it from the server?

By using TCP/IP over Ethernet, that is how. Indeed, that is three more protocols. Instead of continuing inside out, I am now going to talk about Ethernet, simply because it is easier to explain the rest that way.

Ethernet is an interesting system of connecting computers in a *local area network* (LAN). Each computer has a *network interface card* (NIC), which has a unique 48-bit ID called its *address*. No two Ethernet NICs in the world have the same address.

These NICs are all connected with each other. Whenever one computer wants to communicate with another in the same Ethernet LAN, it sends a message over the network. Every NIC sees the message. But as part of the Ethernet *protocol*, the data contains the address of the destination NIC (among other things). So, only one of all the network interface cards will pay attention to it, the rest will ignore it.

But not all computers are connected to the same network. Just because we have received the data over our Ethernet does not mean it originated in our own local area network. It could have come to us from some other network (which may not even be Ethernet based) connected with our own network via the Internet.

All data is transferred over the Internet using IP, which stands for *Internet Protocol*. Its basic role is to let us know where in the world the data has arrived from, and where it is supposed to go to. It does not *guarantee* we will receive the data, only that we will know where it came from *if* we do receive it.

Even if we do receive the data, IP does not guarantee we will receive various chunks of data in the same order the other computer has sent it to us. So, we can receive the center of our image before we receive the upper left corner and after the lower right, for example.

It is TCP (*Transmission Control Protocol*) that asks the sender to resend any lost data and that places it all into the proper order.

All in all, it took *five* different protocols for one computer to communicate to another what an image looks like. We received the data wrapped into the PNG protocol, which was wrapped into the HTTP protocol, which was wrapped into the TCP protocol, which was wrapped into the IP protocol, which was wrapped into the Ethernet protocol.

Oh, and by the way, there probably were several other protocols involved somewhere on the way. For example, if our LAN was connected to the Internet through a dial-up call, it used the PPP protocol over the modem which used one (or several) of the various modem protocols, et cetera, et cetera, et cetera...

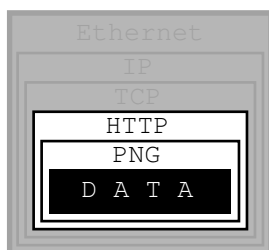
As a developer you should be asking by now, “*How am I supposed to handle it all?*”

Luckily for you, you are *not* supposed to handle it all. You *are* supposed to handle some of it, but not all of it. Specifically, you need not worry about the physical connection (in our case Ethernet and possibly PPP, etc). Nor do you need to handle the Internet Protocol, or the Transmission Control Protocol.

In other words, you do not have to do anything to receive the data from the other computer. Well, you do have to *ask* for it, but that is almost as simple as opening a file.

Once you have received the data, it is up to you to figure out what to do with it. In our case, you would need to understand the HTTP protocol and the PNG file structure.

To use an analogy, all the internetworking protocols become a gray area: Not so much because we do not understand how it works, but because we are no longer concerned about it. The sockets interface takes care of this gray area for us:



We only need to understand any protocols that tell us how to *interpret the data*, not how to *receive* it from another process, nor how to *send* it to another process.

## 7.4 The Sockets Model

BSD sockets are built on the basic Unix model: *Everything is a file*. In our example, then, sockets would let us receive an *HTTP file*, so to speak. It would then be up to us to extract the *PNG file* from it.

Because of the complexity of internetworking, we cannot just use the `open` system call, or the `open()` C function. Instead, we need to take several steps to “opening” a socket.

Once we do, however, we can start treating the *socket* the same way we treat any *file descriptor*: We can `read` from it, `write` to it, `pipe` it, and, eventually, `close` it.

## 7.5 Essential Socket Functions

While FreeBSD offers different functions to work with sockets, we only *need* four to “open” a socket. And in some cases we only need two.

### 7.5.1 The Client-Server Difference

Typically, one of the ends of a socket-based data communication is a *server*, the other is a *client*.

#### 7.5.1.1 The Common Elements

##### 7.5.1.1.1 `socket`

The one function used by both, clients and servers, is `socket(2)`. It is declared this way:

```
int socket(int domain, int type, int protocol);
```

The return value is of the same type as that of `open`, an integer. FreeBSD allocates its value from the same pool as that of file handles. That is what allows sockets to be treated the same way as files.

The `domain` argument tells the system what *protocol family* you want it to use. Many of them exist, some are vendor specific, others are very common. They are declared in `sys/socket.h`.

Use `PF_INET` for UDP, TCP and other Internet protocols (IPv4).

Five values are defined for the `type` argument, again, in `sys/socket.h`. All of them start with “`SOCK_`”. The most common one is `SOCK_STREAM`, which tells the system you are asking for a *reliable stream delivery service* (which is TCP when used with `PF_INET`).

If you asked for `SOCK_DGRAM`, you would be requesting a *connectionless datagram delivery service* (in our case, UDP).

If you wanted to be in charge of the low-level protocols (such as IP), or even network interfaces (e.g., the Ethernet), you would need to specify `SOCK_RAW`.

Finally, the `protocol` argument depends on the previous two arguments, and is not always meaningful. In that case, use 0 for its value.

**The Unconnected Socket:** Nowhere, in the `socket` function have we specified to what other system we should be connected. Our newly created socket remains *unconnected*.

This is on purpose: To use a telephone analogy, we have just attached a modem to the phone line. We have neither told the modem to make a call, nor to answer if the phone rings.

#### 7.5.1.1.2 `sockaddr`

Various functions of the sockets family expect the address of (or pointer to, to use C terminology) a small area of the memory. The various C declarations in the `sys/socket.h` refer to it as `struct sockaddr`. This structure is declared in the same file:

```
/*
 * Structure used by kernel to store most
 * addresses.
 */
struct sockaddr {
    u_char sa_len; /* total length */
    sa_family_t sa_family; /* address family */
    char sa_data[14]; /* actually longer; address value */
};
#define SOCK_MAXADDRLLEN 255 /* longest possible addresses */
```

Please note the *vagueness* with which the `sa_data` field is declared, just as an array of 14 bytes, with the comment hinting there can be more than 14 of them.

This vagueness is quite deliberate. Sockets is a very powerful interface. While most people perhaps think of it as nothing more than the Internet interface—and most applications probably use it for that nowadays—sockets can be used for just about *any* kind of interprocess communications, of which the Internet (or, more precisely, IP) is only one.

The `sys/socket.h` refers to the various types of protocols sockets will handle as *address families*, and lists them right before the definition of `sockaddr`:

```
/*
 * Address families.
 */
```

```

#define AF_UNSPEC 0 /* unspecified */
#define AF_LOCAL 1 /* local to host (pipes, portals) */
#define AF_UNIX AF_LOCAL /* backward compatibility */
#define AF_INET 2 /* internetwork: UDP, TCP, etc. */
#define AF_IMPLINK 3 /* arpanet imp addresses */
#define AF_PUP 4 /* pup protocols: e.g. BSP */
#define AF_CHAOS 5 /* mit CHAOS protocols */
#define AF_NS 6 /* XEROX NS protocols */
#define AF_ISO 7 /* ISO protocols */
#define AF_OSI AF_ISO
#define AF_ECMA 8 /* European computer manufacturers */
#define AF_DATAKIT 9 /* datakit protocols */
#define AF_CCITT 10 /* CCITT protocols, X.25 etc */
#define AF_SNA 11 /* IBM SNA */
#define AF_DECnet 12 /* DECnet */
#define AF_DLI 13 /* DEC Direct data link interface */
#define AF_LAT 14 /* LAT */
#define AF_HYLINK 15 /* NSC Hyperchannel */
#define AF_APPLETALK 16 /* Apple Talk */
#define AF_ROUTE 17 /* Internal Routing Protocol */
#define AF_LINK 18 /* Link layer interface */
#define pseudo_AF_XTP 19 /* eXpress Transfer Protocol (no AF) */
#define AF_COIP 20 /* connection-oriented IP, aka ST II */
#define AF_CNT 21 /* Computer Network Technology */
#define pseudo_AF_RTIP 22 /* Help Identify RTIP packets */
#define AF_IPX 23 /* Novell Internet Protocol */
#define AF_SIP 24 /* Simple Internet Protocol */
#define pseudo_AF_PIP 25 /* Help Identify PIP packets */
#define AF_ISDN 26 /* Integrated Services Digital Network*/
#define AF_E164 AF_ISDN /* CCITT E.164 recommendation */
#define pseudo_AF_KEY 27 /* Internal key-management function */
#define AF_INET6 28 /* IPv6 */
#define AF_NATM 29 /* native ATM access */
#define AF_ATM 30 /* ATM */
#define pseudo_AF_HDRCMPLT 31 /* Used by BPF to not rewrite headers
 * in interface output routine
 */
#define AF_NETGRAPH 32 /* Netgraph sockets */

#define AF_MAX 33

```

The one used for IP is `AF_INET`. It is a symbol for the constant 2.

It is the *address family* listed in the `sa_family` field of `sockaddr` that decides how exactly the vaguely named bytes of `sa_data` will be used.

Specifically, whenever the *address family* is `AF_INET`, we can use `struct sockaddr_in` found in `netinet/in.h`, wherever `sockaddr` is expected:

```

/*
 * Socket address, internet style.
 */
struct sockaddr_in {
    u_char sin_len;

```

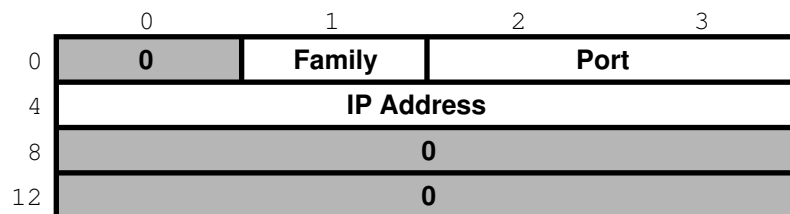


```

u_char sin_family;
u_short sin_port;
struct in_addr sin_addr;
char sin_zero[8];
};

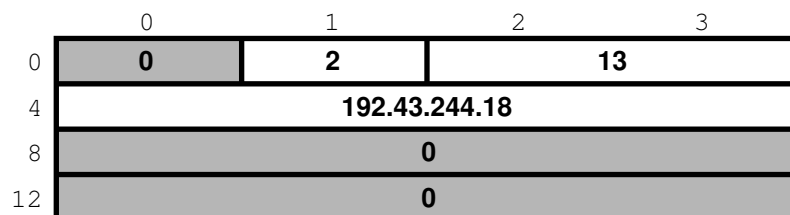
```

We can visualize its organization this way:



The three important fields are `sin_family`, which is byte 1 of the structure, `sin_port`, a 16-bit value found in bytes 2 and 3, and `sin_addr`, a 32-bit integer representation of the IP address, stored in bytes 4-7.

Now, let us try to fill it out. Let us assume we are trying to write a client for the *daytime* protocol, which simply states that its server will write a text string representing the current date and time to port 13. We want to use TCP/IP, so we need to specify `AF_INET` in the address family field. `AF_INET` is defined as 2. Let us use the IP address of 192.43.244.18, which is the time server of US federal government (`time.nist.gov`).



By the way the `sin_addr` field is declared as being of the `struct in_addr` type, which is defined in `netinet/in.h`:

```

/*
 * Internet address (a structure for historical reasons)
 */
struct in_addr {
    in_addr_t s_addr;
};

```

In addition, `in_addr_t` is a 32-bit integer.

The 192.43.244.18 is just a convenient notation of expressing a 32-bit integer by listing all of its 8-bit bytes, starting with the *most significant* one.

So far, we have viewed `sockaddr` as an abstraction. Our computer does not store `short` integers as a single 16-bit entity, but as a sequence of 2 bytes. Similarly, it stores 32-bit integers as a sequence of 4 bytes.

Suppose we coded something like this:

```

sa.sin_family = AF_INET;

```

```

sa.sin_port      = 13;
sa.sin_addr.s_addr = (((((192 << 8) | 43) << 8) | 244) << 8) | 18;

```

What would the result look like?

Well, that depends, of course. On a Pentium, or other x86, based computer, it would look like this:

	0	1	2	3
0	<b>0</b>	<b>2</b>	<b>13</b>	<b>0</b>
4	<b>18</b>	<b>244</b>	<b>43</b>	<b>192</b>
8	<b>0</b>			
12	<b>0</b>			

On a different system, it might look like this:

	0	1	2	3
0	<b>0</b>	<b>2</b>	<b>0</b>	<b>13</b>
4	<b>192</b>	<b>43</b>	<b>244</b>	<b>18</b>
8	<b>0</b>			
12	<b>0</b>			

And on a PDP it might look different yet. But the above two are the most common ways in use today.

Ordinarily, wanting to write portable code, programmers pretend that these differences do not exist. And they get away with it (except when they code in assembly language). Alas, you cannot get away with it that easily when coding for sockets.

Why?

Because when communicating with another computer, you usually do not know whether it stores data *most significant byte* (MSB) or *least significant byte* (LSB) first.

You might be wondering, “*So, will sockets not handle it for me?*”

It will not.

While that answer may surprise you at first, remember that the general sockets interface only understands the `sa_len` and `sa_family` fields of the `sockaddr` structure. You do not have to worry about the byte order there (of course, on FreeBSD `sa_family` is only 1 byte anyway, but many other Unix systems do not have `sa_len` and use 2 bytes for `sa_family`, and expect the data in whatever order is native to the computer).

But the rest of the data is just `sa_data[14]` as far as sockets goes. Depending on the *address family*, sockets just forwards that data to its destination.

Indeed, when we enter a port number, it is because we want the other computer to know what service we are asking for. And, when we are the server, we read the port number so we know what service the other computer is expecting from us. Either way, sockets only has to forward the port number as data. It does not interpret it in any way.

Similarly, we enter the IP address to tell everyone on the way where to send our data to. Sockets, again, only forwards it as data.

That is why, we (the *programmers*, not the *sockets*) have to distinguish between the byte order used by our computer and a conventional byte order to send the data in to the other computer.

We will call the byte order our computer uses the *host byte order*, or just the *host order*.

There is a convention of sending the multi-byte data over IP *MSB first*. This, we will refer to as the *network byte order*, or simply the *network order*.

Now, if we compiled the above code for an Intel based computer, our *host byte order* would produce:

	0	1	2	3
0	0	2	13	0
4	18	244	43	192
8	0			
12	0			

But the *network byte order* requires that we store the data MSB first:

	0	1	2	3
0	0	2	0	13
4	192	43	244	18
8	0			
12	0			

Unfortunately, our *host order* is the exact opposite of the *network order*.

We have several ways of dealing with it. One would be to *reverse* the values in our code:

```
sa.sin_family      = AF_INET;
sa.sin_port        = 13 << 8;
sa.sin_addr.s_addr = (((((18 << 8) | 244) << 8) | 43) << 8) | 192;
```

This will *trick* our compiler into storing the data in the *network byte order*. In some cases, this is exactly the way to do it (e.g., when programming in assembly language). In most cases, however, it can cause a problem.

Suppose, you wrote a sockets-based program in C. You know it is going to run on a Pentium, so you enter all your constants in reverse and force them to the *network byte order*. It works well.

Then, some day, your trusted old Pentium becomes a rusty old Pentium. You replace it with a system whose *host order* is the same as the *network order*. You need to recompile all your software. All of your software continues to perform well, except the one program you wrote.

You have since forgotten that you had forced all of your constants to the opposite of the *host order*. You spend some quality time tearing out your hair, calling the names of all gods you ever heard of (and some you made up), hitting your monitor with a nerf bat, and performing all the other traditional ceremonies of trying to figure out why something that has worked so well is suddenly not working at all.

Eventually, you figure it out, say a couple of swear words, and start rewriting your code.

Luckily, you are not the first one to face the problem. Someone else has created the `htons(3)` and `htonl(3)` C functions to convert a `short` and `long` respectively from the *host byte order* to the *network byte order*, and the `ntohs(3)` and `ntohl(3)` C functions to go the other way.

On *MSB-first* systems these functions do nothing. On *LSB-first* systems they convert values to the proper order.

So, regardless of what system your software is compiled on, your data will end up in the correct order if you use these functions.

### 7.5.1.2 Client Functions

Typically, the client initiates the connection to the server. The client knows which server it is about to call: It knows its IP address, and it knows the *port* the server resides at. It is akin to you picking up the phone and dialing the number (the *address*), then, after someone answers, asking for the person in charge of wingdings (the *port*).

#### 7.5.1.2.1 connect

Once a client has created a socket, it needs to connect it to a specific port on a remote system. It uses `connect(2)`:

```
int connect(int s, const struct sockaddr *name, socklen_t namelen);
```

The `s` argument is the socket, i.e., the value returned by the `socket` function. The `name` is a pointer to `sockaddr`, the structure we have talked about extensively. Finally, `namelen` informs the system how many bytes are in our `sockaddr` structure.

If `connect` is successful, it returns 0. Otherwise it returns `-1` and stores the error code in `errno`.

There are many reasons why `connect` may fail. For example, with an attempt to an Internet connection, the IP address may not exist, or it may be down, or just too busy, or it may not have a server listening at the specified port. Or it may outright *refuse* any request for specific code.

#### 7.5.1.2.2 Our First Client

We now know enough to write a very simple client, one that will get current time from `192.43.244.18` and print it to `stdout`.

```
/*
 * daytime.c
 *
 * Programmed by G. Adam Stanislav
 */
#include <stdio.h>
#include <sys/types.h>
#include <sys/socket.h>
#include <netinet/in.h>

int main() {
    register int s;
    register int bytes;
    struct sockaddr_in sa;
    char buffer[BUFSIZ+1];
```

```

if ((s = socket(PF_INET, SOCK_STREAM, 0)) < 0) {
    perror("socket");
    return 1;
}

bzero(&sa, sizeof sa);

sa.sin_family = AF_INET;
sa.sin_port = htons(13);
sa.sin_addr.s_addr = htonl((((192 << 8) | 43) << 8) | 244) << 8) | 18);
if (connect(s, (struct sockaddr *)&sa, sizeof sa) < 0) {
    perror("connect");
    close(s);
    return 2;
}

while ((bytes = read(s, buffer, BUFSIZ)) > 0)
    write(1, buffer, bytes);

close(s);
return 0;
}

```

Go ahead, enter it in your editor, save it as `daytime.c`, then compile and run it:

```

% cc -O3 -o daytime daytime.c
% ./daytime

52079 01-06-19 02:29:25 50 0 1 543.9 UTC(NIST) *
%

```

In this case, the date was June 19, 2001, the time was 02:29:25 UTC. Naturally, your results will vary.

### 7.5.1.3 Server Functions

The typical server does not initiate the connection. Instead, it waits for a client to call it and request services. It does not know when the client will call, nor how many clients will call. It may be just sitting there, waiting patiently, one moment, The next moment, it can find itself swamped with requests from a number of clients, all calling in at the same time.

The sockets interface offers three basic functions to handle this.

#### 7.5.1.3.1 `bind`

Ports are like extensions to a phone line: After you dial a number, you dial the extension to get to a specific person or department.

There are 65535 IP ports, but a server usually processes requests that come in on only one of them. It is like telling the phone room operator that we are now at work and available to answer the phone at a specific extension. We use `bind(2)` to tell sockets which port we want to serve.

```
int bind(int s, const struct sockaddr *addr, socklen_t addrlen);
```

Beside specifying the port in `addr`, the server may include its IP address. However, it can just use the symbolic constant `INADDR_ANY` to indicate it will serve all requests to the specified port regardless of what its IP address is. This symbol, along with several similar ones, is declared in `netinet/in.h`

```
#define INADDR_ANY (u_int32_t)0x00000000
```

Suppose we were writing a server for the *daytime* protocol over TCP/IP. Recall that it uses port 13. Our `sockaddr_in` structure would look like this:

	0	1	2	3
0	0	2	0	13
4	0			
8	0			
12	0			

### 7.5.1.3.2 listen

To continue our office phone analogy, after you have told the phone central operator what extension you will be at, you now walk into your office, and make sure your own phone is plugged in and the ringer is turned on. Plus, you make sure your call waiting is activated, so you can hear the phone ring even while you are talking to someone.

The server ensures all of that with the `listen(2)` function.

```
int listen(int s, int backlog);
```

In here, the `backlog` variable tells sockets how many incoming requests to accept while you are busy processing the last request. In other words, it determines the maximum size of the queue of pending connections.

### 7.5.1.3.3 accept

After you hear the phone ringing, you accept the call by answering the call. You have now established a connection with your client. This connection remains active until either you or your client hang up.

The server accepts the connection by using the `accept(2)` function.

```
int accept(int s, struct sockaddr *addr, socklen_t *addrlen);
```

Note that this time `addrlen` is a pointer. This is necessary because in this case it is the socket that fills out `addr`, the `sockaddr_in` structure.

The return value is an integer. Indeed, the `accept` returns a *new socket*. You will use this new socket to communicate with the client.

What happens to the old socket? It continues to listen for more requests (remember the `backlog` variable we passed to `listen`?) until we close it.

Now, the new socket is meant only for communications. It is fully connected. We cannot pass it to `listen` again, trying to accept additional connections.

### 7.5.1.3.4 Our First Server

Our first server will be somewhat more complex than our first client was: Not only do we have more sockets functions to use, but we need to write it as a daemon.

This is best achieved by creating a *child process* after binding the port. The main process then exits and returns control to the **shell** (or whatever program invoked it).

The child calls `listen`, then starts an endless loop, which accepts a connection, serves it, and eventually closes its socket.

```

/*
 * daytimed - a port 13 server
 *
 * Programmed by G. Adam Stanislav
 * June 19, 2001
 */
#include <stdio.h>
#include <time.h>
#include <unistd.h>
#include <sys/types.h>
#include <sys/socket.h>
#include <netinet/in.h>

#define BACKLOG 4

int main() {
    register int s, c;
    int b;
    struct sockaddr_in sa;
    time_t t;
    struct tm *tm;
    FILE *client;

    if ((s = socket(PF_INET, SOCK_STREAM, 0)) < 0) {
        perror("socket");
        return 1;
    }

    bzero(&sa, sizeof sa);

    sa.sin_family = AF_INET;
    sa.sin_port = htons(13);

    if (INADDR_ANY)
        sa.sin_addr.s_addr = htonl(INADDR_ANY);

    if (bind(s, (struct sockaddr *)&sa, sizeof sa) < 0) {
        perror("bind");
        return 2;
    }

    switch (fork()) {
        case -1:

```

```

        perror("fork");
        return 3;
        break;
default:
    close s;
    return 0;
    break;
case 0:
    break;
}

listen(s, BACKLOG);

for (;;) {
    b = sizeof sa;

    if ((c = accept(s, (struct sockaddr *)&sa, &b)) < 0) {
        perror("daytimed accept");
        return 4;
    }

    if ((client = fdopen(c, "w")) == NULL) {
        perror("daytimed fdopen");
        return 5;
    }

    if ((t = time(NULL)) < 0) {
        perror("daytimed time");

        return 6;
    }

    tm = gmtime(&t);
    fprintf(client, "%.4i-%.2i-%.2iT%.2i:%.2i:%.2iZ\n",
            tm->tm_year + 1900,
            tm->tm_mon + 1,
            tm->tm_mday,
            tm->tm_hour,
            tm->tm_min,
            tm->tm_sec);

    fclose(client);
}
}

```

We start by creating a socket. Then we fill out the `sockaddr_in` structure in `sa`. Note the conditional use of `INADDR_ANY`:

```

if (INADDR_ANY)
    sa.sin_addr.s_addr = htonl(INADDR_ANY);

```

Its value is 0. Since we have just used `bzero` on the entire structure, it would be redundant to set it to 0 again. But if we port our code to some other system where `INADDR_ANY` is perhaps not a zero, we need to assign it to



`sa.sin_addr.s_addr`. Most modern C compilers are clever enough to notice that `INADDR_ANY` is a constant. As long as it is a zero, they will optimize the entire conditional statement out of the code.

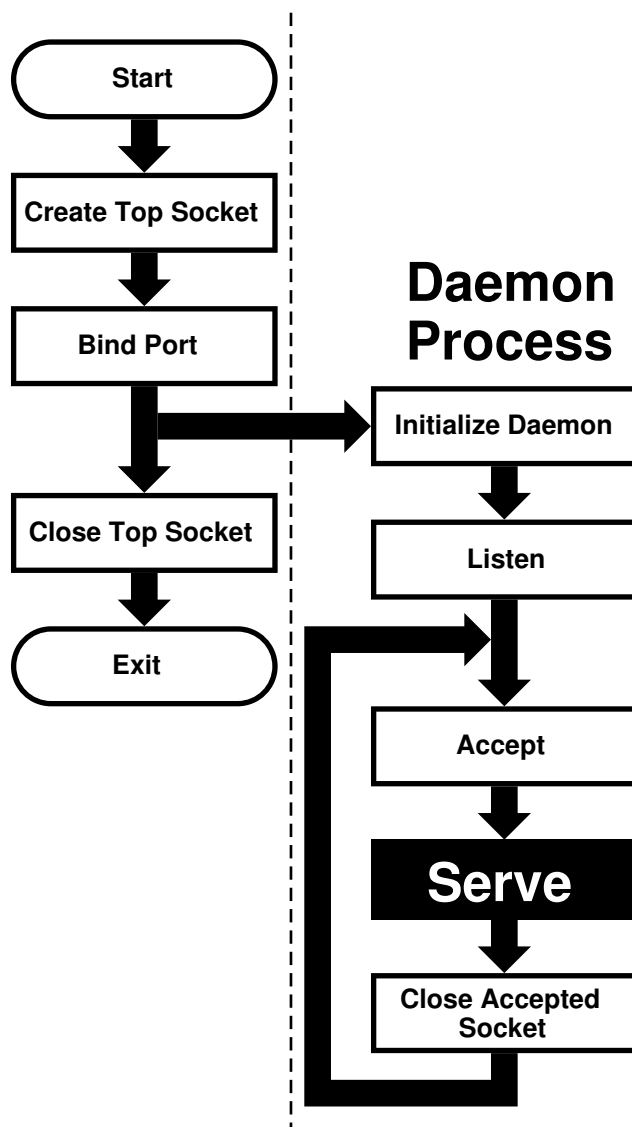
After we have called `bind` successfully, we are ready to become a *daemon*: We use `fork` to create a child process. In both, the parent and the child, the `s` variable is our socket. The parent process will not need it, so it calls `close`, then it returns 0 to inform its own parent it had terminated successfully.

Meanwhile, the child process continues working in the background. It calls `listen` and sets its backlog to 4. It does not need a large value here because *daytime* is not a protocol many clients request all the time, and because it can process each request instantly anyway.

Finally, the daemon starts an endless loop, which performs the following steps:

1. Call `accept`. It waits here until a client contacts it. At that point, it receives a new socket, `c`, which it can use to communicate with this particular client.
2. It uses the C function `fdopen` to turn the socket from a low-level *file descriptor* to a C-style `FILE` pointer. This will allow the use of `fprintf` later on.
3. It checks the time, and prints it in the *ISO 8601* format to the `client` “file”. It then uses `fclose` to close the file. That will automatically close the socket as well.

We can *generalize* this, and use it as a model for many other servers:



This flowchart is good for *sequential servers*, i.e., servers that can serve one client at a time, just as we were able to with our *daytime* server. This is only possible whenever there is no real “conversation” going on between the client and the server: As soon as the server detects a connection to the client, it sends out some data and closes the connection. The entire operation may take nanoseconds, and it is finished.

The advantage of this flowchart is that, except for the brief moment after the parent `forks` and before it exits, there is always only one *process* active: Our server does not take up much memory and other system resources.

Note that we have added *initialize daemon* in our flowchart. We did not need to initialize our own daemon, but this is a good place in the flow of the program to set up any `signal` handlers, open any files we may need, etc.

Just about everything in the flow chart can be used literally on many different servers. The *serve* entry is the exception. We think of it as a “*black box*”, i.e., something you design specifically for your own server, and just “plug it into the rest.”

Not all protocols are that simple. Many receive a request from the client, reply to it, then receive another request from the same client. Because of that, they do not know in advance how long they will be serving the client. Such

servers usually start a new process for each client. While the new process is serving its client, the daemon can continue listening for more connections.

Now, go ahead, save the above source code as `daytimed.c` (it is customary to end the names of daemons with the letter `d`). After you have compiled it, try running it:

```
% ./daytimed
bind: Permission denied
%
```

What happened here? As you will recall, the *daytime* protocol uses port 13. But all ports below 1024 are reserved to the superuser (otherwise, anyone could start a daemon pretending to serve a commonly used port, while causing a security breach).

Try again, this time as the superuser:

```
# ./daytimed
#
```

What... Nothing? Let us try again:

```
# ./daytimed

bind: Address already in use
#
```

Every port can only be bound by one program at a time. Our first attempt was indeed successful: It started the child daemon and returned quietly. It is still running and will continue to run until you either kill it, or any of its system calls fail, or you reboot the system.

Fine, we know it is running in the background. But is it working? How do we know it is a proper *daytime* server? Simple:

```
% telnet localhost 13

Trying ::1...
telnet: connect to address ::1: Connection refused
Trying 127.0.0.1...
Connected to localhost.
Escape character is '^]'.
2001-06-19T21:04:42Z
Connection closed by foreign host.
%
```

**telnet** tried the new IPv6, and failed. It retried with IPv4 and succeeded. The daemon works.

If you have access to another Unix system via **telnet**, you can use it to test accessing the server remotely. My computer does not have a static IP address, so this is what I did:

```
% who

whizkid          tty0    Jun 19 16:59  (216.127.220.143)
xxx              tty1    Jun 19 16:06  (xx.xx.xx.xx)
% telnet 216.127.220.143 13
```

```
Trying 216.127.220.143...
Connected to r47.bfm.org.
Escape character is '^]'.
2001-06-19T21:31:11Z
Connection closed by foreign host.
%
```

Again, it worked. Will it work using the domain name?

```
% telnet r47.bfm.org 13

Trying 216.127.220.143...
Connected to r47.bfm.org.
Escape character is '^]'.
2001-06-19T21:31:40Z
Connection closed by foreign host.
%
```

By the way, **telnet** prints the *Connection closed by foreign host* message after our daemon has closed the socket. This shows us that, indeed, using `fclose(client)`; in our code works as advertised.

## 7.6 Helper Functions

FreeBSD C library contains many helper functions for sockets programming. For example, in our sample client we hard coded the `time.nist.gov` IP address. But we do not always know the IP address. Even if we do, our software is more flexible if it allows the user to enter the IP address, or even the domain name.

### 7.6.1 `gethostbyname`

While there is no way to pass the domain name directly to any of the sockets functions, the FreeBSD C library comes with the `gethostbyname(3)` and `gethostbyname2(3)` functions, declared in `netdb.h`.

```
struct hostent * gethostbyname(const char *name);
struct hostent * gethostbyname2(const char *name, int af);
```

Both return a pointer to the `hostent` structure, with much information about the domain. For our purposes, the `h_addr_list[0]` field of the structure points at `h_length` bytes of the correct address, already stored in the *network byte order*.

This allows us to create a much more flexible—and much more useful—version of our **daytime** program:

```
/*
 * daytime.c
 *
 * Programmed by G. Adam Stanislav
 * 19 June 2001
 */
```

```

#include <stdio.h>
#include <string.h>
#include <sys/types.h>
#include <sys/socket.h>
#include <netinet/in.h>
#include <netdb.h>

int main(int argc, char *argv[]) {
    register int s;
    register int bytes;
    struct sockaddr_in sa;
    struct hostent *he;
    char buf[BUFSIZ+1];
    char *host;

    if ((s = socket(PF_INET, SOCK_STREAM, 0)) < 0) {
        perror("socket");
        return 1;
    }

    bzero(&sa, sizeof sa);

    sa.sin_family = AF_INET;
    sa.sin_port = htons(13);

    host = (argc > 1) ? (char *)argv[1] : "time.nist.gov";

    if ((he = gethostbyname(host)) == NULL) {
        perror(host);
        return 2;
    }

    bcopy(he->h_addr_list[0], &sa.sin_addr, he->h_length);

    if (connect(s, (struct sockaddr *)&sa, sizeof sa) < 0) {
        perror("connect");
        return 3;
    }

    while ((bytes = read(s, buf, BUFSIZ)) > 0)
        write(1, buf, bytes);

    close(s);
    return 0;
}

```

We now can type a domain name (or an IP address, it works both ways) on the command line, and the program will try to connect to its *daytime* server. Otherwise, it will still default to `time.nist.gov`. However, even in this case we will use `gethostbyname` rather than hard coding `192.43.244.18`. That way, even if its IP address changes in the future, we will still find it.

Since it takes virtually no time to get the time from your local server, you could run **daytime** twice in a row: First to get the time from `time.nist.gov`, the second time from your own system. You can then compare the results and see how exact your system clock is:

```
% daytime ; daytime localhost

52080 01-06-20 04:02:33 50 0 0 390.2 UTC(NIST) *
2001-06-20T04:02:35Z
%
```

As you can see, my system was two seconds ahead of the NIST time.

## 7.6.2 getservbyname

Sometimes you may not be sure what port a certain service uses. The `getservbyname(3)` function, also declared in `netdb.h` comes in very handy in those cases:

```
struct servent * getservbyname(const char *name, const char *proto);
```

The `servent` structure contains the `s_port`, which contains the proper port, already in *network byte order*.

Had we not known the correct port for the *daytime* service, we could have found it this way:

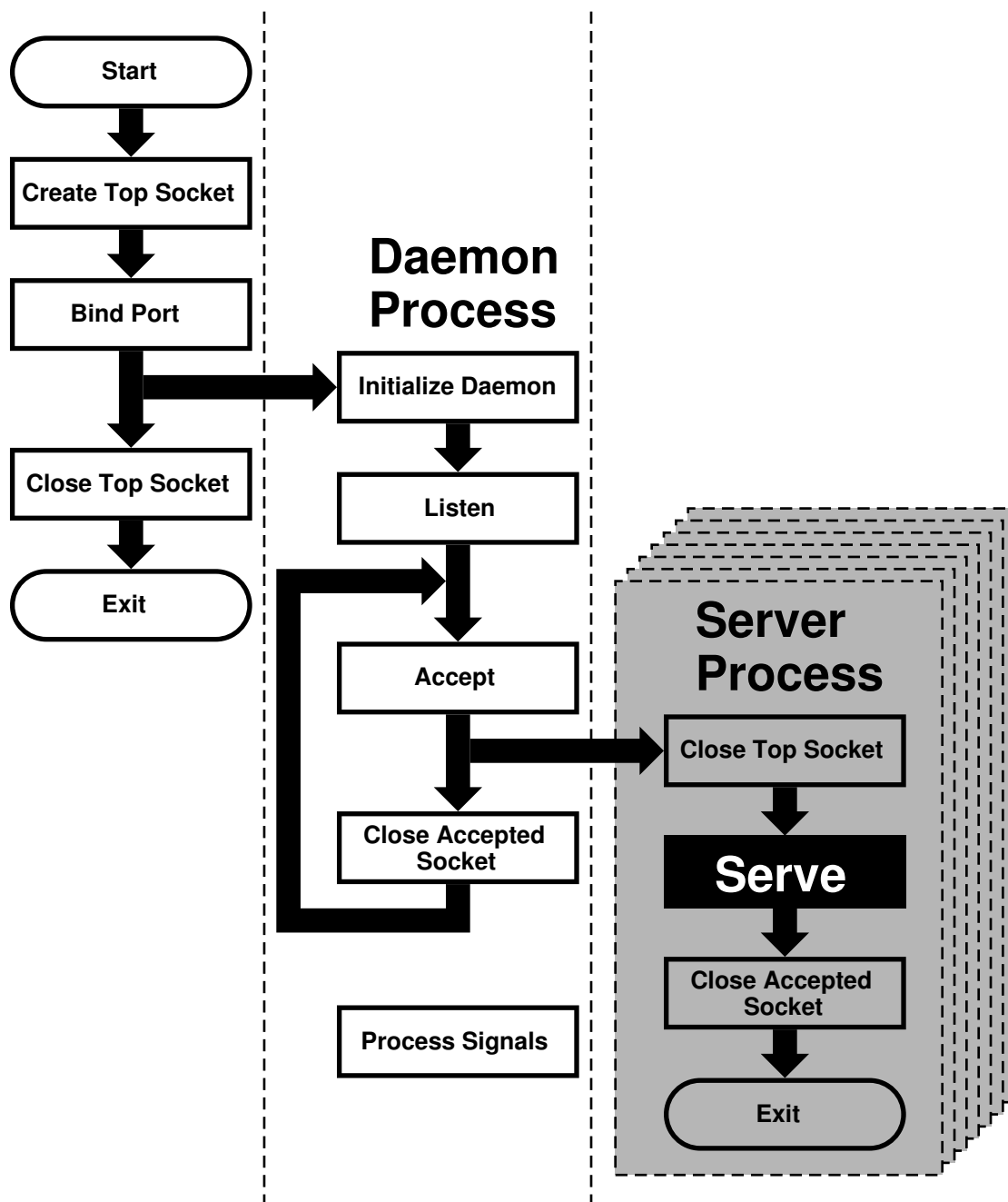
```
struct servent *se;
...
if ((se = getservbyname("daytime", "tcp")) == NULL {
    fprintf(stderr, "Cannot determine which port to use.\n");
    return 7;
}
sa.sin_port = se->s_port;
```

You usually do know the port. But if you are developing a new protocol, you may be testing it on an unofficial port. Some day, you will register the protocol and its port (if nowhere else, at least in your `/etc/services`, which is where `getservbyname` looks). Instead of returning an error in the above code, you just use the temporary port number. Once you have listed the protocol in `/etc/services`, your software will find its port without you having to rewrite the code.

## 7.7 Concurrent Servers

Unlike a sequential server, a *concurrent server* has to be able to serve more than one client at a time. For example, a *chat server* may be serving a specific client for hours—it cannot wait till it stops serving a client before it serves the next one.

This requires a significant change in our flowchart:



We moved the *serve* from the *daemon process* to its own *server process*. However, because each child process inherits all open files (and a socket is treated just like a file), the new process inherits not only the “*accepted handle*,” i.e., the socket returned by the `accept` call, but also the *top socket*, i.e., the one opened by the top process right at the beginning.

However, the *server process* does not need this socket and should `close` it immediately. Similarly, the *daemon process* no longer needs the *accepted socket*, and not only should, but *must* `close` it—otherwise, it will run out of available *file descriptors* sooner or later.

After the *server process* is done serving, it should close the *accepted socket*. Instead of returning to `accept`, it now

exits.

Under Unix, a process does not really *exit*. Instead, it *returns* to its parent. Typically, a parent process `wait`s for its child process, and obtains a return value. However, our *daemon process* cannot simply stop and wait. That would defeat the whole purpose of creating additional processes. But if it never does `wait`, its children will become *zombies*—no longer functional but still roaming around.

For that reason, the *daemon process* needs to set *signal handlers* in its *initialize daemon* phase. At least a `SIGCHLD` signal has to be processed, so the daemon can remove the zombie return values from the system and release the system resources they are taking up.

That is why our flowchart now contains a *process signals* box, which is not connected to any other box. By the way, many servers also process `SIGHUP`, and typically interpret as the signal from the superuser that they should reread their configuration files. This allows us to change settings without having to kill and restart these servers.



# Chapter 8 IPv6 Internals

## 8.1 IPv6/IPsec Implementation

*Contributed by Yoshinobu Inoue <shin@FreeBSD.org>, 5 March 2000.*

This section should explain IPv6 and IPsec related implementation internals. These functionalities are derived from KAME project (<http://www.kame.net/>)

### 8.1.1 IPv6

#### 8.1.1.1 Conformance

The IPv6 related functions conforms, or tries to conform to the latest set of IPv6 specifications. For future reference we list some of the relevant documents below (*NOTE*: this is not a complete list - this is too hard to maintain...).

For details please refer to specific chapter in the document, RFCs, man pages, or comments in the source code.

Conformance tests have been performed on the KAME STABLE kit at TAHI project. Results can be viewed at <http://www.tahi.org/report/KAME/> (<http://www.tahi.org/report/KAME/>). We also attended Univ. of New Hampshire IOL tests (<http://www.iol.unh.edu/>) in the past, with our past snapshots.

- RFC1639: FTP Operation Over Big Address Records (FOOBAR)
  - RFC2428 is preferred over RFC1639. FTP clients will first try RFC2428, then RFC1639 if failed.
- RFC1886: DNS Extensions to support IPv6
- RFC1933: Transition Mechanisms for IPv6 Hosts and Routers
  - IPv4 compatible address is not supported.
  - automatic tunneling (described in 4.3 of this RFC) is not supported.
  - gif(4) interface implements IPv[46]-over-IPv[46] tunnel in a generic way, and it covers "configured tunnel" described in the spec. See 23.5.1.5 in this document for details.
- RFC1981: Path MTU Discovery for IPv6
- RFC2080: RIPng for IPv6
  - `usr.sbin/route6d` support this.
- RFC2292: Advanced Sockets API for IPv6
  - For supported library functions/kernel APIs, see `sys/netinet6/ADVAPI`.
- RFC2362: Protocol Independent Multicast-Sparse Mode (PIM-SM)

- RFC2362 defines packet formats for PIM-SM. `draft-ietf-pim-ipv6-01.txt` is written based on this.
- RFC2373: IPv6 Addressing Architecture
  - supports node required addresses, and conforms to the scope requirement.
- RFC2374: An IPv6 Aggregatable Global Unicast Address Format
  - supports 64-bit length of Interface ID.
- RFC2375: IPv6 Multicast Address Assignments
  - Userland applications use the well-known addresses assigned in the RFC.
- RFC2428: FTP Extensions for IPv6 and NATs
  - RFC2428 is preferred over RFC1639. FTP clients will first try RFC2428, then RFC1639 if failed.
- RFC2460: IPv6 specification
- RFC2461: Neighbor discovery for IPv6
  - See 23.5.1.2 in this document for details.
- RFC2462: IPv6 Stateless Address Autoconfiguration
  - See 23.5.1.4 in this document for details.
- RFC2463: ICMPv6 for IPv6 specification
  - See 23.5.1.9 in this document for details.
- RFC2464: Transmission of IPv6 Packets over Ethernet Networks
- RFC2465: MIB for IPv6: Textual Conventions and General Group
  - Necessary statistics are gathered by the kernel. Actual IPv6 MIB support is provided as a patchkit for `ucd-snmp`.
- RFC2466: MIB for IPv6: ICMPv6 group
  - Necessary statistics are gathered by the kernel. Actual IPv6 MIB support is provided as patchkit for `ucd-snmp`.
- RFC2467: Transmission of IPv6 Packets over FDDI Networks
- RFC2497: Transmission of IPv6 packet over ARCnet Networks
- RFC2553: Basic Socket Interface Extensions for IPv6

- IPv4 mapped address (3.7) and special behavior of IPv6 wildcard bind socket (3.8) are supported. See 23.5.1.12 in this document for details.
- RFC2675: IPv6 Jumbograms
  - See 23.5.1.7 in this document for details.
- RFC2710: Multicast Listener Discovery for IPv6
- RFC2711: IPv6 router alert option
- draft-ietf-ipngwg-router-renum-08: Router renumbering for IPv6
- draft-ietf-ipngwg-icmp-namelookups-02: IPv6 Name Lookups Through ICMP
- draft-ietf-ipngwg-icmp-name-lookups-03: IPv6 Name Lookups Through ICMP
- draft-ietf-pim-ipv6-01.txt: PIM for IPv6
  - pim6dd(8) implements dense mode. pim6sd(8) implements sparse mode.
- draft-itojun-ipv6-tcp-to-anycast-00: Disconnecting TCP connection toward IPv6 anycast address
- draft-yamamoto-wideipv6-comm-model-00
  - See 23.5.1.6 in this document for details.
- draft-ietf-ipngwg-scopedaddr-format-00.txt : An Extension of Format for IPv6 Scoped Addresses

### 8.1.1.2 Neighbor Discovery

Neighbor Discovery is fairly stable. Currently Address Resolution, Duplicated Address Detection, and Neighbor Unreachability Detection are supported. In the near future we will be adding Proxy Neighbor Advertisement support in the kernel and Unsolicited Neighbor Advertisement transmission command as admin tool.

If DAD fails, the address will be marked "duplicated" and message will be generated to syslog (and usually to console). The "duplicated" mark can be checked with `ifconfig(8)`. It is administrators' responsibility to check for and recover from DAD failures. The behavior should be improved in the near future.

Some of the network driver loops multicast packets back to itself, even if instructed not to do so (especially in promiscuous mode). In such cases DAD may fail, because DAD engine sees inbound NS packet (actually from the node itself) and considers it as a sign of duplicate. You may want to look at #if condition marked "heuristics" in `sys/netinet6/nd6_nbr.c:nd6_dad_timer()` as workaround (note that the code fragment in "heuristics" section is not spec conformant).

Neighbor Discovery specification (RFC2461) does not talk about neighbor cache handling in the following cases:

1. when there was no neighbor cache entry, node received unsolicited RS/NS/NA/redirect packet without link-layer address
2. neighbor cache handling on medium without link-layer address (we need a neighbor cache entry for IsRouter bit)

For first case, we implemented workaround based on discussions on IETF ipngwg mailing list. For more details, see the comments in the source code and email thread started from (IPng 7155), dated Feb 6 1999.

IPv6 on-link determination rule (RFC2461) is quite different from assumptions in BSD network code. At this moment, no on-link determination rule is supported where default router list is empty (RFC2461, section 5.2, last sentence in 2nd paragraph - note that the spec misuse the word "host" and "node" in several places in the section).

To avoid possible DoS attacks and infinite loops, only 10 options on ND packet is accepted now. Therefore, if you have 20 prefix options attached to RA, only the first 10 prefixes will be recognized. If this troubles you, please ask it on FREEBSD-CURRENT mailing list and/or modify `nd6_maxndopt` in `sys/netinet6/nd6.c`. If there are high demands we may provide `sysctl` knob for the variable.

### 8.1.1.3 Scope Index

IPv6 uses scoped addresses. Therefore, it is very important to specify scope index (interface index for link-local address, or site index for site-local address) with an IPv6 address. Without scope index, scoped IPv6 address is ambiguous to the kernel, and kernel will not be able to determine the outbound interface for a packet.

Ordinary userland applications should use advanced API (RFC2292) to specify scope index, or interface index. For similar purpose, `sin6_scope_id` member in `sockaddr_in6` structure is defined in RFC2553. However, the semantics for `sin6_scope_id` is rather vague. If you care about portability of your application, we suggest you to use advanced API rather than `sin6_scope_id`.

In the kernel, an interface index for link-local scoped address is embedded into 2nd 16bit-word (3rd and 4th byte) in IPv6 address. For example, you may see something like:

```
fe80:1::200:f8ff:fe01:6317
```

in the routing table and interface address structure (struct `in6_ifaddr`). The address above is a link-local unicast address which belongs to a network interface whose interface identifier is 1. The embedded index enables us to identify IPv6 link local addresses over multiple interfaces effectively and with only a little code change.

Routing daemons and configuration programs, like `route6d(8)` and `ifconfig(8)`, will need to manipulate the "embedded" scope index. These programs use routing sockets and `ioctl`s (like `SIOCGIFADDR_IN6`) and the kernel API will return IPv6 addresses with 2nd 16bit-word filled in. The APIs are for manipulating kernel internal structure. Programs that use these APIs have to be prepared about differences in kernels anyway.

When you specify scoped address to the command line, NEVER write the embedded form (such as `ff02:1::1` or `fe80:2::fedc`). This is not supposed to work. Always use standard form, like `ff02::1` or `fe80::fedc`, with command line option for specifying interface (like `ping6 -I ne0 ff02::1`). In general, if a command does not have command line option to specify outgoing interface, that command is not ready to accept scoped address. This may seem to be opposite from IPv6's premise to support "dentist office" situation. We believe that specifications need some improvements for this.

Some of the userland tools support extended numeric IPv6 syntax, as documented in `draft-ietf-ipngwg-scopedaddr-format-00.txt`. You can specify outgoing link, by using name of the outgoing interface like `"fe80::1%ne0"`. This way you will be able to specify link-local scoped address without much trouble.

To use this extension in your program, you will need to use `getaddrinfo(3)`, and `getnameinfo(3)` with `NI_WITHSCOPEID`. The implementation currently assumes 1-to-1 relationship between a link and an interface, which is stronger than what specs say.

### 8.1.1.4 Plug and Play

Most of the IPv6 stateless address autoconfiguration is implemented in the kernel. Neighbor Discovery functions are implemented in the kernel as a whole. Router Advertisement (RA) input for hosts is implemented in the kernel. Router Solicitation (RS) output for endhosts, RS input for routers, and RA output for routers are implemented in the userland.

#### 8.1.1.4.1 Assignment of link-local, and special addresses

IPv6 link-local address is generated from IEEE802 address (Ethernet MAC address). Each of interface is assigned an IPv6 link-local address automatically, when the interface becomes up (IFF\_UP). Also, direct route for the link-local address is added to routing table.

Here is an output of netstat command:

```
Internet6:
Destination          Gateway              Flags      Netif  Expire
fe80:1::%ed0/64      link#1              UC         ed0
fe80:2::%ep0/64      link#2              UC         ep0
```

Interfaces that has no IEEE802 address (pseudo interfaces like tunnel interfaces, or ppp interfaces) will borrow IEEE802 address from other interfaces, such as Ethernet interfaces, whenever possible. If there is no IEEE802 hardware attached, last-resort pseudorandom value, which is from MD5(hostname), will be used as source of link-local address. If it is not suitable for your usage, you will need to configure the link-local address manually.

If an interface is not capable of handling IPv6 (such as lack of multicast support), link-local address will not be assigned to that interface. See section 2 for details.

Each interface joins the solicited multicast address and the link-local all-nodes multicast addresses (e.g. fe80::1:ff01:6317 and ff02::1, respectively, on the link the interface is attached). In addition to a link-local address, the loopback address (::1) will be assigned to the loopback interface. Also, ::1/128 and ff01::/32 are automatically added to routing table, and loopback interface joins node-local multicast group ff01::1.

#### 8.1.1.4.2 Stateless address autoconfiguration on hosts

In IPv6 specification, nodes are separated into two categories: *routers* and *hosts*. Routers forward packets addressed to others, hosts does not forward the packets. net.inet6.ip6.forwarding defines whether this node is router or host (router if it is 1, host if it is 0).

When a host hears Router Advertisement from the router, a host may autoconfigure itself by stateless address autoconfiguration. This behavior can be controlled by net.inet6.ip6.accept\_rtadv (host autoconfigures itself if it is set to 1). By autoconfiguration, network address prefix for the receiving interface (usually global address prefix) is added. Default route is also configured. Routers periodically generate Router Advertisement packets. To request an adjacent router to generate RA packet, a host can transmit Router Solicitation. To generate a RS packet at any time, use the *rtsof* command. *rtsof*(8) daemon is also available. *rtsof*(8) generates Router Solicitation whenever necessary, and it works great for nomadic usage (notebooks/laptops). If one wishes to ignore Router Advertisements, use *sysctl* to set net.inet6.ip6.accept\_rtadv to 0.

To generate Router Advertisement from a router, use the *rtadvd*(8) daemon.

Note that, IPv6 specification assumes the following items, and nonconforming cases are left unspecified:

- Only hosts will listen to router advertisements

- Hosts have single network interface (except loopback)

Therefore, this is unwise to enable `net.inet6.ip6.accept_rtadv` on routers, or multi-interface host. A misconfigured node can behave strange (nonconforming configuration allowed for those who would like to do some experiments).

To summarize the `sysctl` knob:

```
accept_rtadv forwarding role of the node
--- --- ---
0 0 host (to be manually configured)
0 1 router
1 0 autoconfigured host
(spec assumes that host has single
interface only, autoconfigured host
with multiple interface is
out-of-scope)
1 1 invalid, or experimental
(out-of-scope of spec)
```

RFC2462 has validation rule against incoming RA prefix information option, in 5.5.3 (e). This is to protect hosts from malicious (or misconfigured) routers that advertise very short prefix lifetime. There was an update from Jim Bound to `ipngwg` mailing list (look for "(ipng 6712)" in the archive) and it is implemented Jim's update.

See 23.5.1.2 in the document for relationship between DAD and autoconfiguration.

### 8.1.1.5 Generic tunnel interface

GIF (Generic InterFace) is a pseudo interface for configured tunnel. Details are described in `gif(4)`. Currently

- v6 in v6
- v6 in v4
- v4 in v6
- v4 in v4

are available. Use `gifconfig(8)` to assign physical (outer) source and destination address to gif interfaces. Configuration that uses same address family for inner and outer IP header (v4 in v4, or v6 in v6) is dangerous. It is very easy to configure interfaces and routing tables to perform infinite level of tunneling. *Please be warned.*

`gif` can be configured to be ECN-friendly. See 23.5.4.5 for ECN-friendliness of tunnels, and `gif(4)` for how to configure.

If you would like to configure an IPv4-in-IPv6 tunnel with gif interface, read `gif(4)` carefully. You will need to remove IPv6 link-local address automatically assigned to the gif interface.

### 8.1.1.6 Source Address Selection

Current source selection rule is scope oriented (there are some exceptions - see below). For a given destination, a source IPv6 address is selected by the following rule:

1. If the source address is explicitly specified by the user (e.g. via the advanced API), the specified address is used.

2. If there is an address assigned to the outgoing interface (which is usually determined by looking up the routing table) that has the same scope as the destination address, the address is used.

This is the most typical case.

3. If there is no address that satisfies the above condition, choose a global address assigned to one of the interfaces on the sending node.
4. If there is no address that satisfies the above condition, and destination address is site local scope, choose a site local address assigned to one of the interfaces on the sending node.
5. If there is no address that satisfies the above condition, choose the address associated with the routing table entry for the destination. This is the last resort, which may cause scope violation.

For instance, ::1 is selected for ff01::1, fe80:1::200:f8ff:fe01:6317 for fe80:1::2a0:24ff:feab:839b (note that embedded interface index - described in 23.5.1.3 - helps us choose the right source address. Those embedded indices will not be on the wire). If the outgoing interface has multiple address for the scope, a source is selected longest match basis (rule 3). Suppose 3ffe:501:808:1:200:f8ff:fe01:6317 and 3ffe:2001:9:124:200:f8ff:fe01:6317 are given to the outgoing interface. 3ffe:501:808:1:200:f8ff:fe01:6317 is chosen as the source for the destination 3ffe:501:800::1.

Note that the above rule is not documented in the IPv6 spec. It is considered "up to implementation" item. There are some cases where we do not use the above rule. One example is connected TCP session, and we use the address kept in tcb as the source. Another example is source address for Neighbor Advertisement. Under the spec (RFC2461 7.2.2) NA's source should be the target address of the corresponding NS's target. In this case we follow the spec rather than the above longest-match rule.

For new connections (when rule 1 does not apply), deprecated addresses (addresses with preferred lifetime = 0) will not be chosen as source address if other choices are available. If no other choices are available, deprecated address will be used as a last resort. If there are multiple choice of deprecated addresses, the above scope rule will be used to choose from those deprecated addresses. If you would like to prohibit the use of deprecated address for some reason, configure net.inet6.ip6.use\_deprecated to 0. The issue related to deprecated address is described in RFC2462 5.5.4 (NOTE: there is some debate underway in IETF ipngwg on how to use "deprecated" address).

### 8.1.1.7 Jumbo Payload

The Jumbo Payload hop-by-hop option is implemented and can be used to send IPv6 packets with payloads longer than 65,535 octets. But currently no physical interface whose MTU is more than 65,535 is supported, so such payloads can be seen only on the loopback interface (i.e. lo0).

If you want to try jumbo payloads, you first have to reconfigure the kernel so that the MTU of the loopback interface is more than 65,535 bytes; add the following to the kernel configuration file:

```
options "LARGE_LOMTU" #To test jumbo payload
```

and recompile the new kernel.

Then you can test jumbo payloads by the ping6(8) command with -b and -s options. The -b option must be specified to enlarge the size of the socket buffer and the -s option specifies the length of the packet, which should be more than 65,535. For example, type as follows:

```
% ping6 -b 70000 -s 68000 ::1
```

The IPv6 specification requires that the Jumbo Payload option must not be used in a packet that carries a fragment header. If this condition is broken, an ICMPv6 Parameter Problem message must be sent to the sender. specification is followed, but you cannot usually see an ICMPv6 error caused by this requirement.

When an IPv6 packet is received, the frame length is checked and compared to the length specified in the payload length field of the IPv6 header or in the value of the Jumbo Payload option, if any. If the former is shorter than the latter, the packet is discarded and statistics are incremented. You can see the statistics as output of netstat(8) command with '-s -p ip6' option:

```
% netstat -s -p ip6
ip6:
(snip)
1 with data size < data length
```

So, kernel does not send an ICMPv6 error unless the erroneous packet is an actual Jumbo Payload, that is, its packet size is more than 65,535 bytes. As described above, currently no physical interface with such a huge MTU is supported, so it rarely returns an ICMPv6 error.

TCP/UDP over jumbogram is not supported at this moment. This is because we have no medium (other than loopback) to test this. Contact us if you need this.

IPsec does not work on jumbograms. This is due to some specification twists in supporting AH with jumbograms (AH header size influences payload length, and this makes it real hard to authenticate inbound packet with jumbo payload option as well as AH).

There are fundamental issues in \*BSD support for jumbograms. We would like to address those, but we need more time to finalize these. To name a few:

- mbuf pkthdr.len field is typed as "int" in 4.4BSD, so it will not hold jumbogram with len > 2G on 32bit architecture CPUs. If we would like to support jumbogram properly, the field must be expanded to hold 4G + IPv6 header + link-layer header. Therefore, it must be expanded to at least int64\_t (u\_int32\_t is NOT enough).
- We mistakenly use "int" to hold packet length in many places. We need to convert them into larger integral type. It needs a great care, as we may experience overflow during packet length computation.
- We mistakenly check for ip6\_plen field of IPv6 header for packet payload length in various places. We should be checking mbuf pkthdr.len instead. ip6\_input() will perform sanity check on jumbo payload option on input, and we can safely use mbuf pkthdr.len afterwards.
- TCP code needs a careful update in bunch of places, of course.

### 8.1.1.8 Loop prevention in header processing

IPv6 specification allows arbitrary number of extension headers to be placed onto packets. If we implement IPv6 packet processing code in the way BSD IPv4 code is implemented, kernel stack may overflow due to long function call chain. sys/netinet6 code is carefully designed to avoid kernel stack overflow. Because of this, sys/netinet6 code defines its own protocol switch structure, as "struct ip6protosw" (see netinet6/ip6protosw.h). There is no such update to IPv4 part (sys/netinet) for compatibility, but small change is added to its pr\_input() prototype. So "struct ipprotosw" is also defined. Because of this, if you receive IPsec-over-IPv4 packet with massive number of IPsec headers, kernel stack may blow up. IPsec-over-IPv6 is okay. (Off-course, for those all IPsec headers to be processed, each such IPsec header must pass each IPsec check. So an anonymous attacker will not be able to do such an attack.)



### 8.1.1.9 ICMPv6

After RFC2463 was published, IETF ipngwg has decided to disallow ICMPv6 error packet against ICMPv6 redirect, to prevent ICMPv6 storm on a network medium. This is already implemented into the kernel.

### 8.1.1.10 Applications

For userland programming, we support IPv6 socket API as specified in RFC2553, RFC2292 and upcoming Internet drafts.

TCP/UDP over IPv6 is available and quite stable. You can enjoy telnet(1), ftp(1), rlogin(1), rsh(1), ssh(1), etc. These applications are protocol independent. That is, they automatically chooses IPv4 or IPv6 according to DNS.

### 8.1.1.11 Kernel Internals

While `ip_forward()` calls `ip_output()`, `ip6_forward()` directly calls `if_output()` since routers must not divide IPv6 packets into fragments.

ICMPv6 should contain the original packet as long as possible up to 1280. UDP6/IP6 port unreachable, for instance, should contain all extension headers and the *\*unchanged\** UDP6 and IP6 headers. So, all IP6 functions except TCP never convert network byte order into host byte order, to save the original packet.

`tcp_input()`, `udp6_input()` and `icmp6_input()` can not assume that IP6 header is preceding the transport headers due to extension headers. So, `in6_cksum()` was implemented to handle packets whose IP6 header and transport header is not continuous. TCP/IP6 nor UDP6/IP6 header structures do not exist for checksum calculation.

To process IP6 header, extension headers and transport headers easily, network drivers are now required to store packets in one internal mbuf or one or more external mbufs. A typical old driver prepares two internal mbufs for 96 - 204 bytes data, however, now such packet data is stored in one external mbuf.

`netstat -s -p ip6` tells you whether or not your driver conforms such requirement. In the following example, "cce0" violates the requirement. (For more information, refer to Section 2.)

```
Mbuf statistics:
    317 one mbuf
    two or more mbuf::
        lo0 = 8
cce0 = 10
    3282 one ext mbuf
    0 two or more ext mbuf
```

Each input function calls `IP6_EXTHDR_CHECK` in the beginning to check if the region between IP6 and its header is continuous. `IP6_EXTHDR_CHECK` calls `m_pullup()` only if the mbuf has `M_LOOP` flag, that is, the packet comes from the loopback interface. `m_pullup()` is never called for packets coming from physical network interfaces.

Both IP and IP6 reassemble functions never call `m_pullup()`.

### 8.1.1.12 IPv4 mapped address and IPv6 wildcard socket

RFC2553 describes IPv4 mapped address (3.7) and special behavior of IPv6 wildcard bind socket (3.8). The spec allows you to:

- Accept IPv4 connections by AF\_INET6 wildcard bind socket.
- Transmit IPv4 packet over AF\_INET6 socket by using special form of the address like ::ffff:10.1.1.1.

but the spec itself is very complicated and does not specify how the socket layer should behave. Here we call the former one "listening side" and the latter one "initiating side", for reference purposes.

You can perform wildcard bind on both of the address families, on the same port.

The following table show the behavior of FreeBSD 4.x.

	listening side	initiating side
		(AF_INET6 wildcard socket gets IPv4 conn.)
	---	---
FreeBSD 4.x	configurable default: enabled	supported

The following sections will give you more details, and how you can configure the behavior.

Comments on listening side:

It looks that RFC2553 talks too little on wildcard bind issue, especially on the port space issue, failure mode and relationship between AF\_INET/INET6 wildcard bind. There can be several separate interpretation for this RFC which conform to it but behaves differently. So, to implement portable application you should assume nothing about the behavior in the kernel. Using getaddrinfo(3) is the safest way. Port number space and wildcard bind issues were discussed in detail on ipv6imp mailing list, in mid March 1999 and it looks that there is no concrete consensus (means, up to implementers). You may want to check the mailing list archives.

If a server application would like to accept IPv4 and IPv6 connections, there will be two alternatives.

One is using AF\_INET and AF\_INET6 socket (you will need two sockets). Use getaddrinfo(3) with AI\_PASSIVE into ai\_flags, and socket(2) and bind(2) to all the addresses returned. By opening multiple sockets, you can accept connections onto the socket with proper address family. IPv4 connections will be accepted by AF\_INET socket, and IPv6 connections will be accepted by AF\_INET6 socket.

Another way is using one AF\_INET6 wildcard bind socket. Use getaddrinfo(3) with AI\_PASSIVE into ai\_flags and with AF\_INET6 into ai\_family, and set the 1st argument hostname to NULL. And socket(2) and bind(2) to the address returned. (should be IPv6 unspecified addr). You can accept either of IPv4 and IPv6 packet via this one socket.

To support only IPv6 traffic on AF\_INET6 wildcard binded socket portably, always check the peer address when a connection is made toward AF\_INET6 listening socket. If the address is IPv4 mapped address, you may want to reject the connection. You can check the condition by using IN6\_IS\_ADDR\_V4MAPPED() macro.

To resolve this issue more easily, there is system dependent setsockopt(2) option, IPV6\_BINDV6ONLY, used like below.

```
int on;

setsockopt(s, IPPROTO_IPV6, IPV6_BINDV6ONLY,
```

```
(char *)&on, sizeof (on) < 0));
```

When this call succeed, then this socket only receive IPv6 packets.

Comments on initiating side:

Advise to application implementers: to implement a portable IPv6 application (which works on multiple IPv6 kernels), we believe that the following is the key to the success:

- NEVER hardcode AF\_INET nor AF\_INET6.
- Use getaddrinfo(3) and getnameinfo(3) throughout the system. Never use gethostby\*(), getaddrby\*(), inet\_\*() or getipnodeby\*(). (To update existing applications to be IPv6 aware easily, sometime getipnodeby\*() will be useful. But if possible, try to rewrite the code to use getaddrinfo(3) and getnameinfo(3).)
- If you would like to connect to destination, use getaddrinfo(3) and try all the destination returned, like telnet(1) does.
- Some of the IPv6 stack is shipped with buggy getaddrinfo(3). Ship a minimal working version with your application and use that as last resort.

If you would like to use AF\_INET6 socket for both IPv4 and IPv6 outgoing connection, you will need to use getipnodebyname(3). When you would like to update your existing application to be IPv6 aware with minimal effort, this approach might be chosen. But please note that it is a temporal solution, because getipnodebyname(3) itself is not recommended as it does not handle scoped IPv6 addresses at all. For IPv6 name resolution, getaddrinfo(3) is the preferred API. So you should rewrite your application to use getaddrinfo(3), when you get the time to do it.

When writing applications that make outgoing connections, story goes much simpler if you treat AF\_INET and AF\_INET6 as totally separate address family. {set,get}sockopt issue goes simpler, DNS issue will be made simpler. We do not recommend you to rely upon IPv4 mapped address.

### 8.1.1.12.1 unified tcp and inpcb code

FreeBSD 4.x uses shared tcp code between IPv4 and IPv6 (from sys/netinet/tcp\*) and separate udp4/6 code. It uses unified inpcb structure.

The platform can be configured to support IPv4 mapped address. Kernel configuration is summarized as follows:

- By default, AF\_INET6 socket will grab IPv4 connections in certain condition, and can initiate connection to IPv4 destination embedded in IPv4 mapped IPv6 address.
- You can disable it on entire system with sysctl like below.

```
sysctl net.inet6.ip6.mapped_addr=0
```

#### 8.1.1.12.1.1 listening side

Each socket can be configured to support special AF\_INET6 wildcard bind (enabled by default). You can disable it on each socket basis with setsockopt(2) like below.

```
int on;

setsockopt(s, IPPROTO_IPV6, IPV6_BINDV6ONLY,
```

```
(char *)&on, sizeof (on) < 0));
```

Wildcard AF\_INET6 socket grabs IPv4 connection if and only if the following conditions are satisfied:

- there is no AF\_INET socket that matches the IPv4 connection
- the AF\_INET6 socket is configured to accept IPv4 traffic, i.e. getsockopt(IPV6\_BINDV6ONLY) returns 0.

There is no problem with open/close ordering.

#### 8.1.1.12.1.2 initiating side

FreeBSD 4.x supports outgoing connection to IPv4 mapped address (::ffff:10.1.1.1), if the node is configured to support IPv4 mapped address.

#### 8.1.1.13 sockaddr\_storage

When RFC2553 was about to be finalized, there was discussion on how struct sockaddr\_storage members are named. One proposal is to prepend "\_\_" to the members (like "\_\_ss\_len") as they should not be touched. The other proposal was not to prepend it (like "ss\_len") as we need to touch those members directly. There was no clear consensus on it.

As a result, RFC2553 defines struct sockaddr\_storage as follows:

```
struct sockaddr_storage {
    u_char __ss_len; /* address length */
    u_char __ss_family; /* address family */
    /* and bunch of padding */
};
```

On the contrary, XNET draft defines as follows:

```
struct sockaddr_storage {
    u_char ss_len; /* address length */
    u_char ss_family; /* address family */
    /* and bunch of padding */
};
```

In December 1999, it was agreed that RFC2553bis should pick the latter (XNET) definition.

Current implementation conforms to XNET definition, based on RFC2553bis discussion.

If you look at multiple IPv6 implementations, you will be able to see both definitions. As an userland programmer, the most portable way of dealing with it is to:

1. ensure ss\_family and/or ss\_len are available on the platform, by using GNU autoconf,
2. have -Dss\_family=\_\_ss\_family to unify all occurrences (including header file) into \_\_ss\_family, or
3. never touch \_\_ss\_family. cast to sockaddr \* and use sa\_family like:

```
struct sockaddr_storage ss;
family = ((struct sockaddr *)&ss)->sa_family
```

## 8.1.2 Network Drivers

Now following two items are required to be supported by standard drivers:

1. mbuf clustering requirement. In this stable release, we changed MINCLSIZE into MHLEN+1 for all the operating systems in order to make all the drivers behave as we expect.
2. multicast. If ifmcstat(8) yields no multicast group for a interface, that interface has to be patched.

If any of the drivers do not support the requirements, then the drivers can not be used for IPv6 and/or IPsec communication. If you find any problem with your card using IPv6/IPsec, then, please report it to the FreeBSD problem reports mailing list <freebsd-bugs@FreeBSD.org>.

(NOTE: In the past we required all PCMCIA drivers to have a call to in6\_ifattach(). We have no such requirement any more)

## 8.1.3 Translator

We categorize IPv4/IPv6 translator into 4 types:

- *Translator A* --- It is used in the early stage of transition to make it possible to establish a connection from an IPv6 host in an IPv6 island to an IPv4 host in the IPv4 ocean.
- *Translator B* --- It is used in the early stage of transition to make it possible to establish a connection from an IPv4 host in the IPv4 ocean to an IPv6 host in an IPv6 island.
- *Translator C* --- It is used in the late stage of transition to make it possible to establish a connection from an IPv4 host in an IPv4 island to an IPv6 host in the IPv6 ocean.
- *Translator D* --- It is used in the late stage of transition to make it possible to establish a connection from an IPv6 host in the IPv6 ocean to an IPv4 host in an IPv4 island.

TCP relay translator for category A is supported. This is called "FAITH". We also provide IP header translator for category A. (The latter is not yet put into FreeBSD 4.x yet.)

### 8.1.3.1 FAITH TCP relay translator

FAITH system uses TCP relay daemon called faithd(8) helped by the kernel. FAITH will reserve an IPv6 address prefix, and relay TCP connection toward that prefix to IPv4 destination.

For example, if the reserved IPv6 prefix is 3ffe:0501:0200:ffff::, and the IPv6 destination for TCP connection is 3ffe:0501:0200:ffff::163.221.202.12, the connection will be relayed toward IPv4 destination 163.221.202.12.

```
destination IPv4 node (163.221.202.12)
^
```

```

| IPv4 tcp toward 163.221.202.12
FAITH-relay dual stack node
^
| IPv6 TCP toward 3ffe:0501:0200:ffff::163.221.202.12
source IPv6 node

```

faithd(8) must be invoked on FAITH-relay dual stack node.

For more details, consult `src/usr.sbin/faithd/README`

## 8.1.4 IPsec

IPsec is mainly organized by three components.

1. Policy Management
2. Key Management
3. AH and ESP handling

### 8.1.4.1 Policy Management

The kernel implements experimental policy management code. There are two way to manage security policy. One is to configure per-socket policy using `setsockopt(2)`. In this cases, policy configuration is described in `ipsec_set_policy(3)`. The other is to configure kernel packet filter-based policy using `PF_KEY` interface, via `setkey(8)`.

The policy entry is not re-ordered with its indexes, so the order of entry when you add is very significant.

### 8.1.4.2 Key Management

The key management code implemented in this kit (`sys/netkey`) is a home-brew `PFKEY v2` implementation. This conforms to `RFC2367`.

The home-brew IKE daemon, "racoon" is included in the kit (`kame/kame/racoon`). Basically you will need to run `racoon` as daemon, then setup a policy to require keys (like `ping -P 'out ipsec esp/transport//use'`). The kernel will contact `racoon` daemon as necessary to exchange keys.

### 8.1.4.3 AH and ESP handling

IPsec module is implemented as "hooks" to the standard IPv4/IPv6 processing. When sending a packet, `ip{,6}_output()` checks if ESP/AH processing is required by checking if a matching SPD (Security Policy Database) is found. If ESP/AH is needed, `{esp,ah}{4,6}_output()` will be called and `mbuf` will be updated accordingly. When a packet is received, `{esp,ah}4_input()` will be called based on protocol number, i.e. `(*inetsw[proto])()`. `{esp,ah}4_input()` will decrypt/check authenticity of the packet, and strips off daisy-chained header and padding for ESP/AH. It is safe to strip off the ESP/AH header on packet reception, since we will never use the received packet in "as is" form.

By using ESP/AH, TCP4/6 effective data segment size will be affected by extra daisy-chained headers inserted by ESP/AH. Our code takes care of the case.

Basic crypto functions can be found in directory "sys/crypto". ESP/AH transform are listed in {esp,ah}\_core.c with wrapper functions. If you wish to add some algorithm, add wrapper function in {esp,ah}\_core.c, and add your crypto algorithm code into sys/crypto.

Tunnel mode is partially supported in this release, with the following restrictions:

- IPsec tunnel is not combined with GIF generic tunneling interface. It needs a great care because we may create an infinite loop between ip\_output() and tunnelif->if\_output(). Opinion varies if it is better to unify them, or not.
- MTU and Don't Fragment bit (IPv4) considerations need more checking, but basically works fine.
- Authentication model for AH tunnel must be revisited. We will need to improve the policy management engine, eventually.

#### 8.1.4.4 Conformance to RFCs and IDs

The IPsec code in the kernel conforms (or, tries to conform) to the following standards:

"old IPsec" specification documented in `rfc182[5-9].txt`

"new IPsec" specification documented in `rfc240[1-6].txt`, `rfc241[01].txt`, `rfc2451.txt` and `draft-mcdonald-simple-ipsec-api-01.txt` (draft expired, but you can take from `ftp://ftp.kame.net/pub/internet-drafts/` (`ftp://ftp.kame.net/pub/internet-drafts/`)). (NOTE: IKE specifications, `rfc241[7-9].txt` are implemented in userland, as "racoon" IKE daemon)

Currently supported algorithms are:

- old IPsec AH
  - null crypto checksum (no document, just for debugging)
  - keyed MD5 with 128bit crypto checksum (`rfc1828.txt`)
  - keyed SHA1 with 128bit crypto checksum (no document)
  - HMAC MD5 with 128bit crypto checksum (`rfc2085.txt`)
  - HMAC SHA1 with 128bit crypto checksum (no document)
- old IPsec ESP
  - null encryption (no document, similar to `rfc2410.txt`)
  - DES-CBC mode (`rfc1829.txt`)
- new IPsec AH
  - null crypto checksum (no document, just for debugging)
  - keyed MD5 with 96bit crypto checksum (no document)
  - keyed SHA1 with 96bit crypto checksum (no document)

- HMAC MD5 with 96bit crypto checksum (`rfc2403.txt`)
- HMAC SHA1 with 96bit crypto checksum (`rfc2404.txt`)
  
- new IPsec ESP
  - null encryption (`rfc2410.txt`)
  - DES-CBC with derived IV (`draft-ietf-ipsec-ciph-des-derived-01.txt`, draft expired)
  - DES-CBC with explicit IV (`rfc2405.txt`)
  - 3DES-CBC with explicit IV (`rfc2451.txt`)
  - BLOWFISH CBC (`rfc2451.txt`)
  - CAST128 CBC (`rfc2451.txt`)
  - RC5 CBC (`rfc2451.txt`)
  - each of the above can be combined with:
    - ESP authentication with HMAC-MD5(96bit)
    - ESP authentication with HMAC-SHA1(96bit)

The following algorithms are NOT supported:

- old IPsec AH
  - HMAC MD5 with 128bit crypto checksum + 64bit replay prevention (`rfc2085.txt`)
  - keyed SHA1 with 160bit crypto checksum + 32bit padding (`rfc1852.txt`)

IPsec (in kernel) and IKE (in userland as "racoon") has been tested at several interoperability test events, and it is known to interoperate with many other implementations well. Also, current IPsec implementation has quite wide coverage for IPsec crypto algorithms documented in RFC (we cover algorithms without intellectual property issues only).

#### 8.1.4.5 ECN consideration on IPsec tunnels

ECN-friendly IPsec tunnel is supported as described in `draft-ipsec-ecn-00.txt`.

Normal IPsec tunnel is described in RFC2401. On encapsulation, IPv4 TOS field (or, IPv6 traffic class field) will be copied from inner IP header to outer IP header. On decapsulation outer IP header will be simply dropped. The decapsulation rule is not compatible with ECN, since ECN bit on the outer IP TOS/traffic class field will be lost.

To make IPsec tunnel ECN-friendly, we should modify encapsulation and decapsulation procedure. This is described in <http://www.aciri.org/floyd/papers/draft-ipsec-ecn-00.txt> (<http://www.aciri.org/floyd/papers/draft-ipsec-ecn-00.txt>), chapter 3.

IPsec tunnel implementation can give you three behaviors, by setting `net.inet.ipsec.ecn` (or `net.inet6.ipsec6.ecn`) to some value:



- RFC2401: no consideration for ECN (sysctl value -1)
- ECN forbidden (sysctl value 0)
- ECN allowed (sysctl value 1)

Note that the behavior is configurable in per-node manner, not per-SA manner (draft-ipsec-ecn-00 wants per-SA configuration, but it looks too much for me).

The behavior is summarized as follows (see source code for more detail):

	encapsulate	decapsulate
	---	---
RFC2401	copy all TOS bits from inner to outer.	drop TOS bits on outer (use inner TOS bits as is)
ECN forbidden	copy TOS bits except for ECN (masked with 0xfc) from inner to outer. set ECN bits to 0.	drop TOS bits on outer (use inner TOS bits as is)
ECN allowed	copy TOS bits except for ECN CE (masked with 0xfe) from inner to outer. set ECN CE bit to 0.	use inner TOS bits with some change. if outer ECN CE bit is 1, enable ECN CE bit on the inner.

General strategy for configuration is as follows:

- if both IPsec tunnel endpoint are capable of ECN-friendly behavior, you should better configure both end to "ECN allowed" (sysctl value 1).
- if the other end is very strict about TOS bit, use "RFC2401" (sysctl value -1).
- in other cases, use "ECN forbidden" (sysctl value 0).

The default behavior is "ECN forbidden" (sysctl value 0).

For more information, please refer to:

<http://www.aciri.org/floyd/papers/draft-ipsec-ecn-00.txt> (<http://www.aciri.org/floyd/papers/draft-ipsec-ecn-00.txt>),  
RFC2481 (Explicit Congestion Notification), `src/sys/netinet6/{ah,esp}_input.c`

(Thanks goes to Kenjiro Cho <kjc@csl.sony.co.jp> for detailed analysis)

#### 8.1.4.6 Interoperability

Here are (some of) platforms that KAME code have tested IPsec/IKE interoperability in the past. Note that both ends may have modified their implementation, so use the following list just for reference purposes.

Altiga, Ashley-laurent (vpcom.com), Data Fellows (F-Secure), Ericsson ACC, FreeS/WAN, HITACHI, IBM AIX, IJ, Intel, Microsoft WinNT, NIST (linux IPsec + plutoplus), Netscreen, OpenBSD, RedCreek, Routerware, SSH, Secure Computing, Soliton, Toshiba, VPNet, Yamaha RT100i

## III. Kernel

# Chapter 9 \* History of the Unix Kernel

Some history of the Unix/BSD kernel, system calls, how processes work, blocking, scheduling, threads (kernel), context switching, signals, interrupts, modules, etc.

# Chapter 10 Locking Notes

*This chapter is maintained by the FreeBSD SMP Next Generation Project. Please direct any comments or suggestions to its FreeBSD symmetric multiprocessing mailing list <freebsd-smp@FreeBSD.org>.*

This document outlines the locking used in the FreeBSD kernel to permit effective multi-processing within the kernel. Locking can be achieved via several means. Data structures can be protected by mutexes or lockmgr(9) locks. A few variables are protected simply by always using atomic operations to access them.

## 10.1 Mutexes

A mutex is simply a lock used to guarantee mutual exclusion. Specifically, a mutex may only be owned by one entity at a time. If another entity wishes to obtain a mutex that is already owned, it must wait until the mutex is released. In the FreeBSD kernel, mutexes are owned by processes.

Mutexes may be recursively acquired, but they are intended to be held for a short period of time. Specifically, one may not sleep while holding a mutex. If you need to hold a lock across a sleep, use a lockmgr(9) lock.

Each mutex has several properties of interest:

### Variable Name

The name of the struct `mtx` variable in the kernel source.

### Logical Name

The name of the mutex assigned to it by `mtx_init`. This name is displayed in KTR trace messages and witness errors and warnings and is used to distinguish mutexes in the witness code.

### Type

The type of the mutex in terms of the `MTX_*` flags. The meaning for each flag is related to its meaning as documented in `mutex(9)`.

### MTX\_DEF

A sleep mutex

### MTX\_SPIN

A spin mutex

### MTX\_COLD

This mutex is initialized very early. Thus, it must be declared via `MUTEX_DECLARE`, and the `MTX_COLD` flag must be passed to `mtx_init`.

### MTX\_TOPHALF

This spin mutex does not disable interrupts.

MTX\_NORECURSE

This mutex is not allowed to recurse.

Protectees

A list of data structures or data structure members that this entry protects. For data structure members, the name will be in the form of structure name.*member name*.

Dependent Functions

Functions that can only be called if this mutex is held.

**Table 10-1. Mutex List**

<b>Variable Name</b>	<b>Logical Name</b>	<b>Type</b>	<b>Protectees</b>	<b>Dependent Functions</b>
----------------------	---------------------	-------------	-------------------	----------------------------

Variable Name	Logical Name	Type	Protectees	Dependent Functions
sched_lock	“sched lock”	MTX_SPIN   MTX_COLD	_gmonparam, cnt.v_swch, cp_time, curpriority, mtx.mtx_blocked, mtx.mtx_contested, proc.p_contested, proc.p_blocked, proc.p_flag (P_PROFIL XXX, P_INMEM, P_SINTR, P_TIMEOUT, P_SWAPINREQ XXX, P_INMEN XXX), proc.p_nice, proc.p_procq, proc.p_blocked, proc.p_estcpu, proc.p_nativepri, proc.p_priority, proc.p_usrpri, proc.p_rtprio, proc.p_rqindex, proc.p_stats- >p_prof, proc.p_stats- >p_ru, proc.p_stat, proc.p_cpticks proc.p_iticks, proc.p_uticks, proc.p_sticks, proc.p_swtime, proc.p_slptime, proc.p_runtime, proc.p_pctcpu, proc.p_oncpu, proc.p_asleep, proc.p_wchan, proc.p_wmesg, proc.p_slpq, proc.p_vmSPACE (XXX - in statclock), psent, slpqe, itqueuebits, itqueues, rtqueuebits, rtqueues, queuebits, queues, idqueuebits, idqueues, switchtime,	setrunqueue, remrunqueue, mi_switch, chooseproc, schedclock, resetpriority, updatepri, maybe_resched, cpu_switch, cpu_throw

Variable Name	Logical Name	Type	Protectees	Dependent Functions
vm86pcb_lock	“vm86pcb lock”	MTX_DEF   MTX_COLD	vm86pcb	vm86_bioscall
Giant	“Giant”	MTX_DEF   MTX_COLD	nearly everything	lots
callout_lock	“callout lock”	MTX_SPIN	callfree, callwheel, nextsoftcheck, proc.p_itcallout, proc.p_slpcallout, softticks, ticks	

## 10.2 Lock Manager Locks

Locks that are provided via the lockmgr(9) interface are lock manager locks. These locks are reader-writer locks and may be held by a sleeping process.

**Table 10-2. lockmgr(9) Lock List**

Variable Name	Protectees	
allproc_lock	allproc zombproc pidhashtbl proc.p_list proc.p_hash nextpid	proctree_lock

## 10.3 Atomically Protected Variables

An atomically protected variable is a special variable that is not protected by an explicit lock. Instead, all data accesses to the variables use special atomic operations as described in atomic(9). Very few variables are treated this way, although other synchronization primitives such as mutexes are implemented with atomically protected variables.

- `astpending`
- `mtx.mtx_lock`

# Chapter 11 Kernel Objects

Kernel Objects, or *Kobj* provides an object-oriented C programming system for the kernel. As such the data being operated on carries the description of how to operate on it. This allows operations to be added and removed from an interface at run time and without breaking binary compatibility.

## 11.1 Terminology

Object

A set of data - data structure - data allocation.

Method

An operation - function.

Class

One or more methods.

Interface

A standard set of one or more methods.

## 11.2 Kobj Operation

Kobj works by generating descriptions of methods. Each description holds a unique id as well as a default function. The description's address is used to uniquely identify the method within a class' method table.

A class is built by creating a method table associating one or more functions with method descriptions. Before use the class is compiled. The compilation allocates a cache and associates it with the class. A unique id is assigned to each method description within the method table of the class if not already done so by another referencing class compilation. For every method to be used a function is generated by script to qualify arguments and automatically reference the method description for a lookup. The generated function looks up the method by using the unique id associated with the method description as a hash into the cache associated with the object's class. If the method is not cached the generated function proceeds to use the class' table to find the method. If the method is found then the associated function within the class is used; otherwise, the default function associated with the method description is used.

These indirections can be visualized as the following:

```
object->cache<->class
```



## 11.3 Using Kobj

### 11.3.1 Structures

```
struct kobj_method
```

### 11.3.2 Functions

```
void kobj_class_compile(kobj_class_t cls);
void kobj_class_compile_static(kobj_class_t cls, kobj_ops_t ops);
void kobj_class_free(kobj_class_t cls);
kobj_t kobj_create(kobj_class_t cls, struct malloc_type *mtype, int mflags);
void kobj_init(kobj_t obj, kobj_class_t cls);
void kobj_delete(kobj_t obj, struct malloc_type *mtype);
```

### 11.3.3 Macros

```
KOBJ_CLASS_FIELDS
KOBJ_FIELDS
DEFINE_CLASS(name, methods, size)
KOBJMETHOD(NAME, FUNC)
```

### 11.3.4 Headers

```
<sys/param.h>
<sys/kobj.h>
```

### 11.3.5 Creating an interface template

The first step in using Kobj is to create an Interface. Creating the interface involves creating a template that the script `src/sys/kern/makeobjops.pl` can use to generate the header and code for the method declarations and method lookup functions.

Within this template the following keywords are used: `#include`, `INTERFACE`, `CODE`, `METHOD`, `STATICMETHOD`, and `DEFAULT`.

The `#include` statement and what follows it is copied verbatim to the head of the generated code file.

For example:

```
#include <sys/foo.h>
```

The `INTERFACE` keyword is used to define the interface name. This name is concatenated with each method name as `[interface name]_[method name]`. Its syntax is `INTERFACE [interface name];`.

For example:

```
INTERFACE foo;
```

The `CODE` keyword copies its arguments verbatim into the code file. Its syntax is `CODE { [whatever] };`

For example:

```
CODE {
    struct foo * foo_alloc_null(struct bar *)
    {
        return NULL;
    }
};
```

The `METHOD` keyword describes a method. Its syntax is `METHOD [return type] [method name] { [object [, arguments]] };`

For example:

```
METHOD int bar {
    struct object *;
    struct foo *;
    struct bar;
};
```

The `DEFAULT` keyword may follow the `METHOD` keyword. It extends the `METHOD` key word to include the default function for method. The extended syntax is `METHOD [return type] [method name] { [object; [other arguments]] }DEFAULT [default function];`

For example:

```
METHOD int bar {
    struct object *;
    struct foo *;
    int bar;
} DEFAULT foo_hack;
```

The `STATICMETHOD` keyword is used like the `METHOD` keyword except the `kobj` data is not at the head of the object structure so casting to `kobj_t` would be incorrect. Instead `STATICMETHOD` relies on the `Kobj` data being referenced as 'ops'. This is also useful for calling methods directly out of a class's method table.

Other complete examples:

```
src/sys/kern/bus_if.m
src/sys/kern/device_if.m
```

### 11.3.6 Creating a Class

The second step in using `Kobj` is to create a class. A class consists of a name, a table of methods, and the size of objects if `Kobj`'s object handling facilities are used. To create the class use the macro `DEFINE_CLASS()`. To create the method table create an array of `kobj_method_t` terminated by a `NULL` entry. Each non-`NULL` entry may be created using the macro `KOBJMETHOD()`.

For example:

```
DEFINE_CLASS(foo_class, foomethods, sizeof(struct foodata));

kobj_method_t foomethods[] = {
    KOBJMETHOD(bar_doo, foo_doo),
    KOBJMETHOD(bar_foo, foo_foo),
    { NULL, NULL}
};
```

The class must be “compiled”. Depending on the state of the system at the time that the class is to be initialized a statically allocated cache, “ops table” have to be used. This can be accomplished by declaring a struct `kobj_ops` and using `kobj_class_compile_static()`; otherwise, `kobj_class_compile()` should be used.

### 11.3.7 Creating an Object

The third step in using Kobj involves how to define the object. Kobj object creation routines assume that Kobj data is at the head of an object. If this is not appropriate you will have to allocate the object yourself and then use `kobj_init()` on the Kobj portion of it; otherwise, you may use `kobj_create()` to allocate and initialize the Kobj portion of the object automatically. `kobj_init()` may also be used to change the class that an object uses.

To integrate Kobj into the object you should use the macro `KOBJ_FIELDS`.

For example

```
struct foo_data {
    KOBJ_FIELDS;
    foo_foo;
    foo_bar;
};
```

### 11.3.8 Calling Methods

The last step in using Kobj is to simply use the generated functions to use the desired method within the object’s class. This is as simple as using the interface name and the method name with a few modifications. The interface name should be concatenated with the method name using a ‘\_’ between them, all in upper case.

For example, if the interface name was `foo` and the method was `bar` then the call would be:

```
[return value = ] FOO_BAR(object [, other parameters]);
```

### 11.3.9 Cleaning Up

When an object allocated through `kobj_create()` is no longer needed `kobj_delete()` may be called on it, and when a class is no longer being used `kobj_class_free()` may be called on it.

# Chapter 12 The Jail Subsystem

Evan Sarmiento

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On most UNIX systems, root has omnipotent power. This promotes insecurity. If an attacker were to gain root on a system, he would have every function at his fingertips. In FreeBSD there are sysctls which dilute the power of root, in order to minimize the damage caused by an attacker. Specifically, one of these functions is called secure levels. Similarly, another function which is present from FreeBSD 4.0 and onward, is a utility called jail(8). **Jail** chroots an environment and sets certain restrictions on processes which are forked from within. For example, a jailed process cannot affect processes outside of the jail, utilize certain system calls, or inflict any damage on the main computer.

**Jail** is becoming the new security model. People are running potentially vulnerable servers such as Apache, BIND, and sendmail within jails, so that if an attacker gains root within the **Jail**, it is only an annoyance, and not a devastation. This article focuses on the internals (source code) of **Jail** and **Jail NG**. It will also suggest improvements upon the jail code base which are already being worked on. If you are looking for a how-to on setting up a **Jail**, I suggest you look at my other article in Sys Admin Magazine, May 2001, entitled "Securing FreeBSD using **Jail**."

## 12.1 Architecture

**Jail** consists of two realms: the user-space program, jail, and the code implemented within the kernel: the jail() system call and associated restrictions. I will be discussing the user-space program and then how jail is implemented within the kernel.

### 12.1.1 Userland code

The source for the user-land jail is located in /usr/src/usr.sbin/jail, consisting of one file, jail.c. The program takes these arguments: the path of the jail, hostname, ip address, and the command to be executed.

#### 12.1.1.1 Data Structures

In jail.c, the first thing I would note is the declaration of an important structure struct jail j; which was included from /usr/include/sys/jail.h.

The definition of the jail structure is:

```
/usr/include/sys/jail.h:

struct jail {
    u_int32_t    version;
    char        *path;
    char        *hostname;
    u_int32_t    ip_number;
};
```

As you can see, there is an entry for each of the arguments passed to the jail program, and indeed, they are set during it's execution.

```

/usr/src/usr.sbin/jail.c
j.version = 0;
j.path = argv[1];
j.hostname = argv[2];

```

### 12.1.1.2 Networking

One of the arguments passed to the Jail program is an IP address with which the jail can be accessed over the network. Jail translates the ip address given into network byte order and then stores it in `j` (the jail structure).

```

/usr/src/usr.sbin/jail/jail.c:
struct in_addr in;
...
i = inet.aton(argv[3], &in);
...
j.ip.number = ntohl(in.s.addr);

```

The `inet_aton(3)` function "interprets the specified character string as an Internet address, placing the address into the structure provided." The `ip` number node in the jail structure is set only when the ip address placed onto the `in` structure by `inet aton` is translated into network byte order by `ntohl()`.

### 12.1.1.3 Jailing The Process

Finally, the `userland` program jails the process, and executes the command specified. Jail now becomes an imprisoned process itself and forks a child process which then executes the command given using `execv(3)`

```

/usr/src/sys/usr.sbin/jail/jail.c
i = jail(&j);
...
i = execv(argv[4], argv + 4);

```

As you can see, the `jail` function is being called, and its argument is the jail structure which has been filled with the arguments given to the program. Finally, the program you specify is executed. I will now discuss how Jail is implemented within the kernel.

## 12.1.2 Kernel Space

We will now be looking at the file `/usr/src/sys/kern/kern_jail.c`. This is the file where the jail system call, appropriate `sysctls`, and networking functions are defined.

### 12.1.2.1 sysctls

In `kern_jail.c`, the following `sysctls` are defined:

```

/usr/src/sys/kern/kern_jail.c:

```

```

int    jail_set_hostname_allowed = 1;
SYSCTL_INT(_jail, OID_AUTO, set_hostname_allowed, CTLFLAG_RW,
    &jail_set_hostname_allowed, 0,
    "Processes in jail can set their hostnames");

int    jail_socket_unixiproute_only = 1;
SYSCTL_INT(_jail, OID_AUTO, socket_unixiproute_only, CTLFLAG_RW,
    &jail_socket_unixiproute_only, 0,
    "Processes in jail are limited to creating UNIX/IPv4/route sockets only
");

int    jail_sysvipc_allowed = 0;
SYSCTL_INT(_jail, OID_AUTO, sysvipc_allowed, CTLFLAG_RW,
    &jail_sysvipc_allowed, 0,
    "Processes in jail can use System V IPC primitives");

```

Each of these sysctls can be accessed by the user through the `sysctl` program. Throughout the kernel, these specific sysctls are recognized by their name. For example, the name of the first sysctl is `jail.set.hostname.allowed`.

### 12.1.2.2 jail(2) system call

Like all system calls, the `jail(2)` system call takes two arguments, `struct proc *p` and `struct jail_args *uap`. `p` is a pointer to a `proc` structure which describes the calling process. In this context, `uap` is a pointer to a structure which specifies the arguments given to `jail(2)` from the userland program `jail.c`. When I described the userland program before, you saw that the `jail(2)` system call was given a `jail` structure as its own argument.

```

/usr/src/sys/kern/kern_jail.c:
int
jail(p, uap)
    struct proc *p;
    struct jail_args /* {
        syscallarg(struct jail *) jail;
    } */ *uap;

```

Therefore, `uap->jail` would access the `jail` structure which was passed to the system call. Next, the system call copies the `jail` structure into kernel space using the `copyin()` function. `copyin()` takes three arguments: the data which is to be copied into kernel space, `uap->jail`, where to store it, `j` and the size of the storage. The `jail` structure `uap->jail` is copied into kernel space and stored in another `jail` structure, `j`.

```

/usr/src/sys/kern/kern_jail.c:
error = copyin(uap->jail, &j, sizeof j);

```

There is another important structure defined in `jail.h`. It is the `prison` structure (`pr`). The `prison` structure is used exclusively within kernel space. The `jail(2)` system call copies everything from the `jail` structure onto the `prison` structure. Here is the definition of the `prison` structure.

```

/usr/include/sys/jail.h:
struct prison {
    int            pr_ref;
    char          pr_host[MAXHOSTNAMELEN];
    u_int32_t     pr_ip;

```

```

        void                *pr_linux;
};

```

The jail() system call then allocates memory for a pointer to a prison structure and copies data between the two structures.

```

/usr/src/sys/kern/kern_jail.c:
MALLOC(pr, struct prison *, sizeof *pr , M_PRISON, M_WAITOK);
bzero((caddr_t)pr, sizeof *pr);
error = copyinstr(j.hostname, &pr->pr_host, sizeof pr->pr_host, 0);
if (error)
    goto bail;

```

Finally, the jail system call chroots the path specified. The chroot function is given two arguments. The first is p, which represents the calling process, the second is a pointer to the structure chroot args. The structure chroot args contains the path which is to be chrooted. As you can see, the path specified in the jail structure is copied to the chroot args structure and used.

```

/usr/src/sys/kern/kern_jail.c:
ca.path = j.path;
error = chroot(p, &ca);

```

These next three lines in the source are very important, as they specify how the kernel recognizes a process as jailed. Each process on a Unix system is described by its own proc structure. You can see the whole proc structure in /usr/include/sys/proc.h. For example, the p argument in any system call is actually a pointer to that process' proc structure, as stated before. The proc structure contains nodes which can describe the owner's identity (p\_cred), the process resource limits (p\_limit), and so on. In the definition of the process structure, there is a pointer to a prison structure. (p\_prison).

```

/usr/include/sys/proc.h:
struct proc {
...
struct prison *p_prison;
...
};

```

In kern\_jail.c, the function then copies the pr structure, which is filled with all the information from the original jail structure, over to the p->p\_prison structure. It then does a bitwise OR of p->p\_flag with the constant P\_JAILED, meaning that the calling process is now recognized as jailed. The parent process of each process, forked within the jail, is the program jail itself, as it calls the jail(2) system call. When the program is executed through execve, it inherits the properties of its parents proc structure, therefore it has the p->p\_flag set, and the p->p\_prison structure is filled.

```

/usr/src/sys/kern/kern_jail.c
p->p.prison = pr;
p->p.flag |= P.JAILED;

```

When a process is forked from a parent process, the fork(2) system call deals differently with imprisoned processes. In the fork system call, there are two pointers to a proc structure p1 and p2. p1 points to the parent's proc structure and p2 points to the child's unfilled proc structure. After copying all relevant data between the structures, fork(2) checks if the structure p->p\_prison is filled on p2. If it is, it increments the pr.ref by one, and sets the p\_flag to one on the child process.

```

/usr/src/sys/kern/kern_fork.c:
if (p2->p_prison) {
    p2->p_prison->pr_ref++;
    p2->p_flag |= P_JAILED;
}

```

## 12.2 Restrictions

Throughout the kernel there are access restrictions relating to jailed processes. Usually, these restrictions only check if the process is jailed, and if so, returns an error. For example:

```

if (p->p_prison)
    return EPERM;

```

### 12.2.1 SysV IPC

System V IPC is based on messages. Processes can send each other these messages which tell them how to act. The functions which deal with messages are: `msgsys`, `msgctl`, `msgget`, `msgsend` and `msgrcv`. Earlier, I mentioned that there were certain sysctls you could turn on or off in order to affect the behavior of Jail. One of these sysctls was `jail_sysvipc_allowed`. On most systems, this sysctl is set to 0. If it were set to 1, it would defeat the whole purpose of having a jail; privileged users from within the jail would be able to affect processes outside of the environment. The difference between a message and a signal is that the message only consists of the signal number.

```

/usr/src/sys/kern/sysv_msg.c:

```

- `msgget(3)`: `msgget` returns (and possibly creates) a message descriptor that designates a message queue for use in other system calls.
- `msgctl(3)`: Using this function, a process can query the status of a message descriptor.
- `msgsnd(3)`: `msgsnd` sends a message to a process.
- `msgrcv(3)`: a process receives messages using this function

In each of these system calls, there is this conditional:

```

/usr/src/sys/kern/sysv_msg.c:
if (!jail.sysvipc.allowed && p->p_prison != NULL)
    return (ENOSYS);

```

Semaphore system calls allow processes to synchronize execution by doing a set of operations atomically on a set of semaphores. Basically semaphores provide another way for processes lock resources. However, process waiting on a semaphore, that is being used, will sleep until the resources are relinquished. The following semaphore system calls are blocked inside a jail: `semsys`, `semget`, `semctl` and `semop`.

```

/usr/src/sys/kern/sysv_sem.c:

```

- `semctl(2)(id, num, cmd, arg)`: `semctl` does the specified `cmd` on the semaphore queue indicated by `id`.



- `semget(2)(key, nsems, flag)`: `semget` creates an array of semaphores, corresponding to `key`.  
`key` and `flag` take on the same meaning as they do in `msgget`.
- `semop(2)(id, ops, num)`: `semop` does the set of semaphore operations in the array of structures `ops`, to the set of semaphores identified by `id`.

System V IPC allows for processes to share memory. Processes can communicate directly with each other by sharing parts of their virtual address space and then reading and writing data stored in the shared memory. These system calls are blocked within a jailed environment: `shmdt`, `shmat`, `oshmctl`, `shmctl`, `shmget`, and `shmsys`.

```
/usr/src/sys/kern/sysv shm.c:
```

- `shmctl(2)(id, cmd, buf)`: `shmctl` does various control operations on the shared memory region identified by `id`.
- `shmget(2)(key, size, flag)`: `shmget` accesses or creates a shared memory region of size bytes.
- `shmat(2)(id, addr, flag)`: `shmat` attaches a shared memory region identified by `id` to the address space of a process.
- `shmdt(2)(addr)`: `shmdt` detaches the shared memory region previously attached at `addr`.

## 12.2.2 Sockets

Jail treats the `socket(2)` system call and related lower-level socket functions in a special manner. In order to determine whether a certain socket is allowed to be created, it first checks to see if the `sysctl jail.socket.unixiproute.only` is set. If set, sockets are only allowed to be created if the family specified is either `PF_LOCAL`, `PF_INET` or `PF_ROUTE`. Otherwise, it returns an error.

```
/usr/src/sys/kern/uipc_socket.c:
int screate(dom, aso, type, proto, p)
...
register struct protosw *prp;
...
{
    if (p->p_prison && jail_socket_unixiproute_only &&
        prp->pr_domain->dom_family != PR_LOCAL && prp->pr_domain->dom_family != PF_INET
        && prp->pr_domain->dom_family != PF_ROUTE)
        return (EPROTONOSUPPORT);
    ...
}
```

## 12.2.3 Berkeley Packet Filter

The Berkeley Packet Filter provides a raw interface to data link layers in a protocol independent fashion. The function `bpfopen()` opens an Ethernet device. There is a conditional which disallows any jailed processes from accessing this function.

```
/usr/src/sys/net/bpf.c:
static int bpfopen(dev, flags, fmt, p)
```

```

...
{
    if (p->p_prison)
        return (EPERM);
...
}

```

## 12.2.4 Protocols

There are certain protocols which are very common, such as TCP, UDP, IP and ICMP. IP and ICMP are on the same level: the network layer 2. There are certain precautions which are taken in order to prevent a jailed process from binding a protocol to a certain port only if the `nam` parameter is set. `nam` is a pointer to a `sockaddr` structure, which describes the address on which to bind the service. A more exact definition is that `sockaddr` "may be used as a template for referring to the identifying tag and length of each address"[2]. In the function `in_pcbbind`, `sin` is a pointer to a `sockaddr.in` structure, which contains the port, address, length and domain family of the socket which is to be bound. Basically, this disallows any processes from jail to be able to specify the domain family.

```

/usr/src/sys/kern/netinet/in_pcb.c:
int in_pcbbind(int, nam, p)
...
    struct sockaddr *nam;
    struct proc *p;
{
    ...
    struct sockaddr.in *sin;
    ...
    if (nam) {
        sin = (struct sockaddr.in *)nam;
        ...
        if (sin->sin_addr.s_addr != INADDR_ANY)
            if (prison_ip(p, 0, &sin->sin_addr.s_addr))
                return (EINVAL);
        ....
    }
    ...
}

```

You might be wondering what function `prison_ip()` does. `prison_ip` is given three arguments, the current process (represented by `p`), any flags, and an ip address. It returns 1 if the ip address belongs to a jail or 0 if it does not. As you can see from the code, if it is indeed an ip address belonging to a jail, the protocol is not allowed to bind to a certain port.

```

/usr/src/sys/kern/kern_jail.c:
int prison_ip(struct proc *p, int flag, u_int32_t *ip) {
    u_int32_t tmp;

    if (!p->p_prison)
        return (0);
    if (flag)
        tmp = *ip;

```

```

else tmp = ntohl (*ip);

if (tmp == INADDR_ANY) {
    if (flag)
        *ip = p->p_prison->pr_ip;
    else *ip = htonl(p->p_prison->pr_ip);
    return (0);
}

if (p->p_prison->pr_ip != tmp)
    return (1);
return (0);
}

```

Jailed users are not allowed to bind services to an ip which does not belong to the jail. The restriction is also written within the function `in_pcbbind`:

```

/usr/src/sys/net/inet/in_pcb.c
    if (nam) {
        ...
        lport = sin->sin.port;
        ... if (lport) {
            ...
            if (p && p->p_prison)
                prison = 1;
            if (prison &&
                prison_ip(p, 0, &sin->sin_addr.s_addr))
                return (EADDRNOTAVAIL);
        }
    }
}

```

## 12.2.5 Filesystem

Even root users within the jail are not allowed to set any file flags, such as immutable, append, and no unlink flags, if the `securelevel` is greater than 0.

```

/usr/src/sys/ufs/ufs/ufs_vnops.c:
int ufs.setattr(ap)
{
    ...
    if ((cred->cr.uid == 0) && (p->prison == NULL)) {
        if ((ip->i_flags
            & (SF_NOUNLINK | SF_IMMUTABLE | SF_APPEND)) &&
            securelevel > 0)
            return (EPERM);
    }
}

```

## 12.3 Jail NG

Jail NG is a "from-scratch re-implementation of Jail" by Robert Watson, a FreeBSD committer. Some of the new features include the ability to add processes to a jail, an improved management tool, and per-jail sysctls. For example, you could have `sysvipc_permitted` set on one jail while another jail may be allowed to use System V IPC. You can download the kernel patches and utilities for Jail NG from his website at: <http://www.watson.org/~robert/jailng/>.

# Chapter 13 The Sysinit Framework

Sysinit is the framework for a generic call sort and dispatch mechanism. FreeBSD currently uses it for the dynamic initialization of the kernel. Sysinit allows FreeBSD's kernel subsystems to be reordered, and added, removed, and replaced at kernel link time when the kernel or one of its modules is loaded without having to edit a statically ordered initialization routing and recompile the kernel. This system also allows kernel modules, currently called *KLD's*, to be separately compiled, linked, and initialized at boot time and loaded even later while the system is already running. This is accomplished using the "kernel linker" and "linker sets".

## 13.1 Terminology

Linker Set

A linker technique in which the linker gathers statically declared data throughout a program's source files into a single contiguously addressable unit of data.

## 13.2 Sysinit Operation

Sysinit relies on the ability of the linker to take static data declared at multiple locations throughout a program's source and group it together as a single contiguous chunk of data. This linker technique is called a "linker set". Sysinit uses two linker sets to maintain two data sets containing each consumer's call order, function, and a pointer to the data to pass to that function.

Sysinit uses two priorities when ordering the functions for execution. The first priority is a subsystem ID giving an overall order Sysinit's dispatch of functions. Current predeclared ID's are in `<sys/kernel.h>` in the enum list `sysinit_sub_id`. The second priority used is an element order within the subsystem. Current predeclared subsystem element orders are in `<sys/kernel.h>` in the enum list `sysinit_elem_order`.

There are currently two uses for Sysinit. Function dispatch at system startup and kernel module loads, and function dispatch at system shutdown and kernel module unload.

## 13.3 Using Sysinit

### 13.3.1 Interface

#### 13.3.1.1 Headers

`<sys/kernel.h>`

### 13.3.1.2 Macros

```

SYSINIT(uniqifier, subsystem, order, func, ident)
SYSUNINIT(uniqifier, subsystem, order, func, ident)

```

### 13.3.2 Startup

The `SYSINIT()` macro creates the necessary sysinit data in Sysinit's startup data set for Sysinit to sort and dispatch a function at system startup and module load. `SYSINIT()` takes a uniqifier that Sysinit uses identify the particular function dispatch data, the subsystem order, the subsystem element order, the function to call, and the data to pass the function. All functions must take a constant pointer argument.

For example:

```

#include <sys/kernel.h>

void foo_null(void *unused)
{
    foo_doo();
}
SYSINIT(foo_null, SI_SUB_FOO, SI_ORDER_FOO, NULL);

struct foo foo_voodoo = {
    FOO_VOODOO;
}

void foo_arg(void *vdata)
{
    struct foo *foo = (struct foo *)vdata;
    foo_data(foo);
}
SYSINIT(foo_arg, SI_SUB_FOO, SI_ORDER_FOO, foo_voodoo);

```

### 13.3.3 Shutdown

The `SYSUNINIT()` macro behaves similarly to the `SYSINIT()` macro except that it adds the Sysinit data to Sysinit's shutdown data set.

For example:

```

#include <sys/kernel.h>

void foo_cleanup(void *unused)
{
    foo_kill();
}
SYSUNINIT(foo_cleanup, SI_SUB_FOO, SI_ORDER_FOO, NULL);

```

```
struct foo_stack foo_stack = {
    FOO_STACK_VOODOO;
}

void foo_flush(void *vdata)
{
}

SYSUNINIT(foo_flush, SI_SUB_FOO, SI_ORDER_FOO, foo_stack);
```

# Chapter 14 Virtual Memory System

## 14.1 The FreeBSD VM System

*Contributed by Matthew Dillon <dillon@FreeBSD.org>. 6 Feb 1999*

### 14.1.1 Management of physical memory—`vm_page_t`

Physical memory is managed on a page-by-page basis through the `vm_page_t` structure. Pages of physical memory are categorized through the placement of their respective `vm_page_t` structures on one of several paging queues.

A page can be in a wired, active, inactive, cache, or free state. Except for the wired state, the page is typically placed in a doubly link list queue representing the state that it is in. Wired pages are not placed on any queue.

FreeBSD implements a more involved paging queue for cached and free pages in order to implement page coloring. Each of these states involves multiple queues arranged according to the size of the processor's L1 and L2 caches. When a new page needs to be allocated, FreeBSD attempts to obtain one that is reasonably well aligned from the point of view of the L1 and L2 caches relative to the VM object the page is being allocated for.

Additionally, a page may be held with a reference count or locked with a busy count. The VM system also implements an “ultimate locked” state for a page using the `PG_BUSY` bit in the page's flags.

In general terms, each of the paging queues operates in a LRU fashion. A page is typically placed in a wired or active state initially. When wired, the page is usually associated with a page table somewhere. The VM system ages the page by scanning pages in a more active paging queue (LRU) in order to move them to a less-active paging queue. Pages that get moved into the cache are still associated with a VM object but are candidates for immediate reuse. Pages in the free queue are truly free. FreeBSD attempts to minimize the number of pages in the free queue, but a certain minimum number of truly free pages must be maintained in order to accommodate page allocation at interrupt time.

If a process attempts to access a page that does not exist in its page table but does exist in one of the paging queues (such as the inactive or cache queues), a relatively inexpensive page reactivation fault occurs which causes the page to be reactivated. If the page does not exist in system memory at all, the process must block while the page is brought in from disk.

FreeBSD dynamically tunes its paging queues and attempts to maintain reasonable ratios of pages in the various queues as well as attempts to maintain a reasonable breakdown of clean vs. dirty pages. The amount of rebalancing that occurs depends on the system's memory load. This rebalancing is implemented by the pageout daemon and involves laundering dirty pages (syncing them with their backing store), noticing when pages are activity referenced (resetting their position in the LRU queues or moving them between queues), migrating pages between queues when the queues are out of balance, and so forth. FreeBSD's VM system is willing to take a reasonable number of reactivation page faults to determine how active or how idle a page actually is. This leads to better decisions being made as to when to launder or swap-out a page.

### 14.1.2 The unified buffer cache—`vm_object_t`

FreeBSD implements the idea of a generic “VM object”. VM objects can be associated with backing store of various types—unbacked, swap-backed, physical device-backed, or file-backed storage. Since the filesystem uses the same



VM objects to manage in-core data relating to files, the result is a unified buffer cache.

VM objects can be *shadowed*. That is, they can be stacked on top of each other. For example, you might have a swap-backed VM object stacked on top of a file-backed VM object in order to implement a `MAP_PRIVATE` `mmap()`ing. This stacking is also used to implement various sharing properties, including copy-on-write, for forked address spaces.

It should be noted that a `vm_page_t` can only be associated with one VM object at a time. The VM object shadowing implements the perceived sharing of the same page across multiple instances.

### 14.1.3 Filesystem I/O—`struct buf`

vnode-backed VM objects, such as file-backed objects, generally need to maintain their own clean/dirty info independent from the VM system's idea of clean/dirty. For example, when the VM system decides to synchronize a physical page to its backing store, the VM system needs to mark the page clean before the page is actually written to its backing store. Additionally, filesystems need to be able to map portions of a file or file metadata into KVM in order to operate on it.

The entities used to manage this are known as filesystem buffers, `struct buf`'s, or `bp`'s. When a filesystem needs to operate on a portion of a VM object, it typically maps part of the object into a `struct buf` and then maps the pages in the `struct buf` into KVM. In the same manner, disk I/O is typically issued by mapping portions of objects into buffer structures and then issuing the I/O on the buffer structures. The underlying `vm_page_t`'s are typically busied for the duration of the I/O. Filesystem buffers also have their own notion of being busy, which is useful to filesystem driver code which would rather operate on filesystem buffers instead of hard VM pages.

FreeBSD reserves a limited amount of KVM to hold mappings from `struct buf`s, but it should be made clear that this KVM is used solely to hold mappings and does not limit the ability to cache data. Physical data caching is strictly a function of `vm_page_t`'s, not filesystem buffers. However, since filesystem buffers are used to placeholder I/O, they do inherently limit the amount of concurrent I/O possible. However, as there are usually a few thousand filesystem buffers available, this is not usually a problem.

### 14.1.4 Mapping Page Tables - `vm_map_t`, `vm_entry_t`

FreeBSD separates the physical page table topology from the VM system. All hard per-process page tables can be reconstructed on the fly and are usually considered throwaway. Special page tables such as those managing KVM are typically permanently preallocated. These page tables are not throwaway.

FreeBSD associates portions of `vm_objects` with address ranges in virtual memory through `vm_map_t` and `vm_entry_t` structures. Page tables are directly synthesized from the `vm_map_t/vm_entry_t/vm_object_t` hierarchy. Recall that I mentioned that physical pages are only directly associated with a `vm_object`; that is not quite true. `vm_page_t`'s are also linked into page tables that they are actively associated with. One `vm_page_t` can be linked into several *pmaps*, as page tables are called. However, the hierarchical association holds, so all references to the same page in the same object reference the same `vm_page_t` and thus give us buffer cache unification across the board.

## 14.1.5 KVM Memory Mapping

FreeBSD uses KVM to hold various kernel structures. The single largest entity held in KVM is the filesystem buffer cache. That is, mappings relating to `struct buf` entities.

Unlike Linux, FreeBSD does *not* map all of physical memory into KVM. This means that FreeBSD can handle memory configurations up to 4G on 32 bit platforms. In fact, if the mmu were capable of it, FreeBSD could theoretically handle memory configurations up to 8TB on a 32 bit platform. However, since most 32 bit platforms are only capable of mapping 4GB of ram, this is a moot point.

KVM is managed through several mechanisms. The main mechanism used to manage KVM is the *zone allocator*. The zone allocator takes a chunk of KVM and splits it up into constant-sized blocks of memory in order to allocate a specific type of structure. You can use `vmstat -m` to get an overview of current KVM utilization broken down by zone.

## 14.1.6 Tuning the FreeBSD VM system

A concerted effort has been made to make the FreeBSD kernel dynamically tune itself. Typically you do not need to mess with anything beyond the `maxusers` and `NMBCLUSTERS` kernel config options. That is, kernel compilation options specified in (typically) `/usr/src/sys/i386/conf/CONFIG_FILE`. A description of all available kernel configuration options can be found in `/usr/src/sys/i386/conf/LINT`.

In a large system configuration you may wish to increase `maxusers`. Values typically range from 10 to 128. Note that raising `maxusers` too high can cause the system to overflow available KVM resulting in unpredictable operation. It is better to leave `maxusers` at some reasonable number and add other options, such as `NMBCLUSTERS`, to increase specific resources.

If your system is going to use the network heavily, you may want to increase `NMBCLUSTERS`. Typical values range from 1024 to 4096.

The `NBUF` parameter is also traditionally used to scale the system. This parameter determines the amount of KVA the system can use to map filesystem buffers for I/O. Note that this parameter has nothing whatsoever to do with the unified buffer cache! This parameter is dynamically tuned in 3.0-CURRENT and later kernels and should generally not be adjusted manually. We recommend that you *not* try to specify an `NBUF` parameter. Let the system pick it. Too small a value can result in extremely inefficient filesystem operation while too large a value can starve the page queues by causing too many pages to become wired down.

By default, FreeBSD kernels are not optimized. You can set debugging and optimization flags with the `makeoptions` directive in the kernel configuration. Note that you should not use `-g` unless you can accommodate the large (typically 7 MB+) kernels that result.

```
makeoptions      DEBUG="-g"
makeoptions      COPTFLAGS="-O -pipe"
```

`Sysctl` provides a way to tune kernel parameters at run-time. You typically do not need to mess with any of the `sysctl` variables, especially the VM related ones.

Run time VM and system tuning is relatively straightforward. First, use `softupdates` on your UFS/FFS filesystems whenever possible. `/usr/src/sys/ufs/ffs/README.softupdates` contains instructions (and restrictions) on how to configure it.

Second, configure sufficient swap. You should have a swap partition configured on each physical disk, up to four, even on your “work” disks. You should have at least 2x the swap space as you have main memory, and possibly even

more if you do not have a lot of memory. You should also size your swap partition based on the maximum memory configuration you ever intend to put on the machine so you do not have to repartition your disks later on. If you want to be able to accommodate a crash dump, your first swap partition must be at least as large as main memory and `/var/crash` must have sufficient free space to hold the dump.

NFS-based swap is perfectly acceptable on 4.x or later systems, but you must be aware that the NFS server will take the brunt of the paging load.

# Chapter 15 DMA

## 15.1 DMA: What it is and How it Works

*Copyright © 1995,1997 Frank Durda IV <uhc1em@FreeBSD.org>, All Rights Reserved. 10 December 1996. Last Update 8 October 1997.*

Direct Memory Access (DMA) is a method of allowing data to be moved from one location to another in a computer without intervention from the central processor (CPU).

The way that the DMA function is implemented varies between computer architectures, so this discussion will limit itself to the implementation and workings of the DMA subsystem on the IBM Personal Computer (PC), the IBM PC/AT and all of its successors and clones.

The PC DMA subsystem is based on the Intel 8237 DMA controller. The 8237 contains four DMA channels that can be programmed independently and any one of the channels may be active at any moment. These channels are numbered 0, 1, 2 and 3. Starting with the PC/AT, IBM added a second 8237 chip, and numbered those channels 4, 5, 6 and 7.

The original DMA controller (0, 1, 2 and 3) moves one byte in each transfer. The second DMA controller (4, 5, 6, and 7) moves 16-bits from two adjacent memory locations in each transfer, with the first byte always coming from an even-numbered address. The two controllers are identical components and the difference in transfer size is caused by the way the second controller is wired into the system.

The 8237 has two electrical signals for each channel, named DRQ and -DACK. There are additional signals with the names HRQ (Hold Request), HLDA (Hold Acknowledge), -EOP (End of Process), and the bus control signals -MEMR (Memory Read), -MEMW (Memory Write), -IOR (I/O Read), and -IOW (I/O Write).

The 8237 DMA is known as a “fly-by” DMA controller. This means that the data being moved from one location to another does not pass through the DMA chip and is not stored in the DMA chip. Subsequently, the DMA can only transfer data between an I/O port and a memory address, but not between two I/O ports or two memory locations.

**Note:** The 8237 does allow two channels to be connected together to allow memory-to-memory DMA operations in a non-“fly-by” mode, but nobody in the PC industry uses this scarce resource this way since it is faster to move data between memory locations using the CPU.

In the PC architecture, each DMA channel is normally activated only when the hardware that uses a given DMA channel requests a transfer by asserting the DRQ line for that channel.

### 15.1.1 A Sample DMA transfer

Here is an example of the steps that occur to cause and perform a DMA transfer. In this example, the floppy disk controller (FDC) has just read a byte from a diskette and wants the DMA to place it in memory at location 0x00123456. The process begins by the FDC asserting the DRQ2 signal (the DRQ line for DMA channel 2) to alert the DMA controller.

The DMA controller will note that the DRQ2 signal is asserted. The DMA controller will then make sure that DMA channel 2 has been programmed and is unmasked (enabled). The DMA controller also makes sure that none of the

other DMA channels are active or want to be active and have a higher priority. Once these checks are complete, the DMA asks the CPU to release the bus so that the DMA may use the bus. The DMA requests the bus by asserting the HRQ signal which goes to the CPU.

The CPU detects the HRQ signal, and will complete executing the current instruction. Once the processor has reached a state where it can release the bus, it will. Now all of the signals normally generated by the CPU (-MEMR, -MEMW, -IOR, -IOW and a few others) are placed in a tri-stated condition (neither high or low) and then the CPU asserts the HLDA signal which tells the DMA controller that it is now in charge of the bus.

Depending on the processor, the CPU may be able to execute a few additional instructions now that it no longer has the bus, but the CPU will eventually have to wait when it reaches an instruction that must read something from memory that is not in the internal processor cache or pipeline.

Now that the DMA “is in charge”, the DMA activates its -MEMR, -MEMW, -IOR, -IOW output signals, and the address outputs from the DMA are set to 0x3456, which will be used to direct the byte that is about to be transferred to a specific memory location.

The DMA will then let the device that requested the DMA transfer know that the transfer is commencing. This is done by asserting the -DACK signal, or in the case of the floppy disk controller, -DACK2 is asserted.

The floppy disk controller is now responsible for placing the byte to be transferred on the bus Data lines. Unless the floppy controller needs more time to get the data byte on the bus (and if the peripheral does need more time it alerts the DMA via the READY signal), the DMA will wait one DMA clock, and then de-assert the -MEMW and -IOR signals so that the memory will latch and store the byte that was on the bus, and the FDC will know that the byte has been transferred.

Since the DMA cycle only transfers a single byte at a time, the FDC now drops the DRQ2 signal, so the DMA knows that it is no longer needed. The DMA will de-assert the -DACK2 signal, so that the FDC knows it must stop placing data on the bus.

The DMA will now check to see if any of the other DMA channels have any work to do. If none of the channels have their DRQ lines asserted, the DMA controller has completed its work and will now tri-state the -MEMR, -MEMW, -IOR, -IOW and address signals.

Finally, the DMA will de-assert the HRQ signal. The CPU sees this, and de-asserts the HOLDA signal. Now the CPU activates its -MEMR, -MEMW, -IOR, -IOW and address lines, and it resumes executing instructions and accessing main memory and the peripherals.

For a typical floppy disk sector, the above process is repeated 512 times, once for each byte. Each time a byte is transferred, the address register in the DMA is incremented and the counter in the DMA that shows how many bytes are to be transferred is decremented.

When the counter reaches zero, the DMA asserts the EOP signal, which indicates that the counter has reached zero and no more data will be transferred until the DMA controller is reprogrammed by the CPU. This event is also called the Terminal Count (TC). There is only one EOP signal, and since only one DMA channel can be active at any instant, the DMA channel that is currently active must be the DMA channel that just completed its task.

If a peripheral wants to generate an interrupt when the transfer of a buffer is complete, it can test for its -DACKn signal and the EOP signal both being asserted at the same time. When that happens, it means the DMA will not transfer any more information for that peripheral without intervention by the CPU. The peripheral can then assert one of the interrupt signals to get the processors’ attention. In the PC architecture, the DMA chip itself is not capable of generating an interrupt. The peripheral and its associated hardware is responsible for generating any interrupt that occurs. Subsequently, it is possible to have a peripheral that uses DMA but does not use interrupts.

It is important to understand that although the CPU always releases the bus to the DMA when the DMA makes the request, this action is invisible to both applications and the operating system, except for slight changes in the amount of time the processor takes to execute instructions when the DMA is active. Subsequently, the processor must poll the peripheral, poll the registers in the DMA chip, or receive an interrupt from the peripheral to know for certain when a DMA transfer has completed.

## 15.1.2 DMA Page Registers and 16Meg address space limitations

You may have noticed earlier that instead of the DMA setting the address lines to 0x00123456 as we said earlier, the DMA only set 0x3456. The reason for this takes a bit of explaining.

When the original IBM PC was designed, IBM elected to use both DMA and interrupt controller chips that were designed for use with the 8085, an 8-bit processor with an address space of 16 bits (64K). Since the IBM PC supported more than 64K of memory, something had to be done to allow the DMA to read or write memory locations above the 64K mark. What IBM did to solve this problem was to add an external data latch for each DMA channel that holds the upper bits of the address to be read to or written from. Whenever a DMA channel is active, the contents of that latch are written to the address bus and kept there until the DMA operation for the channel ends. IBM called these latches “Page Registers”.

So for our example above, the DMA would put the 0x3456 part of the address on the bus, and the Page Register for DMA channel 2 would put 0x0012xxxx on the bus. Together, these two values form the complete address in memory that is to be accessed.

Because the Page Register latch is independent of the DMA chip, the area of memory to be read or written must not span a 64K physical boundary. For example, if the DMA accesses memory location 0xffff, after that transfer the DMA will then increment the address register and the DMA will access the next byte at location 0x0000, not 0x10000. The results of letting this happen are probably not intended.

**Note:** “Physical” 64K boundaries should not be confused with 8086-mode 64K “Segments”, which are created by mathematically adding a segment register with an offset register. Page Registers have no address overlap and are mathematically OR-ed together.

To further complicate matters, the external DMA address latches on the PC/AT hold only eight bits, so that gives us  $8+16=24$  bits, which means that the DMA can only point at memory locations between 0 and 16Meg. For newer computers that allow more than 16Meg of memory, the standard PC-compatible DMA cannot access memory locations above 16Meg.

To get around this restriction, operating systems will reserve a RAM buffer in an area below 16Meg that also does not span a physical 64K boundary. Then the DMA will be programmed to transfer data from the peripheral and into that buffer. Once the DMA has moved the data into this buffer, the operating system will then copy the data from the buffer to the address where the data is really supposed to be stored.

When writing data from an address above 16Meg to a DMA-based peripheral, the data must be first copied from where it resides into a buffer located below 16Meg, and then the DMA can copy the data from the buffer to the hardware. In FreeBSD, these reserved buffers are called “Bounce Buffers”. In the MS-DOS world, they are sometimes called “Smart Buffers”.

**Note:** A new implementation of the 8237, called the 82374, allows 16 bits of page register to be specified and enables access to the entire 32 bit address space, without the use of bounce buffers.

### 15.1.3 DMA Operational Modes and Settings

The 8237 DMA can be operated in several modes. The main ones are:

#### Single

A single byte (or word) is transferred. The DMA must release and re-acquire the bus for each additional byte. This is commonly-used by devices that cannot transfer the entire block of data immediately. The peripheral will request the DMA each time it is ready for another transfer.

The standard PC-compatible floppy disk controller (NEC 765) only has a one-byte buffer, so it uses this mode.

#### Block/Demand

Once the DMA acquires the system bus, an entire block of data is transferred, up to a maximum of 64K. If the peripheral needs additional time, it can assert the READY signal to suspend the transfer briefly. READY should not be used excessively, and for slow peripheral transfers, the Single Transfer Mode should be used instead.

The difference between Block and Demand is that once a Block transfer is started, it runs until the transfer count reaches zero. DRQ only needs to be asserted until -DACK is asserted. Demand Mode will transfer one more bytes until DRQ is de-asserted, at which point the DMA suspends the transfer and releases the bus back to the CPU. When DRQ is asserted later, the transfer resumes where it was suspended.

Older hard disk controllers used Demand Mode until CPU speeds increased to the point that it was more efficient to transfer the data using the CPU, particularly if the memory locations used in the transfer were above the 16Meg mark.

#### Cascade

This mechanism allows a DMA channel to request the bus, but then the attached peripheral device is responsible for placing the addressing information on the bus instead of the DMA. This is also used to implement a technique known as "Bus Mastering".

When a DMA channel in Cascade Mode receives control of the bus, the DMA does not place addresses and I/O control signals on the bus like the DMA normally does when it is active. Instead, the DMA only asserts the -DACK signal for the active DMA channel.

At this point it is up to the peripheral connected to that DMA channel to provide address and bus control signals. The peripheral has complete control over the system bus, and can do reads and/or writes to any address below 16Meg. When the peripheral is finished with the bus, it de-asserts the DRQ line, and the DMA controller can then return control to the CPU or to some other DMA channel.

Cascade Mode can be used to chain multiple DMA controllers together, and this is exactly what DMA Channel 4 is used for in the PC architecture. When a peripheral requests the bus on DMA channels 0, 1, 2 or 3, the slave DMA controller asserts HLDREQ, but this wire is actually connected to DRQ4 on the primary DMA controller instead of to the CPU. The primary DMA controller, thinking it has work to do on Channel 4, requests the bus from the CPU using HLDREQ signal. Once the CPU grants the bus to the primary DMA controller, -DACK4 is

asserted, and that wire is actually connected to the HLDA signal on the slave DMA controller. The slave DMA controller then transfers data for the DMA channel that requested it (0, 1, 2 or 3), or the slave DMA may grant the bus to a peripheral that wants to perform its own bus-mastering, such as a SCSI controller.

Because of this wiring arrangement, only DMA channels 0, 1, 2, 3, 5, 6 and 7 are usable with peripherals on PC/AT systems.

**Note:** DMA channel 0 was reserved for refresh operations in early IBM PC computers, but is generally available for use by peripherals in modern systems.

When a peripheral is performing Bus Mastering, it is important that the peripheral transmit data to or from memory constantly while it holds the system bus. If the peripheral cannot do this, it must release the bus frequently so that the system can perform refresh operations on main memory.

The Dynamic RAM used in all PCs for main memory must be accessed frequently to keep the bits stored in the components “charged”. Dynamic RAM essentially consists of millions of capacitors with each one holding one bit of data. These capacitors are charged with power to represent a 1 or drained to represent a 0. Because all capacitors leak, power must be added at regular intervals to keep the 1 values intact. The RAM chips actually handle the task of pumping power back into all of the appropriate locations in RAM, but they must be told when to do it by the rest of the computer so that the refresh activity will not interfere with the computer wanting to access RAM normally. If the computer is unable to refresh memory, the contents of memory will become corrupted in just a few milliseconds.

Since memory read and write cycles “count” as refresh cycles (a dynamic RAM refresh cycle is actually an incomplete memory read cycle), as long as the peripheral controller continues reading or writing data to sequential memory locations, that action will refresh all of memory.

Bus-mastering is found in some SCSI host interfaces and other high-performance peripheral controllers.

#### Autoinitialize

This mode causes the DMA to perform Byte, Block or Demand transfers, but when the DMA transfer counter reaches zero, the counter and address are set back to where they were when the DMA channel was originally programmed. This means that as long as the peripheral requests transfers, they will be granted. It is up to the CPU to move new data into the fixed buffer ahead of where the DMA is about to transfer it when doing output operations, and to read new data out of the buffer behind where the DMA is writing when doing input operations.

This technique is frequently used on audio devices that have small or no hardware “sample” buffers. There is additional CPU overhead to manage this “circular” buffer, but in some cases this may be the only way to eliminate the latency that occurs when the DMA counter reaches zero and the DMA stops transfers until it is reprogrammed.

## 15.1.4 Programming the DMA

The DMA channel that is to be programmed should always be “masked” before loading any settings. This is because the hardware might unexpectedly assert the DRQ for that channel, and the DMA might respond, even though not all



of the parameters have been loaded or updated.

Once masked, the host must specify the direction of the transfer (memory-to-I/O or I/O-to-memory), what mode of DMA operation is to be used for the transfer (Single, Block, Demand, Cascade, etc), and finally the address and length of the transfer are loaded. The length that is loaded is one less than the amount you expect the DMA to transfer. The LSB and MSB of the address and length are written to the same 8-bit I/O port, so another port must be written to first to guarantee that the DMA accepts the first byte as the LSB and the second byte as the MSB of the length and address.

Then, be sure to update the Page Register, which is external to the DMA and is accessed through a different set of I/O ports.

Once all the settings are ready, the DMA channel can be un-masked. That DMA channel is now considered to be “armed”, and will respond when the DRQ line for that channel is asserted.

Refer to a hardware data book for precise programming details for the 8237. You will also need to refer to the I/O port map for the PC system, which describes where the DMA and Page Register ports are located. A complete port map table is located below.

## 15.1.5 DMA Port Map

All systems based on the IBM-PC and PC/AT have the DMA hardware located at the same I/O ports. The complete list is provided below. Ports assigned to DMA Controller #2 are undefined on non-AT designs.

### 15.1.5.1 0x00–0x1f DMA Controller #1 (Channels 0, 1, 2 and 3)

#### DMA Address and Count Registers

0x00	write	Channel 0 starting address
0x00	read	Channel 0 current address
0x01	write	Channel 0 starting word count
0x01	read	Channel 0 remaining word count
0x02	write	Channel 1 starting address
0x02	read	Channel 1 current address
0x03	write	Channel 1 starting word count
0x03	read	Channel 1 remaining word count
0x04	write	Channel 2 starting address
0x04	read	Channel 2 current address
0x05	write	Channel 2 starting word count
0x05	read	Channel 2 remaining word count
0x06	write	Channel 3 starting address
0x06	read	Channel 3 current address
0x07	write	Channel 3 starting word count
0x07	read	Channel 3 remaining word count

#### DMA Command Registers

0x08	write	Command Register
0x08	read	Status Register
0x09	write	Request Register
0x09	read	-
0x0a	write	Single Mask Register Bit
0x0a	read	-
0x0b	write	Mode Register
0x0b	read	-
0x0c	write	Clear LSB/MSB Flip-Flop
0x0c	read	-
0x0d	write	Master Clear/Reset
0x0d	read	Temporary Register (not available on newer versions)
0x0e	write	Clear Mask Register
0x0e	read	-
0x0f	write	Write All Mask Register Bits
0x0f	read	Read All Mask Register Bits (only in Intel 82374)

### 15.1.5.2 0xc0–0xdf DMA Controller #2 (Channels 4, 5, 6 and 7)

#### DMA Address and Count Registers

0xc0	write	Channel 4 starting address
0xc0	read	Channel 4 current address
0xc2	write	Channel 4 starting word count
0xc2	read	Channel 4 remaining word count
0xc4	write	Channel 5 starting address
0xc4	read	Channel 5 current address
0xc6	write	Channel 5 starting word count
0xc6	read	Channel 5 remaining word count
0xc8	write	Channel 6 starting address
0xc8	read	Channel 6 current address
0xca	write	Channel 6 starting word count
0xca	read	Channel 6 remaining word count
0xcc	write	Channel 7 starting address
0xcc	read	Channel 7 current address
0xce	write	Channel 7 starting word count
0xce	read	Channel 7 remaining word count

#### DMA Command Registers

0xd0	write	Command Register
0xd0	read	Status Register
0xd2	write	Request Register
0xd2	read	-
0xd4	write	Single Mask Register Bit
0xd4	read	-
0xd6	write	Mode Register
0xd6	read	-
0xd8	write	Clear LSB/MSB Flip-Flop
0xd8	read	-
0xda	write	Master Clear/Reset
0xda	read	Temporary Register (not present in Intel 82374)
0xdc	write	Clear Mask Register
0xdc	read	-
0xde	write	Write All Mask Register Bits
0xdf	read	Read All Mask Register Bits (only in Intel 82374)

### 15.1.5.3 0x80–0x9f DMA Page Registers

0x87	r/w	Channel 0 Low byte (23-16) page Register
0x83	r/w	Channel 1 Low byte (23-16) page Register
0x81	r/w	Channel 2 Low byte (23-16) page Register
0x82	r/w	Channel 3 Low byte (23-16) page Register
0x8b	r/w	Channel 5 Low byte (23-16) page Register
0x89	r/w	Channel 6 Low byte (23-16) page Register
0x8a	r/w	Channel 7 Low byte (23-16) page Register
0x8f	r/w	Low byte page Refresh

### 15.1.5.4 0x400–0x4ff 82374 Enhanced DMA Registers

The Intel 82374 EISA System Component (ESC) was introduced in early 1996 and includes a DMA controller that

provides a superset of 8237 functionality as well as other PC-compatible core peripheral components in a single package. This chip is targeted at both EISA and PCI platforms, and provides modern DMA features like scatter-gather, ring buffers as well as direct access by the system DMA to all 32 bits of address space.

If these features are used, code should also be included to provide similar functionality in the previous 16 years worth of PC-compatible computers. For compatibility reasons, some of the 82374 registers must be programmed *after* programming the traditional 8237 registers for each transfer. Writing to a traditional 8237 register forces the contents of some of the 82374 enhanced registers to zero to provide backward software compatibility.

0x401	r/w	Channel 0 High byte (bits 23-16) word count
0x403	r/w	Channel 1 High byte (bits 23-16) word count
0x405	r/w	Channel 2 High byte (bits 23-16) word count
0x407	r/w	Channel 3 High byte (bits 23-16) word count
0x4c6	r/w	Channel 5 High byte (bits 23-16) word count
0x4ca	r/w	Channel 6 High byte (bits 23-16) word count
0x4ce	r/w	Channel 7 High byte (bits 23-16) word count
0x487	r/w	Channel 0 High byte (bits 31-24) page Register
0x483	r/w	Channel 1 High byte (bits 31-24) page Register
0x481	r/w	Channel 2 High byte (bits 31-24) page Register
0x482	r/w	Channel 3 High byte (bits 31-24) page Register
0x48b	r/w	Channel 5 High byte (bits 31-24) page Register
0x489	r/w	Channel 6 High byte (bits 31-24) page Register
0x48a	r/w	Channel 6 High byte (bits 31-24) page Register
0x48f	r/w	High byte page Refresh
0x4e0	r/w	Channel 0 Stop Register (bits 7-2)
0x4e1	r/w	Channel 0 Stop Register (bits 15-8)
0x4e2	r/w	Channel 0 Stop Register (bits 23-16)
0x4e4	r/w	Channel 1 Stop Register (bits 7-2)
0x4e5	r/w	Channel 1 Stop Register (bits 15-8)
0x4e6	r/w	Channel 1 Stop Register (bits 23-16)
0x4e8	r/w	Channel 2 Stop Register (bits 7-2)

0x4e9	r/w	Channel 2 Stop Register (bits 15-8)
0x4ea	r/w	Channel 2 Stop Register (bits 23-16)
0x4ec	r/w	Channel 3 Stop Register (bits 7-2)
0x4ed	r/w	Channel 3 Stop Register (bits 15-8)
0x4ee	r/w	Channel 3 Stop Register (bits 23-16)
0x4f4	r/w	Channel 5 Stop Register (bits 7-2)
0x4f5	r/w	Channel 5 Stop Register (bits 15-8)
0x4f6	r/w	Channel 5 Stop Register (bits 23-16)
0x4f8	r/w	Channel 6 Stop Register (bits 7-2)
0x4f9	r/w	Channel 6 Stop Register (bits 15-8)
0x4fa	r/w	Channel 6 Stop Register (bits 23-16)
0x4fc	r/w	Channel 7 Stop Register (bits 7-2)
0x4fd	r/w	Channel 7 Stop Register (bits 15-8)
0x4fe	r/w	Channel 7 Stop Register (bits 23-16)
0x40a	write	Channels 0-3 Chaining Mode Register
0x40a	read	Channel Interrupt Status Register
0x4d4	write	Channels 4-7 Chaining Mode Register
0x4d4	read	Chaining Mode Status
0x40c	read	Chain Buffer Expiration Control Register
0x410	write	Channel 0 Scatter-Gather Command Register
0x411	write	Channel 1 Scatter-Gather Command Register
0x412	write	Channel 2 Scatter-Gather Command Register
0x413	write	Channel 3 Scatter-Gather Command Register
0x415	write	Channel 5 Scatter-Gather Command Register
0x416	write	Channel 6 Scatter-Gather Command Register
0x417	write	Channel 7 Scatter-Gather Command Register
0x418	read	Channel 0 Scatter-Gather Status Register
0x419	read	Channel 1 Scatter-Gather Status Register
0x41a	read	Channel 2 Scatter-Gather Status Register
0x41b	read	Channel 3 Scatter-Gather Status Register

0x41d	read	Channel 5 Scatter-Gather Status Register
0x41e	read	Channel 5 Scatter-Gather Status Register
0x41f	read	Channel 7 Scatter-Gather Status Register
0x420-0x423	r/w	Channel 0 Scatter-Gather Descriptor Table Pointer Register
0x424-0x427	r/w	Channel 1 Scatter-Gather Descriptor Table Pointer Register
0x428-0x42b	r/w	Channel 2 Scatter-Gather Descriptor Table Pointer Register
0x42c-0x42f	r/w	Channel 3 Scatter-Gather Descriptor Table Pointer Register
0x434-0x437	r/w	Channel 5 Scatter-Gather Descriptor Table Pointer Register
0x438-0x43b	r/w	Channel 6 Scatter-Gather Descriptor Table Pointer Register
0x43c-0x43f	r/w	Channel 7 Scatter-Gather Descriptor Table Pointer Register

# Chapter 16 Kernel Debugging

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## 16.1 Debugging a Kernel Crash Dump with `gdb`

Here are some instructions for getting kernel debugging working on a crash dump. They assume that you have enough swap space for a crash dump. Typically you want to specify one of the swap devices specified in `/etc/fstab`. Dumps to non-swap devices, tapes for example, are currently not supported.

**Note:** Use the `dumpon(8)` command to tell the kernel where to dump to (note that this will have to be done after configuring the partition in question as swap space via `swapon(8)`). This is normally arranged by setting the `dumpdev` variable in `/etc/rc.conf`.

Alternatively, you can hard-code the dump device via the `dump` clause in the `config` line of your kernel configuration file. This approach is deprecated and should be used only if you want a crash dump from a kernel that crashes during booting.

**Note:** In the following, the term `gdb` refers to the debugger `gdb` run in “kernel debug mode”. This can be accomplished by starting the `gdb` with the option `-k`. In kernel debug mode, `gdb` changes its prompt to `(kgdb)`.

**Tip:** If you are using FreeBSD 3 or earlier, you should make a stripped copy of the debug kernel, rather than installing the large debug kernel itself:

```
# cp kernel kernel.debug
# strip -g kernel
```

This stage is not necessary, but it is recommended. (In FreeBSD 4 and later releases this step is performed automatically at the end of the kernel `make` process.) When the kernel has been stripped, either automatically or by using the commands above, you may install it as usual by typing `make install`.

Note that older releases of FreeBSD (up to but not including 3.1) used `a.out` kernels by default, which must have their symbol tables permanently resident in physical memory. With the larger symbol table in an unstripped debug kernel, this is wasteful. Recent FreeBSD releases use ELF kernels where this is no longer a problem.

If you are testing a new kernel, for example by typing the new kernel’s name at the boot prompt, but need to boot a different one in order to get your system up and running again, boot it only into single user state using the `-s` flag at the boot prompt, and then perform the following steps:

```
# fsck -p
# mount -a -t ufs          # so your filesystem for /var/crash is writable
# savecore -N /kernel.panicked /var/crash
# exit                    # ...to multi-user
```

This instructs savecore(8) to use another kernel for symbol name extraction. It would otherwise default to the currently running kernel and most likely not do anything at all since the crash dump and the kernel symbols differ.

Now, after a crash dump, go to `/sys/compile/WHATEVER` and run `gdb -k`. From `gdb` do:

```
symbol-file kernel.debug
exec-file /var/crash/kernel.0
core-file /var/crash/vmcore.0
```

and voila, you can debug the crash dump using the kernel sources just like you can for any other program.

Here is a script log of a `gdb` session illustrating the procedure. Long lines have been folded to improve readability, and the lines are numbered for reference. Despite this, it is a real-world error trace taken during the development of the `pcvt` console driver.

```
1:Script started on Fri Dec 30 23:15:22 1994
2:# cd /sys/compile/URIAH
3:# gdb -k kernel /var/crash/vmcore.1
4:Reading symbol data from /usr/src/sys/compile/URIAH/kernel
...done.
5:IdlePTD 1f3000
6:panic: because you said to!
7:current pcb at 1e3f70
8:Reading in symbols for ../../i386/i386/machdep.c...done.
9:(kgdb) where
10:#0 boot (arghowto=256) (../../i386/i386/machdep.c line 767)
11:#1 0xf0115159 in panic ()
12:#2 0xf01955bd in diediedie () (../../i386/i386/machdep.c line 698)
13:#3 0xf010185e in db_fncall ()
14:#4 0xf0101586 in db_command (-266509132, -266509516, -267381073)
15:#5 0xf0101711 in db_command_loop ()
16:#6 0xf01040a0 in db_trap ()
17:#7 0xf0192976 in kdb_trap (12, 0, -272630436, -266743723)
18:#8 0xf019d2eb in trap_fatal (...)
19:#9 0xf019ce60 in trap_pfault (...)
20:#10 0xf019cb2f in trap (...)
21:#11 0xf01932a1 in exception:calltrap ()
22:#12 0xf0191503 in cnopen (...)
23:#13 0xf0132c34 in spec_open ()
24:#14 0xf012d014 in vn_open ()
25:#15 0xf012a183 in open ()
26:#16 0xf019d4eb in syscall (...)
27:(kgdb) up 10
28:Reading in symbols for ../../i386/i386/trap.c...done.
29:#10 0xf019cb2f in trap (frame={tf_es = -260440048, tf_ds = 16, tf_
30:edi = 3072, tf_esi = -266445372, tf_ebp = -272630356, tf_esp = -27
31:2630396, tf_ebx = -266427884, tf_edx = 12, tf_ecx = -266427884, tf_
32:_eax = 64772224, tf_trapno = 12, tf_err = -272695296, tf_eip = -26
33:6672343, tf_cs = -266469368, tf_eflags = 66066, tf_esp = 3072, tf_
34:ss = -266427884}) (../../i386/i386/trap.c line 283)
35:283 (void) trap_pfault(&frame, FALSE);
36:(kgdb) frame frame->tf_ebp frame->tf_eip
37:Reading in symbols for ../../i386/isa/pcvt/pcvt_drv.c...done.
38:#0 0xf01ae729 in pclose (dev=3072, flag=3, mode=8192, p=(struct p\
```



```

39:roc *) 0xf07c0c00) (../../i386/isa/pcvt/pcvt_drv.c line 403)
40:403         return ((*linesw[tp->t_line].l_open)(dev, tp));
41:(kgdb) list
42:398
43:399         tp->t_state |= TS_CARR_ON;
44:400         tp->t_cflag |= CLOCAL; /* cannot be a modem (:-) */
45:401
46:402     #if PCVT_NETBSD || (PCVT_FREEBSD >= 200)
47:403         return ((*linesw[tp->t_line].l_open)(dev, tp));
48:404     #else
49:405         return ((*linesw[tp->t_line].l_open)(dev, tp, flag));
50:406     #endif /* PCVT_NETBSD || (PCVT_FREEBSD >= 200) */
51:407     }
52:(kgdb) print tp
53:Reading in symbols for ../../i386/i386/cons.c...done.
54:$1 = (struct tty *) 0xlbae
55:(kgdb) print tp->t_line
56:$2 = 1767990816
57:(kgdb) up
58:#1  0xf0191503 in cnopen (dev=0x00000000, flag=3, mode=8192, p=(st\
59:ruct proc *) 0xf07c0c00) (../../i386/i386/cons.c line 126)
60:     return ((*cdevsw[major(dev)].d_open)(dev, flag, mode, p));
61:(kgdb) up
62:#2  0xf0132c34 in spec_open ()
63:(kgdb) up
64:#3  0xf012d014 in vn_open ()
65:(kgdb) up
66:#4  0xf012a183 in open ()
67:(kgdb) up
68:#5  0xf019d4eb in syscall (frame={tf_es = 39, tf_ds = 39, tf_edi =\
69: 2158592, tf_esi = 0, tf_ebp = -272638436, tf_esp = -272629788, tf\
70:_ebx = 7086, tf_edx = 1, tf_ecx = 0, tf_eax = 5, tf_trapno = 582, \
71:tf_err = 582, tf_eip = 75749, tf_cs = 31, tf_eflags = 582, tf_esp \
72:= -272638456, tf_ss = 39}) (../../i386/i386/trap.c line 673)
73:673         error = (*callp->sy_call)(p, args, rval);
74:(kgdb) up
75:Initial frame selected; you cannot go up.
76:(kgdb) quit
77:# exit
78:exit
79:
80:Script done on Fri Dec 30 23:18:04 1994

```

Comments to the above script:

line 6:

This is a dump taken from within DDB (see below), hence the panic comment “because you said to!”, and a rather long stack trace; the initial reason for going into DDB has been a page fault trap though.

line 20:

This is the location of function trap() in the stack trace.

line 36:

Force usage of a new stack frame; this is no longer necessary. The stack frames are supposed to point to the right locations now, even in case of a trap. From looking at the code in source line 403, there is a high probability that either the pointer access for “tp” was messed up, or the array access was out of bounds.

line 52:

The pointer looks suspicious, but happens to be a valid address.

line 56:

However, it obviously points to garbage, so we have found our error! (For those unfamiliar with that particular piece of code: `tp->t_line` refers to the line discipline of the console device here, which must be a rather small integer number.)

## 16.2 Debugging a Crash Dump with DDD

Examining a kernel crash dump with a graphical debugger like `ddd` is also possible (you will need to install the `devel/ddd` port in order to use the `ddd` debugger). Add the `-k` option to the `ddd` command line you would use normally. For example;

```
# ddd -k /var/crash/kernel.0 /var/crash/vmcore.0
```

You should then be able to go about looking at the crash dump using `ddd`'s graphical interface.

## 16.3 Post-Mortem Analysis of a Dump

What do you do if a kernel dumped core but you did not expect it, and it is therefore not compiled using `config -g`? Not everything is lost here. Do not panic!

Of course, you still need to enable crash dumps. See above for the options you have to specify in order to do this.

Go to your kernel config directory (`/usr/src/sys/arch/conf`) and edit your configuration file. Uncomment (or add, if it does not exist) the following line:

```
makeoptions      DEBUG=-g                #Build kernel with gdb(1) debug symbols
```

Rebuild the kernel. Due to the time stamp change on the Makefile, there some other object files will be rebuilt, for example `trap.o`. With a bit of luck, the added `-g` option will not change anything for the generated code, so you will finally get a new kernel with similar code to the faulting one but some debugging symbols. You should at least verify the old and new sizes with the `size(1)` command. If there is a mismatch, you probably need to give up here.

Go and examine the dump as described above. The debugging symbols might be incomplete for some places, as can be seen in the stack trace in the example above where some functions are displayed without line numbers and argument lists. If you need more debugging symbols, remove the appropriate object files, recompile the kernel again and repeat the `gdb -k` session until you know enough.

All this is not guaranteed to work, but it will do it fine in most cases.

## 16.4 On-Line Kernel Debugging Using DDB

While `gdb -k` as an off-line debugger provides a very high level of user interface, there are some things it cannot do. The most important ones being breakpointing and single-stepping kernel code.

If you need to do low-level debugging on your kernel, there is an on-line debugger available called DDB. It allows setting of breakpoints, single-stepping kernel functions, examining and changing kernel variables, etc. However, it cannot access kernel source files, and only has access to the global and static symbols, not to the full debug information like `gdb` does.

To configure your kernel to include DDB, add the option line

```
options DDB
```

to your config file, and rebuild. (See The FreeBSD Handbook ([../handbook/index.html](http://handbook/index.html)) for details on configuring the FreeBSD kernel).

**Note:** If you have an older version of the boot blocks, your debugger symbols might not be loaded at all. Update the boot blocks; the recent ones load the DDB symbols automatically.

Once your DDB kernel is running, there are several ways to enter DDB. The first, and earliest way is to type the boot flag `-d` right at the boot prompt. The kernel will start up in debug mode and enter DDB prior to any device probing. Hence you can even debug the device probe/attach functions.

The second scenario is to drop to the debugger once the system has booted. There are two simple ways to accomplish this. If you would like to break to the debugger from the command prompt, simply type the command:

```
# sysctl debug.enter_debugger=ddb
```

Alternatively, if you are at the system console, you may use a hot-key on the keyboard. The default break-to-debugger sequence is **Ctrl+Alt+ESC**. For syscons, this sequence can be remapped and some of the distributed maps out there do this, so check to make sure you know the right sequence to use. There is an option available for serial consoles that allows the use of a serial line BREAK on the console line to enter DDB (`options BREAK_TO_DEBUGGER` in the kernel config file). It is not the default since there are a lot of serial adapters around that gratuitously generate a BREAK condition, for example when pulling the cable.

The third way is that any panic condition will branch to DDB if the kernel is configured to use it. For this reason, it is not wise to configure a kernel with DDB for a machine running unattended.

The DDB commands roughly resemble some `gdb` commands. The first thing you probably need to do is to set a breakpoint:

```
b function-name
b address
```

Numbers are taken hexadecimal by default, but to make them distinct from symbol names; hexadecimal numbers starting with the letters `a-f` need to be preceded with `0x` (this is optional for other numbers). Simple expressions are allowed, for example: `function-name + 0x103`.

To continue the operation of an interrupted kernel, simply type:

```
c
```

To get a stack trace, use:

```
trace
```

**Note:** Note that when entering DDB via a hot-key, the kernel is currently servicing an interrupt, so the stack trace might be not of much use to you.

If you want to remove a breakpoint, use

```
del
del address-expression
```

The first form will be accepted immediately after a breakpoint hit, and deletes the current breakpoint. The second form can remove any breakpoint, but you need to specify the exact address; this can be obtained from:

```
show b
```

To single-step the kernel, try:

```
s
```

This will step into functions, but you can make DDB trace them until the matching return statement is reached by:

```
n
```

**Note:** This is different from `gdb's next statement`; it is like `gdb's finish`.

To examine data from memory, use (for example):

```
x/wx 0xf0133fe0,40
x/hd db_syntab_space
x/bc termbuf,10
x/s stringbuf
```

for word/halfword/byte access, and hexadecimal/decimal/character/ string display. The number after the comma is the object count. To display the next 0x10 items, simply use:

```
x ,10
```

Similarly, use

```
x/ia foofunc,10
```

to disassemble the first 0x10 instructions of `foofunc`, and display them along with their offset from the beginning of `foofunc`.

To modify memory, use the write command:

```
w/b termbuf 0xa 0xb 0
w/w 0xf0010030 0 0
```

The command modifier (b/h/w) specifies the size of the data to be written, the first following expression is the address to write to and the remainder is interpreted as data to write to successive memory locations.

If you need to know the current registers, use:

```
show reg
```

Alternatively, you can display a single register value by e.g.

```
p $eax
```

and modify it by:

```
set $eax new-value
```

Should you need to call some kernel functions from DDB, simply say:

```
call func(arg1, arg2, ...)
```

The return value will be printed.

For a ps(1) style summary of all running processes, use:

```
ps
```

Now you have examined why your kernel failed, and you wish to reboot. Remember that, depending on the severity of previous malfunctioning, not all parts of the kernel might still be working as expected. Perform one of the following actions to shut down and reboot your system:

```
panic
```

This will cause your kernel to dump core and reboot, so you can later analyze the core on a higher level with `gdb`. This command usually must be followed by another `continue` statement.

```
call boot(0)
```

Which might be a good way to cleanly shut down the running system, `sync()` all disks, and finally reboot. As long as the disk and filesystem interfaces of the kernel are not damaged, this might be a good way for an almost clean shutdown.

```
call cpu_reset()
```

This is the final way out of disaster and almost the same as hitting the Big Red Button.

If you need a short command summary, simply type:

```
help
```

However, it is highly recommended to have a printed copy of the `ddb(4)` manual page ready for a debugging session. Remember that it is hard to read the on-line manual while single-stepping the kernel.

## 16.5 On-Line Kernel Debugging Using Remote GDB

This feature has been supported since FreeBSD 2.2, and it is actually a very neat one.

GDB has already supported *remote debugging* for a long time. This is done using a very simple protocol along a serial line. Unlike the other methods described above, you will need two machines for doing this. One is the host providing the debugging environment, including all the sources, and a copy of the kernel binary with all the symbols in it, and the other one is the target machine that simply runs a similar copy of the very same kernel (but stripped of the debugging information).

You should configure the kernel in question with `config -g`, include DDB into the configuration, and compile it as usual. This gives a large binary, due to the debugging information. Copy this kernel to the target machine, strip the debugging symbols off with `strip -x`, and boot it using the `-d` boot option. Connect the serial line of the target machine that has "flags 080" set on its sio device to any serial line of the debugging host. Now, on the debugging machine, go to the compile directory of the target kernel, and start `gdb`:

```
% gdb -k kernel
GDB is free software and you are welcome to distribute copies of it
  under certain conditions; type "show copying" to see the conditions.
There is absolutely no warranty for GDB; type "show warranty" for details.
GDB 4.16 (i386-unknown-freebsd),
Copyright 1996 Free Software Foundation, Inc...
(kgdb)
```

Initialize the remote debugging session (assuming the first serial port is being used) by:

```
(kgdb) target remote /dev/cuaa0
```

Now, on the target host (the one that entered DDB right before even starting the device probe), type:

```
Debugger("Boot flags requested debugger")
Stopped at Debugger+0x35: movb $0, edata+0x51bc
db> gdb
```

DDB will respond with:

```
Next trap will enter GDB remote protocol mode
```

Every time you type `gdb`, the mode will be toggled between remote GDB and local DDB. In order to force a next trap immediately, simply type `s` (step). Your hosting GDB will now gain control over the target kernel:

```
Remote debugging using /dev/cuaa0
Debugger (msg=0xf01b0383 "Boot flags requested debugger")
  at ../../i386/i386/db_interface.c:257
(kgdb)
```

You can use this session almost as any other GDB session, including full access to the source, running it in `gud`-mode inside an Emacs window (which gives you an automatic source code display in another Emacs window), etc.

## 16.6 Debugging Loadable Modules Using GDB

When debugging a panic that occurred within a module, or using remote GDB against a machine that uses dynamic modules, you need to tell GDB how to obtain symbol information for those modules.

First, you need to build the module(s) with debugging information:

```
# cd /sys/modules/linux
# make clean; make COPTS=-g
```

If you are using remote GDB, you can run `kldstat` on the target machine to find out where the module was loaded:

```
# kldstat
Id Refs Address      Size      Name
 1   4 0xc0100000 1c1678   kernel
 2   1 0xc0a9e000 6000     linprocfs.ko
 3   1 0xc0ad7000 2000     warp_saver.ko
 4   1 0xc0adc000 11000    linux.ko
```

If you are debugging a crash dump, you will need to walk the `linker_files` list, starting at `linker_files->tqh_first` and following the `link.tqe_next` pointers until you find the entry with the filename you are looking for. The `address` member of that entry is the load address of the module.

Next, you need to find out the offset of the text section within the module:

```
# objdump --section-headers /sys/modules/linux/linux.ko | grep text
 3 .rel.text      000016e0 000038e0 000038e0 000038e0 2**2
10 .text          00007f34 000062d0 000062d0 000062d0 2**2
```

The one you want is the `.text` section, section 10 in the above example. The fourth hexadecimal field (sixth field overall) is the offset of the text section within the file. Add this offset to the load address of the module to obtain the relocation address for the module's code. In our example, we get  $0xc0adc000 + 0x62d0 = 0xc0ae22d0$ . Use the `add-symbol-file` command in GDB to tell the debugger about the module:

```
(kgdb) add-symbol-file /sys/modules/linux/linux.ko 0xc0ae22d0
add symbol table from file "/sys/modules/linux/linux.ko" at text_addr = 0xc0ae22d0?
(y or n) y
Reading symbols from /sys/modules/linux/linux.ko...done.
(kgdb)
```

You should now have access to all the symbols in the module.

## 16.7 Debugging a Console Driver

Since you need a console driver to run DDB on, things are more complicated if the console driver itself is failing. You might remember the use of a serial console (either with modified boot blocks, or by specifying `-h` at the `Boot:` prompt), and hook up a standard terminal onto your first serial port. DDB works on any configured console driver, including a serial console.

# Chapter 17 \* UFS

UFS, FFS, Ext2FS, JFS, inodes, buffer cache, labeling, locking, metadata, soft-updates, LFS, portals, procs, vnodes, memory sharing, memory objects, TLBs, caching



# Chapter 18 \* AFS

AFS, NFS, SANs, etc.

# Chapter 19 \* Syscons

Syscons, tty, PCVT, serial console, screen savers, etc.

# Chapter 20 \* Compatibility Layers

## 20.1 \* Linux

Linux, SVR4, etc.

## **IV. Device Drivers**

# Chapter 21 Writing FreeBSD Device Drivers

This chapter was written by Murray Stokely <murray@FreeBSD.org> with selections from a variety of sources including the intro(4) man page by Jörg Wunsch <joerg@FreeBSD.org>.

## 21.1 Introduction

This chapter provides a brief introduction to writing device drivers for FreeBSD. A device in this context is a term used mostly for hardware-related stuff that belongs to the system, like disks, printers, or a graphics display with its keyboard. A device driver is the software component of the operating system that controls a specific device. There are also so-called pseudo-devices where a device driver emulates the behaviour of a device in software without any particular underlying hardware. Device drivers can be compiled into the system statically or loaded on demand through the dynamic kernel linker facility 'kld'.

Most devices in a Unix-like operating system are accessed through device-nodes, sometimes also called special files. These files are usually located under the directory `/dev` in the filesystem hierarchy. Until devfs is fully integrated into FreeBSD, each device node must be created statically and independent of the existence of the associated device driver. Most device nodes on the system are created by running `MAKEDEV`.

Device drivers can roughly be broken down into two categories; character and network device drivers.

## 21.2 Dynamic Kernel Linker Facility - KLD

The `kld` interface allows system administrators to dynamically add and remove functionality from a running system. This allows device driver writers to load their new changes into a running kernel without constantly rebooting to test changes.

The `kld` interface is used through the following privileged commands:

- `kldload` - loads a new kernel module
- `kldunload` - unloads a kernel module
- `kldstat` - lists the currently loaded modules

Skeleton Layout of a kernel module

```
/*
 * KLD Skeleton
 * Inspired by Andrew Reiter's Daemonnews article
 */

#include <sys/types.h>
#include <sys/module.h>
#include <sys/system.h> /* uprintf */
#include <sys/errno.h>
#include <sys/param.h> /* defines used in kernel.h */
#include <sys/kernel.h> /* types used in module initialization */
```

```

/*
 * Load handler that deals with the loading and unloading of a KLD.
 */

static int
skel_loader(struct module *m, int what, void *arg)
{
    int err = 0;

    switch (what) {
    case MOD_LOAD:          /* kldload */
        uprintf("Skeleton KLD loaded.\n");
        break;
    case MOD_UNLOAD:
        uprintf("Skeleton KLD unloaded.\n");
        break;
    default:
        err = EINVAL;
        break;
    }
    return(err);
}

/* Declare this module to the rest of the kernel */

static moduledata_t skel_mod = {
    "skel",
    skel_loader,
    NULL
};

DECLARE_MODULE(skeleton, skel_mod, SI_SUB_KLD, SI_ORDER_ANY);

```

## 21.2.1 Makefile

FreeBSD provides a makefile include that you can use to quickly compile your kernel addition.

```

SRCS=skeleton.c
KMOD=skeleton

.include <bsd.kmod.mk>

```

Simply running make with this makefile will create a file `skeleton.ko` that can be loaded into your system by typing:

```
# kldload -v ./skeleton.ko
```

## 21.3 Accessing a device driver

Unix provides a common set of system calls for user applications to use. The upper layers of the kernel dispatch these calls to the corresponding device driver when a user accesses a device node. The `/dev/MAKEDEV` script makes most of the device nodes for your system but if you are doing your own driver development it may be necessary to create your own device nodes with `mknod`.

### 21.3.1 Creating static device nodes

The `mknod` command requires four arguments to create a device node. You must specify the name of the device node, the type of device, the major number of the device, and the minor number of the device.

### 21.3.2 Dynamic device nodes

The device filesystem, or `devfs`, provides access to the kernel's device namespace in the global filesystem namespace. This eliminates the problems of potentially having a device driver without a static device node, or a device node without an installed device driver. `Devfs` is still a work in progress, but it is already working quite nicely.

## 21.4 Character Devices

A character device driver is one that transfers data directly to and from a user process. This is the most common type of device driver and there are plenty of simple examples in the source tree.

This simple example pseudo-device remembers whatever values you write to it and can then supply them back to you when you read from it.

```

/*
 * Simple 'echo' pseudo-device KLD
 *
 * Murray Stokely
 */

#define MIN(a,b) (((a) < (b)) ? (a) : (b))

#include <sys/types.h>
#include <sys/module.h>
#include <sys/systm.h> /* uprintf */
#include <sys/errno.h>
#include <sys/param.h> /* defines used in kernel.h */
#include <sys/kernel.h> /* types used in module initialization */
#include <sys/conf.h> /* cdevsw struct */
#include <sys/uio.h> /* uio struct */
#include <sys/malloc.h>

#define BUFFERSIZE 256

/* Function prototypes */

```

```

d_open_t      echo_open;
d_close_t    echo_close;
d_read_t     echo_read;
d_write_t    echo_write;

/* Character device entry points */
static struct cdevsw echo_cdevsw = {
    echo_open,
    echo_close,
    echo_read,
    echo_write,
    noioctl,
    nopoll,
    nommap,
    nostrategy,
    "echo",
    33,                /* reserved for lkms - /usr/src/sys/conf/majors */
    nodump,
    nopsize,
    D_TTY,
    -1
};

typedef struct s_echo {
    char msg[BUFFERSIZE];
    int len;
} t_echo;

/* vars */
static dev_t sdev;
static int len;
static int count;
static t_echo *echomsg;

MALLOC_DECLARE(M_ECHOBUF);
MALLOC_DEFINE(M_ECHOBUF, "echobuffer", "buffer for echo module");

/*
 * This function acts is called by the kld[un]load(2) system calls to
 * determine what actions to take when a module is loaded or unloaded.
 */

static int
echo_loader(struct module *m, int what, void *arg)
{
    int err = 0;

    switch (what) {
    case MOD_LOAD:                /* kldload */
        sdev = make_dev(&echo_cdevsw,
            0,
            UID_ROOT,
            GID_WHEEL,

```



```

    0600,
    "echo");
/* kcalloc memory for use by this driver */
/*    malloc(256,M_ECHobuf,M_WAITOK); */
MALLOC(echomsg, t_echo *, sizeof(t_echo), M_ECHobuf, M_WAITOK);
printf("Echo device loaded.\n");
break;
case MOD_UNLOAD:
    destroy_dev(sdev);
    FREE(echomsg,M_ECHobuf);
    printf("Echo device unloaded.\n");
    break;
default:
    err = EINVAL;
    break;
}
return(err);
}

int
echo_open(dev_t dev, int oflags, int devtype, struct proc *p)
{
    int err = 0;

    uprintf("Opened device \"echo\" successfully.\n");
    return(err);
}

int
echo_close(dev_t dev, int fflag, int devtype, struct proc *p)
{
    uprintf("Closing device \"echo.\n");
    return(0);
}

/*
 * The read function just takes the buf that was saved via
 * echo_write() and returns it to userland for accessing.
 * uio(9)
 */

int
echo_read(dev_t dev, struct uio *uio, int ioflag)
{
    int err = 0;
    int amt;

    /* How big is this read operation?  Either as big as the user wants,
       or as big as the remaining data */
    amt = MIN(uio->uio_resid, (echomsg->len - uio->uio_offset > 0) ? echomsg->len - uio-
>uio_offset : 0);
    if ((err = uiomove(echomsg->msg + uio->uio_offset,amt,uio)) != 0) {
        uprintf("uiomove failed!\n");
    }
}

```

```

    }

    return err;
}

/*
 * echo_write takes in a character string and saves it
 * to buf for later accessing.
 */

int
echo_write(dev_t dev, struct uio *uio, int ioflag)
{
    int err = 0;

    /* Copy the string in from user memory to kernel memory */
    err = copyin(uio->uio_iov->iiov_base, echomsg->msg, MIN(uio->uio_iov->iiov_len,BUFFERSIZE));

    /* Now we need to null terminate */
    *(echomsg->msg + MIN(uio->uio_iov->iiov_len,BUFFERSIZE)) = 0;
    /* Record the length */
    echomsg->len = MIN(uio->uio_iov->iiov_len,BUFFERSIZE);

    if (err != 0) {
        uprintf("Write failed: bad address!\n");
    }

    count++;
    return(err);
}

DEV_MODULE(echo,echo_loader,NULL);

```

To install this driver you will first need to make a node on your filesystem with a command such as:

```
# mknod /dev/echo c 33 0
```

With this driver loaded you should now be able to type something like:

```
# echo -n "Test Data" > /dev/echo
# cat /dev/echo
Test Data
```

Real hardware devices in the next chapter..

#### Additional Resources

- Dynamic Kernel Linker (KLD) Facility Programming Tutorial (<http://www.daemonnews.org/200010/blueprints.html>) - Daemonnews (<http://www.daemonnews.org/>) October 2000
- How to Write Kernel Drivers with NEWBUS (<http://www.daemonnews.org/200007/newbus-intro.html>) - Daemonnews (<http://www.daemonnews.org/>) July 2000

## **21.5 Network Drivers**

Drivers for network devices do not use device nodes in order to be accessed. Their selection is based on other decisions made inside the kernel and instead of calling `open()`, use of a network device is generally introduced by using the system call `socket(2)`.

`man ifnet()`, loopback device, Bill Paul's drivers, etc..

# Chapter 22 ISA device drivers

*This chapter was written by Sergey Babkin <babkin@FreeBSD.org> Modifications for the handbook made by Murray Stokely <murray@FreeBSD.org>, Wylie Stilwell <>wylie@magnesium.net>, and Valentino Vaschetto <logo@FreeBSD.org>.*

## 22.1 Synopsis

This chapter introduces the issues relevant to writing a driver for an ISA device. The pseudo-code presented here is rather detailed and reminiscent of the real code but is still only pseudo-code. It avoids the details irrelevant to the subject of the discussion. The real-life examples can be found in the source code of real drivers. In particular the drivers `ep` and `aha` are good sources of information.

## 22.2 Basic information

A typical ISA driver would need the following include files:

```
#include <sys/module.h>
#include <sys/bus.h>
#include <machine/bus.h>
#include <machine/resource.h>
#include <sys/rman.h>

#include <isa/isavar.h>
#include <isa/pnpvar.h>
```

They describe the things specific to the ISA and generic bus subsystem.

The bus subsystem is implemented in an object-oriented fashion, its main structures are accessed by associated method functions.

The list of bus methods implemented by an ISA driver is like one for any other bus. For a hypothetical driver named “xxx” they would be:

- `static void xxx_isa_identify (driver_t *, device_t);` Normally used for bus drivers, not device drivers. But for ISA devices this method may have special use: if the device provides some device-specific (non-PnP) way to auto-detect devices this routine may implement it.
- `static int xxx_isa_probe (device_t dev);` Probe for a device at a known (or PnP) location. This routine can also accommodate device-specific auto-detection of parameters for partially configured devices.
- `static int xxx_isa_attach (device_t dev);` Attach and initialize device.
- `static int xxx_isa_detach (device_t dev);` Detach device before unloading the driver module.
- `static int xxx_isa_shutdown (device_t dev);` Execute shutdown of the device before system shutdown.
- `static int xxx_isa_suspend (device_t dev);` Suspend the device before the system goes to the power-save state. May also abort transition to the power-save state.

- `static int xxx_isa_resume (device_t dev);` Resume the device activity after return from power-save state.

`xxx_isa_probe()` and `xxx_isa_attach()` are mandatory, the rest of the routines are optional, depending on the device's needs.

The driver is linked to the system with the following set of descriptions.

```

/* table of supported bus methods */
static device_method_t xxx_isa_methods[] = {
    /* list all the bus method functions supported by the driver */
    /* omit the unsupported methods */
    DEVMETHOD(device_identify, xxx_isa_identify),
    DEVMETHOD(device_probe, xxx_isa_probe),
    DEVMETHOD(device_attach, xxx_isa_attach),
    DEVMETHOD(device_detach, xxx_isa_detach),
    DEVMETHOD(device_shutdown, xxx_isa_shutdown),
    DEVMETHOD(device_suspend, xxx_isa_suspend),
    DEVMETHOD(device_resume, xxx_isa_resume),

    { 0, 0 }
};

static driver_t xxx_isa_driver = {
    "xxx",
    xxx_isa_methods,
    sizeof(struct xxx_softc),
};

static devclass_t xxx_devclass;

DRIVER_MODULE(xxx, isa, xxx_isa_driver, xxx_devclass,
    load_function, load_argument);

```

Here `struct xxx_softc` is a device-specific structure that contains private driver data and descriptors for the driver's resources. The bus code automatically allocates one `softc` descriptor per device as needed.

If the driver is implemented as a loadable module then `load_function()` is called to do driver-specific initialization or clean-up when the driver is loaded or unloaded and `load_argument` is passed as one of its arguments. If the driver does not support dynamic loading (in other words it must always be linked into kernel) then these values should be set to 0 and the last definition would look like:

```

DRIVER_MODULE(xxx, isa, xxx_isa_driver,
    xxx_devclass, 0, 0);

```

If the driver is for a device which supports PnP then a table of supported PnP IDs must be defined. The table consists of a list of PnP IDs supported by this driver and human-readable descriptions of the hardware types and models having these IDs. It looks like:

```

static struct isa_pnp_id xxx_pnp_ids[] = {
    /* a line for each supported PnP ID */
    { 0x12345678, "Our device model 1234A" },
    { 0x12345679, "Our device model 1234B" },
};

```

```

    { 0,          NULL }, /* end of table */
};

```

If the driver does not support PnP devices it still needs an empty PnP ID table, like:

```

static struct isa_pnp_id xxx_pnp_ids[] = {
    { 0,          NULL }, /* end of table */
};

```

## 22.3 Device\_t pointer

Device\_t is the pointer type for the device structure. Here we consider only the methods interesting from the device driver writer's standpoint. The methods to manipulate values in the device structure are:

- `device_t device_get_parent(dev)` Get the parent bus of a device.
- `driver_t device_get_driver(dev)` Get pointer to its driver structure.
- `char *device_get_name(dev)` Get the driver name, such as "xxx" for our example.
- `int device_get_unit(dev)` Get the unit number (units are numbered from 0 for the devices associated with each driver).
- `char *device_get_nameunit(dev)` Get the device name including the unit number, such as "xxx0", "xxx1" and so on.
- `char *device_get_desc(dev)` Get the device description. Normally it describes the exact model of device in human-readable form.
- `device_set_desc(dev, desc)` Set the description. This makes the device description point to the string desc which may not be deallocated or changed after that.
- `device_set_desc_copy(dev, desc)` Set the description. The description is copied into an internal dynamically allocated buffer, so the string desc may be changed afterwards without adverse effects.
- `void *device_get_softc(dev)` Get pointer to the device descriptor (struct xxx\_softc) associated with this device.
- `u_int32_t device_get_flags(dev)` Get the flags specified for the device in the configuration file.

A convenience function `device_printf(dev, fmt, ...)` may be used to print the messages from the device driver. It automatically prepends the unitname and colon to the message.

The `device_t` methods are implemented in the file `kern/bus_subr.c`.

## 22.4 Configuration file and the order of identifying and probing during auto-configuration

The ISA devices are described in the kernel configuration file like:

```

device xxx0 at isa? port 0x300 irq 10 drq 5

```

```
iomem 0xd0000 flags 0x1 sensitive
```

The values of port, IRQ and so on are converted to the resource values associated with the device. They are optional, depending on the device's needs and abilities for auto-configuration. For example, some devices do not need DRQ at all and some allow the driver to read the IRQ setting from the device configuration ports. If a machine has multiple ISA buses the exact bus may be specified in the configuration line, like `isa0` or `isa1`, otherwise the device would be searched for on all the ISA buses.

`sensitive` is a resource requesting that this device must be probed before all non-sensitive devices. It is supported but does not seem to be used in any current driver.

For legacy ISA devices in many cases the drivers are still able to detect the configuration parameters. But each device to be configured in the system must have a config line. If two devices of some type are installed in the system but there is only one configuration line for the corresponding driver, ie:

```
device xxx0 at isa?
```

then only one device will be configured.

But for the devices supporting automatic identification by the means of Plug-n-Play or some proprietary protocol one configuration line is enough to configure all the devices in the system, like the one above or just simply:

```
device xxx at isa?
```

If a driver supports both auto-identified and legacy devices and both kinds are installed at once in one machine then it is enough to describe in the config file the legacy devices only. The auto-identified devices will be added automatically.

When an ISA bus is auto-configured the events happen as follows:

All the drivers' identify routines (including the PnP identify routine which identifies all the PnP devices) are called in random order. As they identify the devices they add them to the list on the ISA bus. Normally the drivers' identify routines associate their drivers with the new devices. The PnP identify routine does not know about the other drivers yet so it does not associate any with the new devices it adds.

The PnP devices are put to sleep using the PnP protocol to prevent them from being probed as legacy devices.

The probe routines of non-PnP devices marked as `sensitive` are called. If probe for a device went successfully, the attach routine is called for it.

The probe and attach routines of all non-PnP devices are called likewise.

The PnP devices are brought back from the sleep state and assigned the resources they request: I/O and memory address ranges, IRQs and DRQs, all of them not conflicting with the attached legacy devices.

Then for each PnP device the probe routines of all the present ISA drivers are called. The first one that claims the device gets attached. It is possible that multiple drivers would claim the device with different priority; in this case, the highest-priority driver wins. The probe routines must call `ISA_PNP_PROBE()` to compare the actual PnP ID with the list of the IDs supported by the driver and if the ID is not in the table return failure. That means that absolutely every driver, even the ones not supporting any PnP devices must call `ISA_PNP_PROBE()`, at least with an empty PnP ID table to return failure on unknown PnP devices.

The probe routine returns a positive value (the error code) on error, zero or negative value on success.

The negative return values are used when a PnP device supports multiple interfaces. For example, an older compatibility interface and a newer advanced interface which are supported by different drivers. Then both drivers

would detect the device. The driver which returns a higher value in the probe routine takes precedence (in other words, the driver returning 0 has highest precedence, returning -1 is next, returning -2 is after it and so on). In result the devices which support only the old interface will be handled by the old driver (which should return -1 from the probe routine) while the devices supporting the new interface as well will be handled by the new driver (which should return 0 from the probe routine). If multiple drivers return the same value then the one called first wins. So if a driver returns value 0 it may be sure that it won the priority arbitration.

The device-specific identify routines can also assign not a driver but a class of drivers to the device. Then all the drivers in the class are probed for this device, like the case with PnP. This feature is not implemented in any existing driver and is not considered further in this document.

Because the PnP devices are disabled when probing the legacy devices they will not be attached twice (once as legacy and once as PnP). But in case of device-dependent identify routines it is the responsibility of the driver to make sure that the same device will not be attached by the driver twice: once as legacy user-configured and once as auto-identified.

Another practical consequence for the auto-identified devices (both PnP and device-specific) is that the flags can not be passed to them from the kernel configuration file. So they must either not use the flags at all or use the flags from the device unit 0 for all the auto-identified devices or use the `sysctl` interface instead of flags.

Other unusual configurations may be accommodated by accessing the configuration resources directly with functions of families `resource_query_*`() and `resource_*_value()`. Their implementations are located in `kern/subr_bus.h`. The old IDE disk driver `i386/isa/wd.c` contains examples of such use. But the standard means of configuration must always be preferred. Leave parsing the configuration resources to the bus configuration code.

## 22.5 Resources

The information that a user enters into the kernel configuration file is processed and passed to the kernel as configuration resources. This information is parsed by the bus configuration code and transformed into a value of structure `device_t` and the bus resources associated with it. The drivers may access the configuration resources directly using functions `resource_*` for more complex cases of configuration. However, generally this is neither needed nor recommended, so this issue is not discussed further here.

The bus resources are associated with each device. They are identified by type and number within the type. For the ISA bus the following types are defined:

- `SYS_RES_IRQ` - interrupt number
- `SYS_RES_DRQ` - ISA DMA channel number
- `SYS_RES_MEMORY` - range of device memory mapped into the system memory space
- `SYS_RES_IOPORT` - range of device I/O registers

The enumeration within types starts from 0, so if a device has two memory regions it would have resources of type `SYS_RES_MEMORY` numbered 0 and 1. The resource type has nothing to do with the C language type, all the resource values have the C language type `unsigned long` and must be cast as necessary. The resource numbers do not have to be contiguous, although for ISA they normally would be. The permitted resource numbers for ISA devices are:

IRQ: 0-1



```
DRQ: 0-1
MEMORY: 0-3
IOPORT: 0-7
```

All the resources are represented as ranges, with a start value and count. For IRQ and DRQ resources the count would normally be equal to 1. The values for memory refer to the physical addresses.

Three types of activities can be performed on resources:

- set/get
- allocate/release
- activate/deactivate

Setting sets the range used by the resource. Allocation reserves the requested range that no other driver would be able to reserve it (and checking that no other driver reserved this range already). Activation makes the resource accessible to the driver by doing whatever is necessary for that (for example, for memory it would be mapping into the kernel virtual address space).

The functions to manipulate resources are:

- `int bus_set_resource(device_t dev, int type, int rid, u_long start, u_long count)`

Set a range for a resource. Returns 0 if successful, error code otherwise. Normally, this function will return an error only if one of `type`, `rid`, `start` or `count` has a value that falls out of the permitted range.

- `dev` - driver's device
- `type` - type of resource, `SYS_RES_*`
- `rid` - resource number (ID) within type
- `start, count` - resource range

- `int bus_get_resource(device_t dev, int type, int rid, u_long *startp, u_long *countp)`

Get the range of resource. Returns 0 if successful, error code if the resource is not defined yet.

- `u_long bus_get_resource_start(device_t dev, int type, int rid)` `u_long bus_get_resource_count (device_t dev, int type, int rid)`

Convenience functions to get only the start or count. Return 0 in case of error, so if the resource start has 0 among the legitimate values it would be impossible to tell if the value is 0 or an error occurred. Luckily, no ISA resources for add-on drivers may have a start value equal to 0.

- `void bus_delete_resource(device_t dev, int type, int rid)`

Delete a resource, make it undefined.

- `struct resource * bus_alloc_resource(device_t dev, int type, int *rid, u_long start, u_long end, u_long count, u_int flags)`

Allocate a resource as a range of count values not allocated by anyone else, somewhere between start and end. Alas, alignment is not supported. If the resource was not set yet it is automatically created. The special values of start 0 and end ~0 (all ones) means that the fixed values previously set by `bus_set_resource()` must be used instead: start and count as themselves and `end=(start+count)`, in this case if the resource was not defined before then an error is returned. Although `rid` is passed by reference it is not set anywhere by the resource allocation code of the ISA bus. (The other buses may use a different approach and modify it).

Flags are a bitmap, the flags interesting for the caller are:

- `RF_ACTIVE` - causes the resource to be automatically activated after allocation.
- `RF_SHAREABLE` - resource may be shared at the same time by multiple drivers.
- `RF_TIMESHARE` - resource may be time-shared by multiple drivers, i.e. allocated at the same time by many but activated only by one at any given moment of time.
- Returns 0 on error. The allocated values may be obtained from the returned handle using methods `rhand_*()`.
- `int bus_release_resource(device_t dev, int type, int rid, struct resource *r)`
- Release the resource, `r` is the handle returned by `bus_alloc_resource()`. Returns 0 on success, error code otherwise.
- `int bus_activate_resource(device_t dev, int type, int rid, struct resource *r) int bus_deactivate_resource(device_t dev, int type, int rid, struct resource *r)`
- Activate or deactivate resource. Return 0 on success, error code otherwise. If the resource is time-shared and currently activated by another driver then `EBUSY` is returned.
- `int bus_setup_intr(device_t dev, struct resource *r, int flags, driver_intr_t *handler, void *arg, void **cookie) int bus_tearardown_intr(device_t dev, struct resource *r, void *cookie)`
- Associate or de-associate the interrupt handler with a device. Return 0 on success, error code otherwise.
- `r` - the activated resource handler describing the IRQ

`flags` - the interrupt priority level, one of:

- `INTR_TYPE_TTY` - terminals and other likewise character-type devices. To mask them use `spltty()`.
- `(INTR_TYPE_TTY | INTR_TYPE_FAST)` - terminal type devices with small input buffer, critical to the data loss on input (such as the old-fashioned serial ports). To mask them use `spltty()`.
- `INTR_TYPE_BIO` - block-type devices, except those on the CAM controllers. To mask them use `splbio()`.
- `INTR_TYPE_CAM` - CAM (Common Access Method) bus controllers. To mask them use `splcam()`.
- `INTR_TYPE_NET` - network interface controllers. To mask them use `splimp()`.
- `INTR_TYPE_MISC` - miscellaneous devices. There is no other way to mask them than by `splhigh()` which masks all interrupts.

When an interrupt handler executes all the other interrupts matching its priority level will be masked. The only exception is the MISC level for which no other interrupts are masked and which is not masked by any other interrupt.

- *handler* - pointer to the handler function, the type `driver_intr_t` is defined as `void driver_intr_t(void *)`
- *arg* - the argument passed to the handler to identify this particular device. It is cast from `void*` to any real type by the handler. The old convention for the ISA interrupt handlers was to use the unit number as argument, the new (recommended) convention is using a pointer to the device `softc` structure.
- *cookie[p]* - the value received from `setup()` is used to identify the handler when passed to `teardown()`

A number of methods are defined to operate on the resource handlers (struct `resource *`). Those of interest to the device driver writers are:

- `u_long rman_get_start(r)` `u_long rman_get_end(r)` Get the start and end of allocated resource range.
- `void *rman_get_virtual(r)` Get the virtual address of activated memory resource.

## 22.6 Bus memory mapping

In many cases data is exchanged between the driver and the device through the memory. Two variants are possible:

- memory is located on the device card
- memory is the main memory of the computer

In case (a) the driver always copies the data back and forth between the on-card memory and the main memory as necessary. To map the on-card memory into the kernel virtual address space the physical address and length of the on-card memory must be defined as a `SYS_RES_MEMORY` resource. That resource can then be allocated and activated, and its virtual address obtained using `rman_get_virtual()`. The older drivers used the function `pmap_mapdev()` for this purpose, which should not be used directly any more. Now it is one of the internal steps of resource activation.

Most of the ISA cards will have their memory configured for physical location somewhere in range 640KB-1MB. Some of the ISA cards require larger memory ranges which should be placed somewhere under 16MB (because of the 24-bit address limitation on the ISA bus). In that case if the machine has more memory than the start address of the device memory (in other words, they overlap) a memory hole must be configured at the address range used by devices. Many BIOSes allow configuration of a memory hole of 1MB starting at 14MB or 15MB. FreeBSD can handle the memory holes properly if the BIOS reports them properly (this feature may be broken on old BIOSes).

In case (b) just the address of the data is sent to the device, and the device uses DMA to actually access the data in the main memory. Two limitations are present: First, ISA cards can only access memory below 16MB. Second, the contiguous pages in virtual address space may not be contiguous in physical address space, so the device may have to do scatter/gather operations. The bus subsystem provides ready solutions for some of these problems, the rest has to be done by the drivers themselves.

Two structures are used for DMA memory allocation, `bus_dma_tag_t` and `bus_dmamap_t`. Tag describes the properties required for the DMA memory. Map represents a memory block allocated according to these properties. Multiple maps may be associated with the same tag.

Tags are organized into a tree-like hierarchy with inheritance of the properties. A child tag inherits all the requirements of its parent tag, and may make them more strict but never more loose.

Normally one top-level tag (with no parent) is created for each device unit. If multiple memory areas with different requirements are needed for each device then a tag for each of them may be created as a child of the parent tag.

The tags can be used to create a map in two ways.

First, a chunk of contiguous memory conformant with the tag requirements may be allocated (and later may be freed). This is normally used to allocate relatively long-living areas of memory for communication with the device. Loading of such memory into a map is trivial: it is always considered as one chunk in the appropriate physical memory range.

Second, an arbitrary area of virtual memory may be loaded into a map. Each page of this memory will be checked for conformance to the map requirement. If it conforms then it is left at its original location. If it is not then a fresh conformant “bounce page” is allocated and used as intermediate storage. When writing the data from the non-conformant original pages they will be copied to their bounce pages first and then transferred from the bounce pages to the device. When reading the data would go from the device to the bounce pages and then copied to their non-conformant original pages. The process of copying between the original and bounce pages is called synchronization. This is normally used on a per-transfer basis: buffer for each transfer would be loaded, transfer done and buffer unloaded.

The functions working on the DMA memory are:

- `int bus_dma_tag_create(bus_dma_tag_t parent, bus_size_t alignment, bus_size_t boundary, bus_addr_t lowaddr, bus_addr_t highaddr, bus_dma_filter_t *filter, void *filterarg, bus_size_t maxsize, int nsegments, bus_size_t maxsegsz, int flags, bus_dma_tag_t *dmat)`

Create a new tag. Returns 0 on success, the error code otherwise.

- *parent* - parent tag, or NULL to create a top-level tag *alignment* - required physical alignment of the memory area to be allocated for this tag. Use value 1 for “no specific alignment”. Applies only to the future `bus_dmamem_alloc()` but not `bus_dmamap_create()` calls.
- *boundary* - physical address boundary that must not be crossed when allocating the memory. Use value 0 for “no boundary”. Applies only to the future `bus_dmamem_alloc()` but not `bus_dmamap_create()` calls. Must be power of 2. If the memory is planned to be used in non-cascaded DMA mode (i.e. the DMA addresses will be supplied not by the device itself but by the ISA DMA controller) then the boundary must be no larger than 64KB (64\*1024) due to the limitations of the DMA hardware.
- *lowaddr*, *highaddr* - the names are slightly misleading; these values are used to limit the permitted range of physical addresses used to allocate the memory. The exact meaning varies depending on the planned future use:
  - For `bus_dmamem_alloc()` all the addresses from 0 to `lowaddr-1` are considered permitted, the higher ones are forbidden.
  - For `bus_dmamap_create()` all the addresses outside the inclusive range [`lowaddr`; `highaddr`] are considered accessible. The addresses of pages inside the range are passed to the filter function which decides if they are accessible. If no filter function is supplied then all the range is considered unaccessible.
  - For the ISA devices the normal values (with no filter function) are:
    - `lowaddr = BUS_SPACE_MAXADDR_24BIT`
    - `highaddr = BUS_SPACE_MAXADDR`

- *filter, filterarg* - the filter function and its argument. If NULL is passed for filter then the whole range [lowaddr, highaddr] is considered unaccessible when doing `bus_dmamap_create()`. Otherwise the physical address of each attempted page in range [lowaddr; highaddr] is passed to the filter function which decides if it is accessible. The prototype of the filter function is: `int filterfunc(void *arg, bus_addr_t paddr)`. It must return 0 if the page is accessible, non-zero otherwise.
  - *maxsize* - the maximal size of memory (in bytes) that may be allocated through this tag. In case it is difficult to estimate or could be arbitrarily big, the value for ISA devices would be `BUS_SPACE_MAXSIZE_24BIT`.
  - *nsegments* - maximal number of scatter-gather segments supported by the device. If unrestricted then the value `BUS_SPACE_UNRESTRICTED` should be used. This value is recommended for the parent tags, the actual restrictions would then be specified for the descendant tags. Tags with *nsegments* equal to `BUS_SPACE_UNRESTRICTED` may not be used to actually load maps, they may be used only as parent tags. The practical limit for *nsegments* seems to be about 250-300, higher values will cause kernel stack overflow (the hardware can not normally support that many scatter-gather buffers anyway).
  - *maxsegsz* - maximal size of a scatter-gather segment supported by the device. The maximal value for ISA device would be `BUS_SPACE_MAXSIZE_24BIT`.
  - *flags* - a bitmap of flags. The only interesting flags are:
    - *BUS\_DMA\_ALLOCNOW* - requests to allocate all the potentially needed bounce pages when creating the tag.
    - *BUS\_DMA\_ISA* - mysterious flag used only on Alpha machines. It is not defined for the i386 machines. Probably it should be used by all the ISA drivers for Alpha machines but it looks like there are no such drivers yet.
  - *dmata* - pointer to the storage for the new tag to be returned.
- 
- `int bus_dma_tag_destroy(bus_dma_tag_t dmata)`  
 Destroy a tag. Returns 0 on success, the error code otherwise.  
*dmata* - the tag to be destroyed.
  - `int bus_dmamem_alloc(bus_dma_tag_t dmata, void** vaddr, int flags, bus_dmamap_t *mapp)`  
 Allocate an area of contiguous memory described by the tag. The size of memory to be allocated is tag's *maxsize*. Returns 0 on success, the error code otherwise. The result still has to be loaded by `bus_dmamap_load()` before being used to get the physical address of the memory.
    - *dmata* - the tag
    - *vaddr* - pointer to the storage for the kernel virtual address of the allocated area to be returned.
    - *flags* - a bitmap of flags. The only interesting flag is:
      - *BUS\_DMA\_NOWAIT* - if the memory is not immediately available return the error. If this flag is not set then the routine is allowed to sleep until the memory becomes available.

- *mapp* - pointer to the storage for the new map to be returned.
- `void bus_dmamem_free(bus_dma_tag_t dmat, void *vaddr, bus_dmamap_t map)`  
Free the memory allocated by `bus_dmamem_alloc()`. At present, freeing of the memory allocated with ISA restrictions is not implemented. Because of this the recommended model of use is to keep and re-use the allocated areas for as long as possible. Do not lightly free some area and then shortly allocate it again. That does not mean that `bus_dmamem_free()` should not be used at all: hopefully it will be properly implemented soon.
- *dmat* - the tag
  - *vaddr* - the kernel virtual address of the memory
  - *map* - the map of the memory (as returned from `bus_dmamem_alloc()`)
- `int bus_dmamap_create(bus_dma_tag_t dmat, int flags, bus_dmamap_t *mapp)`  
Create a map for the tag, to be used in `bus_dmamap_load()` later. Returns 0 on success, the error code otherwise.
- *dmat* - the tag
  - *flags* - theoretically, a bit map of flags. But no flags are defined yet, so at present it will be always 0.
  - *mapp* - pointer to the storage for the new map to be returned
- `int bus_dmamap_destroy(bus_dma_tag_t dmat, bus_dmamap_t map)`  
Destroy a map. Returns 0 on success, the error code otherwise.
- *dmat* - the tag to which the map is associated
  - *map* - the map to be destroyed
- `int bus_dmamap_load(bus_dma_tag_t dmat, bus_dmamap_t map, void *buf, bus_size_t buflen, bus_dmamap_callback_t *callback, void *callback_arg, int flags)`  
Load a buffer into the map (the map must be previously created by `bus_dmamap_create()` or `bus_dmamem_alloc()`). All the pages of the buffer are checked for conformance to the tag requirements and for those not conformant the bounce pages are allocated. An array of physical segment descriptors is built and passed to the callback routine. This callback routine is then expected to handle it in some way. The number of bounce buffers in the system is limited, so if the bounce buffers are needed but not immediately available the request will be queued and the callback will be called when the bounce buffers will become available. Returns 0 if the callback was executed immediately or `EINPROGRESS` if the request was queued for future execution. In the latter case the synchronization with queued callback routine is the responsibility of the driver.
- *dmat* - the tag
  - *map* - the map
  - *buf* - kernel virtual address of the buffer

- *buflen* - length of the buffer
- *callback*, *callback\_arg* - the callback function and its argument

The prototype of callback function is:

```
void callback(void *arg, bus_dma_segment_t *seg, int nseg, int error)
```

- *arg* - the same as *callback\_arg* passed to `bus_dmamap_load()`
- *seg* - array of the segment descriptors
- *nseg* - number of descriptors in array
- *error* - indication of the segment number overflow: if it is set to `EFBIG` then the buffer did not fit into the maximal number of segments permitted by the tag. In this case only the permitted number of descriptors will be in the array. Handling of this situation is up to the driver: depending on the desired semantics it can either consider this an error or split the buffer in two and handle the second part separately

Each entry in the segments array contains the fields:

- *ds\_addr* - physical bus address of the segment
- *ds\_len* - length of the segment

- `void bus_dmamap_unload(bus_dma_tag_t dmat, bus_dmamap_t map)`

unload the map.

- *dmat* - tag
- *map* - loaded map

- `void bus_dmamap_sync (bus_dma_tag_t dmat, bus_dmamap_t map, bus_dmasync_op_t op)`

Synchronise a loaded buffer with its bounce pages before and after physical transfer to or from device. This is the function that does all the necessary copying of data between the original buffer and its mapped version. The buffers must be synchronized both before and after doing the transfer.

- *dmat* - tag
- *map* - loaded map
- *op* - type of synchronization operation to perform:
  - `BUS_DMASYNC_PREREAD` - before reading from device into buffer
  - `BUS_DMASYNC_POSTREAD` - after reading from device into buffer
  - `BUS_DMASYNC_PREWRITE` - before writing the buffer to device
  - `BUS_DMASYNC_POSTWRITE` - after writing the buffer to device

As of now `PREREAD` and `POSTWRITE` are null operations but that may change in the future, so they must not be ignored in the driver. Synchronization is not needed for the memory obtained from `bus_dmamem_alloc()`.

Before calling the callback function from `bus_dmamap_load()` the segment array is stored in the stack. And it gets pre-allocated for the maximal number of segments allowed by the tag. Because of this the practical limit for the number of segments on i386 architecture is about 250-300 (the kernel stack is 4KB minus the size of the user structure, size of a segment array entry is 8 bytes, and some space must be left). Because the array is allocated based on the maximal number this value must not be set higher than really needed. Fortunately, for most of hardware the maximal supported number of segments is much lower. But if the driver wants to handle buffers with a very large number of scatter-gather segments it should do that in portions: load part of the buffer, transfer it to the device, load next part of the buffer, and so on.

Another practical consequence is that the number of segments may limit the size of the buffer. If all the pages in the buffer happen to be physically non-contiguous then the maximal supported buffer size for that fragmented case would be  $(nsegments * page\_size)$ . For example, if a maximal number of 10 segments is supported then on i386 maximal guaranteed supported buffer size would be 40K. If a higher size is desired then special tricks should be used in the driver.

If the hardware does not support scatter-gather at all or the driver wants to support some buffer size even if it is heavily fragmented then the solution is to allocate a contiguous buffer in the driver and use it as intermediate storage if the original buffer does not fit.

Below are the typical call sequences when using a map depend on the use of the map. The characters `->` are used to show the flow of time.

For a buffer which stays practically fixed during all the time between attachment and detachment of a device:

```
bus_dmamem_alloc -> bus_dmamap_load -> ...use buffer... -> -> bus_dmamap_unload -> bus_dmamem_free
```

For a buffer that changes frequently and is passed from outside the driver:

```
bus_dmamap_create ->
-> bus_dmamap_load -> bus_dmamap_sync(PRE...) -> do transfer ->
-> bus_dmamap_sync(POST...) -> bus_dmamap_unload ->
...
-> bus_dmamap_load -> bus_dmamap_sync(PRE...) -> do transfer ->
-> bus_dmamap_sync(POST...) -> bus_dmamap_unload ->
-> bus_dmamap_destroy
```

When loading a map created by `bus_dmamem_alloc()` the passed address and size of the buffer must be the same as used in `bus_dmamem_alloc()`. In this case it is guaranteed that the whole buffer will be mapped as one segment (so the callback may be based on this assumption) and the request will be executed immediately (EINPROGRESS will never be returned). All the callback needs to do in this case is to save the physical address.

A typical example would be:

```
static void
alloc_callback(void *arg, bus_dma_segment_t *seg, int nseg, int error)
{
    *(bus_addr_t *)arg = seg[0].ds_addr;
}

...
int error;
struct somedata {
    ....
}
```



```

};
struct somedata *vsomedata; /* virtual address */
bus_addr_t psomedata; /* physical bus-relative address */
bus_dma_tag_t tag_somedata;
bus_dmamap_t map_somedata;
...

error=bus_dma_tag_create(parent_tag, alignment,
    boundary, lowaddr, highaddr, /*filter*/ NULL, /*filterarg*/ NULL,
    /*maxsize*/ sizeof(struct somedata), /*nsegments*/ 1,
    /*maxsegsz*/ sizeof(struct somedata), /*flags*/ 0,
    &tag_somedata);
if(error)
return error;

error = bus_dmamem_alloc(tag_somedata, &vsomedata, /* flags*/ 0,
    &map_somedata);
if(error)
    return error;

bus_dmamap_load(tag_somedata, map_somedata, (void *)vsomedata,
    sizeof (struct somedata), alloc_callback,
    (void *) &psomedata, /*flags*/0);

```

Looks a bit long and complicated but that is the way to do it. The practical consequence is: if multiple memory areas are allocated always together it would be a really good idea to combine them all into one structure and allocate as one (if the alignment and boundary limitations permit).

When loading an arbitrary buffer into the map created by `bus_dmamap_create()` special measures must be taken to synchronize with the callback in case it would be delayed. The code would look like:

```

{
    int s;
    int error;

    s = splsoftvm();
    error = bus_dmamap_load(
        dmat,
        dmamap,
        buffer_ptr,
        buffer_len,
        callback,
        /*callback_arg*/ buffer_descriptor,
        /*flags*/0);
    if (error == EINPROGRESS) {
        /*
         * Do whatever is needed to ensure synchronization
         * with callback. Callback is guaranteed not to be started
         * until we do splx() or tsleep().
         */
    }
    splx(s);
}

```

Two possible approaches for the processing of requests are:

1. If requests are completed by marking them explicitly as done (such as the CAM requests) then it would be simpler to put all the further processing into the callback driver which would mark the request when it is done. Then not much extra synchronization is needed. For the flow control reasons it may be a good idea to freeze the request queue until this request gets completed.
2. If requests are completed when the function returns (such as classic read or write requests on character devices) then a synchronization flag should be set in the buffer descriptor and `tsleep()` called. Later when the callback gets called it will do its processing and check this synchronization flag. If it is set then the callback should issue a wakeup. In this approach the callback function could either do all the needed processing (just like the previous case) or simply save the segments array in the buffer descriptor. Then after callback completes the calling function could use this saved segments array and do all the processing.

## 22.7 DMA

The Direct Memory Access (DMA) is implemented in the ISA bus through the DMA controller (actually, two of them but that is an irrelevant detail). To make the early ISA devices simple and cheap the logic of the bus control and address generation was concentrated in the DMA controller. Fortunately, FreeBSD provides a set of functions that mostly hide the annoying details of the DMA controller from the device drivers.

The simplest case is for the fairly intelligent devices. Like the bus master devices on PCI they can generate the bus cycles and memory addresses all by themselves. The only thing they really need from the DMA controller is bus arbitration. So for this purpose they pretend to be cascaded slave DMA controllers. And the only thing needed from the system DMA controller is to enable the cascaded mode on a DMA channel by calling the following function when attaching the driver:

```
void isa_dmacascade(int channel_number)
```

All the further activity is done by programming the device. When detaching the driver no DMA-related functions need to be called.

For the simpler devices things get more complicated. The functions used are:

- `int isa_dma_acquire(int channel_number)`

Reserve a DMA channel. Returns 0 on success or `EBUSY` if the channel was already reserved by this or a different driver. Most of the ISA devices are not able to share DMA channels anyway, so normally this function is called when attaching a device. This reservation was made redundant by the modern interface of bus resources but still must be used in addition to the latter. If not used then later, other DMA routines will panic.

- `int isa_dma_release(int channel_number)`

Release a previously reserved DMA channel. No transfers must be in progress when the channel is released (in addition the device must not try to initiate transfer after the channel is released).

- `void isa_dmainit(int chan, u_int bouncebufsize)`

Allocate a bounce buffer for use with the specified channel. The requested size of the buffer can not exceed 64KB. This bounce buffer will be automatically used later if a transfer buffer happens to be not physically contiguous or

outside of the memory accessible by the ISA bus or crossing the 64KB boundary. If the transfers will be always done from buffers which conform to these conditions (such as those allocated by `bus_dmamem_alloc()` with proper limitations) then `isa_dmainit()` does not have to be called. But it is quite convenient to transfer arbitrary data using the DMA controller. The bounce buffer will automatically care of the scatter-gather issues.

- *chan* - channel number
  - *bouncebufsize* - size of the bounce buffer in bytes
- `void isa_dmastart(int flags, caddr_t addr, u_int nbytes, int chan)`  
 Prepare to start a DMA transfer. This function must be called to set up the DMA controller before actually starting transfer on the device. It checks that the buffer is contiguous and falls into the ISA memory range, if not then the bounce buffer is automatically used. If bounce buffer is required but not set up by `isa_dmainit()` or too small for the requested transfer size then the system will panic. In case of a write request with bounce buffer the data will be automatically copied to the bounce buffer.
  - *flags* - a bitmask determining the type of operation to be done. The direction bits `B_READ` and `B_WRITE` are mutually exclusive.
    - `B_READ` - read from the ISA bus into memory
    - `B_WRITE` - write from the memory to the ISA bus
    - `B_RAW` - if set then the DMA controller will remember the buffer and after the end of transfer will automatically re-initialize itself to repeat transfer of the same buffer again (of course, the driver may change the data in the buffer before initiating another transfer in the device). If not set then the parameters will work only for one transfer, and `isa_dmastart()` will have to be called again before initiating the next transfer. Using `B_RAW` makes sense only if the bounce buffer is not used.
  - *addr* - virtual address of the buffer
  - *nbytes* - length of the buffer. Must be less or equal to 64KB. Length of 0 is not allowed: the DMA controller will understand it as 64KB while the kernel code will understand it as 0 and that would cause unpredictable effects. For channels number 4 and higher the length must be even because these channels transfer 2 bytes at a time. In case of an odd length the last byte will not be transferred.
  - *chan* - channel number
  - `void isa_dmadone(int flags, caddr_t addr, int nbytes, int chan)`  
 Synchronize the memory after device reports that transfer is done. If that was a read operation with a bounce buffer then the data will be copied from the bounce buffer to the original buffer. Arguments are the same as for `isa_dmastart()`. Flag `B_RAW` is permitted but it does not affect `isa_dmadone()` in any way.
  - `int isa_dmastatus(int channel_number)`  
 Returns the number of bytes left in the current transfer to be transferred. In case the flag `B_READ` was set in `isa_dmastart()` the number returned will never be equal to zero. At the end of transfer it will be automatically reset back to the length of buffer. The normal use is to check the number of bytes left after the device signals that the transfer is completed. If the number of bytes is not 0 then something probably went wrong with that transfer.

- `int isa_dmastop(int channel_number)`

Aborts the current transfer and returns the number of bytes left untransferred.

## 22.8 xxx\_isa\_probe

This function probes if a device is present. If the driver supports auto-detection of some part of device configuration (such as interrupt vector or memory address) this auto-detection must be done in this routine.

As for any other bus, if the device cannot be detected or is detected but failed the self-test or some other problem happened then it returns a positive value of error. The value `ENXIO` must be returned if the device is not present. Other error values may mean other conditions. Zero or negative values mean success. Most of the drivers return zero as success.

The negative return values are used when a PnP device supports multiple interfaces. For example, an older compatibility interface and a newer advanced interface which are supported by different drivers. Then both drivers would detect the device. The driver which returns a higher value in the probe routine takes precedence (in other words, the driver returning 0 has highest precedence, one returning -1 is next, one returning -2 is after it and so on). In result the devices which support only the old interface will be handled by the old driver (which should return -1 from the probe routine) while the devices supporting the new interface as well will be handled by the new driver (which should return 0 from the probe routine).

The device descriptor struct `xxx_softc` is allocated by the system before calling the probe routine. If the probe routine returns an error the descriptor will be automatically deallocated by the system. So if a probing error occurs the driver must make sure that all the resources it used during probe are deallocated and that nothing keeps the descriptor from being safely deallocated. If the probe completes successfully the descriptor will be preserved by the system and later passed to the routine `xxx_isa_attach()`. If a driver returns a negative value it can not be sure that it will have the highest priority and its attach routine will be called. So in this case it also must release all the resources before returning and if necessary allocate them again in the attach routine. When `xxx_isa_probe()` returns 0 releasing the resources before returning is also a good idea and a well-behaved driver should do so. But in cases where there is some problem with releasing the resources the driver is allowed to keep resources between returning 0 from the probe routine and execution of the attach routine.

A typical probe routine starts with getting the device descriptor and unit:

```
struct xxx_softc *sc = device_get_softc(dev);
int unit = device_get_unit(dev);
int pnperror;
int error = 0;

sc->dev = dev; /* link it back */
sc->unit = unit;
```

Then check for the PnP devices. The check is carried out by a table containing the list of PnP IDs supported by this driver and human-readable descriptions of the device models corresponding to these IDs.

```
pnperror=ISA_PNP_PROBE(device_get_parent(dev), dev,
xxx_pnp_ids); if(pnperror == ENXIO) return ENXIO;
```

The logic of `ISA_PNP_PROBE` is the following: If this card (device unit) was not detected as PnP then `ENOENT` will be returned. If it was detected as PnP but its detected ID does not match any of the IDs in the table then `ENXIO` is returned. Finally, if it has PnP support and it matches one of the IDs in the table, 0 is returned and the appropriate description from the table is set by `device_set_desc()`.

If a driver supports only PnP devices then the condition would look like:

```
if(pnperror != 0)
    return pnperror;
```

No special treatment is required for the drivers which do not support PnP because they pass an empty PnP ID table and will always get `ENXIO` if called on a PnP card.

The probe routine normally needs at least some minimal set of resources, such as I/O port number to find the card and probe it. Depending on the hardware the driver may be able to discover the other necessary resources automatically. The PnP devices have all the resources pre-set by the PnP subsystem, so the driver does not need to discover them by itself.

Typically the minimal information required to get access to the device is the I/O port number. Then some devices allow to get the rest of information from the device configuration registers (though not all devices do that). So first we try to get the port start value:

```
sc->port0 = bus_get_resource_start(dev,
    SYS_RES_IOPORT, 0 /*rid*/); if(sc->port0 == 0) return ENXIO;
```

The base port address is saved in the structure `softc` for future use. If it will be used very often then calling the resource function each time would be prohibitively slow. If we do not get a port we just return an error. Some device drivers can instead be clever and try to probe all the possible ports, like this:

```
/* table of all possible base I/O port addresses for this device */
static struct xxx_allports {
    u_short port; /* port address */
    short used; /* flag: if this port is already used by some unit */
} xxx_allports = {
    { 0x300, 0 },
    { 0x320, 0 },
    { 0x340, 0 },
    { 0, 0 } /* end of table */
};

...
int port, i;
...

port = bus_get_resource_start(dev, SYS_RES_IOPORT, 0 /*rid*/);
if(port !=0 ) {
    for(i=0; xxx_allports[i].port!=0; i++) {
        if(xxx_allports[i].used || xxx_allports[i].port != port)
            continue;
```

```

        /* found it */
        xxx_allports[i].used = 1;
        /* do probe on a known port */
        return xxx_really_probe(dev, port);
    }
    return ENXIO; /* port is unknown or already used */
}

/* we get here only if we need to guess the port */
for(i=0; xxx_allports[i].port!=0; i++) {
    if(xxx_allports[i].used)
        continue;

    /* mark as used - even if we find nothing at this port
     * at least we won't probe it in future
     */
    xxx_allports[i].used = 1;

    error = xxx_really_probe(dev, xxx_allports[i].port);
    if(error == 0) /* found a device at that port */
        return 0;
}
/* probed all possible addresses, none worked */
return ENXIO;

```

Of course, normally the driver's `identify()` routine should be used for such things. But there may be one valid reason why it may be better to be done in `probe()`: if this probe would drive some other sensitive device crazy. The probe routines are ordered with consideration of the `sensitive` flag: the sensitive devices get probed first and the rest of the devices later. But the `identify()` routines are called before any probes, so they show no respect to the sensitive devices and may upset them.

Now, after we got the starting port we need to set the port count (except for PnP devices) because the kernel does not have this information in the configuration file.

```

if(pnperror /* only for non-PnP devices */
&& bus_set_resource(dev, SYS_RES_IOPORT, 0, sc->port0,
XXX_PORT_COUNT)<0)
    return ENXIO;

```

Finally allocate and activate a piece of port address space (special values of start and end mean "use those we set by `bus_set_resource()`"):

```

sc->port0_rid = 0;
sc->port0_r = bus_alloc_resource(dev, SYS_RES_IOPORT,
&sc->port0_rid,
    /*start*/ 0, /*end*/ ~0, /*count*/ 0, RF_ACTIVE);

if(sc->port0_r == NULL)
    return ENXIO;

```

Now having access to the port-mapped registers we can poke the device in some way and check if it reacts like it is expected to. If it does not then there is probably some other device or no device at all at this address.

Normally drivers do not set up the interrupt handlers until the attach routine. Instead they do probes in the polling mode using the `DELAY()` function for timeout. The probe routine must never hang forever, all the waits for the device must be done with timeouts. If the device does not respond within the time it is probably broken or misconfigured and the driver must return error. When determining the timeout interval give the device some extra time to be on the safe side: although `DELAY()` is supposed to delay for the same amount of time on any machine it has some margin of error, depending on the exact CPU.

If the probe routine really wants to check that the interrupts really work it may configure and probe the interrupts too. But that is not recommended.

```
/* implemented in some very device-specific way */
if(error = xxx_probe_ports(sc))
    goto bad; /* will deallocate the resources before returning */
```

The function `xxx_probe_ports()` may also set the device description depending on the exact model of device it discovers. But if there is only one supported device model this can be as well done in a hardcoded way. Of course, for the PnP devices the PnP support sets the description from the table automatically.

```
if(pnperror)
    device_set_desc(dev, "Our device model 1234");
```

Then the probe routine should either discover the ranges of all the resources by reading the device configuration registers or make sure that they were set explicitly by the user. We will consider it with an example of on-board memory. The probe routine should be as non-intrusive as possible, so allocation and check of functionality of the rest of resources (besides the ports) would be better left to the attach routine.

The memory address may be specified in the kernel configuration file or on some devices it may be pre-configured in non-volatile configuration registers. If both sources are available and different, which one should be used? Probably if the user bothered to set the address explicitly in the kernel configuration file they know what they are doing and this one should take precedence. An example of implementation could be:

```
/* try to find out the config address first */
sc->mem0_p = bus_get_resource_start(dev, SYS_RES_MEMORY, 0 /*rid*/);
if(sc->mem0_p == 0) { /* nope, not specified by user */
    sc->mem0_p = xxx_read_mem0_from_device_config(sc);

if(sc->mem0_p == 0)
    /* can't get it from device config registers either */
    goto bad;
} else {
    if(xxx_set_mem0_address_on_device(sc) < 0)
        goto bad; /* device does not support that address */
}

/* just like the port, set the memory size,
 * for some devices the memory size would not be constant
 * but should be read from the device configuration registers instead
 * to accommodate different models of devices. Another option would
```

```

* be to let the user set the memory size as "msize" configuration
* resource which will be automatically handled by the ISA bus.
*/
if(pnperror) { /* only for non-PnP devices */
    sc->mem0_size = bus_get_resource_count(dev, SYS_RES_MEMORY, 0 /*rid*/);
    if(sc->mem0_size == 0) /* not specified by user */
        sc->mem0_size = xxx_read_mem0_size_from_device_config(sc);

    if(sc->mem0_size == 0) {
        /* suppose this is a very old model of device without
        * auto-configuration features and the user gave no preference,
        * so assume the minimalistic case
        * (of course, the real value will vary with the driver)
        */
        sc->mem0_size = 8*1024;
    }

    if(xxx_set_mem0_size_on_device(sc) < 0)
        goto bad; /* device does not support that size */

    if(bus_set_resource(dev, SYS_RES_MEMORY, /*rid*/0,
        sc->mem0_p, sc->mem0_size)<0)
        goto bad;
} else {
    sc->mem0_size = bus_get_resource_count(dev, SYS_RES_MEMORY, 0 /*rid*/);
}

```

Resources for IRQ and DRQ are easy to check by analogy.

If all went well then release all the resources and return success.

```

xxx_free_resources(sc);
return 0;

```

Finally, handle the troublesome situations. All the resources should be deallocated before returning. We make use of the fact that before the structure `softc` is passed to us it gets zeroed out, so we can find out if some resource was allocated: then its descriptor is non-zero.

```

bad:

xxx_free_resources(sc);
if(error)
    return error;
else /* exact error is unknown */
    return ENXIO;

```

That would be all for the probe routine. Freeing of resources is done from multiple places, so it is moved to a function which may look like:

```

static void
xxx_free_resources(sc)
    struct xxx_softc *sc;
{
    /* check every resource and free if not zero */

```



```

/* interrupt handler */
if(sc->intr_r) {
    bus_tearardown_intr(sc->dev, sc->intr_r, sc->intr_cookie);
    bus_release_resource(sc->dev, SYS_RES_IRQ, sc->intr_rid,
        sc->intr_r);
    sc->intr_r = 0;
}

/* all kinds of memory maps we could have allocated */
if(sc->data_p) {
    bus_dmamap_unload(sc->data_tag, sc->data_map);
    sc->data_p = 0;
}
if(sc->data) { /* sc->data_map may be legitimately equal to 0 */
    /* the map will also be freed */
    bus_dmamem_free(sc->data_tag, sc->data, sc->data_map);
    sc->data = 0;
}
if(sc->data_tag) {
    bus_dma_tag_destroy(sc->data_tag);
    sc->data_tag = 0;
}

... free other maps and tags if we have them ...

if(sc->parent_tag) {
    bus_dma_tag_destroy(sc->parent_tag);
    sc->parent_tag = 0;
}

/* release all the bus resources */
if(sc->mem0_r) {
    bus_release_resource(sc->dev, SYS_RES_MEMORY, sc->mem0_rid,
        sc->mem0_r);
    sc->mem0_r = 0;
}
...
if(sc->port0_r) {
    bus_release_resource(sc->dev, SYS_RES_IOPORT, sc->port0_rid,
        sc->port0_r);
    sc->port0_r = 0;
}
}

```

## 22.9 xxx\_isa\_attach

The attach routine actually connects the driver to the system if the probe routine returned success and the system had chosen to attach that driver. If the probe routine returned 0 then the attach routine may expect to receive the device structure softc intact, as it was set by the probe routine. Also if the probe routine returns 0 it may expect that the

attach routine for this device shall be called at some point in the future. If the probe routine returns a negative value then the driver may make none of these assumptions.

The attach routine returns 0 if it completed successfully or error code otherwise.

The attach routine starts just like the probe routine, with getting some frequently used data into more accessible variables.

```
struct xxx_softc *sc = device_get_softc(dev);
int unit = device_get_unit(dev);
int error = 0;
```

Then allocate and activate all the necessary resources. Because normally the port range will be released before returning from probe, it has to be allocated again. We expect that the probe routine had properly set all the resource ranges, as well as saved them in the structure `softc`. If the probe routine had left some resource allocated then it does not need to be allocated again (which would be considered an error).

```
sc->port0_rid = 0;
sc->port0_r = bus_alloc_resource(dev, SYS_RES_IOPORT, &sc->port0_rid,
    /*start*/ 0, /*end*/ ~0, /*count*/ 0, RF_ACTIVE);

if(sc->port0_r == NULL)
    return ENXIO;

/* on-board memory */
sc->mem0_rid = 0;
sc->mem0_r = bus_alloc_resource(dev, SYS_RES_MEMORY, &sc->mem0_rid,
    /*start*/ 0, /*end*/ ~0, /*count*/ 0, RF_ACTIVE);

if(sc->mem0_r == NULL)
    goto bad;

/* get its virtual address */
sc->mem0_v = rman_get_virtual(sc->mem0_r);
```

The DMA request channel (DRQ) is allocated likewise. To initialize it use functions of the `isa_dma*`( ) family. For example:

```
isa_dmacascade(sc->drq0);
```

The interrupt request line (IRQ) is a bit special. Besides allocation the driver's interrupt handler should be associated with it. Historically in the old ISA drivers the argument passed by the system to the interrupt handler was the device unit number. But in modern drivers the convention suggests passing the pointer to structure `softc`. The important reason is that when the structures `softc` are allocated dynamically then getting the unit number from `softc` is easy while getting `softc` from the unit number is difficult. Also this convention makes the drivers for different buses look more uniform and allows them to share the code: each bus gets its own probe, attach, detach and other bus-specific routines while the bulk of the driver code may be shared among them.

```
sc->intr_rid = 0;
sc->intr_r = bus_alloc_resource(dev, SYS_RES_MEMORY, &sc->intr_rid,
    /*start*/ 0, /*end*/ ~0, /*count*/ 0, RF_ACTIVE);

if(sc->intr_r == NULL)
    goto bad;
```

```

/*
 * XXX_INTR_TYPE is supposed to be defined depending on the type of
 * the driver, for example as INTR_TYPE_CAM for a CAM driver
 */
error = bus_setup_intr(dev, sc->intr_r, XXX_INTR_TYPE,
    (driver_intr_t *) xxx_intr, (void *) sc, &sc->intr_cookie);
if(error)
    goto bad;

```

If the device needs to make DMA to the main memory then this memory should be allocated like described before:

```

error=bus_dma_tag_create(NULL, /*alignment*/ 4,
    /*boundary*/ 0, /*lowaddr*/ BUS_SPACE_MAXADDR_24BIT,
    /*highaddr*/ BUS_SPACE_MAXADDR, /*filter*/ NULL, /*filterarg*/ NULL,
    /*maxsize*/ BUS_SPACE_MAXSIZE_24BIT,
    /*nsegments*/ BUS_SPACE_UNRESTRICTED,
    /*maxsegsz*/ BUS_SPACE_MAXSIZE_24BIT, /*flags*/ 0,
    &sc->parent_tag);
if(error)
    goto bad;

/* many things get inherited from the parent tag
 * sc->data is supposed to point to the structure with the shared data,
 * for example for a ring buffer it could be:
 * struct {
 *     u_short rd_pos;
 *     u_short wr_pos;
 *     char    bf[XXX_RING_BUFFER_SIZE]
 * } *data;
 */
error=bus_dma_tag_create(sc->parent_tag, 1,
    0, BUS_SPACE_MAXADDR, 0, /*filter*/ NULL, /*filterarg*/ NULL,
    /*maxsize*/ sizeof(* sc->data), /*nsegments*/ 1,
    /*maxsegsz*/ sizeof(* sc->data), /*flags*/ 0,
    &sc->data_tag);
if(error)
    goto bad;

error = bus_dmamem_alloc(sc->data_tag, &sc->data, /* flags*/ 0,
    &sc->data_map);
if(error)
    goto bad;

/* xxx_alloc_callback() just saves the physical address at
 * the pointer passed as its argument, in this case &sc->data_p.
 * See details in the section on bus memory mapping.
 * It can be implemented like:
 *
 * static void
 * xxx_alloc_callback(void *arg, bus_dma_segment_t *seg,

```

```

*     int nseg, int error)
* {
*     *(bus_addr_t *)arg = seg[0].ds_addr;
* }
*/
bus_dmamap_load(sc->data_tag, sc->data_map, (void *)sc->data,
               sizeof (* sc->data), xxx_alloc_callback, (void *) &sc->data_p,
               /*flags*/0);

```

After all the necessary resources are allocated the device should be initialized. The initialization may include testing that all the expected features are functional.

```

if(xxx_initialize(sc) < 0)
    goto bad;

```

The bus subsystem will automatically print on the console the device description set by probe. But if the driver wants to print some extra information about the device it may do so, for example:

```

device_printf(dev, "has on-card FIFO buffer of %d bytes\n", sc->fifosize);

```

If the initialization routine experiences any problems then printing messages about them before returning error is also recommended.

The final step of the attach routine is attaching the device to its functional subsystem in the kernel. The exact way to do it depends on the type of the driver: a character device, a block device, a network device, a CAM SCSI bus device and so on.

If all went well then return success.

```

error = xxx_attach_subsystem(sc);
if(error)
    goto bad;

return 0;

```

Finally, handle the troublesome situations. All the resources should be deallocated before returning an error. We make use of the fact that before the structure `softc` is passed to us it gets zeroed out, so we can find out if some resource was allocated: then its descriptor is non-zero.

```

bad:

xxx_free_resources(sc);
if(error)
    return error;
else /* exact error is unknown */
    return ENXIO;

```

That would be all for the attach routine.

## 22.10 xxx\_isa\_detach

If this function is present in the driver and the driver is compiled as a loadable module then the driver gets the ability to be unloaded. This is an important feature if the hardware supports hot plug. But the ISA bus does not support hot plug, so this feature is not particularly important for the ISA devices. The ability to unload a driver may be useful when debugging it, but in many cases installation of the new version of the driver would be required only after the old version somehow wedges the system and a reboot will be needed anyway, so the efforts spent on writing the detach routine may not be worth it. Another argument that unloading would allow upgrading the drivers on a production machine seems to be mostly theoretical. Installing a new version of a driver is a dangerous operation which should never be performed on a production machine (and which is not permitted when the system is running in secure mode). Still, the detach routine may be provided for the sake of completeness.

The detach routine returns 0 if the driver was successfully detached or the error code otherwise.

The logic of detach is a mirror of the attach. The first thing to do is to detach the driver from its kernel subsystem. If the device is currently open then the driver has two choices: refuse to be detached or forcibly close and proceed with detach. The choice used depends on the ability of the particular kernel subsystem to do a forced close and on the preferences of the driver's author. Generally the forced close seems to be the preferred alternative.

```
struct xxx_softc *sc = device_get_softc(dev);
int error;

error = xxx_detach_subsystem(sc);
if(error)
    return error;
```

Next the driver may want to reset the hardware to some consistent state. That includes stopping any ongoing transfers, disabling the DMA channels and interrupts to avoid memory corruption by the device. For most of the drivers this is exactly what the shutdown routine does, so if it is included in the driver we can just call it.

```
xxx_isa_shutdown(dev);
```

And finally release all the resources and return success.

```
xxx_free_resources(sc);
return 0;
```

## 22.11 xxx\_isa\_shutdown

This routine is called when the system is about to be shut down. It is expected to bring the hardware to some consistent state. For most of the ISA devices no special action is required, so the function is not really necessary because the device will be re-initialized on reboot anyway. But some devices have to be shut down with a special procedure, to make sure that they will be properly detected after soft reboot (this is especially true for many devices with proprietary identification protocols). In any case disabling DMA and interrupts in the device registers and stopping any ongoing transfers is a good idea. The exact action depends on the hardware, so we do not consider it here in any detail.

## 22.12 xxx\_intr

The interrupt handler is called when an interrupt is received which may be from this particular device. The ISA bus does not support interrupt sharing (except in some special cases) so in practice if the interrupt handler is called then the interrupt almost for sure came from its device. Still, the interrupt handler must poll the device registers and make sure that the interrupt was generated by its device. If not it should just return.

The old convention for the ISA drivers was getting the device unit number as an argument. This is obsolete, and the new drivers receive whatever argument was specified for them in the attach routine when calling `bus_setup_intr()`. By the new convention it should be the pointer to the structure `softc`. So the interrupt handler commonly starts as:

```
static void
xxx_intr(struct xxx_softc *sc)
{
```

It runs at the interrupt priority level specified by the interrupt type parameter of `bus_setup_intr()`. That means that all the other interrupts of the same type as well as all the software interrupts are disabled.

To avoid races it is commonly written as a loop:

```
while(xxx_interrupt_pending(sc)) {
    xxx_process_interrupt(sc);
    xxx_acknowledge_interrupt(sc);
}
```

The interrupt handler has to acknowledge interrupt to the device only but not to the interrupt controller, the system takes care of the latter.

# Chapter 23 PCI Devices

This chapter will talk about the FreeBSD mechanisms for writing a device driver for a device on a PCI bus.

## 23.1 Probe and Attach

Information here about how the PCI bus code iterates through the unattached devices and see if a newly loaded kld will attach to any of them.

```
/*
 * Simple KLD to play with the PCI functions.
 *
 * Murray Stokely
 */

#define MIN(a,b) (((a) < (b)) ? (a) : (b))

#include <sys/types.h>
#include <sys/module.h>
#include <sys/system.h> /* uprintf */
#include <sys/errno.h>
#include <sys/param.h> /* defines used in kernel.h */
#include <sys/kernel.h> /* types used in module initialization */
#include <sys/conf.h> /* cdevsw struct */
#include <sys/uio.h> /* uio struct */
#include <sys/malloc.h>
#include <sys/bus.h> /* structs, prototypes for pci bus stuff */

#include <pci/pcivar.h> /* For get_pci macros! */

/* Function prototypes */
d_open_t mypci_open;
d_close_t mypci_close;
d_read_t mypci_read;
d_write_t mypci_write;

/* Character device entry points */

static struct cdevsw mypci_cdevsw = {
    mypci_open,
    mypci_close,
    mypci_read,
    mypci_write,
    noioctl,
    nopoll,
    nommap,
    nostrategy,
    "mypci",
    36, /* reserved for lkms - /usr/src/sys/conf/majors */
    nodump,
```

```

    nopsize,
    D_TTY,
    -1
};

/* vars */
static dev_t sdev;

/* We're more interested in probe/attach than with
   open/close/read/write at this point */

int
mypci_open(dev_t dev, int oflags, int devtype, struct proc *p)
{
    int err = 0;

    uprintf("Opened device \"mypci\" successfully.\n");
    return(err);
}

int
mypci_close(dev_t dev, int fflag, int devtype, struct proc *p)
{
    int err=0;

    uprintf("Closing device \"mypci.\"\n");
    return(err);
}

int
mypci_read(dev_t dev, struct uio *uio, int ioflag)
{
    int err = 0;

    uprintf("mypci read!\n");
    return err;
}

int
mypci_write(dev_t dev, struct uio *uio, int ioflag)
{
    int err = 0;

    uprintf("mypci write!\n");
    return(err);
}

/* PCI Support Functions */

/*
 * Return identification string if this is device is ours.
 */
static int

```



```

mypci_probe(device_t dev)
{
    uprintf("MyPCI Probe\n"
           "Vendor ID : 0x%x\n"
           "Device ID : 0x%x\n",pci_get_vendor(dev),pci_get_device(dev));

    if (pci_get_vendor(dev) == 0x11c1) {
        uprintf("We've got the Winmodem, probe successful!\n");
        return 0;
    }

    return ENXIO;
}

/* Attach function is only called if the probe is successful */

static int
mypci_attach(device_t dev)
{
    uprintf("MyPCI Attach for : deviceID : 0x%x\n",pci_get_vendor(dev));
    sdev = make_dev(&mypci_cdevsw,
                   0,
                   UID_ROOT,
                   GID_WHEEL,
                   0600,
                   "mypci");
    uprintf("Mypci device loaded.\n");
    return ENXIO;
}

/* Detach device. */

static int
mypci_detach(device_t dev)
{
    uprintf("Mypci detach!\n");
    return 0;
}

/* Called during system shutdown after sync. */

static int
mypci_shutdown(device_t dev)
{
    uprintf("Mypci shutdown!\n");
    return 0;
}

/*
 * Device suspend routine.
 */
static int
mypci_suspend(device_t dev)

```

```

{
    uprintf("Mypci suspend!\n");
    return 0;
}

/*
 * Device resume routine.
 */

static int
mypci_resume(device_t dev)
{
    uprintf("Mypci resume!\n");
    return 0;
}

static device_method_t mypci_methods[] = {
    /* Device interface */
    DEVMETHOD(device_probe, mypci_probe),
    DEVMETHOD(device_attach, mypci_attach),
    DEVMETHOD(device_detach, mypci_detach),
    DEVMETHOD(device_shutdown, mypci_shutdown),
    DEVMETHOD(device_suspend, mypci_suspend),
    DEVMETHOD(device_resume, mypci_resume),

    { 0, 0 }
};

static driver_t mypci_driver = {
    "mypci",
    mypci_methods,
    0,
    /* sizeof(struct mypci_softc), */
};

static devclass_t mypci_devclass;

DRIVER_MODULE(mypci, pci, mypci_driver, mypci_devclass, 0, 0);

```

#### Additional Resources

- PCI Special Interest Group (<http://www.pcisig.org/>)
- PCI System Architecture, Fourth Edition by Tom Shanley, et al.

## 23.2 Bus Resources

FreeBSD provides an object-oriented mechanism for requesting resources from a parent bus. Almost all devices will be a child member of some sort of bus (PCI, ISA, USB, SCSI, etc) and these devices need to acquire resources from their parent bus (such as memory segments, interrupt lines, or DMA channels).

### 23.2.1 Base Address Registers

To do anything particularly useful with a PCI device you will need to obtain the *Base Address Registers* (BARs) from the PCI Configuration space. The PCI-specific details of obtaining the BAR is abstracted in the `bus_alloc_resource()` function.

For example, a typical driver might have something similar to this in the `attach()` function:

```

sc->bar0id = 0x10;
sc->bar0res = bus_alloc_resource(dev, SYS_RES_MEMORY, &(sc->bar0id),
0, ~0, 1, RF_ACTIVE);
if (sc->bar0res == NULL) {
    uprintf("Memory allocation of PCI base register 0 failed!\n");
    error = ENXIO;
    goto fail1;
}

sc->bar1id = 0x14;
sc->bar1res = bus_alloc_resource(dev, SYS_RES_MEMORY, &(sc->bar1id),
0, ~0, 1, RF_ACTIVE);
if (sc->bar1res == NULL) {
    uprintf("Memory allocation of PCI base register 1 failed!\n");
    error = ENXIO;
    goto fail2;
}
sc->bar0_bt = rman_get_bustag(sc->bar0res);
sc->bar0_bh = rman_get_bushandle(sc->bar0res);
sc->bar1_bt = rman_get_bustag(sc->bar1res);
sc->bar1_bh = rman_get_bushandle(sc->bar1res);

```

Handles for each base address register are kept in the `softc` structure so that they can be used to write to the device later.

These handles can then be used to read or write from the device registers with the `bus_space_*` functions. For example, a driver might contain a shorthand function to read from a board specific register like this:

```

uint16_t
board_read(struct ni_softc *sc, uint16_t address) {
    return bus_space_read_2(sc->bar1_bt, sc->bar1_bh, address);
}

```

Similarly, one could write to the registers with:

```

void
board_write(struct ni_softc *sc, uint16_t address, uint16_t value) {
    bus_space_write_2(sc->bar1_bt, sc->bar1_bh, address, value);
}

```

```
}
```

These functions exist in 8bit, 16bit, and 32bit versions and you should use `bus_space_{read|write}_{1|2|4}` accordingly.

## 23.2.2 Interrupts

Interrupts are allocated from the object-oriented bus code in a way similar to the memory resources. First an IRQ resource must be allocated from the parent bus, and then the interrupt handler must be setup to deal with this IRQ.

Again, a sample from a device `attach()` function says more than words.

```
/* Get the IRQ resource */

    sc->irqid = 0x0;
    sc->irqres = bus_alloc_resource(dev, SYS_RES_IRQ, &(sc->irqid),
0, ~0, 1, RF_SHAREABLE | RF_ACTIVE);
    if (sc->irqres == NULL) {
uprintf("IRQ allocation failed!\n");
error = ENXIO;
goto fail3;
    }

    /* Now we should setup the interrupt handler */

    error = bus_setup_intr(dev, sc->irqres, INTR_TYPE_MISC,
my_handler, sc, &(sc->handler));
    if (error) {
printf("Couldn't set up irq\n");
goto fail4;
    }

    sc->irq_bt = rman_get_bustag(sc->irqres);
    sc->irq_bh = rman_get_bushandle(sc->irqres);
```

## 23.2.3 DMA

On the PC, peripherals that want to do bus-mastering DMA must deal with physical addresses. This is a problem since FreeBSD uses virtual memory and deals almost exclusively with virtual addresses. Fortunately, there is a function, `vtophys()` to help.

```
#include <vm/vm.h>
#include <vm/pmap.h>

#define vtophys(virtual_address) (...)
```

The solution is a bit different on the alpha however, and what we really want is a function called `vtobus()`.

```
#if defined(__alpha__)
#define vtobus(va) alpha_XXX_dmamap((vm_offset_t)va)
```

```
#else  
#define vtobus(va)      vtophys(va)  
#endif
```

## 23.2.4 Deallocating Resources

It is very important to deallocate all of the resources that were allocated during `attach()`. Care must be taken to deallocate the correct stuff even on a failure condition so that the system will remain usable while your driver dies.

# Chapter 24 Common Access Method SCSI Controllers

*This chapter was written by Sergey Babkin <babkin@FreeBSD.org> Modifications for the handbook made by Murray Stokely <murray@FreeBSD.org>.*

## 24.1 Synopsis

This document assumes that the reader has a general understanding of device drivers in FreeBSD and of the SCSI protocol. Much of the information in this document was extracted from the drivers:

- `ncr (/sys/pci/ncr.c)` by Wolfgang Stanglmeier and Stefan Esser
- `sym (/sys/pci/sym.c)` by Gerard Roudier
- `aic7xxx (/sys/dev/aic7xxx/aic7xxx.c)` by Justin T. Gibbs

and from the CAM code itself (by Justin T. Gibbs, see `/sys/cam/*`). When some solution looked the most logical and was essentially verbatim extracted from the code by Justin Gibbs, I marked it as “recommended”.

The document is illustrated with examples in pseudo-code. Although sometimes the examples have many details and look like real code, it is still pseudo-code. It was written to demonstrate the concepts in an understandable way. For a real driver other approaches may be more modular and efficient. It also abstracts from the hardware details, as well as issues that would cloud the demonstrated concepts or that are supposed to be described in the other chapters of the developers handbook. Such details are commonly shown as calls to functions with descriptive names, comments or pseudo-statements. Fortunately real life full-size examples with all the details can be found in the real drivers.

## 24.2 General architecture

CAM stands for Common Access Method. It is a generic way to address the I/O buses in a SCSI-like way. This allows a separation of the generic device drivers from the drivers controlling the I/O bus: for example the disk driver becomes able to control disks on both SCSI, IDE, and/or any other bus so the disk driver portion does not have to be rewritten (or copied and modified) for every new I/O bus. Thus the two most important active entities are:

- *Peripheral Modules* - a driver for peripheral devices (disk, tape, CDROM, etc.)
- *SCSI Interface Modules (SIM)* - a Host Bus Adapter drivers for connecting to an I/O bus such as SCSI or IDE.

A peripheral driver receives requests from the OS, converts them to a sequence of SCSI commands and passes these SCSI commands to a SCSI Interface Module. The SCSI Interface Module is responsible for passing these commands to the actual hardware (or if the actual hardware is not SCSI but, for example, IDE then also converting the SCSI commands to the native commands of the hardware).

Because we are interested in writing a SCSI adapter driver here, from this point on we will consider everything from the SIM standpoint.

A typical SIM driver needs to include the following CAM-related header files:

```

#include <cam/cam.h>
#include <cam/cam_ccb.h>
#include <cam/cam_sim.h>
#include <cam/cam_xpt_sim.h>
#include <cam/cam_debug.h>
#include <cam/scsi/scsi_all.h>

```

The first thing each SIM driver must do is register itself with the CAM subsystem. This is done during the driver's `xxx_attach()` function (here and further `xxx_` is used to denote the unique driver name prefix). The `xxx_attach()` function itself is called by the system bus auto-configuration code which we do not describe here.

This is achieved in multiple steps: first it is necessary to allocate the queue of requests associated with this SIM:

```

struct cam_devq *devq;

if(( devq = cam_simq_alloc(SIZE) )!=NULL) {
    error; /* some code to handle the error */
}

```

Here `SIZE` is the size of the queue to be allocated, maximal number of requests it could contain. It is the number of requests that the SIM driver can handle in parallel on one SCSI card. Commonly it can be calculated as:

```

SIZE = NUMBER_OF_SUPPORTED_TARGETS * MAX_SIMULTANEOUS_COMMANDS_PER_TARGET

```

Next we create a descriptor of our SIM:

```

struct cam_sim *sim;

if(( sim = cam_sim_alloc(action_func, poll_func, driver_name,
    softc, unit, max_dev_transactions,
    max_tagged_dev_transactions, devq) )!=NULL) {
    cam_simq_free(devq);
    error; /* some code to handle the error */
}

```

Note that if we are not able to create a SIM descriptor we free the `devq` also because we can do nothing else with it and we want to conserve memory.

If a SCSI card has multiple SCSI buses on it then each bus requires its own `cam_sim` structure.

An interesting question is what to do if a SCSI card has more than one SCSI bus, do we need one `devq` structure per card or per SCSI bus? The answer given in the comments to the CAM code is: either way, as the driver's author prefers.

The arguments are:

- `action_func` - pointer to the driver's `xxx_action` function.

```

static void xxx_action ( struct cam_sim *sim, union ccb *ccb );

```

- `poll_func` - pointer to the driver's `xxx_poll()`

```
static void xxx_poll ( struct cam_sim *sim );
```

- driver\_name - the name of the actual driver, such as “ncr” or “wds”.
- softc - pointer to the driver’s internal descriptor for this SCSI card. This pointer will be used by the driver in future to get private data.
- unit - the controller unit number, for example for controller “wds0” this number will be 0
- max\_dev\_transactions - maximal number of simultaneous transactions per SCSI target in the non-tagged mode. This value will be almost universally equal to 1, with possible exceptions only for the non-SCSI cards. Also the drivers that hope to take advantage by preparing one transaction while another one is executed may set it to 2 but this does not seem to be worth the complexity.
- max\_tagged\_dev\_transactions - the same thing, but in the tagged mode. Tags are the SCSI way to initiate multiple transactions on a device: each transaction is assigned a unique tag and the transaction is sent to the device. When the device completes some transaction it sends back the result together with the tag so that the SCSI adapter (and the driver) can tell which transaction was completed. This argument is also known as the maximal tag depth. It depends on the abilities of the SCSI adapter.

Finally we register the SCSI buses associated with our SCSI adapter:

```
if(xpt_bus_register(sim, bus_number) != CAM_SUCCESS) {
    cam_sim_free(sim, /*free_devq*/ TRUE);
    error; /* some code to handle the error */
}
```

If there is one devq structure per SCSI bus (i.e. we consider a card with multiple buses as multiple cards with one bus each) then the bus number will always be 0, otherwise each bus on the SCSI card should be get a distinct number. Each bus needs its own separate structure cam\_sim.

After that our controller is completely hooked to the CAM system. The value of devq can be discarded now: sim will be passed as an argument in all further calls from CAM and devq can be derived from it.

CAM provides the framework for such asynchronous events. Some events originate from the lower levels (the SIM drivers), some events originate from the peripheral drivers, some events originate from the CAM subsystem itself. Any driver can register callbacks for some types of the asynchronous events, so that it would be notified if these events occur.

A typical example of such an event is a device reset. Each transaction and event identifies the devices to which it applies by the means of “path”. The target-specific events normally occur during a transaction with this device. So the path from that transaction may be re-used to report this event (this is safe because the event path is copied in the event reporting routine but not deallocated nor passed anywhere further). Also it is safe to allocate paths dynamically at any time including the interrupt routines, although that incurs certain overhead, and a possible problem with this approach is that there may be no free memory at that time. For a bus reset event we need to define a wildcard path including all devices on the bus. So we can create the path for the future bus reset events in advance and avoid problems with the future memory shortage:

```
struct cam_path *path;

if(xpt_create_path(&path, /*periph*/NULL,
                 cam_sim_path(sim), CAM_TARGET_WILDCARD,
```



```

        CAM_LUN_WILDCARD) != CAM_REQ_CMP) {
    xpt_bus_deregister(cam_sim_path(sim));
    cam_sim_free(sim, /*free_devq*/TRUE);
    error; /* some code to handle the error */
}

softc->wpath = path;
softc->sim = sim;

```

As you can see the path includes:

- ID of the peripheral driver (NULL here because we have none)
- ID of the SIM driver (`cam_sim_path(sim)`)
- SCSI target number of the device (CAM\_TARGET\_WILDCARD means “all devices”)
- SCSI LUN number of the subdevice (CAM\_LUN\_WILDCARD means “all LUNs”)

If the driver can not allocate this path it will not be able to work normally, so in that case we dismantle that SCSI bus.

And we save the path pointer in the `softc` structure for future use. After that we save the value of `sim` (or we can also discard it on the exit from `xxx_probe()` if we wish).

That is all for a minimalistic initialization. To do things right there is one more issue left.

For a SIM driver there is one particularly interesting event: when a target device is considered lost. In this case resetting the SCSI negotiations with this device may be a good idea. So we register a callback for this event with CAM. The request is passed to CAM by requesting CAM action on a CAM control block for this type of request:

```

struct ccb_setasync csa;

xpt_setup_ccb(&csa.ccb_h, path, /*priority*/5);
csa.ccb_h.func_code = XPT_SASYNC_CB;
csa.event_enable = AC_LOST_DEVICE;
csa.callback = xxx_async;
csa.callback_arg = sim;
xpt_action((union ccb *)&csa);

```

Now we take a look at the `xxx_action()` and `xxx_poll()` driver entry points.

```
static void xxx_action ( struct cam_sim *sim, union ccb *ccb );
```

Do some action on request of the CAM subsystem. `sim` describes the SIM for the request, `CCB` is the request itself. `CCB` stands for “CAM Control Block”. It is a union of many specific instances, each describing arguments for some type of transactions. All of these instances share the `CCB` header where the common part of arguments is stored.

CAM supports the SCSI controllers working in both initiator (“normal”) mode and target (simulating a SCSI device) mode. Here we only consider the part relevant to the initiator mode.

There are a few function and macros (in other words, methods) defined to access the public data in the struct `sim`:

- `cam_sim_path(sim)` - the path ID (see above)

- `cam_sim_name(sim)` - the name of the sim
- `cam_sim_softc(sim)` - the pointer to the `softc` (driver private data) structure
- `cam_sim_unit(sim)` - the unit number
- `cam_sim_bus(sim)` - the bus ID

To identify the device, `xxx_action()` can get the unit number and pointer to its structure `softc` using these functions.

The type of request is stored in `ccb->ccb_h.func_code`. So generally `xxx_action()` consists of a big switch:

```

struct xxx_softc *softc = (struct xxx_softc *) cam_sim_softc(sim);
struct ccb_hdr *ccb_h = &ccb->ccb_h;
int unit = cam_sim_unit(sim);
int bus = cam_sim_bus(sim);

switch(ccb_h->func_code) {
case ...:
    ...
default:
    ccb_h->status = CAM_REQ_INVALID;
    xpt_done(ccb);
    break;
}

```

As can be seen from the default case (if an unknown command was received) the return code of the command is set into `ccb->ccb_h.status` and the completed CCB is returned back to CAM by calling `xpt_done(ccb)`.

`xpt_done()` does not have to be called from `xxx_action()`: For example an I/O request may be enqueued inside the SIM driver and/or its SCSI controller. Then when the device would post an interrupt signaling that the processing of this request is complete `xpt_done()` may be called from the interrupt handling routine.

Actually, the CCB status is not only assigned as a return code but a CCB has some status all the time. Before CCB is passed to the `xxx_action()` routine it gets the status `CCB_REQ_INPROG` meaning that it is in progress. There are a surprising number of status values defined in `/sys/cam/cam.h` which should be able to represent the status of a request in great detail. More interesting yet, the status is in fact a “bitwise or” of an enumerated status value (the lower 6 bits) and possible additional flag-like bits (the upper bits). The enumerated values will be discussed later in more detail. The summary of them can be found in the Errors Summary section. The possible status flags are:

- `CAM_DEV_QFRZN` - if the SIM driver gets a serious error (for example, the device does not respond to the selection or breaks the SCSI protocol) when processing a CCB it should freeze the request queue by calling `xpt_freeze_simq()`, return the other enqueued but not processed yet CCBs for this device back to the CAM queue, then set this flag for the troublesome CCB and call `xpt_done()`. This flag causes the CAM subsystem to unfreeze the queue after it handles the error.
- `CAM_AUTOSNS_VALID` - if the device returned an error condition and the flag `CAM_DIS_AUTOSENSE` is not set in CCB the SIM driver must execute the REQUEST SENSE command automatically to extract the sense (extended error information) data from the device. If this attempt was successful the sense data should be saved in the CCB and this flag set.
- `CAM_RELEASE_SIMQ` - like `CAM_DEV_QFRZN` but used in case there is some problem (or resource shortage) with the SCSI controller itself. Then all the future requests to the controller should be stopped by

`xpt_freeze_simq()`. The controller queue will be restarted after the SIM driver overcomes the shortage and informs CAM by returning some CCB with this flag set.

- *CAM\_SIM\_QUEUED* - when SIM puts a CCB into its request queue this flag should be set (and removed when this CCB gets dequeued before being returned back to CAM). This flag is not used anywhere in the CAM code now, so its purpose is purely diagnostic.

The function `xxx_action()` is not allowed to sleep, so all the synchronization for resource access must be done using SIM or device queue freezing. Besides the aforementioned flags the CAM subsystem provides functions `xpt_release_simq()` and `xpt_release_devq()` to unfreeze the queues directly, without passing a CCB to CAM.

The CCB header contains the following fields:

- *path* - path ID for the request
- *target\_id* - target device ID for the request
- *target\_lun* - LUN ID of the target device
- *timeout* - timeout interval for this command, in milliseconds
- *timeout\_ch* - a convenience place for the SIM driver to store the timeout handle (the CAM subsystem itself does not make any assumptions about it)
- *flags* - various bits of information about the request *spriv\_ptr0*, *spriv\_ptr1* - fields reserved for private use by the SIM driver (such as linking to the SIM queues or SIM private control blocks); actually, they exist as unions: *spriv\_ptr0* and *spriv\_ptr1* have the type (void \*), *spriv\_field0* and *spriv\_field1* have the type unsigned long, *sim\_priv.entries[0].bytes* and *sim\_priv.entries[1].bytes* are byte arrays of the size consistent with the other incarnations of the union and *sim\_priv.bytes* is one array, twice bigger.

The recommended way of using the SIM private fields of CCB is to define some meaningful names for them and use these meaningful names in the driver, like:

```
#define ccb_some_meaningful_name    sim_priv.entries[0].bytes
#define ccb_hcb spriv_ptr1 /* for hardware control block */
```

The most common initiator mode requests are:

- *XPT SCSI IO* - execute an I/O transaction

The instance “struct `ccb_scsiio csio`” of the union `ccb` is used to transfer the arguments. They are:

- *cdb\_io* - pointer to the SCSI command buffer or the buffer itself
- *cdb\_len* - SCSI command length
- *data\_ptr* - pointer to the data buffer (gets a bit complicated if scatter/gather is used)
- *dxfer\_len* - length of the data to transfer
- *splist\_cnt* - counter of the scatter/gather segments
- *scsi\_status* - place to return the SCSI status
- *sense\_data* - buffer for the SCSI sense information if the command returns an error (the SIM driver is supposed to run the REQUEST SENSE command automatically in this case if the CCB flag `CAM_DIS_AUTOSENSE` is not set)

- *sense\_len* - the length of that buffer (if it happens to be higher than size of *sense\_data* the SIM driver must silently assume the smaller value) *resid*, *sense\_resid* - if the transfer of data or SCSI sense returned an error these are the returned counters of the residual (not transferred) data. They do not seem to be especially meaningful, so in a case when they are difficult to compute (say, counting bytes in the SCSI controller's FIFO buffer) an approximate value will do as well. For a successfully completed transfer they must be set to zero.
- *tag\_action* - the kind of tag to use:
  - *CAM\_TAG\_ACTION\_NONE* - do not use tags for this transaction
  - *MSG\_SIMPLE\_Q\_TAG*, *MSG\_HEAD\_OF\_Q\_TAG*, *MSG\_ORDERED\_Q\_TAG* - value equal to the appropriate tag message (see `/sys/cam/scsi/scsi_message.h`); this gives only the tag type, the SIM driver must assign the tag value itself

The general logic of handling this request is the following:

The first thing to do is to check for possible races, to make sure that the command did not get aborted when it was sitting in the queue:

```
struct ccb_scsiio *csio = &ccb->csio;

if ((ccb_h->status & CAM_STATUS_MASK) != CAM_REQ_INPROG) {
    xpt_done(ccb);
    return;
}
```

Also we check that the device is supported at all by our controller:

```
if(ccb_h->target_id > OUR_MAX_SUPPORTED_TARGET_ID
|| ccb_h->target_id == OUR_SCSI_CONTROLLERS_OWN_ID) {
    ccb_h->status = CAM_TID_INVALID;
    xpt_done(ccb);
    return;
}
if(ccb_h->target_lun > OUR_MAX_SUPPORTED_LUN) {
    ccb_h->status = CAM_LUN_INVALID;
    xpt_done(ccb);
    return;
}
```

Then allocate whatever data structures (such as card-dependent hardware control block) we need to process this request. If we can not then freeze the SIM queue and remember that we have a pending operation, return the CCB back and ask CAM to re-queue it. Later when the resources become available the SIM queue must be unfrozen by returning a ccb with the *CAM\_SIMQ\_RELEASE* bit set in its status. Otherwise, if all went well, link the CCB with the hardware control block (HCB) and mark it as queued.

```
struct xxx_hcb *hcb = allocate_hcb(softc, unit, bus);

if(hcb == NULL) {
    softc->flags |= RESOURCE_SHORTAGE;
    xpt_freeze_simq(sim, /*count*/1);
    ccb_h->status = CAM_REQUEUE_REQ;
    xpt_done(ccb);
    return;
}
```

```

hcb->ccb = ccb; ccb_h->ccb_hcb = (void *)hcb;
ccb_h->status |= CAM_SIM_QUEUED;

```

Extract the target data from CCB into the hardware control block. Check if we are asked to assign a tag and if yes then generate a unique tag and build the SCSI tag messages. The SIM driver is also responsible for negotiations with the devices to set the maximal mutually supported bus width, synchronous rate and offset.

```

hcb->target = ccb_h->target_id; hcb->lun = ccb_h->target_lun;
generate_identify_message(hcb);
if( ccb_h->tag_action != CAM_TAG_ACTION_NONE )
    generate_unique_tag_message(hcb, ccb_h->tag_action);
if( !target_negotiated(hcb) )
    generate_negotiation_messages(hcb);

```

Then set up the SCSI command. The command storage may be specified in the CCB in many interesting ways, specified by the CCB flags. The command buffer can be contained in CCB or pointed to, in the latter case the pointer may be physical or virtual. Since the hardware commonly needs physical address we always convert the address to the physical one.

A NOT-QUITE RELATED NOTE: Normally this is done by a call to `vtophys()`, but for the PCI device (which account for most of the SCSI controllers now) drivers' portability to the Alpha architecture the conversion must be done by `vtobus()` instead due to special Alpha quirks. [IMHO it would be much better to have two separate functions, `vtop()` and `ptobus()` then `vtobus()` would be a simple superposition of them.] In case if a physical address is requested it is OK to return the CCB with the status `CAM_REQ_INVALID`, the current drivers do that. But it is also possible to compile the Alpha-specific piece of code, as in this example (there should be a more direct way to do that, without conditional compilation in the drivers). If necessary a physical address can be also converted or mapped back to a virtual address but with big pain, so we do not do that.

```

if(ccb_h->flags & CAM_CDB_POINTER) {
    /* CDB is a pointer */
    if(!(ccb_h->flags & CAM_CDB_PHYS)) {
        /* CDB pointer is virtual */
        hcb->cmd = vtobus(csio->cdb_io.cdb_ptr);
    } else {
        /* CDB pointer is physical */
#ifdef __alpha__
        hcb->cmd = csio->cdb_io.cdb_ptr | alpha_XXX_dmamap_or ;
#else
        hcb->cmd = csio->cdb_io.cdb_ptr ;
#endif
    }
} else {
    /* CDB is in the ccb (buffer) */
    hcb->cmd = vtobus(csio->cdb_io.cdb_bytes);
}
hcb->cmdlen = csio->cdb_len;

```

Now it is time to set up the data. Again, the data storage may be specified in the CCB in many interesting ways, specified by the CCB flags. First we get the direction of the data transfer. The simplest case is if there is no data to transfer:

```

int dir = (ccb_h->flags & CAM_DIR_MASK);

if (dir == CAM_DIR_NONE)
    goto end_data;

```

Then we check if the data is in one chunk or in a scatter-gather list, and the addresses are physical or virtual. The SCSI controller may be able to handle only a limited number of chunks of limited length. If the request hits this limitation we return an error. We use a special function to return the CCB to handle in one place the HCB resource shortages. The functions to add chunks are driver-dependent, and here we leave them without detailed implementation. See description of the SCSI command (CDB) handling for the details on the address-translation issues. If some variation is too difficult or impossible to implement with a particular card it is OK to return the status CAM\_REQ\_INVALID. Actually, it seems like the scatter-gather ability is not used anywhere in the CAM code now. But at least the case for a single non-scattered virtual buffer must be implemented, it is actively used by CAM.

```

int rv;

initialize_hcb_for_data(hcb);

if(!(ccb_h->flags & CAM_SCATTER_VALID)) {
    /* single buffer */
    if(!(ccb_h->flags & CAM_DATA_PHYS)) {
        rv = add_virtual_chunk(hcb, csio->data_ptr, csio->dxfer_len, dir);
    }
    } else {
        rv = add_physical_chunk(hcb, csio->data_ptr, csio->dxfer_len, dir);
    }
} else {
    int i;
    struct bus_dma_segment *segs;
    segs = (struct bus_dma_segment *)csio->data_ptr;

    if ((ccb_h->flags & CAM_SG_LIST_PHYS) != 0) {
        /* The SG list pointer is physical */
        rv = setup_hcb_for_physical_sg_list(hcb, segs, csio->sglist_cnt);
    } else if (!(ccb_h->flags & CAM_DATA_PHYS)) {
        /* SG buffer pointers are virtual */
        for (i = 0; i < csio->sglist_cnt; i++) {
            rv = add_virtual_chunk(hcb, segs[i].ds_addr,
                segs[i].ds_len, dir);
            if (rv != CAM_REQ_CMP)
                break;
        }
    } else {
        /* SG buffer pointers are physical */
        for (i = 0; i < csio->sglist_cnt; i++) {
            rv = add_physical_chunk(hcb, segs[i].ds_addr,
                segs[i].ds_len, dir);
            if (rv != CAM_REQ_CMP)
                break;
        }
    }
}
if(rv != CAM_REQ_CMP) {
    /* we expect that add_*_chunk() functions return CAM_REQ_CMP
    * if they added a chunk successfully, CAM_REQ_TOO_BIG if
    * the request is too big (too many bytes or too many chunks),
    * CAM_REQ_INVALID in case of other troubles

```

```

        */
        free_hcb_and_ccb_done(hcb, ccb, rv);
        return;
    }
end_data:

```

If disconnection is disabled for this CCB we pass this information to the hcb:

```

        if(ccb_h->flags & CAM_DIS_DISCONNECT)
            hcb_disable_disconnect(hcb);

```

If the controller is able to run REQUEST SENSE command all by itself then the value of the flag CAM\_DIS\_AUTOSENSE should also be passed to it, to prevent automatic REQUEST SENSE if the CAM subsystem does not want it.

The only thing left is to set up the timeout, pass our hcb to the hardware and return, the rest will be done by the interrupt handler (or timeout handler).

```

        ccb_h->timeout_ch = timeout(xxx_timeout, (caddr_t) hcb,
            (ccb_h->timeout * hz) / 1000); /* convert milliseconds to ticks */
        put_hcb_into_hardware_queue(hcb);
        return;

```

And here is a possible implementation of the function returning CCB:

```

static void
free_hcb_and_ccb_done(struct xxx_hcb *hcb, union ccb *ccb, u_int32_t status)
{
    struct xxx_softc *softc = hcb->softc;

    ccb->ccb_h.ccb_hcb = 0;
    if(hcb != NULL) {
        untimeout(xxx_timeout, (caddr_t) hcb, ccb->ccb_h.timeout_ch);
        /* we're about to free a hcb, so the shortage has ended */
        if(softc->flags & RESOURCE_SHORTAGE) {
            softc->flags &= ~RESOURCE_SHORTAGE;
            status |= CAM_RELEASE_SIMQ;
        }
        free_hcb(hcb); /* also removes hcb from any internal lists */
    }
    ccb->ccb_h.status = status |
        (ccb->ccb_h.status & ~(CAM_STATUS_MASK|CAM_SIM_QUEUED));
    xpt_done(ccb);
}

```

- *XPT\_RESET\_DEV* - send the SCSI “BUS DEVICE RESET” message to a device

There is no data transferred in CCB except the header and the most interesting argument of it is target\_id. Depending on the controller hardware a hardware control block just like for the XPT SCSI\_IO request may be constructed (see XPT SCSI\_IO request description) and sent to the controller or the SCSI controller may be immediately programmed to send this RESET message to the device or this request may be just not supported (and return the status CAM\_REQ\_INVALID). Also on completion of the request all the disconnected transactions for this target must be aborted (probably in the interrupt routine).

Also all the current negotiations for the target are lost on reset, so they might be cleaned too. Or they clearing may be deferred, because anyway the target would request re-negotiation on the next transaction.

- *XPT\_RESET\_BUS* - send the RESET signal to the SCSI bus

No arguments are passed in the CCB, the only interesting argument is the SCSI bus indicated by the struct *sim* pointer.

A minimalistic implementation would forget the SCSI negotiations for all the devices on the bus and return the status *CAM\_REQ\_CMP*.

The proper implementation would in addition actually reset the SCSI bus (possible also reset the SCSI controller) and mark all the CCBs being processed, both those in the hardware queue and those being disconnected, as done with the status *CAM\_SCSI\_BUS\_RESET*. Like:

```
int targ, lun;
struct xxx_hcb *h, *hh;
struct ccb_trans_settings neg;
struct cam_path *path;

/* The SCSI bus reset may take a long time, in this case its completion
 * should be checked by interrupt or timeout. But for simplicity
 * we assume here that it's really fast.
 */
reset_scsi_bus(softc);

/* drop all enqueued CCBs */
for(h = softc->first_queued_hcb; h != NULL; h = hh) {
    hh = h->next;
    free_hcb_and_ccb_done(h, h->ccb, CAM_SCSI_BUS_RESET);
}

/* the clean values of negotiations to report */
neg.bus_width = 8;
neg.sync_period = neg.sync_offset = 0;
neg.valid = (CCB_TRANS_BUS_WIDTH_VALID
    | CCB_TRANS_SYNC_RATE_VALID | CCB_TRANS_SYNC_OFFSET_VALID);

/* drop all disconnected CCBs and clean negotiations */
for(targ=0; targ <= OUR_MAX_SUPPORTED_TARGET; targ++) {
    clean_negotiations(softc, targ);

    /* report the event if possible */
    if(xpt_create_path(&path, /*periph*/NULL,
        cam_sim_path(sim), targ,
        CAM_LUN_WILDCARD) == CAM_REQ_CMP) {
        xpt_async(AC_TRANSFER_NEG, path, &neg);
        xpt_free_path(path);
    }

    for(lun=0; lun <= OUR_MAX_SUPPORTED_LUN; lun++)
        for(h = softc->first_discon_hcb[targ][lun]; h != NULL; h = hh) {
            hh=h->next;
        }
    }
}
```



```

        free_hcb_and_ccb_done(h, h->ccb, CAM SCSI_BUS_RESET);
    }
}

ccb->ccb_h.status = CAM_REQ_CMP;
xpt_done(ccb);

/* report the event */
xpt_async(AC_BUS_RESET, softc->wpath, NULL);
return;

```

Implementing the SCSI bus reset as a function may be a good idea because it would be re-used by the timeout function as a last resort if the things go wrong.

- *XPT\_ABORT* - abort the specified CCB

The arguments are transferred in the instance “struct ccb\_abort cab” of the union ccb. The only argument field in it is:

*abort\_ccb* - pointer to the CCB to be aborted

If the abort is not supported just return the status CAM\_UA\_ABORT. This is also the easy way to minimally implement this call, return CAM\_UA\_ABORT in any case.

The hard way is to implement this request honestly. First check that abort applies to a SCSI transaction:

```

struct ccb *abort_ccb;
abort_ccb = ccb->cab.abort_ccb;

if(abort_ccb->ccb_h.func_code != XPT SCSI_IO) {
    ccb->ccb_h.status = CAM_UA_ABORT;
    xpt_done(ccb);
    return;
}

```

Then it is necessary to find this CCB in our queue. This can be done by walking the list of all our hardware control blocks in search for one associated with this CCB:

```

struct xxx_hcb *hcb, *h;

hcb = NULL;

/* We assume that softc->first_hcb is the head of the list of all
 * HCBs associated with this bus, including those enqueued for
 * processing, being processed by hardware and disconnected ones.
 */
for(h = softc->first_hcb; h != NULL; h = h->next) {
    if(h->ccb == abort_ccb) {
        hcb = h;
        break;
    }
}

if(hcb == NULL) {
    /* no such CCB in our queue */

```

```

        ccb->ccb_h.status = CAM_PATH_INVALID;
        xpt_done(ccb);
        return;
    }

    hcb=found_hcb;

```

Now we look at the current processing status of the HCB. It may be either sitting in the queue waiting to be sent to the SCSI bus, being transferred right now, or disconnected and waiting for the result of the command, or actually completed by hardware but not yet marked as done by software. To make sure that we do not get in any races with hardware we mark the HCB as being aborted, so that if this HCB is about to be sent to the SCSI bus the SCSI controller will see this flag and skip it.

```

    int hstatus;

    /* shown as a function, in case special action is needed to make
     * this flag visible to hardware
     */
    set_hcb_flags(hcb, HCB_BEING_ABORTED);

    abort_again:

    hstatus = get_hcb_status(hcb);
    switch(hstatus) {
    case HCB_SITTING_IN_QUEUE:
        remove_hcb_from_hardware_queue(hcb);
        /* FALLTHROUGH */
    case HCB_COMPLETED:
        /* this is an easy case */
        free_hcb_and_ccb_done(hcb, abort_ccb, CAM_REQ_ABORTED);
        break;

```

If the CCB is being transferred right now we would like to signal to the SCSI controller in some hardware-dependent way that we want to abort the current transfer. The SCSI controller would set the SCSI ATTENTION signal and when the target responds to it send an ABORT message. We also reset the timeout to make sure that the target is not sleeping forever. If the command would not get aborted in some reasonable time like 10 seconds the timeout routine would go ahead and reset the whole SCSI bus. Because the command will be aborted in some reasonable time we can just return the abort request now as successfully completed, and mark the aborted CCB as aborted (but not mark it as done yet).

```

    case HCB_BEING_TRANSFERRED:
        untimeout(xxx_timeout, (caddr_t) hcb, abort_ccb->ccb_h.timeout_ch);
        abort_ccb->ccb_h.timeout_ch =
            timeout(xxx_timeout, (caddr_t) hcb, 10 * hz);
        abort_ccb->ccb_h.status = CAM_REQ_ABORTED;
        /* ask the controller to abort that HCB, then generate
         * an interrupt and stop
         */
        if(signal_hardware_to_abort_hcb_and_stop(hcb) < 0) {
            /* oops, we missed the race with hardware, this transaction
             * got off the bus before we aborted it, try again */
            goto abort_again;
        }

```

```
break;
```

If the CCB is in the list of disconnected then set it up as an abort request and re-queue it at the front of hardware queue. Reset the timeout and report the abort request to be completed.

```
case HCB_DISCONNECTED:
    untimeout(xxx_timeout, (caddr_t) hcb, abort_ccb->ccb_h.timeout_ch);
    abort_ccb->ccb_h.timeout_ch =
        timeout(xxx_timeout, (caddr_t) hcb, 10 * hz);
    put_abort_message_into_hcb(hcb);
    put_hcb_at_the_front_of_hardware_queue(hcb);
    break;
}
ccb->ccb_h.status = CAM_REQ_CMP;
xpt_done(ccb);
return;
```

That is all for the ABORT request, although there is one more issue. Because the ABORT message cleans all the ongoing transactions on a LUN we have to mark all the other active transactions on this LUN as aborted. That should be done in the interrupt routine, after the transaction gets aborted.

Implementing the CCB abort as a function may be quite a good idea, this function can be re-used if an I/O transaction times out. The only difference would be that the timed out transaction would return the status CAM\_CMD\_TIMEOUT for the timed out request. Then the case XPT\_ABORT would be small, like that:

```
case XPT_ABORT:
    struct ccb *abort_ccb;
    abort_ccb = ccb->cab.abort_ccb;

    if(abort_ccb->ccb_h.func_code != XPT SCSI_IO) {
        ccb->ccb_h.status = CAM-UA_ABORT;
        xpt_done(ccb);
        return;
    }
    if(xxx_abort_ccb(abort_ccb, CAM_REQ_ABORTED) < 0)
        /* no such CCB in our queue */
        ccb->ccb_h.status = CAM_PATH_INVALID;
    else
        ccb->ccb_h.status = CAM_REQ_CMP;
    xpt_done(ccb);
    return;
```

- *XPT\_SET\_TRAN\_SETTINGS* - explicitly set values of SCSI transfer settings

The arguments are transferred in the instance “struct ccb\_trans\_setting cts” of the union ccb:

- *valid* - a bitmask showing which settings should be updated:
- *CCB\_TRANS\_SYNC\_RATE\_VALID* - synchronous transfer rate
- *CCB\_TRANS\_SYNC\_OFFSET\_VALID* - synchronous offset
- *CCB\_TRANS\_BUS\_WIDTH\_VALID* - bus width
- *CCB\_TRANS\_DISC\_VALID* - set enable/disable disconnection

- *CCB\_TRANS\_TQ\_VALID* - set enable/disable tagged queuing
- *flags* - consists of two parts, binary arguments and identification of sub-operations. The binary arguments are:
  - *CCB\_TRANS\_DISC\_ENB* - enable disconnection
  - *CCB\_TRANS\_TAG\_ENB* - enable tagged queuing
- the sub-operations are:
  - *CCB\_TRANS\_CURRENT\_SETTINGS* - change the current negotiations
  - *CCB\_TRANS\_USER\_SETTINGS* - remember the desired user values *sync\_period*, *sync\_offset* - self-explanatory, if *sync\_offset==0* then the asynchronous mode is requested *bus\_width* - bus width, in bits (not bytes)

Two sets of negotiated parameters are supported, the user settings and the current settings. The user settings are not really used much in the SIM drivers, this is mostly just a piece of memory where the upper levels can store (and later recall) its ideas about the parameters. Setting the user parameters does not cause re-negotiation of the transfer rates. But when the SCSI controller does a negotiation it must never set the values higher than the user parameters, so it is essentially the top boundary.

The current settings are, as the name says, current. Changing them means that the parameters must be re-negotiated on the next transfer. Again, these “new current settings” are not supposed to be forced on the device, just they are used as the initial step of negotiations. Also they must be limited by actual capabilities of the SCSI controller: for example, if the SCSI controller has 8-bit bus and the request asks to set 16-bit wide transfers this parameter must be silently truncated to 8-bit transfers before sending it to the device.

One caveat is that the bus width and synchronous parameters are per target while the disconnection and tag enabling parameters are per lun.

The recommended implementation is to keep 3 sets of negotiated (bus width and synchronous transfer) parameters:

- *user* - the user set, as above
- *current* - those actually in effect
- *goal* - those requested by setting of the “current” parameters

The code looks like:

```

struct ccb_trans_settings *cts;
int targ, lun;
int flags;

cts = &ccb->cts;
targ = ccb_h->target_id;
lun = ccb_h->target_lun;
flags = cts->flags;
if(flags & CCB_TRANS_USER_SETTINGS) {
    if(flags & CCB_TRANS_SYNC_RATE_VALID)
        softc->user_sync_period[targ] = cts->sync_period;
    if(flags & CCB_TRANS_SYNC_OFFSET_VALID)
        softc->user_sync_offset[targ] = cts->sync_offset;
    if(flags & CCB_TRANS_BUS_WIDTH_VALID)

```

```

    softc->user_bus_width[targ] = cts->bus_width;

    if(flags & CCB_TRANS_DISC_VALID) {
        softc->user_tflags[targ][lun] &= ~CCB_TRANS_DISC_ENB;
        softc->user_tflags[targ][lun] |= flags & CCB_TRANS_DISC_ENB;
    }
    if(flags & CCB_TRANS_TQ_VALID) {
        softc->user_tflags[targ][lun] &= ~CCB_TRANS_TQ_ENB;
        softc->user_tflags[targ][lun] |= flags & CCB_TRANS_TQ_ENB;
    }
}
if(flags & CCB_TRANS_CURRENT_SETTINGS) {
    if(flags & CCB_TRANS_SYNC_RATE_VALID)
        softc->goal_sync_period[targ] =
            max(cts->sync_period, OUR_MIN_SUPPORTED_PERIOD);
    if(flags & CCB_TRANS_SYNC_OFFSET_VALID)
        softc->goal_sync_offset[targ] =
            min(cts->sync_offset, OUR_MAX_SUPPORTED_OFFSET);
    if(flags & CCB_TRANS_BUS_WIDTH_VALID)
        softc->goal_bus_width[targ] = min(cts->bus_width, OUR_BUS_WIDTH);

    if(flags & CCB_TRANS_DISC_VALID) {
        softc->current_tflags[targ][lun] &= ~CCB_TRANS_DISC_ENB;
        softc->current_tflags[targ][lun] |= flags & CCB_TRANS_DISC_ENB;
    }
    if(flags & CCB_TRANS_TQ_VALID) {
        softc->current_tflags[targ][lun] &= ~CCB_TRANS_TQ_ENB;
        softc->current_tflags[targ][lun] |= flags & CCB_TRANS_TQ_ENB;
    }
}
ccb->ccb_h.status = CAM_REQ_CMP;
xpt_done(ccb);
return;

```

Then when the next I/O request will be processed it will check if it has to re-negotiate, for example by calling the function `target_negotiated(hcb)`. It can be implemented like this:

```

int
target_negotiated(struct xxx_hcb *hcb)
{
    struct softc *softc = hcb->softc;
    int targ = hcb->targ;

    if( softc->current_sync_period[targ] != softc->goal_sync_period[targ]
    || softc->current_sync_offset[targ] != softc->goal_sync_offset[targ]
    || softc->current_bus_width[targ] != softc->goal_bus_width[targ] )
        return 0; /* FALSE */
    else
        return 1; /* TRUE */
}

```

After the values are re-negotiated the resulting values must be assigned to both current and goal parameters, so for future I/O transactions the current and goal parameters would be the same and `target_negotiated()` would return TRUE. When the card is initialized (in `xxx_attach()`) the current negotiation values must be initialized to

narrow asynchronous mode, the goal and current values must be initialized to the maximal values supported by controller.

- *XPT\_GET\_TRAN\_SETTINGS* - get values of SCSI transfer settings

This operations is the reverse of *XPT\_SET\_TRAN\_SETTINGS*. Fill up the CCB instance “struct ccb\_trans\_setting cts” with data as requested by the flags *CCB\_TRANS\_CURRENT\_SETTINGS* or *CCB\_TRANS\_USER\_SETTINGS* (if both are set then the existing drivers return the current settings). Set all the bits in the valid field.

- *XPT\_CALC\_GEOMETRY* - calculate logical (BIOS) geometry of the disk

The arguments are transferred in the instance “struct ccb\_calc\_geometry ccg” of the union ccb:

- *block\_size* - input, block (A.K.A sector) size in bytes
- *volume\_size* - input, volume size in bytes
- *cylinders* - output, logical cylinders
- *heads* - output, logical heads
- *secs\_per\_track* - output, logical sectors per track

If the returned geometry differs much enough from what the SCSI controller BIOS thinks and a disk on this SCSI controller is used as bootable the system may not be able to boot. The typical calculation example taken from the *aic7xxx* driver is:

```

struct    ccb_calc_geometry *ccg;
u_int32_t size_mb;
u_int32_t secs_per_cylinder;
int      extended;

ccg = &ccb->ccg;
size_mb = ccg->volume_size
          / ((1024L * 1024L) / ccg->block_size);
extended = check_cards_EEPROM_for_extended_geometry(softc);

if (size_mb > 1024 && extended) {
    ccg->heads = 255;
    ccg->secs_per_track = 63;
} else {
    ccg->heads = 64;
    ccg->secs_per_track = 32;
}
secs_per_cylinder = ccg->heads * ccg->secs_per_track;
ccg->cylinders = ccg->volume_size / secs_per_cylinder;
ccb->ccb_h.status = CAM_REQ_CMP;
xpt_done(ccb);
return;

```

This gives the general idea, the exact calculation depends on the quirks of the particular BIOS. If BIOS provides no way set the “extended translation” flag in EEPROM this flag should normally be assumed equal to 1. Other popular geometries are:

128 heads, 63 sectors - Symbios controllers  
16 heads, 63 sectors - old controllers

Some system BIOSes and SCSI BIOSes fight with each other with variable success, for example a combination of Symbios 875/895 SCSI and Phoenix BIOS can give geometry 128/63 after power up and 255/63 after a hard reset or soft reboot.

- *XPT\_PATH\_INQ* - path inquiry, in other words get the SIM driver and SCSI controller (also known as HBA - Host Bus Adapter) properties

The properties are returned in the instance “struct ccb\_pathinq cpi” of the union ccb:

- *version\_num* - the SIM driver version number, now all drivers use 1
- *hba\_inquiry* - bitmask of features supported by the controller:
- *PI\_MDP\_ABLE* - supports MDP message (something from SCSI3?)
- *PI\_WIDE\_32* - supports 32 bit wide SCSI
- *PI\_WIDE\_16* - supports 16 bit wide SCSI
- *PI\_SDTR\_ABLE* - can negotiate synchronous transfer rate
- *PI\_LINKED\_CDB* - supports linked commands
- *PI\_TAG\_ABLE* - supports tagged commands
- *PI\_SOFT\_RST* - supports soft reset alternative (hard reset and soft reset are mutually exclusive within a SCSI bus)
- *target\_sprt* - flags for target mode support, 0 if unsupported
- *hba\_misc* - miscellaneous controller features:
- *PIM\_SCANHILO* - bus scans from high ID to low ID
- *PIM\_NOREMOVE* - removable devices not included in scan
- *PIM\_NOINITIATOR* - initiator role not supported
- *PIM\_NOBUSRESET* - user has disabled initial BUS RESET
- *hba\_eng\_cnt* - mysterious HBA engine count, something related to compression, now is always set to 0
- *vuhba\_flags* - vendor-unique flags, unused now
- *max\_target* - maximal supported target ID (7 for 8-bit bus, 15 for 16-bit bus, 127 for Fibre Channel)
- *max\_lun* - maximal supported LUN ID (7 for older SCSI controllers, 63 for newer ones)
- *async\_flags* - bitmask of installed Async handler, unused now
- *hpath\_id* - highest Path ID in the subsystem, unused now
- *unit\_number* - the controller unit number, *cam\_sim\_unit(sim)*
- *bus\_id* - the bus number, *cam\_sim\_bus(sim)*
- *initiator\_id* - the SCSI ID of the controller itself
- *base\_transfer\_speed* - nominal transfer speed in KB/s for asynchronous narrow transfers, equals to 3300 for SCSI

- `sim_vid` - SIM driver's vendor id, a zero-terminated string of maximal length `SIM_IDLEN` including the terminating zero
- `hba_vid` - SCSI controller's vendor id, a zero-terminated string of maximal length `HBA_IDLEN` including the terminating zero
- `dev_name` - device driver name, a zero-terminated string of maximal length `DEV_IDLEN` including the terminating zero, equal to `cam_sim_name(sim)`

The recommended way of setting the string fields is using `strncpy`, like:

```
strncpy(cpi->dev_name, cam_sim_name(sim), DEV_IDLEN);
```

After setting the values set the status to `CAM_REQ_CMP` and mark the CCB as done.

## 24.3 Polling

```
static void xxx_poll ( struct cam_sim *sim );
```

The poll function is used to simulate the interrupts when the interrupt subsystem is not functioning (for example, when the system has crashed and is creating the system dump). The CAM subsystem sets the proper interrupt level before calling the poll routine. So all it needs to do is to call the interrupt routine (or the other way around, the poll routine may be doing the real action and the interrupt routine would just call the poll routine). Why bother about a separate function then? Because of different calling conventions. The `xxx_poll` routine gets the struct `cam_sim` pointer as its argument when the PCI interrupt routine by common convention gets pointer to the struct `xxx_softc` and the ISA interrupt routine gets just the device unit number. So the poll routine would normally look as:

```
static void
xxx_poll(struct cam_sim *sim)
{
    xxx_intr((struct xxx_softc *)cam_sim_softc(sim)); /* for PCI device */
}
```

or

```
static void
xxx_poll(struct cam_sim *sim)
{
    xxx_intr(cam_sim_unit(sim)); /* for ISA device */
}
```

## 24.4 Asynchronous Events

If an asynchronous event callback has been set up then the callback function should be defined.

```
static void
```



```
ahc_async(void *callback_arg, u_int32_t code, struct cam_path *path, void *arg)
```

- `callback_arg` - the value supplied when registering the callback
- `code` - identifies the type of event
- `path` - identifies the devices to which the event applies
- `arg` - event-specific argument

Implementation for a single type of event, `AC_LOST_DEVICE`, looks like:

```
struct xxx_softc *softc;
struct cam_sim *sim;
int targ;
struct ccb_trans_settings neg;

sim = (struct cam_sim *)callback_arg;
softc = (struct xxx_softc *)cam_sim_softc(sim);
switch (code) {
case AC_LOST_DEVICE:
    targ = xpt_path_target_id(path);
    if (targ <= OUR_MAX_SUPPORTED_TARGET) {
        clean_negotiations(softc, targ);
        /* send indication to CAM */
        neg.bus_width = 8;
        neg.sync_period = neg.sync_offset = 0;
        neg.valid = (CCB_TRANS_BUS_WIDTH_VALID
                    | CCB_TRANS_SYNC_RATE_VALID | CCB_TRANS_SYNC_OFFSET_VALID);
        xpt_async(AC_TRANSFER_NEG, path, &neg);
    }
    break;
default:
    break;
}
```

## 24.5 Interrupts

The exact type of the interrupt routine depends on the type of the peripheral bus (PCI, ISA and so on) to which the SCSI controller is connected.

The interrupt routines of the SIM drivers run at the interrupt level `splcam`. So `splcam()` should be used in the driver to synchronize activity between the interrupt routine and the rest of the driver (for a multiprocessor-aware driver things get yet more interesting but we ignore this case here). The pseudo-code in this document happily ignores the problems of synchronization. The real code must not ignore them. A simple-minded approach is to set `splcam()` on the entry to the other routines and reset it on return thus protecting them by one big critical section. To make sure that the interrupt level will be always restored a wrapper function can be defined, like:

```
static void
xxx_action(struct cam_sim *sim, union ccb *ccb)
{
```

```

    int s;
    s = splcam();
    xxx_action1(sim, ccb);
    splx(s);
}

static void
xxx_action1(struct cam_sim *sim, union ccb *ccb)
{
    ... process the request ...
}

```

This approach is simple and robust but the problem with it is that interrupts may get blocked for a relatively long time and this would negatively affect the system's performance. On the other hand the functions of the `spl()` family have rather high overhead, so vast amount of tiny critical sections may not be good either.

The conditions handled by the interrupt routine and the details depend very much on the hardware. We consider the set of "typical" conditions.

First, we check if a SCSI reset was encountered on the bus (probably caused by another SCSI controller on the same SCSI bus). If so we drop all the enqueued and disconnected requests, report the events and re-initialize our SCSI controller. It is important that during this initialization the controller will not issue another reset or else two controllers on the same SCSI bus could ping-pong resets forever. The case of fatal controller error/hang could be handled in the same place, but it will probably need also sending RESET signal to the SCSI bus to reset the status of the connections with the SCSI devices.

```

int fatal=0;
struct ccb_trans_settings neg;
struct cam_path *path;

if( detected_scsi_reset(softc)
|| (fatal = detected_fatal_controller_error(softc)) ) {
    int targ, lun;
    struct xxx_hcb *h, *hh;

    /* drop all enqueued CCBs */
    for(h = softc->first_queued_hcb; h != NULL; h = hh) {
        hh = h->next;
        free_hcb_and_ccb_done(h, h->ccb, CAM_SCSI_BUS_RESET);
    }

    /* the clean values of negotiations to report */
    neg.bus_width = 8;
    neg.sync_period = neg.sync_offset = 0;
    neg.valid = (CCB_TRANS_BUS_WIDTH_VALID
| CCB_TRANS_SYNC_RATE_VALID | CCB_TRANS_SYNC_OFFSET_VALID);

    /* drop all disconnected CCBs and clean negotiations */
    for(targ=0; targ <= OUR_MAX_SUPPORTED_TARGET; targ++) {
        clean_negotiations(softc, targ);

        /* report the event if possible */
        if(xpt_create_path(&path, /*periph*/NULL,

```

```

        cam_sim_path(sim), targ,
        CAM_LUN_WILDCARD) == CAM_REQ_CMP) {
    xpt_async(AC_TRANSFER_NEG, path, &neg);
    xpt_free_path(path);
}

for(lun=0; lun <= OUR_MAX_SUPPORTED_LUN; lun++)
    for(h = softc->first_discon_hcb[targ][lun]; h != NULL; h = hh) {
        hh=h->next;
        if(fatal)
            free_hcb_and_ccb_done(h, h->ccb, CAM_UNREC_HBA_ERROR);
        else
            free_hcb_and_ccb_done(h, h->ccb, CAM_SCSI_BUS_RESET);
    }
}

/* report the event */
xpt_async(AC_BUS_RESET, softc->wpath, NULL);

/* re-initialization may take a lot of time, in such case
 * its completion should be signaled by another interrupt or
 * checked on timeout - but for simplicity we assume here that
 * it's really fast
 */
if(!fatal) {
    reinitialize_controller_without_scsi_reset(softc);
} else {
    reinitialize_controller_with_scsi_reset(softc);
}
schedule_next_hcb(softc);
return;
}

```

If interrupt is not caused by a controller-wide condition then probably something has happened to the current hardware control block. Depending on the hardware there may be other non-HCB-related events, we just do not consider them here. Then we analyze what happened to this HCB:

```

struct xxx_hcb *hcb, *h, *hh;
int hcb_status, scsi_status;
int ccb_status;
int targ;
int lun_to_freeze;

hcb = get_current_hcb(softc);
if(hcb == NULL) {
    /* either stray interrupt or something went very wrong
     * or this is something hardware-dependent
     */
    handle as necessary;
    return;
}

targ = hcb->target;

```

```
hcb_status = get_status_of_current_hcb(softc);
```

First we check if the HCB has completed and if so we check the returned SCSI status.

```
if(hcb_status == COMPLETED) {
    scsi_status = get_completion_status(hcb);
```

Then look if this status is related to the REQUEST SENSE command and if so handle it in a simple way.

```
if(hcb->flags & DOING_AUTOSENSE) {
    if(scsi_status == GOOD) { /* autosense was successful */
        hcb->ccb->ccb_h.status |= CAM_AUTOSNS_VALID;
        free_hcb_and_ccb_done(hcb, hcb->ccb, CAM_SCSI_STATUS_ERROR);
    } else {
autosense_failed:
        free_hcb_and_ccb_done(hcb, hcb->ccb, CAM_AUTOSENSE_FAIL);
    }
    schedule_next_hcb(softc);
    return;
}
```

Else the command itself has completed, pay more attention to details. If auto-sense is not disabled for this CCB and the command has failed with sense data then run REQUEST SENSE command to receive that data.

```
hcb->ccb->csio.scsi_status = scsi_status;
calculate_residue(hcb);

if( (hcb->ccb->ccb_h.flags & CAM_DIS_AUTOSENSE)==0
&& ( scsi_status == CHECK_CONDITION
    || scsi_status == COMMAND_TERMINATED) ) {
    /* start auto-SENSE */
    hcb->flags |= DOING_AUTOSENSE;
    setup_autosense_command_in_hcb(hcb);
    restart_current_hcb(softc);
    return;
}
if(scsi_status == GOOD)
    free_hcb_and_ccb_done(hcb, hcb->ccb, CAM_REQ_CMP);
else
    free_hcb_and_ccb_done(hcb, hcb->ccb, CAM_SCSI_STATUS_ERROR);
schedule_next_hcb(softc);
return;
}
```

One typical thing would be negotiation events: negotiation messages received from a SCSI target (in answer to our negotiation attempt or by target's initiative) or the target is unable to negotiate (rejects our negotiation messages or does not answer them).

```
switch(hcb_status) {
case TARGET_REJECTED_WIDE_NEG:
    /* revert to 8-bit bus */
    softc->current_bus_width[targ] = softc->goal_bus_width[targ] = 8;
    /* report the event */
```

```

    neg.bus_width = 8;
    neg.valid = CCB_TRANS_BUS_WIDTH_VALID;
    xpt_async(AC_TRANSFER_NEG, hcb->ccb.ccb_h.path_id, &neg);
    continue_current_hcb(softc);
    return;
case TARGET_ANSWERED_WIDE_NEG:
    {
        int wd;

        wd = get_target_bus_width_request(softc);
        if(wd <= softc->goal_bus_width[targ]) {
            /* answer is acceptable */
            softc->current_bus_width[targ] =
            softc->goal_bus_width[targ] = neg.bus_width = wd;

            /* report the event */
            neg.valid = CCB_TRANS_BUS_WIDTH_VALID;
            xpt_async(AC_TRANSFER_NEG, hcb->ccb.ccb_h.path_id, &neg);
        } else {
            prepare_reject_message(hcb);
        }
    }
    continue_current_hcb(softc);
    return;
case TARGET_REQUESTED_WIDE_NEG:
    {
        int wd;

        wd = get_target_bus_width_request(softc);
        wd = min (wd, OUR_BUS_WIDTH);
        wd = min (wd, softc->user_bus_width[targ]);

        if(wd != softc->current_bus_width[targ]) {
            /* the bus width has changed */
            softc->current_bus_width[targ] =
            softc->goal_bus_width[targ] = neg.bus_width = wd;

            /* report the event */
            neg.valid = CCB_TRANS_BUS_WIDTH_VALID;
            xpt_async(AC_TRANSFER_NEG, hcb->ccb.ccb_h.path_id, &neg);
        }
        prepare_width_nego_rspnse(hcb, wd);
    }
    continue_current_hcb(softc);
    return;
}

```

Then we handle any errors that could have happened during auto-sense in the same simple-minded way as before. Otherwise we look closer at the details again.

```

if(hcb->flags & DOING_AUTOSENSE)
    goto autosense_failed;

```

```
switch(hcb_status) {
```

The next event we consider is unexpected disconnect. Which is considered normal after an ABORT or BUS DEVICE RESET message and abnormal in other cases.

```
case UNEXPECTED_DISCONNECT:
    if(requested_abort(hcb)) {
        /* abort affects all commands on that target+LUN, so
         * mark all disconnected HCBs on that target+LUN as aborted too
         */
        for(h = softc->first_discon_hcb[hcb->target][hcb->lun];
            h != NULL; h = hh) {
            hh=h->next;
            free_hcb_and_ccb_done(h, h->ccb, CAM_REQ_ABORTED);
        }
        ccb_status = CAM_REQ_ABORTED;
    } else if(requested_bus_device_reset(hcb)) {
        int lun;

        /* reset affects all commands on that target, so
         * mark all disconnected HCBs on that target+LUN as reset
         */

        for(lun=0; lun <= OUR_MAX_SUPPORTED_LUN; lun++)
            for(h = softc->first_discon_hcb[hcb->target][lun];
                h != NULL; h = hh) {
                hh=h->next;
                free_hcb_and_ccb_done(h, h->ccb, CAM_SCSI_BUS_RESET);
            }

        /* send event */
        xpt_async(AC_SENT_BDR, hcb->ccb->ccb_h.path_id, NULL);

        /* this was the CAM_RESET_DEV request itself, it's completed */
        ccb_status = CAM_REQ_CMP;
    } else {
        calculate_residue(hcb);
        ccb_status = CAM_UNEXP_BUSFREE;
        /* request the further code to freeze the queue */
        hcb->ccb->ccb_h.status |= CAM_DEV_QFRZN;
        lun_to_freeze = hcb->lun;
    }
    break;
```

If the target refuses to accept tags we notify CAM about that and return back all commands for this LUN:

```
case TAGS_REJECTED:
    /* report the event */
    neg.flags = 0 & ~CCB_TRANS_TAG_ENB;
    neg.valid = CCB_TRANS_TQ_VALID;
    xpt_async(AC_TRANSFER_NEG, hcb->ccb->ccb_h.path_id, &neg);

    ccb_status = CAM_MSG_REJECT_REC;
```

```

/* request the further code to freeze the queue */
hcb->ccb->ccb_h.status |= CAM_DEV_QFRZN;
lun_to_freeze = hcb->lun;
break;

```

Then we check a number of other conditions, with processing basically limited to setting the CCB status:

```

case SELECTION_TIMEOUT:
    ccb_status = CAM_SEL_TIMEOUT;
    /* request the further code to freeze the queue */
    hcb->ccb->ccb_h.status |= CAM_DEV_QFRZN;
    lun_to_freeze = CAM_LUN_WILDCARD;
    break;
case PARITY_ERROR:
    ccb_status = CAM_UNCOR_PARITY;
    break;
case DATA_OVERRUN:
case ODD_WIDE_TRANSFER:
    ccb_status = CAM_DATA_RUN_ERR;
    break;
default:
    /* all other errors are handled in a generic way */
    ccb_status = CAM_REQ_CMP_ERR;
    /* request the further code to freeze the queue */
    hcb->ccb->ccb_h.status |= CAM_DEV_QFRZN;
    lun_to_freeze = CAM_LUN_WILDCARD;
    break;
}

```

Then we check if the error was serious enough to freeze the input queue until it gets proceeded and do so if it is:

```

if(hcb->ccb->ccb_h.status & CAM_DEV_QFRZN) {
    /* freeze the queue */
    xpt_freeze_devq(ccb->ccb_h.path, /*count*/1);

    /* re-queue all commands for this target/LUN back to CAM */

    for(h = softc->first_queued_hcb; h != NULL; h = hh) {
        hh = h->next;

        if(targ == h->targ
            && (lun_to_freeze == CAM_LUN_WILDCARD || lun_to_freeze == h->lun) )
            free_hcb_and_ccb_done(h, h->ccb, CAM_REQUEUE_REQ);
    }
}
free_hcb_and_ccb_done(hcb, hcb->ccb, ccb_status);
schedule_next_hcb(softc);
return;

```

This concludes the generic interrupt handling although specific controllers may require some additions.

## 24.6 Errors Summary

When executing an I/O request many things may go wrong. The reason of error can be reported in the CCB status with great detail. Examples of use are spread throughout this document. For completeness here is the summary of recommended responses for the typical error conditions:

- *CAM\_RESRC\_UNAVAIL* - some resource is temporarily unavailable and the SIM driver cannot generate an event when it will become available. An example of this resource would be some intra-controller hardware resource for which the controller does not generate an interrupt when it becomes available.
- *CAM\_UNCOR\_PARITY* - unrecovered parity error occurred
- *CAM\_DATA\_RUN\_ERR* - data overrun or unexpected data phase (going in other direction than specified in *CAM\_DIR\_MASK*) or odd transfer length for wide transfer
- *CAM\_SEL\_TIMEOUT* - selection timeout occurred (target does not respond)
- *CAM\_CMD\_TIMEOUT* - command timeout occurred (the timeout function ran)
- *CAM\_SCSI\_STATUS\_ERROR* - the device returned error
- *CAM\_AUTOSENSE\_FAIL* - the device returned error and the REQUEST SENSE COMMAND failed
- *CAM\_MSG\_REJECT\_REC* - MESSAGE REJECT message was received
- *CAM\_SCSI\_BUS\_RESET* - received SCSI bus reset
- *CAM\_REQ\_CMP\_ERR* - “impossible” SCSI phase occurred or something else as weird or just a generic error if further detail is not available
- *CAM\_UNEXP\_BUSFREE* - unexpected disconnect occurred
- *CAM\_BDR\_SENT* - BUS DEVICE RESET message was sent to the target
- *CAM\_UNREC\_HBA\_ERROR* - unrecoverable Host Bus Adapter Error
- *CAM\_REQ\_TOO\_BIG* - the request was too large for this controller
- *CAM\_QUEUE\_REQ* - this request should be re-queued to preserve transaction ordering. This typically occurs when the SIM recognizes an error that should freeze the queue and must place other queued requests for the target at the sim level back into the XPT queue. Typical cases of such errors are selection timeouts, command timeouts and other like conditions. In such cases the troublesome command returns the status indicating the error, the and the other commands which have not be sent to the bus yet get re-queued.
- *CAM\_LUN\_INVALID* - the LUN ID in the request is not supported by the SCSI controller
- *CAM\_TID\_INVALID* - the target ID in the request is not supported by the SCSI controller

## 24.7 Timeout Handling

When the timeout for an HCB expires that request should be aborted, just like with an XPT\_ABORT request. The only difference is that the returned status of aborted request should be *CAM\_CMD\_TIMEOUT* instead of *CAM\_REQ\_ABORTED* (that is why implementation of the abort better be done as a function). But there is one more possible problem: what if the abort request itself will get stuck? In this case the SCSI bus should be reset, just like with an XPT\_RESET\_BUS request (and the idea about implementing it as a function called from both places



applies here too). Also we should reset the whole SCSI bus if a device reset request got stuck. So after all the timeout function would look like:

```
static void
xxx_timeout(void *arg)
{
    struct xxx_hcb *hcb = (struct xxx_hcb *)arg;
    struct xxx_softc *softc;
    struct ccb_hdr *ccb_h;

    softc = hcb->softc;
    ccb_h = &hcb->ccb->ccb_h;

    if(hcb->flags & HCB_BEING_ABORTED
        || ccb_h->func_code == XPT_RESET_DEV) {
        xxx_reset_bus(softc);
    } else {
        xxx_abort_ccb(hcb->ccb, CAM_CMD_TIMEOUT);
    }
}
```

When we abort a request all the other disconnected requests to the same target/LUN get aborted too. So there appears a question, should we return them with status `CAM_REQ_ABORTED` or `CAM_CMD_TIMEOUT`? The current drivers use `CAM_CMD_TIMEOUT`. This seems logical because if one request got timed out then probably something really bad is happening to the device, so if they would not be disturbed they would time out by themselves.

# Chapter 25 USB Devices

*This chapter was written by Nick Hibma <n\_hibma@FreeBSD.org>. Modifications made for the handbook by Murray Stokely <murray@FreeBSD.org>.*

## 25.1 Introduction

The Universal Serial Bus (USB) is a new way of attaching devices to personal computers. The bus architecture features two-way communication and has been developed as a response to devices becoming smarter and requiring more interaction with the host. USB support is included in all current PC chipsets and is therefore available in all recently built PCs. Apple's introduction of the USB-only iMac has been a major incentive for hardware manufacturers to produce USB versions of their devices. The future PC specifications specify that all legacy connectors on PCs should be replaced by one or more USB connectors, providing generic plug and play capabilities. Support for USB hardware was available at a very early stage in NetBSD and was developed by Lennart Augustsson for the NetBSD project. The code has been ported to FreeBSD and we are currently maintaining a shared code base. For the implementation of the USB subsystem a number of features of USB are important.

*Lennart Augustsson has done most of the implementation of the USB support for the NetBSD project. Many thanks for this incredible amount of work. Many thanks also to Ardy and Dirk for their comments and proofreading of this paper.*

- Devices connect to ports on the computer directly or on devices called hubs, forming a treelike device structure.
- The devices can be connected and disconnected at run time.
- Devices can suspend themselves and trigger resumes of the host system
- As the devices can be powered from the bus, the host software has to keep track of power budgets for each hub.
- Different quality of service requirements by the different device types together with the maximum of 126 devices that can be connected to the same bus, require proper scheduling of transfers on the shared bus to take full advantage of the 12Mbps bandwidth available. (over 400Mbps with USB 2.0)
- Devices are intelligent and contain easily accessible information about themselves

The development of drivers for the USB subsystem and devices connected to it is supported by the specifications that have been developed and will be developed. These specifications are publicly available from the USB home pages. Apple has been very strong in pushing for standards based drivers, by making drivers for the generic classes available in their operating system MacOS and discouraging the use of separate drivers for each new device. This chapter tries to collate essential information for a basic understanding of the present implementation of the USB stack in FreeBSD/NetBSD. It is recommended however to read it together with the relevant specifications mentioned in the references below.

### 25.1.1 Structure of the USB Stack

The USB support in FreeBSD can be split into three layers. The lowest layer contains the host controller driver, providing a generic interface to the hardware and its scheduling facilities. It supports initialisation of the hardware, scheduling of transfers and handling of completed and/or failed transfers. Each host controller driver implements a

virtual hub providing hardware independent access to the registers controlling the root ports on the back of the machine.

The middle layer handles the device connection and disconnection, basic initialisation of the device, driver selection, the communication channels (pipes) and does resource management. This services layer also controls the default pipes and the device requests transferred over them.

The top layer contains the individual drivers supporting specific (classes of) devices. These drivers implement the protocol that is used over the pipes other than the default pipe. They also implement additional functionality to make the device available to other parts of the kernel or userland. They use the USB driver interface (USB DI) exposed by the services layer.

## 25.2 Host Controllers

The host controller (HC) controls the transmission of packets on the bus. Frames of 1 millisecond are used. At the start of each frame the host controller generates a Start of Frame (SOF) packet.

The SOF packet is used to synchronise to the start of the frame and to keep track of the frame number. Within each frame packets are transferred, either from host to device (out) or from device to host (in). Transfers are always initiated by the host (polled transfers). Therefore there can only be one host per USB bus. Each transfer of a packet has a status stage in which the recipient of the data can return either ACK (acknowledge reception), NAK (retry), STALL (error condition) or nothing (garbled data stage, device not available or disconnected). Section 8.5 of the USB specification (<http://www.usb.org/developers/docs.html>) explains the details of packets in more detail. Four different types of transfers can occur on a USB bus: control, bulk, interrupt and isochronous. The types of transfers and their characteristics are described below ('Pipes' subsection).

Large transfers between the device on the USB bus and the device driver are split up into multiple packets by the host controller or the HC driver.

Device requests (control transfers) to the default endpoints are special. They consist of two or three phases: SETUP, DATA (optional) and STATUS. The set-up packet is sent to the device. If there is a data phase, the direction of the data packet(s) is given in the set-up packet. The direction in the status phase is the opposite of the direction during the data phase, or IN if there was no data phase. The host controller hardware also provides registers with the current status of the root ports and the changes that have occurred since the last reset of the status change register. Access to these registers is provided through a virtualised hub as suggested in the USB specification [ 2]. The virtual hub must comply with the hub device class given in chapter 11 of that specification. It must provide a default pipe through which device requests can be sent to it. It returns the standard andhub class specific set of descriptors. It should also provide an interrupt pipe that reports changes happening at its ports. There are currently two specifications for host controllers available: Universal Host Controller Interface (<http://developer.intel.com/design/USB/UHCI11D.htm>) (UHCI; Intel) and Open Host Controller Interface (<http://www.compaq.com/productinfo/development/openhci.html>) (OHCI; Compaq, Microsoft, National Semiconductor). The UHCI specification has been designed to reduce hardware complexity by requiring the host controller driver to supply a complete schedule of the transfers for each frame. OHCI type controllers are much more independent by providing a more abstract interface doing a lot of work themselves.

### 25.2.1 UHCI

The UHCI host controller maintains a framelist with 1024 pointers to per frame data structures. It understands two

different data types: transfer descriptors (TD) and queue heads (QH). Each TD represents a packet to be communicated to or from a device endpoint. QHs are a means to group TDs (and QHs) together.

Each transfer consists of one or more packets. The UHCI driver splits large transfers into multiple packets. For every transfer, apart from isochronous transfers, a QH is allocated. For every type of transfer these QHs are collected at a QH for that type. Isochronous transfers have to be executed first because of the fixed latency requirement and are directly referred to by the pointer in the framelist. The last isochronous TD refers to the QH for interrupt transfers for that frame. All QHs for interrupt transfers point at the QH for control transfers, which in turn points at the QH for bulk transfers. The following diagram gives a graphical overview of this:

This results in the following schedule being run in each frame. After fetching the pointer for the current frame from the framelist the controller first executes the TDs for all the isochronous packets in that frame. The last of these TDs refers to the QH for the interrupt transfers for that frame. The host controller will then descend from that QH to the QHs for the individual interrupt transfers. After finishing that queue, the QH for the interrupt transfers will refer the controller to the QH for all control transfers. It will execute all the subqueues scheduled there, followed by all the transfers queued at the bulk QH. To facilitate the handling of finished or failed transfers different types of interrupts are generated by the hardware at the end of each frame. In the last TD for a transfer the Interrupt-On Completion bit is set by the HC driver to flag an interrupt when the transfer has completed. An error interrupt is flagged if a TD reaches its maximum error count. If the short packet detect bit is set in a TD and less than the set packet length is transferred this interrupt is flagged to notify the controller driver of the completed transfer. It is the host controller driver's task to find out which transfer has completed or produced an error. When called the interrupt service routine will locate all the finished transfers and call their callbacks.

See for a more elaborate description the UHCI specification. (<http://developer.intel.com/design/USB/UHCI11D.htm>)

## 25.2.2 OHCI

Programming an OHCI host controller is much simpler. The controller assumes that a set of endpoints is available, and is aware of scheduling priorities and the ordering of the types of transfers in a frame. The main data structure used by the host controller is the endpoint descriptor (ED) to which a queue of transfer descriptors (TDs) is attached. The ED contains the maximum packet size allowed for an endpoint and the controller hardware does the splitting into packets. The pointers to the data buffers are updated after each transfer and when the start and end pointer are equal, the TD is retired to the done-queue. The four types of endpoints have their own queues. Control and bulk endpoints are queued each at their own queue. Interrupt EDs are queued in a tree, with the level in the tree defining the frequency at which they run.

framelist interrupt isochronous control bulk

The schedule being run by the host controller in each frame looks as follows. The controller will first run the non-periodic control and bulk queues, up to a time limit set by the HC driver. Then the interrupt transfers for that frame number are run, by using the lower five bits of the frame number as an index into level 0 of the tree of interrupt EDs. At the end of this tree the isochronous EDs are connected and these are traversed subsequently. The isochronous TDs contain the frame number of the first frame the transfer should be run in. After all the periodic transfers have been run, the control and bulk queues are traversed again. Periodically the interrupt service routine is called to process the done queue and call the callbacks for each transfer and reschedule interrupt and isochronous endpoints.

See for a more elaborate description the OHCI specification (<http://www.compaq.com/productinfo/development/openhci.html>). Services layer The middle layer provides access

to the device in a controlled way and maintains resources in use by the different drivers and the services layer. The layer takes care of the following aspects:

- The device configuration information
- The pipes to communicate with a device
- Probing and attaching and detaching from a device.

## 25.3 USB Device Information

### 25.3.1 Device configuration information

Each device provides different levels of configuration information. Each device has one or more configurations, of which one is selected during probe/attach. A configuration provides power and bandwidth requirements. Within each configuration there can be multiple interfaces. A device interface is a collection of endpoints. For example USB speakers can have an interface for the audio data (Audio Class) and an interface for the knobs, dials and buttons (HID Class). All interfaces in a configuration are active at the same time and can be attached to by different drivers. Each interface can have alternates, providing different quality of service parameters. In for example cameras this is used to provide different frame sizes and numbers of frames per second.

Within each interface 0 or more endpoints can be specified. Endpoints are the unidirectional access points for communicating with a device. They provide buffers to temporarily store incoming or outgoing data from the device. Each endpoint has a unique address within a configuration, the endpoint's number plus its direction. The default endpoint, endpoint 0, is not part of any interface and available in all configurations. It is managed by the services layer and not directly available to device drivers.

Level 0 Level 1 Level 2 Slot 0

Slot 3 Slot 2 Slot 1

(Only 4 out of 32 slots shown)

This hierarchical configuration information is described in the device by a standard set of descriptors (see section 9.6 of the USB specification [ 2]). They can be requested through the Get Descriptor Request. The services layer caches these descriptors to avoid unnecessary transfers on the USB bus. Access to the descriptors is provided through function calls.

- Device descriptors: General information about the device, like Vendor, Product and Revision Id, supported device class, subclass and protocol if applicable, maximum packet size for the default endpoint, etc.
- Configuration descriptors: The number of interfaces in this configuration, suspend and resume functionality supported and power requirements.
- Interface descriptors: interface class, subclass and protocol if applicable, number of alternate settings for the interface and the number of endpoints.
- Endpoint descriptors: Endpoint address, direction and type, maximum packet size supported and polling frequency if type is interrupt endpoint. There is no descriptor for the default endpoint (endpoint 0) and it is never counted in an interface descriptor.

- String descriptors: In the other descriptors string indices are supplied for some fields. These can be used to retrieve descriptive strings, possibly in multiple languages.

Class specifications can add their own descriptor types that are available through the GetDescriptor Request.

Pipes Communication to end points on a device flows through so-called pipes. Drivers submit transfers to endpoints to a pipe and provide a callback to be called on completion or failure of the transfer (asynchronous transfers) or wait for completion (synchronous transfer). Transfers to an endpoint are serialised in the pipe. A transfer can either complete, fail or time-out (if a time-out has been set). There are two types of time-outs for transfers. Time-outs can happen due to time-out on the USBbus (milliseconds). These time-outs are seen as failures and can be due to disconnection of the device. A second form of time-out is implemented in software and is triggered when a transfer does not complete within a specified amount of time (seconds). These are caused by a device acknowledging negatively (NAK) the transferred packets. The cause for this is the device not being ready to receive data, buffer under- or overrun or protocol errors.

If a transfer over a pipe is larger than the maximum packet size specified in the associated endpoint descriptor, the host controller (OHCI) or the HC driver (UHCI) will split the transfer into packets of maximum packet size, with the last packet possibly smaller than the maximum packet size.

Sometimes it is not a problem for a device to return less data than requested. For example a bulk-in-transfer to a modem might request 200 bytes of data, but the modem has only 5 bytes available at that time. The driver can set the short packet (SPD) flag. It allows the host controller to accept a packet even if the amount of data transferred is less than requested. This flag is only valid for in-transfers, as the amount of data to be sent to a device is always known beforehand. If an unrecoverable error occurs in a device during a transfer the pipe is stalled. Before any more data is accepted or sent the driver needs to resolve the cause of the stall and clear the endpoint stall condition through send the clear endpoint halt device request over the default pipe. The default endpoint should never stall.

There are four different types of endpoints and corresponding pipes: - Control pipe / default pipe: There is one control pipe per device, connected to the default endpoint (endpoint 0). The pipe carries the device requests and associated data. The difference between transfers over the default pipe and other pipes is that the protocol for the transfers is described in the USB specification [ 2]. These requests are used to reset and configure the device. A basic set of commands that must be supported by each device is provided in chapter 9 of the USB specification [ 2]. The commands supported on this pipe can be extended by a device class specification to support additional functionality.

- Bulk pipe: This is the USB equivalent to a raw transmission medium.
- Interrupt pipe: The host sends a request for data to the device and if the device has nothing to send, it will NAK the data packet. Interrupt transfers are scheduled at a frequency specified when creating the pipe.
- Isochronous pipe: These pipes are intended for isochronous data, for example video or audio streams, with fixed latency, but no guaranteed delivery. Some support for pipes of this type is available in the current implementation. Packets in control, bulk and interrupt transfers are retried if an error occurs during transmission or the device acknowledges the packet negatively (NAK) due to for example lack of buffer space to store the incoming data. Isochronous packets are however not retried in case of failed delivery or NAK of a packet as this might violate the timing constraints.

The availability of the necessary bandwidth is calculated during the creation of the pipe. Transfers are scheduled within frames of 1 millisecond. The bandwidth allocation within a frame is prescribed by the USB specification, section 5.6 [ 2]. Isochronous and interrupt transfers are allowed to consume up to 90% of the bandwidth within a frame. Packets for control and bulk transfers are scheduled after all isochronous and interrupt packets and will consume all the remaining bandwidth.

More information on scheduling of transfers and bandwidth reclamation can be found in chapter 5 of the USB specification [ 2], section 1.3 of the UHCI specification [ 3] and section 3.4.2 of the OHCI specification [4].

## 25.4 Device probe and attach

After the notification by the hub that a new device has been connected, the service layer switches on the port, providing the device with 100 mA of current. At this point the device is in its default state and listening to device address 0. The services layer will proceed to retrieve the various descriptors through the default pipe. After that it will send a Set Address request to move the device away from the default device address (address 0). Multiple device drivers might be able to support the device. For example a modem driver might be able to support an ISDN TA through the AT compatibility interface. A driver for that specific model of the ISDN adapter might however be able to provide much better support for this device. To support this flexibility, the probes return priorities indicating their level of support. Support for a specific revision of a product ranks the highest and the generic driver the lowest priority. It might also be that multiple drivers could attach to one device if there are multiple interfaces within one configuration. Each driver only needs to support a subset of the interfaces.

The probing for a driver for a newly attached device checks first for device specific drivers. If not found, the probe code iterates over all supported configurations until a driver attaches in a configuration. To support devices with multiple drivers on different interfaces, the probe iterates over all interfaces in a configuration that have not yet been claimed by a driver. Configurations that exceed the power budget for the hub are ignored. During attach the driver should initialise the device to its proper state, but not reset it, as this will make the device disconnect itself from the bus and restart the probing process for it. To avoid consuming unnecessary bandwidth should not claim the interrupt pipe at attach time, but should postpone allocating the pipe until the file is opened and the data is actually used. When the file is closed the pipe should be closed again, even though the device might still be attached.

### 25.4.1 Device disconnect and detach

A device driver should expect to receive errors during any transaction with the device. The design of USB supports and encourages the disconnection of devices at any point in time. Drivers should make sure that they do the right thing when the device disappears.

Furthermore a device that has been disconnected and reconnected will not be reattached at the same device instance. This might change in the future when more devices support serial numbers (see the device descriptor) or other means of defining an identity for a device have been developed.

The disconnection of a device is signaled by a hub in the interrupt packet delivered to the hub driver. The status change information indicates which port has seen a connection change. The device detach method for all device drivers for the device connected on that port are called and the structures cleaned up. If the port status indicates that in the mean time a device has been connected to that port, the procedure for probing and attaching the device will be started. A device reset will produce a disconnect-connect sequence on the hub and will be handled as described above.

## 25.5 USB Drivers Protocol Information

The protocol used over pipes other than the default pipe is undefined by the USB specification. Information on this can be found from various sources. The most accurate source is the developer's section on the USB home pages [ 1]. From these pages a growing number of deviceclass specifications are available. These specifications specify what a compliant device should look like from a driver perspective, basic functionality it needs to provide and the protocol that is to be used over the communication channels. The USB specification [ 2] includes the description of the Hub Class. A class specification for Human Interface Devices (HID) has been created to cater for keyboards, tablets, bar-code readers, buttons, knobs, switches, etc. A third example is the class specification for mass storage devices. For a full list of device classes see the developers section on the USB home pages [ 1].

For many devices the protocol information has not yet been published however. Information on the protocol being used might be available from the company making the device. Some companies will require you to sign a Non-Disclosure Agreement (NDA) before giving you the specifications. This in most cases precludes making the driver open source.

Another good source of information is the Linux driver sources, as a number of companies have started to provide drivers for Linux for their devices. It is always a good idea to contact the authors of those drivers for their source of information.

**Example: Human Interface Devices** The specification for the Human Interface Devices like keyboards, mice, tablets, buttons, dials, etc. is referred to in other device class specifications and is used in many devices.

For example audio speakers provide endpoints to the digital to analogue converters and possibly an extra pipe for a microphone. They also provide a HID endpoint in a separate interface for the buttons and dials on the front of the device. The same is true for the monitor control class. It is straightforward to build support for these interfaces through the available kernel and userland libraries together with the HID class driver or the generic driver. Another device that serves as an example for interfaces within one configuration driven by different device drivers is a cheap keyboard with built-in legacy mouse port. To avoid having the cost of including the hardware for a USB hub in the device, manufacturers combined the mouse data received from the PS/2 port on the back of the keyboard and the key presses from the keyboard into two separate interfaces in the same configuration. The mouse and keyboard drivers each attach to the appropriate interface and allocate the pipes to the two independent endpoints.

**Example: Firmware download** Many devices that have been developed are based on a general purpose processor with an additional USB core added to it. Because the development of drivers and firmware for USB devices is still very new, many devices require the downloading of the firmware after they have been connected.

The procedure followed is straightforward. The device identifies itself through a vendor and product Id. The first driver probes and attaches to it and downloads the firmware into it. After that the device soft resets itself and the driver is detached. After a short pause the device announces its presence on the bus. The device will have changed its vendor/product/revision Id to reflect the fact that it has been supplied with firmware and as a consequence a second driver will probe it and attach to it.

An example of these types of devices is the ActiveWire I/O board, based on the EZ-USB chip. For this chip a generic firmware downloader is available. The firmware downloaded into the ActiveWire board changes the revision Id. It will then perform a soft reset of the USB part of the EZ-USB chip to disconnect from the USB bus and again reconnect.

**Example: Mass Storage Devices** Support for mass storage devices is mainly built around existing protocols. The Iomega USB Zipdrive is based on the SCSI version of their drive. The SCSI commands and status messages are wrapped in blocks and transferred over the bulk pipes to and from the device, emulating a SCSI controller over the USB wire. ATAPI and UFI commands are supported in a similar fashion.



The Mass Storage Specification supports 2 different types of wrapping of the command block. The initial attempt was based on sending the command and status through the default pipe and using bulk transfers for the data to be moved between the host and the device. Based on experience a second approach was designed that was based on wrapping the command and status blocks and sending them over the bulk out and in endpoint. The specification specifies exactly what has to happen when and what has to be done in case an error condition is encountered. The biggest challenge when writing drivers for these devices is to fit USB based protocol into the existing support for mass storage devices. CAM provides hooks to do this in a fairly straight forward way. ATAPI is less simple as historically the IDE interface has never had many different appearances.

The support for the USB floppy from Y-E Data is again less straightforward as a new command set has been designed.

# Chapter 26 \* NewBus

This chapter will talk about the FreeBSD NewBus architecture.

# Chapter 27 Sound subsystem

*Contributed by Jean-Francois Dockes.*

## 27.1 Introduction

The FreeBSD sound subsystem cleanly separates generic sound handling issues from device-specific ones. This makes it easier to add support for new hardware.

The `pcm(4)` framework is the central piece of the sound subsystem. It mainly implements the following elements:

- A system call interface (read, write, ioctls) to digitized sound and mixer functions. The ioctl command set is compatible with the legacy *OSS* or *Voxware* interface, allowing common multimedia applications to be ported without modification.
- Common code for processing sound data (format conversions, virtual channels).
- A uniform software interface to hardware-specific audio interface modules.
- Additional support for some common hardware interfaces (*ac97*), or shared hardware-specific code (ex: ISA DMA routines).

The support for specific sound cards is implemented by hardware-specific drivers, which provide channel and mixer interfaces to plug into the generic `pcm` code.

In this chapter, the term `pcm` will refer to the central, common part of the sound driver, as opposed to the hardware-specific modules.

The prospective driver writer will of course want to start from an existing module and use the code as the ultimate reference. But, while the sound code is nice and clean, it is also mostly devoid of comments. This document tries to give an overview of the framework interface and answer some questions that may arise while adapting the existing code.

As an alternative, or in addition to starting from a working example, you can find a commented driver template at <http://people.freebsd.org/~cg/template.c> (<http://people.freebsd.org/~cg/template.c>)

## 27.2 Files

All the relevant code currently (FreeBSD 4.4) lives in `/usr/src/sys/dev/sound/`, except for the public ioctl interface definitions, found in `/usr/src/sys/sys/soundcard.h`

Under `/usr/src/sys/dev/sound/`, the `pcm/` directory holds the central code, while the `isa/` and `pci/` directories have the drivers for ISA and PCI boards.

## 27.3 Probing, attaching, etc.

Sound drivers probe and attach in almost the same way as any hardware driver module. You might want to look at the ISA or PCI specific sections of the handbook for more information.

However, sound drivers differ in some ways:

- They declare themselves as `pcm` class devices, with a struct `snddev_info` device private structure:

```
static driver_t xxx_driver = {
    "pcm",
    xxx_methods,
    sizeof(struct snddev_info)
};

DRIVER_MODULE(snd_xxxpci, pci, xxx_driver, pcm_devclass, 0, 0);
MODULE_DEPEND(snd_xxxpci, snd_pcm, PCM_MINVER, PCM_PREFVER, PCM_MAXVER);
```

Most sound drivers need to store additional private information about their device. A private data structure is usually allocated in the attach routine. Its address is passed to `pcm` by the calls to `pcm_register()` and `mixer_init()`. `pcm` later passes back this address as a parameter in calls to the sound driver interfaces.

- The sound driver attach routine should declare its MIXER or AC97 interface to `pcm` by calling `mixer_init()`. For a MIXER interface, this causes in turn a call to `xxxmixer_init()`.
- The sound driver attach routine declares its general CHANNEL configuration to `pcm` by calling `pcm_register(dev, sc, nplay, nrec)`, where `sc` is the address for the device data structure, used in further calls from `pcm`, and `nplay` and `nrec` are the number of play and record channels.
- The sound driver attach routine declares each of its channel objects by calls to `pcm_addchan()`. This sets up the channel glue in `pcm` and causes in turn a call to `xxxchannel_init()`.
- The sound driver detach routine should call `pcm_unregister()` before releasing its resources.

There are two possible methods to handle non-PnP devices:

- Use a `device_identify()` method (example: `sound/isa/es1888.c`). The `device_identify()` method probes for the hardware at known addresses and, if it finds a supported device, creates a new `pcm` device which is then passed to `probe/attach`.
- Use a custom kernel configuration with appropriate hints for `pcm` devices (example: `sound/isa/mss.c`).

`pcm` drivers should implement `device_suspend`, `device_resume` and `device_shutdown` routines, so that power management and module unloading function correctly.

## 27.4 Interfaces

The interface between the `pcm` core and the sound drivers is defined in terms of kernel objects.

There are two main interfaces that a sound driver will usually provide: *CHANNEL* and either *MIXER* or *AC97*.

The *AC97* interface is a very small hardware access (register read/write) interface, implemented by drivers for hardware with an *AC97* codec. In this case, the actual *MIXER* interface is provided by the shared *AC97* code in `pcm`.

## 27.4.1 The CHANNEL interface

### 27.4.1.1 Common notes for function parameters

Sound drivers usually have a private data structure to describe their device, and one structure for each play and record data channel that it supports.

For all CHANNEL interface functions, the first parameter is an opaque pointer.

The second parameter is a pointer to the private channel data structure, except for `channel_init()` which has a pointer to the private device structure (and returns the channel pointer for further use by `pcm`).

### 27.4.1.2 Overview of data transfer operations

For sound data transfers, the `pcm` core and the sound drivers communicate through a shared memory area, described by a struct `snd_dbuf`.

struct `snd_dbuf` is private to `pcm`, and sound drivers obtain values of interest by calls to accessor functions (`sndbuf_getxxx()`).

The shared memory area has a size of `sndbuf_getsize()` and is divided into fixed size blocks of `sndbuf_getblksz()` bytes.

When playing, the general transfer mechanism is as follows (reverse the idea for recording):

- `pcm` initially fills up the buffer, then calls the sound driver's `xxxchannel_trigger()` function with a parameter of `PCMTRIG_START`.
- The sound driver then arranges to repeatedly transfer the whole memory area (`sndbuf_getbuf()`, `sndbuf_getsize()`) to the device, in blocks of `sndbuf_getblksz()` bytes. It calls back the `chn_intr()` `pcm` function for each transferred block (this will typically happen at interrupt time).
- `chn_intr()` arranges to copy new data to the area that was transferred to the device (now free), and make appropriate updates to the `snd_dbuf` structure.

### 27.4.1.3 channel\_init

`xxxchannel_init()` is called to initialize each of the play or record channels. The calls are initiated from the sound driver attach routine. (See the probe and attach section).

```
static void *
xxxchannel_init(kobj_t obj, void *data,
               struct snd_dbuf *b, struct pcm_channel *c, int dir)❶
{
    struct xxx_info *sc = data;
    struct xxx_chinfo *ch;
    ...
    return ch;❷
}
```

- ❶ `b` is the address for the channel struct `snd_dbuf`. It should be initialized in the function by calling `sndbuf_alloc()`. The buffer size to use is normally a small multiple of the 'typical' unit transfer size for your device.
- `c` is the `pcm` channel control structure pointer. This is an opaque object. The function should store it in the local channel structure, to be used in later calls to `pcm` (ie: `chn_intr(c)`).
- `dir` indicates the channel direction (`PCMDIR_PLAY` or `PCMDIR_REC`).
- ❷ The function should return a pointer to the private area used to control this channel. This will be passed as a parameter to other channel interface calls.

#### 27.4.1.4 channel\_setformat

`xxxchannel_setformat()` should set up the hardware for the specified channel for the specified sound format.

```
static int
xxxchannel_setformat(kobj_t obj, void *data, u_int32_t format)❶
{
    struct xxx_chinfo *ch = data;
    ...
    return 0;
}
```

- ❶ `format` is specified as an `AFMT_XXX` value (`soundcard.h`).

#### 27.4.1.5 channel\_setspeed

`xxxchannel_setspeed()` sets up the channel hardware for the specified sampling speed, and returns the possibly adjusted speed.

```
static int
xxxchannel_setspeed(kobj_t obj, void *data, u_int32_t speed)
{
    struct xxx_chinfo *ch = data;
    ...
    return speed;
}
```

#### 27.4.1.6 channel\_setblocksize

`xxxchannel_setblocksize()` sets the block size, which is the size of unit transactions between `pcm` and the sound driver, and between the sound driver and the device. Typically, this would be the number of bytes transferred before an interrupt occurs. During a transfer, the sound driver should call `pcm's chn_intr()` every time this size has been transferred.

Most sound drivers only take note of the block size here, to be used when an actual transfer will be started.

```
static int
xxxchannel_setblocksize(kobj_t obj, void *data, u_int32_t blocksize)
```

```

{
    struct xxx_chinfo *ch = data;
    ...
    return blocksize;❶
}

```

- ❶ The function returns the possibly adjusted block size. In case the block size is indeed changed, `sndbuf_resize()` should be called to adjust the buffer.

### 27.4.1.7 channel\_trigger

`xxxchannel_trigger()` is called by `pcm` to control data transfer operations in the driver.

```

static int
xxxchannel_trigger(kobj_t obj, void *data, int go)❶
{
    struct xxx_chinfo *ch = data;
    ...
    return 0;
}

```

- ❶ `go` defines the action for the current call. The possible values are:
- `PCMTRIG_START`: the driver should start a data transfer from or to the channel buffer. If needed, the buffer base and size can be retrieved through `sndbuf_getbuf()` and `sndbuf_getsize()`.
  - `PCMTRIG_EMLDMAWR` / `PCMTRIG_EMLDMARD`: this tells the driver that the input or output buffer may have been updated. Most drivers just ignore these calls.
  - `PCMTRIG_STOP` / `PCMTRIG_ABORT`: the driver should stop the current transfer.

**Note:** If the driver uses ISA DMA, `sndbuf_isadma()` should be called before performing actions on the device, and will take care of the DMA chip side of things.

### 27.4.1.8 channel\_getptr

`xxxchannel_getptr()` returns the current offset in the transfer buffer. This will typically be called by `chn_intr()`, and this is how `pcm` knows where it can transfer new data.

### 27.4.1.9 channel\_free

`xxxchannel_free()` is called to free up channel resources, for example when the driver is unloaded, and should be implemented if the channel data structures are dynamically allocated or if `sndbuf_alloc()` was not used for buffer allocation.

### 27.4.1.10 channel\_getcaps

```

struct pcmchan_caps *
xxxchannel_getcaps(kobj_t obj, void *data)
{
    return &xxx_caps;❶
}

```

- ❶ The routine returns a pointer to a (usually statically-defined) `pcmchan_caps` structure (defined in `sound/pcm/channel.h`). The structure holds the minimum and maximum sampling frequencies, and the accepted sound formats. Look at any sound driver for an example.

### 27.4.1.11 More functions

`channel_reset()`, `channel_resetdone()`, and `channel_notify()` are for special purposes and should not be implemented in a driver without discussing it with the authorities (Cameron Grant <cg@FreeBSD.org>).

`channel_setdir()` is deprecated.

## 27.4.2 The MIXER interface

### 27.4.2.1 mixer\_init

`xxxmixer_init()` initializes the hardware and tells `pcm` what mixer devices are available for playing and recording

```

static int
xxxmixer_init(struct snd_mixer *m)
{
    struct xxx_info    *sc = mix_getdevinfo(m);
    u_int32_t v;

    [Initialize hardware]

    [Set appropriate bits in v for play mixers]❶
    mix_setdevs(m, v);
    [Set appropriate bits in v for record mixers]
    mix_setrecdevs(m, v)

    return 0;
}

```

- ❶ Set bits in an integer value and call `mix_setdevs()` and `mix_setrecdevs()` to tell `pcm` what devices exist. Mixer bits definitions can be found in `soundcard.h` (`SOUND_MASK_XXX` values and `SOUND_MIXER_XXX` bit shifts).



### 27.4.2.2 mixer\_set

`xxxmixer_set()` sets the volume level for one mixer device.

```
static int
xxxmixer_set(struct snd_mixer *m, unsigned dev,
             unsigned left, unsigned right)❶
{
    struct sc_info *sc = mix_getdevinfo(m);
    [set volume level]
    return left | (right << 8);❷
}
```

- ❶ The device is specified as a `SOUND_MIXER_XXX` value  
The volume values are specified in range [0-100]. A value of zero should mute the device.
- ❷ As the hardware levels probably won't match the input scale, and some rounding will occur, the routine returns the actual level values (in range 0-100) as shown.

### 27.4.2.3 mixer\_setrecsrc

`xxxmixer_setrecsrc()` sets the recording source device.

```
static int
xxxmixer_setrecsrc(struct snd_mixer *m, u_int32_t src)❶
{
    struct xxx_info *sc = mix_getdevinfo(m);

    [look for non zero bit(s) in src, set up hardware]

    [update src to reflect actual action]
    return src;❷
}
```

- ❶ The desired recording devices are specified as a bit field
- ❷ The actual devices set for recording are returned. Some drivers can only set one device for recording. The function should return -1 if an error occurs.

### 27.4.2.4 mixer\_uninit, mixer\_reinit

`xxxmixer_uninit()` should ensure that all sound is muted and if possible mixer hardware should be powered down

`xxxmixer_reinit()` should ensure that the mixer hardware is powered up and any settings not controlled by `mixer_set()` or `mixer_setrecsrc()` are restored.

### 27.4.3 The AC97 interface

The AC97 interface is implemented by drivers with an AC97 codec. It only has three methods:

- `xxxac97_init()` returns the number of ac97 codecs found.
- `ac97_read()` and `ac97_write()` read or write a specified register.

The AC97 interface is used by the AC97 code in `pcm` to perform higher level operations. Look at `sound/pci/maestro3.c` or many others under `sound/pci/` for an example.

# V. Architectures

# Chapter 28 x86 Assembly Language Programming

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## 28.1 Synopsis

Assembly language programming under Unix is highly undocumented. It is generally assumed that no one would ever want to use it because various Unix systems run on different microprocessors, so everything should be written in C for portability.

In reality, C portability is quite a myth. Even C programs need to be modified when ported from one Unix to another, regardless of what processor each runs on. Typically, such a program is full of conditional statements depending on the system it is compiled for.

Even if we believe that all of Unix software should be written in C, or some other high-level language, we still need assembly language programmers: Who else would write the section of C library that accesses the kernel?

In this chapter I will attempt to show you how you can use assembly language writing Unix programs, specifically under FreeBSD.

This chapter does not explain the basics of assembly language. There are enough resources about that (for a complete online course in assembly language, see Randall Hyde's Art of Assembly Language (<http://webster.cs.ucr.edu/>); or if you prefer a printed book, take a look at Jeff Duntemann's Assembly Language Step-by-Step (<http://www.int80h.org/cgi-bin/isbn?isbn=0471375233>)). However, once the chapter is finished, any assembly language programmer will be able to write programs for FreeBSD quickly and efficiently.

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## 28.2 The Tools

### 28.2.1 The Assembler

The most important tool for assembly language programming is the assembler, the software that converts assembly language code into machine language.

Two very different assemblers are available for FreeBSD. One is `as(1)`, which uses the traditional Unix assembly language syntax. It comes with the system.

The other is `/usr/ports/devel/nasm`. It uses the Intel syntax. Its main advantage is that it can assemble code for many operating systems. It needs to be installed separately, but is completely free.

This chapter uses `nasm` syntax because most assembly language programmers coming to FreeBSD from other operating systems will find it easier to understand. And, because, quite frankly, that is what I am used to.

## 28.2.2 The Linker

The output of the assembler, like that of any compiler, needs to be linked to form an executable file.

The standard `ld(1)` linker comes with FreeBSD. It works with the code assembled with either assembler.

## 28.3 System Calls

### 28.3.1 Default Calling Convention

By default, the FreeBSD kernel uses the C calling convention. Further, although the kernel is accessed using `int 80h`, it is assumed the program will call a function that issues `int 80h`, rather than issuing `int 80h` directly.

This convention is very convenient, and quite superior to the Microsoft convention used by MS DOS. Why? Because the Unix convention allows any program written in any language to access the kernel.

An assembly language program can do that as well. For example, we could open a file:

```
kernel:
    int 80h ; Call kernel
    ret

open:
    push dword mode
    push dword flags
    push dword path
    mov eax, 5
    call kernel
    add esp, byte 12
    ret
```

This is a very clean and portable way of coding. If you need to port the code to a Unix system which uses a different interrupt, or a different way of passing parameters, all you need to change is the kernel procedure.

But assembly language programmers like to shave off cycles. The above example requires a `call/ret` combination. We can eliminate it by pushing an extra dword:

```
open:
    push dword mode
    push dword flags
    push dword path
    mov eax, 5
    push eax ; Or any other dword
    int 80h
    add esp, byte 16
```

The 5 that we have placed in `EAX` identifies the kernel function, in this case `open`.

## 28.3.2 Alternate Calling Convention

FreeBSD is an extremely flexible system. It offers other ways of calling the kernel. For it to work, however, the system must have Linux emulation installed.

Linux is a Unix-like system. However, its kernel uses the same system-call convention of passing parameters in registers MS DOS does. As with the Unix convention, the function number is placed in `EAX`. The parameters, however, are not passed on the stack but in `EBX`, `ECX`, `EDX`, `ESI`, `EDI`, `EBP`:

```
open:
    mov eax, 5
    mov ebx, path
    mov ecx, flags
    mov edx, mode
    int 80h
```

This convention has a great disadvantage over the Unix way, at least as far as assembly language programming is concerned: Every time you make a kernel call you must `push` the registers, then `pop` them later. This makes your code bulkier and slower. Nevertheless, FreeBSD gives you a choice.

If you do choose the Linux convention, you must let the system know about it. After your program is assembled and linked, you need to brand the executable:

```
% brandelf -f Linux filename
```

## 28.3.3 Which Convention Should You Use?

If you are coding specifically for FreeBSD, you should always use the Unix convention: It is faster, you can store global variables in registers, you do not have to brand the executable, and you do not impose the installation of the Linux emulation package on the target system.

If you want to create portable code that can also run on Linux, you will probably still want to give the FreeBSD users as efficient a code as possible. I will show you how you can accomplish that after I have explained the basics.

## 28.3.4 Call Numbers

To tell the kernel which system service you are calling, place its number in `EAX`. Of course, you need to know what the number is.

### 28.3.4.1 The `syscalls` File

The numbers are listed in `syscalls`. `locate syscalls` finds this file in several different formats, all produced automatically from `syscalls.master`.

You can find the master file for the default Unix calling convention in `/usr/src/sys/kern/syscalls.master`. If you need to use the other convention implemented in the Linux emulation mode, read `/usr/src/sys/i386/linux/syscalls.master`.

**Note:** Not only do FreeBSD and Linux use different calling conventions, they sometimes use different numbers for the same functions.

`syscalls.master` describes how the call is to be made:

```

0 STD NOHIDE { int nosys(void); } syscall nosys_args int
1 STD NOHIDE { void exit(int rval); } exit rexit_args void
2 STD POSIX { int fork(void); }
3 STD POSIX { ssize_t read(int fd, void *buf, size_t nbyte); }
4 STD POSIX { ssize_t write(int fd, const void *buf, size_t nbyte); }
5 STD POSIX { int open(char *path, int flags, int mode); }
6 STD POSIX { int close(int fd); }
etc...
```

It is the leftmost column that tells us the number to place in `EAX`.

The rightmost column tells us what parameters to push. They are pushed *from right to left*.

For example, to open a file, we need to push the mode first, then flags, then the address at which the path is stored.

## 28.4 Return Values

A system call would not be useful most of the time if it did not return some kind of a value: The file descriptor of an open file, the number of bytes read to a buffer, the system time, etc.

Additionally, the system needs to inform us if an error occurs: A file does not exist, system resources are exhausted, we passed an invalid parameter, etc.

### 28.4.1 Man Pages

The traditional place to look for information about various system calls under Unix systems are the man pages. FreeBSD describes its system calls in section 2, sometimes in section 3.

For example, `open(2)` says:

If successful, `open()` returns a non-negative integer, termed a file descriptor. It returns `-1` on failure, and sets `errno` to indicate the error.

The assembly language programmer new to Unix and FreeBSD will immediately ask the puzzling question: Where is `errno` and how do I get to it?

**Note:** The information presented in the man pages applies to C programs. The assembly language programmer needs additional information.

## 28.4.2 Where Are the Return Values?

Unfortunately, it depends... For most system calls it is in `EAX`, but not for all. A good rule of thumb, when working with a system call for the first time, is to look for the return value in `EAX`. If it is not there, you need further research.

**Note:** I am aware of one system call that returns the value in `EDX`: `SYS_fork`. All others I have worked with use `EAX`. But I have not worked with them all yet.

**Tip:** If you cannot find the answer here or anywhere else, study `libc` source code and see how it interfaces with the kernel.

## 28.4.3 Where Is `errno`?

Actually, nowhere...

`errno` is part of the C language, not the Unix kernel. When accessing kernel services directly, the error code is returned in `EAX`, the same register the proper return value generally ends up in.

This makes perfect sense. If there is no error, there is no error code. If there is an error, there is no return value. One register can contain either.

## 28.4.4 Determining an Error Occurred

When using the standard FreeBSD calling convention, the `carry` flag is cleared upon success, set upon failure.

When using the Linux emulation mode, the signed value in `EAX` is non-negative upon success, and contains the return value. In case of an error, the value is negative, i.e., `-errno`.

## 28.5 Creating Portable Code

Portability is generally not one of the strengths of assembly language. Yet, writing assembly language programs for different platforms is possible, especially with `nasm`. I have written assembly language libraries that can be assembled for such different operating systems as Windows and FreeBSD.

It is all the more possible when you want your code to run on two platforms which, while different, are based on similar architectures.

For example, FreeBSD is Unix, Linux is Unix-like. I only mentioned three differences between them (from an assembly language programmer's perspective): The calling convention, the function numbers, and the way of returning values.



## 28.5.1 Dealing with Function Numbers

In many cases the function numbers are the same. However, even when they are not, the problem is easy to deal with: Instead of using numbers in your code, use constants which you have declared differently depending on the target architecture:

```
%ifdef LINUX
#define SYS_execve 11
#else
#define SYS_execve 59
#endif
```

## 28.5.2 Dealing with Conventions

Both, the calling convention, and the return value (the `errno` problem) can be resolved with macros:

```
%ifdef LINUX

%macro system 0
    call kernel
%endmacro

align 4
kernel:
    push ebx
    push ecx
    push edx
    push esi
    push edi
    push ebp

    mov ebx, [esp+32]
    mov ecx, [esp+36]
    mov edx, [esp+40]
    mov esi, [esp+44]
    mov ebp, [esp+48]
    int 80h

    pop ebp
    pop edi
    pop esi
    pop edx
    pop ecx
    pop ebx

    or eax, eax
    js .errno
    clc
    ret

.errno:
```

```

neg eax
stc
ret

%else

%macro system 0
int 80h
%endmacro

%endif

```

### 28.5.3 Dealing with Other Portability Issues

The above solutions can handle most cases of writing code portable between FreeBSD and Linux. Nevertheless, with some kernel services the differences are deeper.

In that case, you need to write two different handlers for those particular system calls, and use conditional assembly. Luckily, most of your code does something other than calling the kernel, so usually you will only need a few such conditional sections in your code.

### 28.5.4 Using a Library

You can avoid portability issues in your main code altogether by writing a library of system calls. Create a separate library for FreeBSD, a different one for Linux, and yet other libraries for more operating systems.

In your library, write a separate function (or procedure, if you prefer the traditional assembly language terminology) for each system call. Use the C calling convention of passing parameters. But still use `EAX` to pass the call number in. In that case, your FreeBSD library can be very simple, as many seemingly different functions can be just labels to the same code:

```

sys.open:
sys.close:
[etc...]
int 80h
ret

```

Your Linux library will require more different functions. But even here you can group system calls using the same number of parameters:

```

sys.exit:
sys.close:
[etc... one-parameter functions]
push ebx
mov ebx, [esp+12]
int 80h
pop ebx
jmp sys.return

...

```

```

sys.return:
    or  eax, eax
    js  sys.err
    clc
    ret

sys.err:
    neg eax
    stc
    ret

```

The library approach may seem inconvenient at first because it requires you to produce a separate file your code depends on. But it has many advantages: For one, you only need to write it once and can use it for all your programs. You can even let other assembly language programmers use it, or perhaps use one written by someone else. But perhaps the greatest advantage of the library is that your code can be ported to other systems, even by other programmers, by simply writing a new library without any changes to your code.

If you do not like the idea of having a library, you can at least place all your system calls in a separate assembly language file and link it with your main program. Here, again, all porters have to do is create a new object file to link with your main program.

## 28.5.5 Using an Include File

If you are releasing your software as (or with) source code, you can use macros and place them in a separate file, which you include in your code.

Porters of your software will simply write a new include file. No library or external object file is necessary, yet your code is portable without any need to edit the code.

**Note:** This is the approach we will use throughout this chapter. We will name our include file `system.inc`, and add to it whenever we deal with a new system call.

We can start our `system.inc` by declaring the standard file descriptors:

```

#define stdin 0
#define stdout 1
#define stderr 2

```

Next, we create a symbolic name for each system call:

```

#define SYS_nosys 0
#define SYS_exit 1
#define SYS_fork 2
#define SYS_read 3
#define SYS_write 4
; [etc...]

```

We add a short, non-global procedure with a long name, so we do not accidentally reuse the name in our code:

```

section .text
align 4
access.the.bsd.kernel:
    int 80h
    ret

```

We create a macro which takes one argument, the syscall number:

```

%macro system 1
    mov eax, %1
    call access.the.bsd.kernel
%endmacro

```

Finally, we create macros for each syscall. These macros take no arguments.

```

%macro sys.exit 0
    system SYS_exit
%endmacro

%macro sys.fork 0
    system SYS_fork
%endmacro

%macro sys.read 0
    system SYS_read
%endmacro

%macro sys.write 0
    system SYS_write
%endmacro

; [etc...]

```

Go ahead, enter it into your editor and save it as `system.inc`. We will add more to it as we discuss more syscalls.

## 28.6 Our First Program

We are now ready for our first program, the mandatory **Hello, World!**

```

1: %include 'system.inc'
2:
3: section .data
4: hello db 'Hello, World!', 0Ah
5: hbytes equ $-hello
6:
7: section .text
8: global _start
9: _start:
10: push dword hbytes
11: push dword hello
12: push dword stdout

```

```

13: sys.write
14:
15: push dword 0
16: sys.exit

```

Here is what it does: Line 1 includes the defines, the macros, and the code from `system.inc`.

Lines 3-5 are the data: Line 3 starts the data section/segment. Line 4 contains the string "Hello, World!" followed by a new line (0Ah). Line 5 creates a constant that contains the length of the string from line 4 in bytes.

Lines 7-16 contain the code. Note that FreeBSD uses the *elf* file format for its executables, which requires every program to start at the point labeled `_start` (or, more precisely, the linker expects that). This label has to be global.

Lines 10-13 ask the system to write `hbytes` bytes of the `hello` string to `stdout`.

Lines 15-16 ask the system to end the program with the return value of 0. The `SYS_exit` syscall never returns, so the code ends there.

**Note:** If you have come to Unix from MS DOS assembly language background, you may be used to writing directly to the video hardware. You will never have to worry about this in FreeBSD, or any other flavor of Unix. As far as you are concerned, you are writing to a file known as `stdout`. This can be the video screen, or a **telnet** terminal, or an actual file, or even the input of another program. Which one it is, is for the system to figure out.

## 28.6.1 Assembling the Code

Type the code (except the line numbers) in an editor, and save it in a file named `hello.asm`. You need **nasm** to assemble it.

### 28.6.1.1 Installing nasm

If you do not have **nasm**, type:

```

% su
Password:your root password
# cd /usr/ports/devel/nasm
# make install
# exit
%

```

You may type `make install clean` instead of just `make install` if you do not want to keep **nasm** source code.

Either way, FreeBSD will automatically download **nasm** from the Internet, compile it, and install it on your system.

**Note:** If your system is not FreeBSD, you need to get **nasm** from its home page (<http://www.web-sites.co.uk/nasm/>). You can still use it to assemble FreeBSD code.

Now you can assemble, link, and run the code:

```

% nasm -f elf hello.asm

```

```
% ld -s -o hello hello.o
% ./hello
Hello, World!
%
```

## 28.7 Writing Unix Filters

A common type of Unix application is a filter—a program that reads data from the `stdin`, processes it somehow, then writes the result to `stdout`.

In this chapter, we shall develop a simple filter, and learn how to read from `stdin` and write to `stdout`. This filter will convert each byte of its input into a hexadecimal number followed by a blank space.

```
%include 'system.inc'

section .data
hex db '0123456789ABCDEF'
buffer db 0, 0, ' '

section .text
global _start
_start:
; read a byte from stdin
push dword 1
push dword buffer
push dword stdin
sys.read
add esp, byte 12
or eax, eax
je .done

; convert it to hex
movzx eax, byte [buffer]
mov edx, eax
shr dl, 4
mov dl, [hex+edx]
mov [buffer], dl
and al, 0Fh
mov al, [hex+eax]
mov [buffer+1], al

; print it
push dword 3
push dword buffer
push dword stdout
sys.write
add esp, byte 12
jmp short _start
```

```
.done:
push dword 0
sys.exit
```

In the data section we create an array called `hex`. It contains the 16 hexadecimal digits in ascending order. The array is followed by a buffer which we will use for both input and output. The first two bytes of the buffer are initially set to 0. This is where we will write the two hexadecimal digits (the first byte also is where we will read the input). The third byte is a space.

The code section consists of four parts: Reading the byte, converting it to a hexadecimal number, writing the result, and eventually exiting the program.

To read the byte, we ask the system to read one byte from `stdin`, and store it in the first byte of the `buffer`. The system returns the number of bytes read in `EAX`. This will be 1 while data is coming, or 0, when no more input data is available. Therefore, we check the value of `EAX`. If it is 0, we jump to `.done`, otherwise we continue.

**Note:** For simplicity sake, we are ignoring the possibility of an error condition at this time.

The hexadecimal conversion reads the byte from the `buffer` into `EAX`, or actually just `AL`, while clearing the remaining bits of `EAX` to zeros. We also copy the byte to `EDX` because we need to convert the upper four bits (nibble) separately from the lower four bits. We store the result in the first two bytes of the buffer.

Next, we ask the system to write the three bytes of the buffer, i.e., the two hexadecimal digits and the blank space, to `stdout`. We then jump back to the beginning of the program and process the next byte.

Once there is no more input left, we ask the system to exit our program, returning a zero, which is the traditional value meaning the program was successful.

Go ahead, and save the code in a file named `hex.asm`, then type the following (the `^D` means press the control key and type `D` while holding the control key down):

```
% nasm -f elf hex.asm
% ld -s -o hex hex.o
% ./hex
Hello, World!
48 65 6C 6C 6F 2C 20 57 6F 72 6C 64 21 0A Here I come!
48 65 72 65 20 49 20 63 6F 6D 65 21 0A ^D %
```

**Note:** If you are migrating to Unix from MS DOS, you may be wondering why each line ends with `0A` instead of `0D 0A`. This is because Unix does not use the `cr/lf` convention, but a "new line" convention, which is `0A` in hexadecimal.

Can we improve this? Well, for one, it is a bit confusing because once we have converted a line of text, our input no longer starts at the beginning of the line. We can modify it to print a new line instead of a space after each `0A`:

```
%include 'system.inc'

section .data
hex db '0123456789ABCDEF'
buffer db 0, 0, ' '
```

```

section .text
global _start
_start:
    mov cl, ' '

.loop:
    ; read a byte from stdin
    push dword 1
    push dword buffer
    push dword stdin
    sys.read
    add esp, byte 12
    or eax, eax
    je .done

    ; convert it to hex
    movzx eax, byte [buffer]
    mov [buffer+2], cl
    cmp al, 0Ah
    jne .hex
    mov [buffer+2], al

.hex:
    mov edx, eax
    shr dl, 4
    mov dl, [hex+edx]
    mov [buffer], dl
    and al, 0Fh
    mov al, [hex+eax]
    mov [buffer+1], al

    ; print it
    push dword 3
    push dword buffer
    push dword stdout
    sys.write
    add esp, byte 12
    jmp short .loop

.done:
    push dword 0
    sys.exit

```

We have stored the space in the CL register. We can do this safely because, unlike Microsoft Windows, Unix system calls do not modify the value of any register they do not use to return a value in.

That means we only need to set CL once. We have, therefore, added a new label `.loop` and jump to it for the next byte instead of jumping at `_start`. We have also added the `.hex` label so we can either have a blank space or a new line as the third byte of the `buffer`.

Once you have changed `hex.asm` to reflect these changes, type:

```
% nasm -f elf hex.asm
```



```

% ld -s -o hex hex.o
% ./hex
Hello, World!
48 65 6C 6C 6F 2C 20 57 6F 72 6C 64 21 0A
Here I come!
48 65 72 65 20 49 20 63 6F 6D 65 21 0A
^D %

```

That looks better. But this code is quite inefficient! We are making a system call for every single byte twice (once to read it, another time to write the output).

## 28.8 Buffered Input and Output

We can improve the efficiency of our code by buffering our input and output. We create an input buffer and read a whole sequence of bytes at one time. Then we fetch them one by one from the buffer.

We also create an output buffer. We store our output in it until it is full. At that time we ask the kernel to write the contents of the buffer to `stdout`.

The program ends when there is no more input. But we still need to ask the kernel to write the contents of our output buffer to `stdout` one last time, otherwise some of our output would make it to the output buffer, but never be sent out. Do not forget that, or you will be wondering why some of your output is missing.

```

#include 'system.inc'

#define BUFSIZE 2048

section .data
hex db '0123456789ABCDEF'

section .bss
ibuffer resb BUFSIZE
obuffer resb BUFSIZE

section .text
global _start
_start:
    sub eax, eax
    sub ebx, ebx
    sub ecx, ecx
    mov edi, obuffer

.loop:
    ; read a byte from stdin
    call getchar

    ; convert it to hex
    mov dl, al
    shr al, 4
    mov al, [hex+eax]
    call putchar

```

```

mov al, dl
and al, 0Fh
mov al, [hex+eax]
call putchar

mov al, ' '
cmp dl, 0Ah
jne .put
mov al, dl

.put:
call putchar
jmp short .loop

align 4
getchar:
or ebx, ebx
jne .fetch

call read

.fetch:
lodsb
dec ebx
ret

read:
push dword BUFSIZE
mov esi, ibuffer
push esi
push dword stdin
sys.read
add esp, byte 12
mov ebx, eax
or eax, eax
je .done
sub eax, eax
ret

align 4
.done:
call write ; flush output buffer
push dword 0
sys.exit

align 4
putchar:
stosb
inc ecx
cmp ecx, BUFSIZE
je write
ret

```

```

align 4
write:
    sub edi, ecx ; start of buffer
    push ecx
    push edi
    push dword stdout
    sys.write
    add esp, byte 12
    sub eax, eax
    sub ecx, ecx ; buffer is empty now
    ret

```

We now have a third section in the source code, named `.bss`. This section is not included in our executable file, and, therefore, cannot be initialized. We use `resb` instead of `db`. It simply reserves the requested size of uninitialized memory for our use.

We take advantage of the fact that the system does not modify the registers: We use registers for what, otherwise, would have to be global variables stored in the `.data` section. This is also why the Unix convention of passing parameters to system calls on the stack is superior to the Microsoft convention of passing them in the registers: We can keep the registers for our own use.

We use `EDI` and `ESI` as pointers to the next byte to be read from or written to. We use `EBX` and `ECX` to keep count of the number of bytes in the two buffers, so we know when to dump the output to, or read more input from, the system.

Let us see how it works now:

```

% nasm -f elf hex.asm
% ld -s -o hex hex.o
% ./hex
Hello, World!
Here I come!
48 65 6C 6C 6F 2C 20 57 6F 72 6C 64 21 0A
48 65 72 65 20 49 20 63 6F 6D 65 21 0A
^D %

```

Not what you expected? The program did not print the output until we pressed `^D`. That is easy to fix by inserting three lines of code to write the output every time we have converted a new line to `0A`. I have marked the three lines with `>` (do not copy the `>` in your `hex.asm`).

```

#include 'system.inc'

#define BUFSIZE 2048

section .data
hex db '0123456789ABCDEF'

section .bss
ibuffer resb BUFSIZE
obuffer resb BUFSIZE

section .text
global _start
_start:

```

```

sub eax, eax
sub ebx, ebx
sub ecx, ecx
mov edi, obuffer

.loop:
; read a byte from stdin
call getchar

; convert it to hex
mov dl, al
shr al, 4
mov al, [hex+eax]
call putchar

mov al, dl
and al, 0Fh
mov al, [hex+eax]
call putchar

mov al, ' '
cmp dl, 0Ah
jne .put
mov al, dl

.put:
call putchar
> cmp al, 0Ah
> jne .loop
> call write
jmp short .loop

align 4
getchar:
or ebx, ebx
jne .fetch

call read

.fetch:
lodsb
dec ebx
ret

read:
push dword BUFSIZE
mov esi, ibuffer
push esi
push dword stdin
sys.read
add esp, byte 12
mov ebx, eax
or eax, eax

```

```

je .done
sub eax, eax
ret

align 4
.done:
call write ; flush output buffer
push dword 0
sys.exit

align 4
putchar:
stosb
inc ecx
cmp ecx, BUFSIZE
je write
ret

align 4
write:
sub edi, ecx ; start of buffer
push ecx
push edi
push dword stdout
sys.write
add esp, byte 12
sub eax, eax
sub ecx, ecx ; buffer is empty now
ret

```

Now, let us see how it works:

```

% nasm -f elf hex.asm
% ld -s -o hex hex.o
% ./hex
Hello, World!
48 65 6C 6C 6F 2C 20 57 6F 72 6C 64 21 0A
Here I come!
48 65 72 65 20 49 20 63 6F 6D 65 21 0A
^D %

```

Not bad for a 644-byte executable, is it!

**Note:** This approach to buffered input/output still contains a hidden danger. I will discuss—and fix—it later, when I talk about the dark side of buffering.

## 28.8.1 How to Unread a Character

**Warning:** This may be a somewhat advanced topic, mostly of interest to programmers familiar with the theory of compilers. If you wish, you may skip to the next section, and perhaps read this later.

While our sample program does not require it, more sophisticated filters often need to look ahead. In other words, they may need to see what the next character is (or even several characters). If the next character is of a certain value, it is part of the token currently being processed. Otherwise, it is not.

For example, you may be parsing the input stream for a textual string (e.g., when implementing a language compiler): If a character is followed by another character, or perhaps a digit, it is part of the token you are processing. If it is followed by white space, or some other value, then it is not part of the current token.

This presents an interesting problem: How to return the next character back to the input stream, so it can be read again later?

One possible solution is to store it in a character variable, then set a flag. We can modify `getchar` to check the flag, and if it is set, fetch the byte from that variable instead of the input buffer, and reset the flag. But, of course, that slows us down.

The C language has an `ungetc()` function, just for that purpose. Is there a quick way to implement it in our code? I would like you to scroll back up and take a look at the `getchar` procedure and see if you can find a nice and fast solution before reading the next paragraph. Then come back here and see my own solution.

The key to returning a character back to the stream is in how we are getting the characters to start with:

First we check if the buffer is empty by testing the value of `EBX`. If it is zero, we call the `read` procedure.

If we do have a character available, we use `lodsb`, then decrease the value of `EBX`. The `lodsb` instruction is effectively identical to:

```
mov al, [esi]
inc esi
```

The byte we have fetched remains in the buffer until the next time `read` is called. We do not know when that happens, but we do know it will not happen until the next call to `getchar`. Hence, to "return" the last-read byte back to the stream, all we have to do is decrease the value of `ESI` and increase the value of `EBX`:

```
ungetc:
  dec esi
  inc ebx
  ret
```

But, be careful! We are perfectly safe doing this if our look-ahead is at most one character at a time. If we are examining more than one upcoming character and call `ungetc` several times in a row, it will work most of the time, but not all the time (and will be tough to debug). Why?

Because as long as `getchar` does not have to call `read`, all of the pre-read bytes are still in the buffer, and our `ungetc` works without a glitch. But the moment `getchar` calls `read`, the contents of the buffer change.

We can always rely on `ungetc` working properly on the last character we have read with `getchar`, but not on anything we have read before that.

If your program reads more than one byte ahead, you have at least two choices:

If possible, modify the program so it only reads one byte ahead. This is the simplest solution.

If that option is not available, first of all determine the maximum number of characters your program needs to return to the input stream at one time. Increase that number slightly, just to be sure, preferably to a multiple of 16—so it aligns nicely. Then modify the `.bss` section of your code, and create a small "spare" buffer right before your input buffer, something like this:

```
section .bss
    resb 16 ; or whatever the value you came up with
    ibuffer resb BUFSIZE
    obuffer resb BUFSIZE
```

You also need to modify your `ungetc` to pass the value of the byte to `unget` in `AL`:

```
ungetc:
    dec esi
    inc ebx
    mov [esi], al
    ret
```

With this modification, you can call `ungetc` up to 17 times in a row safely (the first call will still be within the buffer, the remaining 16 may be either within the buffer or within the "spare").

## 28.9 Command Line Arguments

Our `hex` program will be more useful if it can read the names of an input and output file from its command line, i.e., if it can process the command line arguments. But... Where are they?

Before a Unix system starts a program, it pushes some data on the stack, then jumps at the `_start` label of the program. Yes, I said jumps, not calls. That means the data can be accessed by reading `[esp+offset]`, or by simply popping it.

The value at the top of the stack contains the number of command line arguments. It is traditionally called `argc`, for "argument count."

Command line arguments follow next, all `argc` of them. These are typically referred to as `argv`, for "argument value(s)." That is, we get `argv[0]`, `argv[1]`, . . . , `argv[argc-1]`. These are not the actual arguments, but pointers to arguments, i.e., memory addresses of the actual arguments. The arguments themselves are NUL-terminated character strings.

The `argv` list is followed by a NULL pointer, which is simply a 0. There is more, but this is enough for our purposes right now.

**Note:** If you have come from the MS DOS programming environment, the main difference is that each argument is in a separate string. The second difference is that there is no practical limit on how many arguments there can be.

Armed with this knowledge, we are almost ready for the next version of `hex.asm`. First, however, we need to add a few lines to `system.inc`:

First, we need to add two new entries to our list of system call numbers:

```
%define SYS_open 5
%define SYS_close 6
```

Then we add two new macros at the end of the file:

```
%macro sys.open 0
    system SYS_open
%endmacro

%macro sys.close 0
    system SYS_close
%endmacro
```

Here, then, is our modified source code:

```
%include 'system.inc'

%define BUFSIZE 2048

section .data
fd.in dd stdin
fd.out dd stdout
hex db '0123456789ABCDEF'

section .bss
ibuffer resb BUFSIZE
obuffer resb BUFSIZE

section .text
align 4
err:
    push dword 1 ; return failure
    sys.exit

align 4
global _start
_start:
    add esp, byte 8 ; discard argc and argv[0]

    pop ecx
    jecxz .init ; no more arguments

    ; ECX contains the path to input file
    push dword 0 ; O_RDONLY
    push ecx
    sys.open
    jc err ; open failed

    add esp, byte 8
    mov [fd.in], eax
```



```

pop ecx
jecxz .init ; no more arguments

; ECX contains the path to output file
push dword 420 ; file mode (644 octal)
push dword 0200h | 0400h | 01h
; O_CREAT | O_TRUNC | O_WRONLY
push ecx
sys.open
jc err

add esp, byte 12
mov [fd.out], eax

.init:
sub eax, eax
sub ebx, ebx
sub ecx, ecx
mov edi, obuffer

.loop:
; read a byte from input file or stdin
call getchar

; convert it to hex
mov dl, al
shr al, 4
mov al, [hex+eax]
call putchar

mov al, dl
and al, 0Fh
mov al, [hex+eax]
call putchar

mov al, ' '
cmp dl, 0Ah
jne .put
mov al, dl

.put:
call putchar
cmp al, dl
jne .loop
call write
jmp short .loop

align 4
getchar:
or ebx, ebx
jne .fetch

call read

```

```

.fetch:
  lodsb
  dec ebx
  ret

read:
  push dword BUFSIZE
  mov esi, ibuffer
  push esi
  push dword [fd.in]
  sys.read
  add esp, byte 12
  mov ebx, eax
  or eax, eax
  je .done
  sub eax, eax
  ret

align 4
.done:
  call write ; flush output buffer

  ; close files
  push dword [fd.in]
  sys.close

  push dword [fd.out]
  sys.close

  ; return success
  push dword 0
  sys.exit

align 4
putchar:
  stosb
  inc ecx
  cmp ecx, BUFSIZE
  je write
  ret

align 4
write:
  sub edi, ecx ; start of buffer
  push ecx
  push edi
  push dword [fd.out]
  sys.write
  add esp, byte 12
  sub eax, eax
  sub ecx, ecx ; buffer is empty now
  ret

```

In our `.data` section we now have two new variables, `fd.in` and `fd.out`. We store the input and output file descriptors here.

In the `.text` section we have replaced the references to `stdin` and `stdout` with `[fd.in]` and `[fd.out]`.

The `.text` section now starts with a simple error handler, which does nothing but exit the program with a return value of 1. The error handler is before `_start` so we are within a short distance from where the errors occur.

Naturally, the program execution still begins at `_start`. First, we remove `argc` and `argv[0]` from the stack: They are of no interest to us (in this program, that is).

We pop `argv[1]` to `ECX`. This register is particularly suited for pointers, as we can handle `NULL` pointers with `jecz`. If `argv[1]` is not `NULL`, we try to open the file named in the first argument. Otherwise, we continue the program as before: Reading from `stdin`, writing to `stdout`. If we fail to open the input file (e.g., it does not exist), we jump to the error handler and quit.

If all went well, we now check for the second argument. If it is there, we open the output file. Otherwise, we send the output to `stdout`. If we fail to open the output file (e.g., it exists and we do not have the write permission), we, again, jump to the error handler.

The rest of the code is the same as before, except we close the input and output files before exiting, and, as mentioned, we use `[fd.in]` and `[fd.out]`.

Our executable is now a whopping 768 bytes long.

Can we still improve it? Of course! Every program can be improved. Here are a few ideas of what we could do:

- Have our error handler print a message to `stderr`.
- Add error handlers to the `read` and `write` functions.
- Close `stdin` when we open an input file, `stdout` when we open an output file.
- Add command line switches, such as `-i` and `-o`, so we can list the input and output files in any order, or perhaps read from `stdin` and write to a file.
- Print a usage message if command line arguments are incorrect.

I shall leave these enhancements as an exercise to the reader: You already know everything you need to know to implement them.

## 28.10 Unix Environment

An important Unix concept is the environment, which is defined by *environment variables*. Some are set by the system, others by you, yet others by the **shell**, or any program that loads another program.

### 28.10.1 How to Find Environment Variables

I said earlier that when a program starts executing, the stack contains `argc` followed by the `NULL`-terminated `argv` array, followed by something else. The "something else" is the *environment*, or, to be more precise, a `NULL`-terminated array of pointers to *environment variables*. This is often referred to as `env`.

The structure of `env` is the same as that of `argv`, a list of memory addresses followed by a `NULL` (0). In this case, there is no `"envc"`—we figure out where the array ends by searching for the final `NULL`.

The variables usually come in the `name=value` format, but sometimes the `=value` part may be missing. We need to account for that possibility.

## 28.10.2 webvars

I could just show you some code that prints the environment the same way the Unix `env` command does. But I thought it would be more interesting to write a simple assembly language CGI utility.

### 28.10.2.1 CGI: A Quick Overview

I have a detailed CGI tutorial (<http://www.whizkidtech.net/cgi-bin/tutorial>) on my web site, but here is a very quick overview of CGI:

- The web server communicates with the CGI program by setting *environment variables*.
- The CGI program sends its output to `stdout`. The web server reads it from there.
- It must start with an HTTP header followed by two blank lines.
- It then prints the HTML code, or whatever other type of data it is producing.

**Note:** While certain *environment variables* use standard names, others vary, depending on the web server. That makes **webvars** quite a useful diagnostic tool.

### 28.10.2.2 The Code

Our **webvars** program, then, must send out the HTTP header followed by some HTML mark-up. It then must read the *environment variables* one by one and send them out as part of the HTML page.

The code follows. I placed comments and explanations right inside the code:

```

;;;;;;;;; webvars.asm ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;
; Copyright (c) 2000 G. Adam Stanislav
; All rights reserved.
;
; Redistribution and use in source and binary forms, with or without
; modification, are permitted provided that the following conditions
; are met:
; 1. Redistributions of source code must retain the above copyright
;    notice, this list of conditions and the following disclaimer.
; 2. Redistributions in binary form must reproduce the above copyright
;    notice, this list of conditions and the following disclaimer in the
;    documentation and/or other materials provided with the distribution.
;
; THIS SOFTWARE IS PROVIDED BY THE AUTHOR AND CONTRIBUTORS "AS IS" AND
; ANY EXPRESS OR IMPLIED WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE
; IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE
; ARE DISCLAIMED.  IN NO EVENT SHALL THE AUTHOR OR CONTRIBUTORS BE LIABLE

```



```

section .text
global _start
_start:
; First, send out all the http and xhtml stuff that is
; needed before we start showing the environment
push dword httpplen
push dword http
push dword stdout
sys.write

; Now find how far on the stack the environment pointers
; are. We have 12 bytes we have pushed before "argc"
mov eax, [esp+12]

; We need to remove the following from the stack:
;
; The 12 bytes we pushed for sys.write
; The 4 bytes of argc
; The EAX*4 bytes of argv
; The 4 bytes of the NULL after argv
;
; Total:
; 20 + eax * 4
;
; Because stack grows down, we need to ADD that many bytes
; to ESP.
lea esp, [esp+20+eax*4]
cld ; This should already be the case, but let's be sure.

; Loop through the environment, printing it out
.loop:
pop edi
or edi, edi ; Done yet?
je near .wrap

; Print the left part of HTML
push dword leftlen
push dword left
push dword stdout
sys.write

; It may be tempting to search for the '=' in the env string next.
; But it is possible there is no '=', so we search for the
; terminating NUL first.
mov esi, edi ; Save start of string
sub ecx, ecx
not ecx ; ECX = FFFFFFFF
sub eax, eax
repne scasb
not ecx ; ECX = string length + 1
mov ebx, ecx ; Save it in EBX

```

```

; Now is the time to find '='
mov edi, esi ; Start of string
mov al, '='
repne scasb
not ecx
add ecx, ebx ; Length of name

push ecx
push esi
push dword stdout
sys.write

; Print the middle part of HTML table code
push dword midlen
push dword middle
push dword stdout
sys.write

; Find the length of the value
not ecx
lea ebx, [ebx+ecx-1]

; Print "undefined" if 0
or ebx, ebx
jne .value

mov ebx, undeflen
mov edi, undef

.value:
push ebx
push edi
push dword stdout
sys.write

; Print the right part of the table row
push dword rightlen
push dword right
push dword stdout
sys.write

; Get rid of the 60 bytes we have pushed
add esp, byte 60

; Get the next variable
jmp .loop

.wrap:
; Print the rest of HTML
push dword wraplen
push dword wrap
push dword stdout
sys.write

```

```

; Return success
push dword 0
sys.exit

```

This code produces a 1,396-byte executable. Most of it is data, i.e., the HTML mark-up we need to send out.

Assemble and link it as usual:

```

% nasm -f elf webvars.asm
% ld -s -o webvars webvars.o

```

To use it, you need to upload `webvars` to your web server. Depending on how your web server is set up, you may have to store it in a special `cgi-bin` directory, or perhaps rename it with a `.cgi` extension.

Then you need to use your browser to view its output. To see its output on my web server, please go to <http://www.int80h.org/webvars/>. If curious about the additional environment variables present in a password protected web directory, go to <http://www.int80h.org/private/>, using the name **asm** and password **programmer**.

## 28.11 Working with Files

We have already done some basic file work: We know how to open and close them, how to read and write them using buffers. But Unix offers much more functionality when it comes to files. We will examine some of it in this section, and end up with a nice file conversion utility.

Indeed, let us start at the end, that is, with the file conversion utility. It always makes programming easier when we know from the start what the end product is supposed to do.

One of the first programs I wrote for Unix was **tuc** (<ftp://ftp.int80h.org/unix/tuc/>), a text-to-Unix file converter. It converts a text file from other operating systems to a Unix text file. In other words, it changes from different kind of line endings to the newline convention of Unix. It saves the output in a different file. Optionally, it converts a Unix text file to a DOS text file.

I have used **tuc** extensively, but always only to convert from some other OS to Unix, never the other way. I have always wished it would just overwrite the file instead of me having to send the output to a different file. Most of the time, I end up using it like this:

```

% tuc myfile tempfile
% mv tempfile myfile

```

It would be nice to have a **ftuc**, i.e., *fast tuc*, and use it like this:

```

% ftuc myfile

```

In this chapter, then, we will write **ftuc** in assembly language (the original **tuc** is in C), and study various file-oriented kernel services in the process.

At first sight, such a file conversion is very simple: All you have to do is strip the carriage returns, right?



If you answered yes, think again: That approach will work most of the time (at least with MS DOS text files), but will fail occasionally.

The problem is that not all non-Unix text files end their line with the carriage return / line feed sequence. Some use carriage returns without line feeds. Others combine several blank lines into a single carriage return followed by several line feeds. And so on.

A text file converter, then, must be able to handle any possible line endings:

- carriage return / line feed
- carriage return
- line feed / carriage return
- line feed

It should also handle files that use some kind of a combination of the above (e.g., carriage return followed by several line feeds).

### 28.11.1 Finite State Machine

The problem is easily solved by the use of a technique called *finite state machine*, originally developed by the designers of digital electronic circuits. A *finite state machine* is a digital circuit whose output is dependent not only on its input but on its previous input, i.e., on its state. The microprocessor is an example of a *finite state machine*: Our assembly language code is assembled to machine language in which some assembly language code produces a single byte of machine language, while others produce several bytes. As the microprocessor fetches the bytes from the memory one by one, some of them simply change its state rather than produce some output. When all the bytes of the op code are fetched, the microprocessor produces some output, or changes the value of a register, etc.

Because of that, all software is essentially a sequence of state instructions for the microprocessor. Nevertheless, the concept of *finite state machine* is useful in software design as well.

Our text file converter can be designed as a *finite state machine* with three possible states. We could call them states 0-2, but it will make our life easier if we give them symbolic names:

- ordinary
- cr
- lf

Our program will start in the ordinary state. During this state, the program action depends on its input as follows:

- If the input is anything other than a carriage return or line feed, the input is simply passed on to the output. The state remains unchanged.
- If the input is a carriage return, the state is changed to cr. The input is then discarded, i.e., no output is made.
- If the input is a line feed, the state is changed to lf. The input is then discarded.

Whenever we are in the cr state, it is because the last input was a carriage return, which was unprocessed. What our software does in this state again depends on the current input:

- If the input is anything other than a carriage return or line feed, output a line feed, then output the input, then change the state to ordinary.
- If the input is a carriage return, we have received two (or more) carriage returns in a row. We discard the input, we output a line feed, and leave the state unchanged.
- If the input is a line feed, we output the line feed and change the state to ordinary. Note that this is not the same as the first case above – if we tried to combine them, we would be outputting two line feeds instead of one.

Finally, we are in the *If* state after we have received a line feed that was not preceded by a carriage return. This will happen when our file already is in Unix format, or whenever several lines in a row are expressed by a single carriage return followed by several line feeds, or when line ends with a line feed / carriage return sequence. Here is how we need to handle our input in this state:

- If the input is anything other than a carriage return or line feed, we output a line feed, then output the input, then change the state to ordinary. This is exactly the same action as in the *cr* state upon receiving the same kind of input.
- If the input is a carriage return, we discard the input, we output a line feed, then change the state to ordinary.
- If the input is a line feed, we output the line feed, and leave the state unchanged.

### 28.11.1.1 The Final State

The above *finite state machine* works for the entire file, but leaves the possibility that the final line end will be ignored. That will happen whenever the file ends with a single carriage return or a single line feed. I did not think of it when I wrote `tuc`, just to discover that occasionally it strips the last line ending.

This problem is easily fixed by checking the state after the entire file was processed. If the state is not ordinary, we simply need to output one last line feed.

**Note:** Now that we have expressed our algorithm as a *finite state machine*, we could easily design a dedicated digital electronic circuit (a "chip") to do the conversion for us. Of course, doing so would be considerably more expensive than writing an assembly language program.

### 28.11.1.2 The Output Counter

Because our file conversion program may be combining two characters into one, we need to use an output counter. We initialize it to 0, and increase it every time we send a character to the output. At the end of the program, the counter will tell us what size we need to set the file to.

## 28.11.2 Implementing FSM in Software

The hardest part of working with a *finite state machine* is analyzing the problem and expressing it as a *finite state machine*. That accomplished, the software almost writes itself.

In a high-level language, such as C, there are several main approaches. One is to use a `switch` statement which chooses what function should be run. For example,

```

switch (state) {
default:
case REGULAR:
regular(inputchar);
break;
case CR:
cr(inputchar);
break;
case LF:
lf(inputchar);
break;
}

```

Another approach is by using an array of function pointers, something like this:

```
(output[state])(inputchar);
```

Yet another is to have `state` be a function pointer, set to point at the appropriate function:

```
(*state)(inputchar);
```

This is the approach we will use in our program because it is very easy to do in assembly language, and very fast, too. We will simply keep the address of the right procedure in `EBX`, and then just issue:

```
call ebx
```

This is possibly faster than hardcoding the address in the code because the microprocessor does not have to fetch the address from the memory—it is already stored in one of its registers. I said *possibly* because with the caching modern microprocessors do, either way may be equally fast.

### 28.11.3 Memory Mapped Files

Because our program works on a single file, we cannot use the approach that worked for us before, i.e., to read from an input file and to write to an output file.

Unix allows us to map a file, or a section of a file, into memory. To do that, we first need to open the file with the appropriate read/write flags. Then we use the `mmap` system call to map it into the memory. One nice thing about `mmap` is that it automatically works with virtual memory: We can map more of the file into the memory than we have physical memory available, yet still access it through regular memory op codes, such as `mov`, `lods`, and `stos`. Whatever changes we make to the memory image of the file will be written to the file by the system. We do not even have to keep the file open: As long as it stays mapped, we can read from it and write to it.

The 32-bit Intel microprocessors can access up to four gigabytes of memory – physical or virtual. The FreeBSD system allows us to use up to a half of it for file mapping.

For simplicity sake, in this tutorial we will only convert files that can be mapped into the memory in their entirety. There are probably not too many text files that exceed two gigabytes in size. If our program encounters one, it will simply display a message suggesting we use the original `tuc` instead.

If you examine your copy of `syscalls.master`, you will find two separate syscalls named `mmap`. This is because of evolution of Unix: There was the traditional BSD `mmap`, syscall 71. That one was superceded by the POSIX `mmap`,

syscall 197. The FreeBSD system supports both because older programs were written by using the original BSD version. But new software uses the POSIX version, which is what we will use.

The `syscalls.master` file lists the POSIX version like this:

```
197 STD BSD { caddr_t mmap(caddr_t addr, size_t len, int prot, \
    int flags, int fd, long pad, off_t pos); }
```

This differs slightly from what `mmap(2)` says. That is because `mmap(2)` describes the C version.

The difference is in the `long pad` argument, which is not present in the C version. However, the FreeBSD syscalls add a 32-bit pad after pushing a 64-bit argument. In this case, `off_t` is a 64-bit value.

When we are finished working with a memory-mapped file, we unmap it with the `munmap` syscall:

**Tip:** For an in-depth treatment of `mmap`, see W. Richard Stevens' *Unix Network Programming, Volume 2, Chapter 12* (<http://www.int80h.org/cgi-bin/isbn?isbn=0130810819>).

## 28.11.4 Determining File Size

Because we need to tell `mmap` how many bytes of the file to map into the memory, and because we want to map the entire file, we need to determine the size of the file.

We can use the `fstat` syscall to get all the information about an open file that the system can give us. That includes the file size.

Again, `syscalls.master` lists two versions of `fstat`, a traditional one (syscall 62), and a POSIX one (syscall 189). Naturally, we will use the POSIX version:

```
189 STD POSIX { int fstat(int fd, struct stat *sb); }
```

This is a very straightforward call: We pass to it the address of a `stat` structure and the descriptor of an open file. It will fill out the contents of the `stat` structure.

I do, however, have to say that I tried to declare the `stat` structure in the `.bss` section, and `fstat` did not like it: It set the carry flag indicating an error. After I changed the code to allocate the structure on the stack, everything was working fine.

## 28.11.5 Changing the File Size

Because our program may combine carriage return / line feed sequences into straight line feeds, our output may be smaller than our input. However, since we are placing our output into the same file we read the input from, we may have to change the size of the file.

The `ftruncate` system call allows us to do just that. Despite its somewhat misleading name, the `ftruncate` system call can be used to both truncate the file (make it smaller) and to grow it.

And yes, we will find two versions of `ftruncate` in `syscalls.master`, an older one (130), and a newer one (201). We will use the newer one:

```
201 STD BSD { int ftruncate(int fd, int pad, off_t length); }
```

Please note that this one contains a `int` pad again.

## 28.11.6 ftuc

We now know everything we need to write **ftuc**. We start by adding some new lines in `system.inc`. First, we define some constants and structures, somewhere at or near the beginning of the file:

```

;;;;;;;;; open flags
#define O_RDONLY 0
#define O_WRONLY 1
#define O_RDWR 2

;;;;;;;;; mmap flags
#define PROT_NONE 0
#define PROT_READ 1
#define PROT_WRITE 2
#define PROT_EXEC 4
;;
#define MAP_SHARED 0001h
#define MAP_PRIVATE 0002h

;;;;;;;;; stat structure
struct stat
st_dev resd 1 ; = 0
st_ino resd 1 ; = 4
st_mode resw 1 ; = 8, size is 16 bits
st_nlink resw 1 ; = 10, ditto
st_uid resd 1 ; = 12
st_gid resd 1 ; = 16
st_rdev resd 1 ; = 20
st_atime resd 1 ; = 24
st_atimensec resd 1 ; = 28
st_mtime resd 1 ; = 32
st_mtimensec resd 1 ; = 36
st_ctime resd 1 ; = 40
st_ctimensec resd 1 ; = 44
st_size resd 2 ; = 48, size is 64 bits
st_blocks resd 2 ; = 56, ditto
st_blksize resd 1 ; = 64
st_flags resd 1 ; = 68
st_gen resd 1 ; = 72
st_lspare resd 1 ; = 76
st_qspare resd 4 ; = 80
endstruc

```

We define the new syscalls:

```

#define SYS_mmap 197
#define SYS_munmap 73
#define SYS_fstat 189
#define SYS_ftruncate 201

```

We add the macros for their use:

```
%macro sys.mmap 0
  system SYS_mmap
%endmacro

%macro sys.munmap 0
  system SYS_munmap
%endmacro

%macro sys.ftruncate 0
  system SYS_ftruncate
%endmacro

%macro sys.fstat 0
  system SYS_fstat
%endmacro
```

And here is our code:

```
;;;;;;;; Fast Text-to-Unix Conversion (ftuc.asm) ;;;;;;;;;;
;;
;; Started: 21-Dec-2000
;; Updated: 22-Dec-2000
;;
;; Copyright 2000 G. Adam Stanislav.
;; All rights reserved.
;;
;;;;;;;; v.1 ;;;;;;;;;;
%include 'system.inc'

section .data
  db 'Copyright 2000 G. Adam Stanislav.', 0Ah
  db 'All rights reserved.', 0Ah
  usg db 'Usage: ftuc filename', 0Ah
  usglen equ $-usg
  co db "ftuc: Can't open file.", 0Ah
  colen equ $-co
  fae db 'ftuc: File access error.', 0Ah
  faelen equ $-fae
  ftl db 'ftuc: File too long, use regular tuc instead.', 0Ah
  ftllen equ $-ftl
  mae db 'ftuc: Memory allocation error.', 0Ah
  maelen equ $-mae

section .text

align 4
memerr:
  push dword maelen
  push dword mae
  jmp short error
```

```

align 4
toolong:
    push dword ftllen
    push dword ftl
    jmp short error

align 4
facerr:
    push dword faelen
    push dword fae
    jmp short error

align 4
cantopen:
    push dword colen
    push dword co
    jmp short error

align 4
usage:
    push dword usglen
    push dword usg

error:
    push dword stderr
    sys.write

    push dword 1
    sys.exit

align 4
global _start
_start:
    pop eax ; argc
    pop eax ; program name
    pop ecx ; file to convert
    jecxz usage

    pop eax
    or eax, eax ; Too many arguments?
    jne usage

    ; Open the file
    push dword O_RDWR
    push ecx
    sys.open
    jc cantopen

    mov ebp, eax ; Save fd

    sub esp, byte stat_size
    mov ebx, esp

```

```

; Find file size
push ebx
push ebp ; fd
sys.fstat
jc facerr

mov edx, [ebx + st_size + 4]

; File is too long if EDX != 0 ...
or edx, edx
jne near toolong
mov ecx, [ebx + st_size]
; ... or if it is above 2 GB
or ecx, ecx
js near toolong

; Do nothing if the file is 0 bytes in size
jecxz .quit

; Map the entire file in memory
push edx
push edx ; starting at offset 0
push edx ; pad
push ebp ; fd
push dword MAP_SHARED
push dword PROT_READ | PROT_WRITE
push ecx ; entire file size
push edx ; let system decide on the address
sys.mmap
jc near memerr

mov edi, eax
mov esi, eax
push ecx ; for SYS_munmap
push edi

; Use EBX for state machine
mov ebx, ordinary
mov ah, 0Ah
cld

.loop:
lodsb
call ebx
loop .loop

cmp ebx, ordinary
je .filesize

; Output final lf
mov al, ah
stosb
inc edx

```



```

.filesize:
; truncate file to new size
push dword 0 ; high dword
push edx ; low dword
push eax ; pad
push ebp
sys.ftruncate

; close it (ebp still pushed)
sys.close

add esp, byte 16
sys.munmap

.quit:
push dword 0
sys.exit

align 4
ordinary:
cmp al, 0Dh
je .cr

cmp al, ah
je .lf

stosb
inc edx
ret

align 4
.cr:
mov ebx, cr
ret

align 4
.lf:
mov ebx, lf
ret

align 4
cr:
cmp al, 0Dh
je .cr

cmp al, ah
je .lf

xchg al, ah
stosb
inc edx

```

```

xchg al, ah
; fall through

.lf:
stosb
inc edx
mov ebx, ordinary
ret

align 4
.cr:
mov al, ah
stosb
inc edx
ret

align 4
lf:
cmp al, ah
je .lf

cmp al, 0Dh
je .cr

xchg al, ah
stosb
inc edx

xchg al, ah
stosb
inc edx
mov ebx, ordinary
ret

align 4
.cr:
mov ebx, ordinary
mov al, ah
; fall through

.lf:
stosb
inc edx
ret

```

**Warning:** Do not use this program on files stored on a disk formatted by MS DOS or Windows. There seems to be a subtle bug in the FreeBSD code when using `mmap` on these drives mounted under FreeBSD: If the file is over a certain size, `mmap` will just fill the memory with zeros, and then copy them to the file overwriting its contents.

## 28.12 One-Pointed Mind

As a student of Zen, I like the idea of a one-pointed mind: Do one thing at a time, and do it well.

This, indeed, is very much how Unix works as well. While a typical Windows application is attempting to do everything imaginable (and is, therefore, riddled with bugs), a typical Unix program does only one thing, and it does it well.

The typical Unix user then essentially assembles his own applications by writing a shell script which combines the various existing programs by piping the output of one program to the input of another.

When writing your own Unix software, it is generally a good idea to see what parts of the problem you need to solve can be handled by existing programs, and only write your own programs for that part of the problem that you do not have an existing solution for.

### 28.12.1 CSV

I will illustrate this principle with a specific real-life example I was faced with recently:

I needed to extract the 11th field of each record from a database I downloaded from a web site. The database was a CSV file, i.e., a list of *comma-separated values*. That is quite a standard format for sharing data among people who may be using different database software.

The first line of the file contains the list of various fields separated by commas. The rest of the file contains the data listed line by line, with values separated by commas.

I tried **awk**, using the comma as a separator. But because several lines contained a quoted comma, **awk** was extracting the wrong field from those lines.

Therefore, I needed to write my own software to extract the 11th field from the CSV file. However, going with the Unix spirit, I only needed to write a simple filter that would do the following:

- Remove the first line from the file;
- Change all unquoted commas to a different character;
- Remove all quotation marks.

Strictly speaking, I could use **sed** to remove the first line from the file, but doing so in my own program was very easy, so I decided to do it and reduce the size of the pipeline.

At any rate, writing a program like this took me about 20 minutes. Writing a program that extracts the 11th field from the CSV file would take a lot longer, and I could not reuse it to extract some other field from some other database.

This time I decided to let it do a little more work than a typical tutorial program would:

- It parses its command line for options;
- It displays proper usage if it finds wrong arguments;
- It produces meaningful error messages.

Here is its usage message:

```
Usage: csv [-t<delim>] [-c<comma>] [-p] [-o <outfile>] [-i <infile>]
```

All parameters are optional, and can appear in any order.



```

section .text
align 4
ierr:
    push dword iemlen
    push dword iemsg
    push dword stderr
    sys.write
    push dword 1 ; return failure
    sys.exit

align 4
oerr:
    push dword oemlen
    push dword oemsg
    push dword stderr
    sys.write
    push dword 2
    sys.exit

align 4
usage:
    push dword usglen
    push dword usg
    push dword stderr
    sys.write
    push dword 3
    sys.exit

align 4
global _start
_start:
    add esp, byte 8 ; discard argc and argv[0]
    mov edx, (',' << 8) | 9

.arg:
    pop ecx
    or ecx, ecx
    je near .init ; no more arguments

; ECX contains the pointer to an argument
cmp byte [ecx], '-'
jne usage

inc ecx
mov ax, [ecx]

.o:
cmp al, 'o'
jne .i

; Make sure we are not asked for the output file twice
cmp dword [fd.out], stdout
jne usage

```

```

; Find the path to output file - it is either at [ECX+1],
; i.e., -ofile --
; or in the next argument,
; i.e., -o file

inc ecx
or ah, ah
jne .openoutput
pop ecx
jecxz usage

.openoutput:
push dword 420 ; file mode (644 octal)
push dword 0200h | 0400h | 01h
; O_CREAT | O_TRUNC | O_WRONLY
push ecx
sys.open
jc near oerr

add esp, byte 12
mov [fd.out], eax
jmp short .arg

.i:
cmp al, 'i'
jne .p

; Make sure we are not asked twice
cmp dword [fd.in], stdin
jne near usage

; Find the path to the input file
inc ecx
or ah, ah
jne .openinput
pop ecx
or ecx, ecx
je near usage

.openinput:
push dword 0 ; O_RDONLY
push ecx
sys.open
jc near ierr ; open failed

add esp, byte 8
mov [fd.in], eax
jmp .arg

.p:
cmp al, 'p'
jne .t

```

```

or ah, ah
jne near usage
or edx, 1 << 31
jmp .arg

.t:
cmp al, 't' ; redefine output delimiter
jne .c
or ah, ah
je near usage
mov dl, ah
jmp .arg

.c:
cmp al, 'c'
jne near usage
or ah, ah
je near usage
mov dh, ah
jmp .arg

align 4
.init:
sub eax, eax
sub ebx, ebx
sub ecx, ecx
mov edi, obuffer

; See if we are to preserve the first line
or edx, edx
js .loop

.firstline:
; get rid of the first line
call getchar
cmp al, 0Ah
jne .firstline

.loop:
; read a byte from stdin
call getchar

; is it a comma (or whatever the user asked for)?
cmp al, dh
jne .quote

; Replace the comma with a tab (or whatever the user wants)
mov al, dl

.put:
call putchar
jmp short .loop

```

```

.quote:
  cmp al, '"'
  jne .put

; Print everything until you get another quote or EOL. If it
; is a quote, skip it. If it is EOL, print it.
.qloop:
  call getchar
  cmp al, '"'
  je .loop

  cmp al, 0Ah
  je .put

  call putchar
  jmp short .qloop

align 4
getchar:
  or ebx, ebx
  jne .fetch

  call read

.fetch:
  lodsb
  dec ebx
  ret

read:
  jecxz .read
  call write

.read:
  push dword BUFSIZE
  mov esi, ibuffer
  push esi
  push dword [fd.in]
  sys.read
  add esp, byte 12
  mov ebx, eax
  or eax, eax
  je .done
  sub eax, eax
  ret

align 4
.done:
  call write ; flush output buffer

; close files
  push dword [fd.in]
  sys.close

```



```

push dword [fd.out]
sys.close

; return success
push dword 0
sys.exit

align 4
putchar:
    stosb
    inc ecx
    cmp ecx, BUFSIZE
    je write
    ret

align 4
write:
    jecxz .ret ; nothing to write
    sub edi, ecx ; start of buffer
    push ecx
    push edi
    push dword [fd.out]
    sys.write
    add esp, byte 12
    sub eax, eax
    sub ecx, ecx ; buffer is empty now
.ret:
    ret

```

Much of it is taken from `hex.asm` above. But there is one important difference: I no longer call `write` whenever I am outputting a line feed. Yet, the code can be used interactively.

I have found a better solution for the interactive problem since I first started writing this chapter. I wanted to make sure each line is printed out separately only when needed. After all, there is no need to flush out every line when used non-interactively.

The new solution I use now is to call `write` every time I find the input buffer empty. That way, when running in the interactive mode, the program reads one line from the user's keyboard, processes it, and sees its input buffer is empty. It flushes its output and reads the next line.

### 28.12.1.1 The Dark Side of Buffering

This change prevents a mysterious lockup in a very specific case. I refer to it as the *dark side of buffering*, mostly because it presents a danger that is not quite obvious.

It is unlikely to happen with a program like the `csv` above, so let us consider yet another filter: In this case we expect our input to be raw data representing color values, such as the *red*, *green*, and *blue* intensities of a pixel. Our output will be the negative of our input.

Such a filter would be very simple to write. Most of it would look just like all the other filters we have written so far, so I am only going to show you its inner loop:

```

.loop:
  call getchar
  not al ; Create a negative
  call putchar
  jmp short .loop

```

Because this filter works with raw data, it is unlikely to be used interactively.

But it could be called by image manipulation software. And, unless it calls `write` before each call to `read`, chances are it will lock up.

Here is what might happen:

1. The image editor will load our filter using the C function `popen()`.
2. It will read the first row of pixels from a bitmap or pixmap.
3. It will write the first row of pixels to the *pipe* leading to the `fd.in` of our filter.
4. Our filter will read each pixel from its input, turn it to a negative, and write it to its output buffer.
5. Our filter will call `getchar` to fetch the next pixel.
6. `getchar` will find an empty input buffer, so it will call `read`.
7. `read` will call the `SYS_read` system call.
8. The *kernel* will suspend our filter until the image editor sends more data to the pipe.
9. The image editor will read from the other pipe, connected to the `fd.out` of our filter so it can set the first row of the output image *before* it sends us the second row of the input.
10. The *kernel* suspends the image editor until it receives some output from our filter, so it can pass it on to the image editor.

At this point our filter waits for the image editor to send it more data to process, while the image editor is waiting for our filter to send it the result of the processing of the first row. But the result sits in our output buffer.

The filter and the image editor will continue waiting for each other forever (or, at least, until they are killed). Our software has just entered a race condition.

This problem does not exist if our filter flushes its output buffer *before* asking the *kernel* for more input data.

## 28.13 Using the FPU

Strangely enough, most of assembly language literature does not even mention the existence of the FPU, or *floating point unit*, let alone discuss programming it.

Yet, never does assembly language shine more than when we create highly optimized FPU code by doing things that can be done *only* in assembly language.

### 28.13.1 Organization of the FPU

The FPU consists of 8 80-bit floating-point registers. These are organized in a stack fashion—you can `push` a value on TOS (*top of stack*) and you can `pop` it.

That said, the assembly language op codes are not `push` and `pop` because those are already taken.

You can `push` a value on TOS by using `fild`, `fld`, and `fbld`. Several other op codes let you `push` many common *constants*—such as *pi*—on the TOS.

Similarly, you can `pop` a value by using `fst`, `fstp`, `fist`, `fistp`, and `fbstp`. Actually, only the op codes that end with a *p* will literally `pop` the value, the rest will `store` it somewhere else without removing it from the TOS.

We can transfer the data between the TOS and the computer memory either as a 32-bit, 64-bit, or 80-bit *real*, a 16-bit, 32-bit, or 64-bit *integer*, or an 80-bit *packed decimal*.

The 80-bit *packed decimal* is a special case of *binary coded decimal* which is very convenient when converting between the ASCII representation of data and the internal data of the FPU. It allows us to use 18 significant digits.

No matter how we represent data in the memory, the FPU always stores it in the 80-bit *real* format in its registers.

Its internal precision is at least 19 decimal digits, so even if we choose to display results as ASCII in the full 18-digit precision, we are still showing correct results.

We can perform mathematical operations on the TOS: We can calculate its *sine*, we can *scale* it (i.e., we can multiply or divide it by a power of 2), we can calculate its base-2 *logarithm*, and many other things.

We can also *multiply* or *divide* it by, *add* it to, or *subtract* it from, any of the FPU registers (including itself).

The official Intel op code for the TOS is `st`, and for the *registers* `st(0)–st(7)`. `st` and `st(0)`, then, refer to the same register.

For whatever reasons, the original author of **nasm** has decided to use different op codes, namely `st0–st7`. In other words, there are no parentheses, and the TOS is always `st0`, never just `st`.

#### 28.13.1.1 The Packed Decimal Format

The *packed decimal* format uses 10 bytes (80 bits) of memory to represent 18 digits. The number represented there is always an *integer*.

**Tip:** You can use it to get decimal places by multiplying the TOS by a power of 10 first.

The highest bit of the highest byte (byte 9) is the *sign bit*: If it is set, the number is *negative*, otherwise, it is *positive*. The rest of the bits of this byte are unused/ignored.

The remaining 9 bytes store the 18 digits of the number: 2 digits per byte.

The *more significant digit* is stored in the high *nibble* (4 bits), the *less significant digit* in the low *nibble*.

That said, you might think that `-1234567` would be stored in the memory like this (using hexadecimal notation):

```
80 00 00 00 00 00 01 23 45 67
```

Alas it is not! As with everything else of Intel make, even the *packed decimal* is *little-endian*.

That means our `-1234567` is stored like this:

```
67 45 23 01 00 00 00 00 80
```

Remember that, or you will be pulling your hair out in desperation!

**Note:** The book to read—if you can find it—is Richard Startz' 8087/80287/80387 for the IBM PC & Compatibles (<http://www.int80h.org/cgi-bin/isbn?isbn=013246604X>). Though it does seem to take the fact about the little-endian storage of the *packed decimal* for granted. I kid you not about the desperation of trying to figure out what was wrong with the filter I show below *before* it occurred to me I should try the little-endian order even for this type of data.

## 28.13.2 Excursion to Pinhole Photography

To write meaningful software, we must not only understand our programming tools, but also the field we are creating software for.

Our next filter will help us whenever we want to build a *pinhole camera*, so, we need some background in *pinhole photography* before we can continue.

### 28.13.2.1 The Camera

The easiest way to describe any camera ever built is as some empty space enclosed in some lightproof material, with a small hole in the enclosure.

The enclosure is usually sturdy (e.g., a box), though sometimes it is flexible (the bellows). It is quite dark inside the camera. However, the hole lets light rays in through a single point (though in some cases there may be several). These light rays form an image, a representation of whatever is outside the camera, in front of the hole.

If some light sensitive material (such as film) is placed inside the camera, it can capture the image.

The hole often contains a *lens*, or a lens assembly, often called the *objective*.

### 28.13.2.2 The Pinhole

But, strictly speaking, the lens is not necessary: The original cameras did not use a lens but a *pinhole*. Even today, *pinholes* are used, both as a tool to study how cameras work, and to achieve a special kind of image.

The image produced by the *pinhole* is all equally sharp. Or *blurred*. There is an ideal size for a pinhole: If it is either larger or smaller, the image loses its sharpness.

### 28.13.2.3 Focal Length

This ideal pinhole diameter is a function of the square root of *focal length*, which is the distance of the pinhole from the film.

$$D = PC * \text{sqrt}(FL)$$

In here,  $D$  is the ideal diameter of the pinhole,  $FL$  is the focal length, and  $PC$  is a pinhole constant. According to Jay Bender, its value is 0.04, while Kenneth Connors has determined it to be 0.037. Others have proposed other values. Plus, this value is for the daylight only: Other types of light will require a different constant, whose value can only be determined by experimentation.

### 28.13.2.4 The F-Number

The f-number is a very useful measure of how much light reaches the film. A light meter can determine that, for example, to expose a film of specific sensitivity with f5.6 may require the exposure to last 1/1000 sec.

It does not matter whether it is a 35-mm camera, or a 6x9cm camera, etc. As long as we know the f-number, we can determine the proper exposure.

The f-number is easy to calculate:

$$F = FL / D$$

In other words, the f-number equals the focal length divided by the diameter of the pinhole. It also means a higher f-number either implies a smaller pinhole or a larger focal distance, or both. That, in turn, implies, the higher the f-number, the longer the exposure has to be.

Furthermore, while pinhole diameter and focal distance are one-dimensional measurements, both, the film and the pinhole, are two-dimensional. That means that if you have measured the exposure at f-number A as  $t$ , then the exposure at f-number B is:

$$t * (B / A)^2$$

### 28.13.2.5 Normalized F-Number

While many modern cameras can change the diameter of their pinhole, and thus their f-number, quite smoothly and gradually, such was not always the case.

To allow for different f-numbers, cameras typically contained a metal plate with several holes of different sizes drilled to them.

Their sizes were chosen according to the above formula in such a way that the resultant f-number was one of standard f-numbers used on all cameras everywhere. For example, a very old Kodak Duaflex IV camera in my possession has three such holes for f-numbers 8, 11, and 16.

A more recently made camera may offer f-numbers of 2.8, 4, 5.6, 8, 11, 16, 22, and 32 (as well as others). These numbers were not chosen arbitrarily: They all are powers of the square root of 2, though they may be rounded somewhat.

### 28.13.2.6 The F-Stop

A typical camera is designed in such a way that setting any of the normalized f-numbers changes the feel of the dial. It will naturally *stop* in that position. Because of that, these positions of the dial are called f-stops.

Since the f-numbers at each stop are powers of the square root of 2, moving the dial by 1 stop will double the amount of light required for proper exposure. Moving it by 2 stops will quadruple the required exposure. Moving the dial by 3 stops will require the increase in exposure 8 times, etc.

## 28.13.3 Designing the Pinhole Software

We are now ready to decide what exactly we want our pinhole software to do.

### 28.13.3.1 Processing Program Input

Since its main purpose is to help us design a working pinhole camera, we will use the *focal length* as the input to the program. This is something we can determine without software: Proper focal length is determined by the size of the film and by the need to shoot "regular" pictures, wide angle pictures, or telephoto pictures.

Most of the programs we have written so far worked with individual characters, or bytes, as their input: The **hex** program converted individual bytes into a hexadecimal number, the **csv** program either let a character through, or deleted it, or changed it to a different character, etc.

One program, **ftuc** used the state machine to consider at most two input bytes at a time.

But our **pinhole** program cannot just work with individual characters, it has to deal with larger syntactic units.

For example, if we want the program to calculate the pinhole diameter (and other values we will discuss later) at the focal lengths of 100 mm, 150 mm, and 210 mm, we may want to enter something like this:

```
100, 150, 210
```

Our program needs to consider more than a single byte of input at a time. When it sees the first 1, it must understand it is seeing the first digit of a decimal number. When it sees the 0 and the other 0, it must know it is seeing more digits of the same number.

When it encounters the first comma, it must know it is no longer receiving the digits of the first number. It must be able to convert the digits of the first number into the value of 100. And the digits of the second number into the value of 150. And, of course, the digits of the third number into the numeric value of 210.

We need to decide what delimiters to accept: Do the input numbers have to be separated by a comma? If so, how do we treat two numbers separated by something else?

Personally, I like to keep it simple. Something either is a number, so I process it. Or it is not a number, so I discard it. I do not like the computer complaining about me typing in an extra character when it is *obvious* that it is an extra character. Duh!

Plus, it allows me to break up the monotony of computing and type in a query instead of just a number:

```
What is the best pinhole diameter for the focal length of 150?
```

There is no reason for the computer to spit out a number of complaints:

```
Syntax error: What
Syntax error: is
Syntax error: the
Syntax error: best
```

Et cetera, et cetera, et cetera.

Secondly, I like the # character to denote the start of a comment which extends to the end of the line. This does not take too much effort to code, and lets me treat input files for my software as executable scripts.

In our case, we also need to decide what units the input should come in: We choose *millimeters* because that is how most photographers measure the focus length.

Finally, we need to decide whether to allow the use of the decimal point (in which case we must also consider the fact that much of the world uses a decimal *comma*).

In our case allowing for the decimal point/comma would offer a false sense of precision: There is little if any noticeable difference between the focus lengths of 50 and 51, so allowing the user to input something like 50.5 is not a good idea. This is my opinion, mind you, but I am the one writing this program. You can make other choices in yours, of course.

### 28.13.3.2 Offering Options

The most important thing we need to know when building a pinhole camera is the diameter of the pinhole. Since we want to shoot sharp images, we will use the above formula to calculate the pinhole diameter from focal length. As experts are offering several different values for the `PC` constant, we will need to have the choice.

It is traditional in Unix programming to have two main ways of choosing program parameters, plus to have a default for the time the user does not make a choice.

Why have two ways of choosing?

One is to allow a (relatively) *permanent* choice that applies automatically each time the software is run without us having to tell it over and over what we want it to do.

The permanent choices may be stored in a configuration file, typically found in the user's home directory. The file usually has the same name as the application but is started with a dot. Often *"rc"* is added to the file name. So, ours could be `~/pinhole` or `~/pinholerc`. (The `~/` means current user's home directory.)

The configuration file is used mostly by programs that have many configurable parameters. Those that have only one (or a few) often use a different method: They expect to find the parameter in an *environment variable*. In our case, we might look at an environment variable named `PINHOLE`.

Usually, a program uses one or the other of the above methods. Otherwise, if a configuration file said one thing, but an environment variable another, the program might get confused (or just too complicated).

Because we only need to choose *one* such parameter, we will go with the second method and search the environment for a variable named `PINHOLE`.

The other way allows us to make *ad hoc* decisions: *"Though I usually want you to use 0.039, this time I want 0.03872."* In other words, it allows us to *override* the permanent choice.

This type of choice is usually done with command line parameters.

Finally, a program *always* needs a *default*. The user may not make any choices. Perhaps he does not know what to choose. Perhaps he is "just browsing." Preferably, the default will be the value most users would choose anyway. That way they do not need to choose. Or, rather, they can choose the default without an additional effort.

Given this system, the program may find conflicting options, and handle them this way:

1. If it finds an *ad hoc* choice (e.g., command line parameter), it should accept that choice. It must ignore any permanent choice and any default.
2. *Otherwise*, if it finds a permanent option (e.g., an environment variable), it should accept it, and ignore the default.
3. *Otherwise*, it should use the default.

We also need to decide what *format* our `PC` option should have.

At first site, it seems obvious to use the `PINHOLE=0.04` format for the environment variable, and `-p0.04` for the command line.

Allowing that is actually a security risk. The `PC` constant is a very small number. Naturally, we will test our software using various small values of `PC`. But what will happen if someone runs the program choosing a huge value?

It may crash the program because we have not designed it to handle huge numbers.

Or, we may spend more time on the program so it can handle huge numbers. We might do that if we were writing commercial software for computer illiterate audience.

Or, we might say, *"Tough! The user should know better."*

Or, we just may make it impossible for the user to enter a huge number. This is the approach we will take: We will use an *implied 0.* prefix.

In other words, if the user wants `0.04`, we will expect him to type `-p04`, or set `PINHOLE=04` in his environment. So, if he says `-p9999999`, we will interpret it as `0.9999999`—still ridiculous but at least safer.

Secondly, many users will just want to go with either Bender's constant or Connors' constant. To make it easier on them, we will interpret `-b` as identical to `-p04`, and `-c` as identical to `-p037`.

### 28.13.3.3 The Output

We need to decide what we want our software to send to the output, and in what format.

Since our input allows for an unspecified number of focal length entries, it makes sense to use a traditional database-style output of showing the result of the calculation for each focal length on a separate line, while separating all values on one line by a `tab` character.

Optionally, we should also allow the user to specify the use of the CSV format we have studied earlier. In this case, we will print out a line of comma-separated names describing each field of every line, then show our results as before, but substituting a `comma` for the `tab`.

We need a command line option for the CSV format. We cannot use `-c` because that already means *use Connors' constant*. For some strange reason, many web sites refer to CSV files as *"Excel spreadsheet"* (though the CSV format predates Excel). We will, therefore, use the `-e` switch to inform our software we want the output in the CSV format.

We will start each line of the output with the focal length. This may sound repetitious at first, especially in the interactive mode: The user types in the focal length, and we are repeating it.

But the user can type several focal lengths on one line. The input can also come in from a file or from the output of another program. In that case the user does not see the input at all.

By the same token, the output can go to a file which we will want to examine later, or it could go to the printer, or become the input of another program.

So, it makes perfect sense to start each line with the focal length as entered by the user.

No, wait! Not as entered by the user. What if the user types in something like this:

```
00000000150
```

Clearly, we need to strip those leading zeros.

So, we might consider reading the user input as is, converting it to binary inside the FPU, and printing it out from there.



But...

What if the user types something like this:

```
17459765723452353453534535353530530534563507309676764423
```

Ha! The packed decimal FPU format lets us input 18–digit numbers. But the user has entered more than 18 digits. How do we handle that?

Well, we *could* modify our code to read the first 18 digits, enter it to the FPU, then read more, multiply what we already have on the TOS by 10 raised to the number of additional digits, then add to it.

Yes, we could do that. But in *this* program it would be ridiculous (in a different one it may be just the thing to do): Even the circumference of the Earth expressed in millimeters only takes 11 digits. Clearly, we cannot build a camera that large (not yet, anyway).

So, if the user enters such a huge number, he is either bored, or testing us, or trying to break into the system, or playing games—doing anything but designing a pinhole camera.

What will we do?

We will slap him in the face, in a manner of speaking:

```
17459765723452353453534535353530530534563507309676764423 ??? ??? ??? ??? ???
```

To achieve that, we will simply ignore any leading zeros. Once we find a non–zero digit, we will initialize a counter to 0 and start taking three steps:

1. Send the digit to the output.
2. Append the digit to a buffer we will use later to produce the packed decimal we can send to the FPU.
3. Increase the counter.

Now, while we are taking these three steps, we also need to watch out for one of two conditions:

- If the counter grows above 18, we stop appending to the buffer. We continue reading the digits and sending them to the output.
- If, or rather *when*, the next input character is not a digit, we are done inputting for now.

Incidentally, we can simply discard the non–digit, unless it is a #, which we must return to the input stream. It starts a comment, so we must see it after we are done producing output and start looking for more input.

That still leaves one possibility uncovered: If all the user enters is a zero (or several zeros), we will never find a non–zero to display.

We can determine this has happened whenever our counter stays at 0. In that case we need to send 0 to the output, and perform another "slap in the face":

```
0 ??? ??? ??? ??? ???
```

Once we have displayed the focal length and determined it is valid (greater than 0 but not exceeding 18 digits), we can calculate the pinhole diameter.

It is not by coincidence that *pinhole* contains the word *pin*. Indeed, many a pinhole literally is a *pin hole*, a hole carefully punched with the tip of a pin.

That is because a typical pinhole is very small. Our formula gets the result in millimeters. We will multiply it by 1000, so we can output the result in *microns*.

At this point we have yet another trap to face: *Too much precision*.

Yes, the FPU was designed for high precision mathematics. But we are not dealing with high precision mathematics. We are dealing with physics (optics, specifically).

Suppose we want to convert a truck into a pinhole camera (we would not be the first ones to do that!). Suppose its box is 12 meters long, so we have the focal length of 12000. Well, using Bender's constant, it gives us square root of 12000 multiplied by 0.04, which is 4.381780460 millimeters, or 4381.780460 microns.

Put either way, the result is absurdly precise. Our truck is not *exactly* 12000 millimeters long. We did not measure its length with such a precision, so stating we need a pinhole with the diameter of 4.381780460 millimeters is, well, deceiving. 4.4 millimeters would do just fine.

**Note:** I "only" used ten digits in the above example. Imagine the absurdity of going for all 18!

We need to limit the number of significant digits of our result. One way of doing it is by using an integer representing microns. So, our truck would need a pinhole with the diameter of 4382 microns. Looking at that number, we still decide that 4400 microns, or 4.4 millimeters is close enough.

Additionally, we can decide that no matter how big a result we get, we only want to display four significant digits (or any other number of them, of course). Alas, the FPU does not offer rounding to a specific number of digits (after all, it does not view the numbers as decimal but as binary).

We, therefore, must devise an algorithm to reduce the number of significant digits.

Here is mine (I think it is awkward—if you know a better one, *please*, let me know):

1. Initialize a counter to 0.
2. While the number is greater than or equal to 10000, divide it by 10 and increase the counter.
3. Output the result.
4. While the counter is greater than 0, output 0 and decrease the counter.

**Note:** The 10000 is only good if you want *four* significant digits. For any other number of significant digits, replace 10000 with 10 raised to the number of significant digits.

We will, then, output the pinhole diameter in microns, rounded off to four significant digits.

At this point, we know the *focal length* and the *pinhole diameter*. That means we have enough information to also calculate the *f-number*.

We will display the *f-number*, rounded to four significant digits. Chances are the *f-number* will tell us very little. To make it more meaningful, we can find the nearest *normalized f-number*, i.e., the nearest power of the square root of 2.

We do that by multiplying the actual *f*-number by itself, which, of course, will give us its *square*. We will then calculate its base-2 logarithm, which is much easier to do than calculating the base-square-root-of-2 logarithm! We will round the result to the nearest integer. Next, we will raise 2 to the result. Actually, the FPU gives us a good shortcut to do that: We can use the `fscale` op code to "scale" 1, which is analogous to shifting an integer left. Finally, we calculate the square root of it all, and we have the nearest normalized *f*-number.

If all that sounds overwhelming—or too much work, perhaps—it may become much clearer if you see the code. It takes 9 op codes altogether:

```

    fmul st0, st0
    fld1
    fld st1
    fyl2x
    frndint
    fld1
    fscale
    fsqrt
    fstp st1

```

The first line, `fmul st0, st0`, squares the contents of the TOS (top of the stack, same as `st`, called `st0` by **nasm**). The `fld1` pushes 1 on the TOS.

The next line, `fld st1`, pushes the square back to the TOS. At this point the square is both in `st` and `st(2)` (it will become clear why we leave a second copy on the stack in a moment). `st(1)` contains 1.

Next, `fyl2x` calculates base-2 logarithm of `st` multiplied by `st(1)`. That is why we placed 1 on `st(1)` before.

At this point, `st` contains the logarithm we have just calculated, `st(1)` contains the square of the actual *f*-number we saved for later.

`frndint` rounds the TOS to the nearest integer. `fld1` pushes a 1. `fscale` shifts the 1 we have on the TOS by the value in `st(1)`, effectively raising 2 to `st(1)`.

Finally, `fsqrt` calculates the square root of the result, i.e., the nearest normalized *f*-number.

We now have the nearest normalized *f*-number on the TOS, the base-2 logarithm rounded to the nearest integer in `st(1)`, and the square of the actual *f*-number in `st(2)`. We are saving the value in `st(2)` for later.

But we do not need the contents of `st(1)` anymore. The last line, `fstp st1`, places the contents of `st` to `st(1)`, and pops. As a result, what was `st(1)` is now `st`, what was `st(2)` is now `st(1)`, etc. The new `st` contains the normalized *f*-number. The new `st(1)` contains the square of the actual *f*-number we have stored there for posterity.

At this point, we are ready to output the normalized *f*-number. Because it is normalized, we will not round it off to four significant digits, but will send it out in its full precision.

The normalized *f*-number is useful as long as it is reasonably small and can be found on our light meter. Otherwise we need a different method of determining proper exposure.

Earlier we have figured out the formula of calculating proper exposure at an arbitrary *f*-number from that measured at a different *f*-number.

Every light meter I have ever seen can determine proper exposure at *f*5.6. We will, therefore, calculate an "*f*5.6 multiplier," i.e., by how much we need to multiply the exposure measured at *f*5.6 to determine the proper exposure for our pinhole camera.

From the above formula we know this factor can be calculated by dividing our *f*-number (the actual one, not the normalized one) by 5.6, and squaring the result.

Mathematically, dividing the square of our  $f$ -number by the square of 5.6 will give us the same result.

Computationally, we do not want to square two numbers when we can only square one. So, the first solution seems better at first.

But...

5.6 is a *constant*. We do not have to have our FPU waste precious cycles. We can just tell it to divide the square of the  $f$ -number by whatever 5.6<sup>2</sup> equals to. Or we can divide the  $f$ -number by 5.6, and then square the result. The two ways now seem equal.

But, they are not!

Having studied the principles of photography above, we remember that the 5.6 is actually square root of 2 raised to the fifth power. An *irrational* number. The square of this number is *exactly* 32.

Not only is 32 an integer, it is a power of 2. We do not need to divide the square of the  $f$ -number by 32. We only need to use `fscale` to shift it right by five positions. In the FPU lingo it means we will `fscale` it with `st(1)` equal to -5. That is *much faster* than a division.

So, now it has become clear why we have saved the square of the  $f$ -number on the top of the FPU stack. The calculation of the `f5.6` multiplier is the easiest calculation of this entire program! We will output it rounded to four significant digits.

There is one more useful number we can calculate: The number of stops our  $f$ -number is from `f5.6`. This may help us if our  $f$ -number is just outside the range of our light meter, but we have a shutter which lets us set various speeds, and this shutter uses stops.

Say, our  $f$ -number is 5 stops from `f5.6`, and the light meter says we should use 1/1000 sec. Then we can set our shutter speed to 1/1000 first, then move the dial by 5 stops.

This calculation is quite easy as well. All we have to do is to calculate the base-2 logarithm of the `f5.6` multiplier we had just calculated (though we need its value from before we rounded it off). We then output the result rounded to the nearest integer. We do not need to worry about having more than four significant digits in this one: The result is most likely to have only one or two digits anyway.

## 28.13.4 FPU Optimizations

In assembly language we can optimize the FPU code in ways impossible in high languages, including C.

Whenever a C function needs to calculate a floating-point value, it loads all necessary variables and constants into FPU registers. It then does whatever calculation is required to get the correct result. Good C compilers can optimize that part of the code really well.

It "returns" the value by leaving the result on the TOS. However, before it returns, it cleans up. Any variables and constants it used in its calculation are now gone from the FPU.

It cannot do what we just did above: We calculated the square of the  $f$ -number and kept it on the stack for later use by another function.

We *knew* we would need that value later on. We also knew we had enough room on the stack (which only has room for 8 numbers) to store it there.

A C compiler has no way of knowing that a value it has on the stack will be required again in the very near future.

Of course, the C programmer may know it. But the only recourse he has is to store the value in a memory variable.

That means, for one, the value will be changed from the 80-bit precision used internally by the FPU to a *C double* (64 bits) or even *single* (32 bits).

That also means that the value must be moved from the TOS into the memory, and then back again. Alas, of all FPU operations, the ones that access the computer memory are the slowest.

So, whenever programming the FPU in assembly language, look for the ways of keeping intermediate results on the FPU stack.

We can take that idea even further! In our program we are using a *constant* (the one we named `PC`).

It does not matter how many pinhole diameters we are calculating: 1, 10, 20, 1000, we are always using the same constant. Therefore, we can optimize our program by keeping the constant on the stack all the time.

Early on in our program, we are calculating the value of the above constant. We need to divide our input by 10 for every digit in the constant.

It is much faster to multiply than to divide. So, at the start of our program, we divide 10 into 1 to obtain 0.1, which we then keep on the stack: Instead of dividing the input by 10 for every digit, we multiply it by 0.1.

By the way, we do not input 0.1 directly, even though we could. We have a reason for that: While 0.1 can be expressed with just one decimal place, we do not know how many *binary* places it takes. We, therefore, let the FPU calculate its binary value to its own high precision.

We are using other constants: We multiply the pinhole diameter by 1000 to convert it from millimeters to microns. We compare numbers to 10000 when we are rounding them off to four significant digits. So, we keep both, 1000 and 10000, on the stack. And, of course, we reuse the 0.1 when rounding off numbers to four digits.

Last but not least, we keep -5 on the stack. We need it to scale the square of the `f`-number, instead of dividing it by 32. It is not by coincidence we load this constant last. That makes it the top of the stack when only the constants are on it. So, when the square of the `f`-number is being scaled, the -5 is at `st(1)`, precisely where `fscale` expects it to be.

It is common to create certain constants from scratch instead of loading them from the memory. That is what we are doing with -5:

```
fld1 ; TOS = 1
fadd st0, st0 ; TOS = 2
fadd st0, st0 ; TOS = 4
fld1 ; TOS = 1
faddp st1, st0 ; TOS = 5
fchs ; TOS = -5
```

We can generalize all these optimizations into one rule: *Keep repeat values on the stack!*

**Tip:** *PostScript* is a stack-oriented programming language. There are many more books available about PostScript than about the FPU assembly language: Mastering PostScript will help you master the FPU.

## 28.13.5 pinhole—The Code

```
;;;;;;;; pinhole.asm ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;
```

```

; Find various parameters of a pinhole camera construction and use
;
; Started: 9-Jun-2001
; Updated: 10-Jun-2001
;
; Copyright (c) 2001 G. Adam Stanislav
; All rights reserved.
;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
%include 'system.inc'

%define BUFSIZE 2048

section .data
align 4
ten dd 10
thousand dd 1000
tthou dd 10000
fd.in dd stdin
fd.out dd stdout
envar db 'PINHOLE=' ; Exactly 8 bytes, or 2 dwords long
pinhole db '04,', ; Bender's constant (0.04)
connors db '037', 0Ah ; Connors' constant
usg db 'Usage: pinhole [-b] [-c] [-e] [-p <value>] [-o <outfile>] [-i <infile>]', 0Ah
usglen equ $-usg
iemsg db "pinhole: Can't open input file", 0Ah
iemlen equ $-iemsg
oemsg db "pinhole: Can't create output file", 0Ah
oemlen equ $-oemsg
pinmsg db "pinhole: The PINHOLE constant must not be 0", 0Ah
pinlen equ $-pinmsg
toobig db "pinhole: The PINHOLE constant may not exceed 18 decimal places", 0Ah
biglen equ $-toobig
huhmsg db 9, '???'
separ db 9, '???'
sep2 db 9, '???'
sep3 db 9, '???'
sep4 db 9, '???' , 0Ah
huhlen equ $-huhmsg
header db 'focal length in millimeters,pinhole diameter in microns,'
db 'F-number,normalized F-number,F-5.6 multiplier,stops '
db 'from F-5.6', 0Ah
headlen equ $-header

section .bss
ibuffer resb BUFSIZE
obuffer resb BUFSIZE
dbuffer resb 20 ; decimal input buffer
bbuffer resb 10 ; BCD buffer

section .text
align 4

```

```
huh:
    call write
    push dword huhlen
    push dword huhmsg
    push dword [fd.out]
    sys.write
    add esp, byte 12
    ret

align 4
perr:
    push dword pinlen
    push dword pinmsg
    push dword stderr
    sys.write
    push dword 4 ; return failure
    sys.exit

align 4
consttoobig:
    push dword biglen
    push dword toobig
    push dword stderr
    sys.write
    push dword 5 ; return failure
    sys.exit

align 4
ierr:
    push dword iemlen
    push dword iemsg
    push dword stderr
    sys.write
    push dword 1 ; return failure
    sys.exit

align 4
oerr:
    push dword oemlen
    push dword oemsg
    push dword stderr
    sys.write
    push dword 2
    sys.exit

align 4
usage:
    push dword usglen
    push dword usg
    push dword stderr
    sys.write
    push dword 3
    sys.exit
```

```

align 4
global _start
_start:
    add esp, byte 8 ; discard argc and argv[0]
    sub esi, esi

.arg:
    pop ecx
    or ecx, ecx
    je near .getenv ; no more arguments

; ECX contains the pointer to an argument
    cmp byte [ecx], '-'
    jne usage

    inc ecx
    mov ax, [ecx]
    inc ecx

.o:
    cmp al, 'o'
    jne .i

; Make sure we are not asked for the output file twice
    cmp dword [fd.out], stdout
    jne usage

; Find the path to output file - it is either at [ECX+1],
; i.e., -ofile --
; or in the next argument,
; i.e., -o file

    or ah, ah
    jne .openoutput
    pop ecx
    jecxz usage

.openoutput:
    push dword 420 ; file mode (644 octal)
    push dword 0200h | 0400h | 01h
    ; O_CREAT | O_TRUNC | O_WRONLY
    push ecx
    sys.open
    jc near oerr

    add esp, byte 12
    mov [fd.out], eax
    jmp short .arg

.i:
    cmp al, 'i'
    jne .p

```



```

; Make sure we are not asked twice
cmp dword [fd.in], stdin
jne near usage

; Find the path to the input file
or ah, ah
jne .openinput
pop ecx
or ecx, ecx
je near usage

.openinput:
push dword 0 ; O_RDONLY
push ecx
sys.open
jc near ierr ; open failed

add esp, byte 8
mov [fd.in], eax
jmp .arg

.p:
cmp al, 'p'
jne .c
or ah, ah
jne .pcheck

pop ecx
or ecx, ecx
je near usage

mov ah, [ecx]

.pcheck:
cmp ah, '0'
jl near usage
cmp ah, '9'
ja near usage
mov esi, ecx
jmp .arg

.c:
cmp al, 'c'
jne .b
or ah, ah
jne near usage
mov esi, connors
jmp .arg

.b:
cmp al, 'b'
jne .e

```

```

or ah, ah
jne near usage
mov esi, pinhole
jmp .arg

.e:
cmp al, 'e'
jne near usage
or ah, ah
jne near usage
mov al, ','
mov [huhmsg], al
mov [separ], al
mov [sep2], al
mov [sep3], al
mov [sep4], al
jmp .arg

align 4
.getenv:
; If ESI = 0, we did not have a -p argument,
; and need to check the environment for "PINHOLE="
or esi, esi
jne .init

sub ecx, ecx

.nextenv:
pop esi
or esi, esi
je .default ; no PINHOLE envar found

; check if this envar starts with 'PINHOLE='
mov edi, envar
mov cl, 2 ; 'PINHOLE=' is 2 dwords long
rep cmpsd
jne .nextenv

; Check if it is followed by a digit
mov al, [esi]
cmp al, '0'
jl .default
cmp al, '9'
jbe .init
; fall through

align 4
.default:
; We got here because we had no -p argument,
; and did not find the PINHOLE envar.
mov esi, pinhole
; fall through

```

```

align 4
.init:
  sub eax, eax
  sub ebx, ebx
  sub ecx, ecx
  sub edx, edx
  mov edi, dbuffer+1
  mov byte [dbuffer], '0'

; Convert the pinhole constant to real
.constloop:
  lodsb
  cmp al, '9'
  ja .setconst
  cmp al, '0'
  je .processconst
  jb .setconst

  inc dl

.processconst:
  inc cl
  cmp cl, 18
  ja near consttoobig
  stosb
  jmp short .constloop

align 4
.setconst:
  or dl, dl
  je near perr

finit
fild dword [tthou]

fld1
fild dword [ten]
fdivp st1, st0

fild dword [thousand]
mov edi, obuffer

mov ebp, ecx
call bcdload

.constdiv:
fmul st0, st2
loop .constdiv

fld1
fadd st0, st0
fadd st0, st0
fld1

```

```

faddp st1, st0
fchs

; If we are creating a CSV file,
; print header
cmp byte [separ], ','
jne .bigloop

push dword headlen
push dword header
push dword [fd.out]
sys.write

.bigloop:
call getchar
jc near done

; Skip to the end of the line if you got '#'
cmp al, '#'
jne .num
call skiptoel
jmp short .bigloop

.num:
; See if you got a number
cmp al, '0'
jl .bigloop
cmp al, '9'
ja .bigloop

; Yes, we have a number
sub ebp, ebp
sub edx, edx

.number:
cmp al, '0'
je .number0
mov dl, 1

.number0:
or dl, dl ; Skip leading 0's
je .nextnumber
push eax
call putchar
pop eax
inc ebp
cmp ebp, 19
jae .nextnumber
mov [dbuffer+ebp], al

.nextnumber:
call getchar
jc .work

```

```

cmp al, '#'
je .ungetc
cmp al, '0'
jl .work
cmp al, '9'
ja .work
jmp short .number

.ungetc:
dec esi
inc ebx

.work:
; Now, do all the work
or dl, dl
je near .work0

cmp ebp, 19
jae near .toobig

call bcdload

; Calculate pinhole diameter

fld st0 ; save it
fsqrt
fmul st0, st3
fld st0
fmul st5
sub ebp, ebp

; Round off to 4 significant digits
.diameter:
fcom st0, st7
fstsw ax
sahf
jb .printdiameter
fmul st0, st6
inc ebp
jmp short .diameter

.printdiameter:
call printnumber ; pinhole diameter

; Calculate F-number

fdivp st1, st0
fld st0

sub ebp, ebp

.fnumber:
fcom st0, st6

```

```

fstsw ax
sahf
jb .printfnumber
fmul st0, st5
inc ebp
jmp short .fnumber

.printfnumber:
call printnumber ; F number

; Calculate normalized F-number
fmul st0, st0
fld1
fld st1
fyl2x
frndint
fld1
fscale
fsqrt
fstp st1

sub ebp, ebp
call printnumber

; Calculate time multiplier from F-5.6

fscale
fld st0

; Round off to 4 significant digits
.fmul:
fcom st0, st6
fstsw ax
sahf

jb .printfmul
inc ebp
fmul st0, st5
jmp short .fmul

.printfmul:
call printnumber ; F multiplier

; Calculate F-stops from 5.6

fld1
fxch st1
fyl2x

sub ebp, ebp
call printnumber

mov al, 0Ah

```

```

call putchar
jmp .bigloop

.work0:
mov al, '0'
call putchar

align 4
.toobig:
call huh
jmp .bigloop

align 4
done:
call write ; flush output buffer

; close files
push dword [fd.in]
sys.close

push dword [fd.out]
sys.close

finit

; return success
push dword 0
sys.exit

align 4
skiptoeol:
; Keep reading until you come to cr, lf, or eof
call getchar
jc done
cmp al, 0Ah
jne .cr
ret

.cr:
cmp al, 0Dh
jne skiptoeol
ret

align 4
getchar:
or ebx, ebx
jne .fetch

call read

.fetch:
lodsb
dec ebx

```

```

    clc
    ret

read:
    jecxz .read
    call write

.read:
    push dword BUFSIZE
    mov esi, ibuffer
    push esi
    push dword [fd.in]
    sys.read
    add esp, byte 12
    mov ebx, eax
    or  eax, eax
    je  .empty
    sub eax, eax
    ret

align 4
.empty:
    add esp, byte 4
    stc
    ret

align 4
putchar:
    stosb
    inc ecx
    cmp ecx, BUFSIZE
    je write
    ret

align 4
write:
    jecxz .ret ; nothing to write
    sub edi, ecx ; start of buffer
    push ecx
    push edi
    push dword [fd.out]
    sys.write
    add esp, byte 12
    sub eax, eax
    sub ecx, ecx ; buffer is empty now
.ret:
    ret

align 4
bcdload:
    ; EBP contains the number of chars in dbuffer
    push ecx
    push esi

```



```

push edi

lea ecx, [ebp+1]
lea esi, [dbuffer+ebp-1]
shr ecx, 1

std

mov edi, bbuffer
sub eax, eax
mov [edi], eax
mov [edi+4], eax
mov [edi+2], ax

.loop:
lodsw
sub ax, 3030h
shl al, 4
or al, ah
mov [edi], al
inc edi
loop .loop

fbld [bbuffer]

cld
pop edi
pop esi
pop ecx
sub eax, eax
ret

align 4
printnumber:
push ebp
mov al, [separ]
call putchar

; Print the integer at the TOS
mov ebp, bbuffer+9
fbstp [bbuffer]

; Check the sign
mov al, [ebp]
dec ebp
or al, al
jns .leading

; We got a negative number (should never happen)
mov al, '-'
call putchar

.leading:

```

```

; Skip leading zeros
mov al, [ebp]
dec ebp
or al, al
jne .first
cmp ebp, bbuffer
jae .leading

; We are here because the result was 0.
; Print '0' and return
mov al, '0'
jmp putchar

.first:
; We have found the first non-zero.
; But it is still packed
test al, 0F0h
jz .second
push eax
shr al, 4
add al, '0'
call putchar
pop eax
and al, 0Fh

.second:
add al, '0'
call putchar

.next:
cmp ebp, bbuffer
jb .done

mov al, [ebp]
push eax
shr al, 4
add al, '0'
call putchar
pop eax
and al, 0Fh
add al, '0'
call putchar

dec ebp
jmp short .next

.done:
pop ebp
or ebp, ebp
je .ret

.zeros:
mov al, '0'

```

```

    call putchar
    dec ebp
    jne .zeros

.ret:
    ret

```

The code follows the same format as all the other filters we have seen before, with one subtle exception:

We are no longer assuming that the end of input implies the end of things to do, something we took for granted in the *character-oriented* filters.

This filter does not process characters. It processes a *language* (albeit a very simple one, consisting only of numbers).

When we have no more input, it can mean one of two things:

- We are done and can quit. This is the same as before.
- The last character we have read was a digit. We have stored it at the end of our ASCII-to-float conversion buffer. We now need to convert the contents of that buffer into a number and write the last line of our output.

For that reason, we have modified our `getchar` and our `read` routines to return with the `carry flag clear` whenever we are fetching another character from the input, or the `carry flag set` whenever there is no more input.

Of course, we are still using assembly language magic to do that! Take a good look at `getchar`. It *always* returns with the `carry flag clear`.

Yet, our main code relies on the `carry flag` to tell it when to quit—and it works.

The magic is in `read`. Whenever it receives more input from the system, it just returns to `getchar`, which fetches a character from the input buffer, *clears* the `carry flag` and returns.

But when `read` receives no more input from the system, it does *not* return to `getchar` at all. Instead, the `add esp, byte 4` op code adds 4 to ESP, *sets* the `carry flag`, and returns.

So, where does it return to? Whenever a program uses the `call` op code, the microprocessor pushes the return address, i.e., it stores it on the top of the stack (not the FPU stack, the system stack, which is in the memory). When a program uses the `ret` op code, the microprocessor `pops` the return value from the stack, and jumps to the address that was stored there.

But since we added 4 to ESP (which is the stack pointer register), we have effectively given the microprocessor a minor case of *amnesia*: It no longer remembers it was `getchar` that called `read`.

And since `getchar` never pushed anything before calling `read`, the top of the stack now contains the return address to whatever or whoever called `getchar`. As far as that caller is concerned, he called `getchar`, which returned with the `carry flag set`!

Other than that, the `bcdload` routine is caught up in the middle of a Lilliputian conflict between the Big-Endians and the Little-Endians.

It is converting the text representation of a number into that number: The text is stored in the big-endian order, but the *packed decimal* is little-endian.

To solve the conflict, we use the `std` op code early on. We cancel it with `cld` later on: It is quite important we do not `call` anything that may depend on the default setting of the *direction flag* while `std` is active.

Everything else in this code should be quite clear, providing you have read the entire chapter that precedes it.

It is a classical example of the adage that programming requires a lot of thought and only a little coding. Once we have thought through every tiny detail, the code almost writes itself.

## 28.13.6 Using pinhole

Because we have decided to make the program *ignore* any input except for numbers (and even those inside a comment), we can actually perform *textual queries*. We do not *have to*, but we *can*.

In my humble opinion, forming a textual query, instead of having to follow a very strict syntax, makes software much more user friendly.

Suppose we want to build a pinhole camera to use the 4x5 inch film. The standard focal length for that film is about 150mm. We want to *fine-tune* our focal length so the pinhole diameter is as round a number as possible. Let us also suppose we are quite comfortable with cameras but somewhat intimidated by computers. Rather than just have to type in a bunch of numbers, we want to *ask* a couple of questions.

Our session might look like this:

```
% pinhole

Computer,

What size pinhole do I need for the focal length of 150?
150 490 306 362 2930 12
Hmmm... How about 160?
160 506 316 362 3125 12
Let's make it 155, please.
155 498 311 362 3027 12
Ah, let's try 157...
157 501 313 362 3066 12
156?
156 500 312 362 3047 12
That's it! Perfect! Thank you very much!

^D
```

We have found that while for the focal length of 150, our pinhole diameter should be 490 microns, or 0.49 mm, if we go with the almost identical focal length of 156 mm, we can get away with a pinhole diameter of exactly one half of a millimeter.

## 28.13.7 Scripting

Because we have chosen the # character to denote the start of a comment, we can treat our **pinhole** software as a *scripting language*.

You have probably seen **shell scripts** that start with:

```
#!/bin/sh

...or...

#!/bin/sh
```

...because the blank space after the #! is optional.

Whenever Unix is asked to run an executable file which starts with the #!, it assumes the file is a script. It adds the command to the rest of the first line of the script, and tries to execute that.

Suppose now that we have installed **pinhole** in **/usr/local/bin/**, we can now write a script to calculate various pinhole diameters suitable for various focal lengths commonly used with the 120 film.

The script might look something like this:

```
#!/usr/local/bin/pinhole -b -i
# Find the best pinhole diameter
# for the 120 film

### Standard
80

### Wide angle
30, 40, 50, 60, 70

### Telephoto
100, 120, 140
```

Because 120 is a medium size film, we may name this file **medium**.

We can set its permissions to execute, and run it as if it were a program:

```
% chmod 755 medium
% ./medium
```

Unix will interpret that last command as:

```
% /usr/local/bin/pinhole -b -i ./medium
```

It will run that command and display:

```
80 358 224 256 1562 11
30 219 137 128 586 9
40 253 158 181 781 10
50 283 177 181 977 10
60 310 194 181 1172 10
70 335 209 181 1367 10
100 400 250 256 1953 11
120 438 274 256 2344 11
140 473 296 256 2734 11
```

Now, let us enter:

```
% ./medium -c
```

Unix will treat that as:

```
% /usr/local/bin/pinhole -b -i ./medium -c
```

That gives it two conflicting options: **-b** and **-c** (Use Bender's constant and use Connors' constant). We have programmed it so later options override early ones—our program will calculate everything using Connors' constant:

```
80 331 242 256 1826 11
30 203 148 128 685 9
40 234 171 181 913 10
```

```

50 262 191 181 1141 10
60 287 209 181 1370 10
70 310 226 256 1598 11
100 370 270 256 2283 11
120 405 296 256 2739 11
140 438 320 362 3196 12

```

We decide we want to go with Bender's constant after all. We want to save its values as a comma-separated file:

```

% ./medium -b -e > bender
% cat bender
focal length in millimeters,pinhole diameter in microns,F-number,normalized F-number,F-
5.6 multiplier,stops from F-5.6
80,358,224,256,1562,11
30,219,137,128,586,9
40,253,158,181,781,10
50,283,177,181,977,10
60,310,194,181,1172,10
70,335,209,181,1367,10
100,400,250,256,1953,11
120,438,274,256,2344,11
140,473,296,256,2734,11
%

```

## 28.14 Caveats

Assembly language programmers who "grew up" under MS DOS and Windows often tend to take shortcuts. Reading the keyboard scan codes and writing directly to video memory are two classical examples of practices which, under MS DOS are not frowned upon but considered the right thing to do.

The reason? Both the PC BIOS and MS DOS are notoriously slow when performing these operations.

You may be tempted to continue similar practices in the Unix environment. For example, I have seen a web site which explains how to access the keyboard scan codes on a popular Unix clone.

That is generally a *very bad idea* in Unix environment! Let me explain why.

### 28.14.1 Unix Is Protected

For one thing, it may simply not be possible. Unix runs in protected mode. Only the kernel and device drivers are allowed to access hardware directly. Perhaps a particular Unix clone will let you read the keyboard scan codes, but chances are a real Unix operating system will not. And even if one version may let you do it, the next one may not, so your carefully crafted software may become a dinosaur overnight.

### 28.14.2 Unix Is an Abstraction

But there is a much more important reason not to try accessing the hardware directly (unless, of course, you are writing a device driver), even on the Unix-like systems that let you do it:

*Unix is an abstraction!*

There is a major difference in the philosophy of design between MS DOS and Unix. MS DOS was designed as a single-user system. It is run on a computer with a keyboard and a video screen attached directly to that computer. User input is almost guaranteed to come from that keyboard. Your program's output virtually always ends up on that screen.

This is NEVER guaranteed under Unix. It is quite common for a Unix user to pipe and redirect program input and output:

```
% program1 | program2 | program3 > file1
```

If you have written **program2**, your input does not come from the keyboard but from the output of **program1**. Similarly, your output does not go to the screen but becomes the input for **program3** whose output, in turn, goes to **file1**.

But there is more! Even if you made sure that your input comes from, and your output goes to, the terminal, there is no guarantee the terminal is a PC: It may not have its video memory where you expect it, nor may its keyboard be producing PC-style scan codes. It may be a Macintosh, or any other computer.

Now you may be shaking your head: My software is in PC assembly language, how can it run on a Macintosh? But I did not say your software would be running on a Macintosh, only that its terminal may be a Macintosh.

Under Unix, the terminal does not have to be directly attached to the computer that runs your software, it can even be on another continent, or, for that matter, on another planet. It is perfectly possible that a Macintosh user in Australia connects to a Unix system in North America (or anywhere else) via **telnet**. The software then runs on one computer, while the terminal is on a different computer: If you try to read the scan codes, you will get the wrong input!

Same holds true about any other hardware: A file you are reading may be on a disk you have no direct access to. A camera you are reading images from may be on a space shuttle, connected to you via satellites.

That is why under Unix you must never make any assumptions about where your data is coming from and going to. Always let the system handle the physical access to the hardware.

**Note:** These are caveats, not absolute rules. Exceptions are possible. For example, if a text editor has determined it is running on a local machine, it may want to read the scan codes directly for improved control. I am not mentioning these caveats to tell you what to do or what not to do, just to make you aware of certain pitfalls that await you if you have just arrived to Unix from MS DOS. Of course, creative people often break rules, and it is OK as long as they know they are breaking them and why.

## 28.15 Acknowledgements

This tutorial would never have been possible without the help of many experienced FreeBSD programmers from the FreeBSD technical discussions mailing list <freebsd-hackers@FreeBSD.org>, many of whom have patiently answered my questions, and pointed me in the right direction in my attempts to explore the inner workings of Unix system programming in general and FreeBSD in particular.

Thomas M. Sommers opened the door for me. His *How do I write "Hello, world" in FreeBSD assembler?* (<http://home.ptd.net/~tms2/hello.html>) web page was my first encounter with an example of assembly language programming under FreeBSD.

Jake Burkholder has kept the door open by willingly answering all of my questions and supplying me with example assembly language source code.

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# Chapter 29 \* Alpha

Talk about the architectural specifics of FreeBSD/alpha.

Explanation of alignment errors, how to fix, how to ignore.

Example assembly language code for FreeBSD/alpha.

# Chapter 30 \* IA-64

Talk about the architectural specifics of FreeBSD/ia64.

# VI. Appendices

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