FreeBSD Developers' Handbook

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####

####

I.

####

1.

Contributed by Murray Stokely # Jeroen Ruigrok van der Werven.

1.1. # FreeBSD

############ FreeBSD ######################## ##########FreeBSD ############## ## programer #########

################# programming ############ #################### ############# ## ######### FreeBSD ######################

1.2. The BSD Vision

########### UNIX® like################### ##############(original software tools ideology)#

1.3.

##########

- ####################
- ############################ ###
- ############################# ############
- ##################################
- ## 10% ######### 90% ################
- ############
- ####(mechanism)#####(policy)# ######################

Scheifler & Gettys # "X Window System"

1.4. `/usr/src`

FreeBSD ######## CVS repository ## ## FreeBSD ####### `/usr/src` #

Directory	Description
`bin/`	Source for files in `/bin`

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

2.

Contributed by James Raynard # Murray Stokely.

2.1.

########### FreeBSD ##########(programing tools)# ################ UNIX® ###### # # ### ############## ############################ ##############################

2.2.

FreeBSD ############# ##### C#C++#Fortran # assembler(####)####(compiler), # FreeBSD ############## ### Perl ##### UNIX® #####`sed` ## `awk`# ##########FreeBSD# Ports collection ##############(interpreter), FreeBSD ######### POSIX® # ANSI C# ### ###### BSD ### ### FreeBSD ################################

############ UNIX® ################FreeBSD ############ ##################### ######## ##########################

################################ ########### UNIX® ######## ################# ##

2.3. Programming

####################################### ####################### ######## 2 #### ################(instruction) # “##(commands)”# ####### ###*(interpreter)*# ####### ## #*(compiler)*# ########################## ####(commands)######(###)############### ##########

2.3.1.

############################## ########################## ################# ################ ############################## ###########################(debugger)# ###################

################################## ### ## ####################### ############################# ###################### ###############################

##################################(interpreted languages)# ## Lisp#Smalltalk#Perl # Basic ###UNIX® # shell ## `sh` # `csh` ############################### shell “script”# ##

“housekeeping(##)” ### UNIX® ################# ### shell script
#########

2.3.2. FreeBSD

FreeBSD Ports Collection

Ports Collection ######### FreeBSD Handbook ## Ports###

BASIC

BASIC # Beginner's ALL-purpose Symbolic Instruction Code #### BASIC # 1950 ##### ############################### ## 1980#BASIC##### programmer ############ ###BASIC ## Visual Basic ####

FreeBSD Ports Collection ####### BASIC #### Bywater Basic ##### lang/bwbasic# # Phil Cockroft's Basic ###(#### Rabbit Basic)## lang/pbasic#

Lisp

LISP ## 1950 ################# LISP #### “number-crunching” languages(####### ######)################ LISP #########(numbers)######(lists)# ###### LISP #### ##### LISP # “List Processing” #### #####(Artificial Intelligence, AI)### LISP ###### ####

LISP #################################

LISP ####### UNIX® ######## FreeBSD # Ports Collection ##### GNU Common Lisp ### lang/gcl# Bruno Haible # Michael Stoll # CLISP ### lang/clisp ### CMUCL(## ###########)# ######## LISP ###(### C #### SLisp############### Common Lisp # ##) ####### lang/cmucl ## lang/slisp#

Perl

############ perl ### scripts ###### ######## WWW #### CGI Script ###

Perl # Ports Collection ## lang/perl5# # FreeBSD 4.X ### Perl ## `/usr/bin/perl` #

Scheme

Scheme # LISP ######Scheme ###### Common LISP ####### ## Scheme ########## ############### ###########################

Scheme ### lang/elk# Elk Scheme ###(########### Scheme ###)### lang/mit-scheme# SCM Scheme Interpreter ### lang/scm#

Icon

Icon #######Icon #######(String)###(Structure)##### FreeBSD Ports Collection ## ## Icon ######### lang/icon#

Logo

Logo ################################ #################Logo ######### #### ########## Logo ###################

Logo # FreeBSD Ports Collection ######## lang/logo#

Python

Python ############ Python ######## Python ########### ## Python ########### ###############(## Perl # Tcl)# #### Python ##################

FreeBSD Ports Collection ### lang/python#

Ruby

Ruby ############# Ruby ################################ ################# ####

FreeBSD Ports Collection ### lang/ruby8#

Tcl and Tk

Tcl ############ Tcl ############ Tcl ##### Tcl ############################# ###

Tcl ######## FreeBSD ######## Tcl ### Tcl 8.4# FreeBSD Ports Collection ### lang/tcl84#

2.3.3.

######################################[1]

########################## ############################### ################### ############ ######################## ############################ ########### ########################### ############################# #################### ############ ###########

########## Pascal#C # C++# C # C++ ####################### Programmer# Pascal ### ########################## FreeBSD ###### Pascal ### base system ## ## GNU Pascal Compiler # Free Pascal Compiler ##### lang/gpc # lang/fpc ####

########################-##-##-############## ############################### IDE (Integrated Development Environments) ##### FreeBSD ###### IDE ### base system ## ###### devel/kdevelop ## kdevelop ### Emacs ### IDE ##### #### # 2.7, “Using Emacs as a Development Environment” ######### Emacs ### IDE #####

2.4. # cc

######## GNU C compiler # GNU C++ compiler #### #### FreeBSD base system ##### ### `cc` # `gcc` ###### ##

---

[1] ################### core dump#

####################### FreeBSD #### #############################

1. ####(Pre-process)##################### ## expanding(##) C # marco#
2. ############## C/C++ ######################
3. ########## —— ######(machine code)#################(#######)# [2]
4. ########### —— ################# bit # byte#### 1 # 0#
5. ##
6. ########################
7. ################ run-time loader ##############
8. #################

##(*compiling*) ### 1 ## 4 #### —— ####### ##(*linking*)# ##### 1 ##### ####(*pre-processing*)# ### 3 ### 4 ## ##(*assembling*)#

########################### ## cc ########(front end)###################### ####

```
% cc foobar.c
```

`foobar.c` #############

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

########## —— ########### ############################## binary sort ### bubble sort# [3]

cc ################### #####################

`-o ##`

-o ###################### ############# `a.out` [4]

```
% cc foobar.c               ##### a.out
% cc -o foobar foobar.c     ##### foobar
```

`-c`

-c ###############(linking)# ############## Makefile

---

[2] ########### cc ################# #### machine-independent # *p-code*#

[3] #### binary sort # bubble sort ### ##########binary sort ###### bubble sort ##

[4] ## -o ##############

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

`foobar` # *object file*(####)# ######## object file

`-g`

-g ###### gdb ######################### ################################### ################################### -g ##################### ######## “#### (release version)” ################## -g #####

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

#################[5]

`-O`

-O ########### ############################### ##### O ################## ## ################# FreeBSD 2.10 release ## cc ### -O2 ##################

###############################

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

`foobar`

########## cc ################### ####### ANSI ### # ANSI ##### ISO ###

`-Wall`

-Wall ## cc ################## ####################### cc #############

`-ansi`

-ansi ## cc ######## ANSI C ##### ############################## ANSI ###

`-pedantic`

cc ##### ANSI C

#######cc ############################### ####################### ############ ############################## ################ *portable code*(#########)#

###################### #################################

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

####### `foobar.c` ########### ###### `foobar` #####

---

[5] ########## -o ######### ####### `a.out` ### ######## `foobar` ############ #############

`-l`*`library`*

gcc ###(linking)################

################## C ###### #############################(library)## ###########
######################

################ `libsomething.a` # ############ `-l`*`something`* ### #############
`libm.a` # ###### cc ##### `-lm`# ########################

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

####### gcc #################################

########### C++ ############# `-lg++` ### `-lstdc++` # #### FreeBSD # 2.2(#)##### ##
c++ ### cc# # FreeBSD # c++ #### g++

```
% cc -o foobar foobar.cc -lg++       ## FreeBSD 2.1.6 #######
% cc -o foobar foobar.cc -lstdc++    ## FreeBSD 2.2 ######
% c++ -o foobar foobar.cc
```

########## `foobar.cc` ###### `fooboar` ##### ######## UNIX® ### C++ ###### `.C`#
`.cxx` ### `.cc` ###### ## MS-DOS® ### `.cpp` ##########(#########)# gcc #########
######### ################# ######### `.cpp` ## C++ ########

2.4.1. ### cc

`sin()` ######### ########(##)######

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

`sin()` ######### ##### cc ##########(linking)######

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

-lm ##(###### 2.1 # 6 ##)

```
#include <stdio.h>

int main() {
 float f;

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

#######

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

################

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

########################

############################(prototype)# ################## int(##)# ##### ################# int#

###############

##########(prototype)#### `math.h` # #### include ############################

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

int main() {
...
```

####################

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

############### include `math.h` ### ###############

`foobar.c` # ######## `foobar` ####

a.out# # `-o` *`filename`* ###

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

`foobar` # # `ls` ########

MS-DOS® ################# ## UNIX® ###################### ###### `./foobar` ## “########### `foobar` ###”# ####### PATH

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

"." ##“######################”#

`test` ####

UNIX® ####### `/usr/bin` ###### ############## `test`### shell ####### `/usr/bin` # `test`#

```
% ./test
```

######################

core dumped

core dumped ######## ######## UNIX® ###### core memory ####### ######### ######### ###### core memory ###### `core` ##### ### programmer

core dumped

`gdb` ### core ##(##### # 2.6, “Debugging”)#

core memory ## dump #### ########## segmentation fault

###############################(illegal operation)# UNIX® #################

####“segmentation fault”#######

- ##### NULL ###(pointer)########

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

- #########(initialized)######

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

  ########################### ########### kernel ########### kernel ###### ################### #######################(data structures)#### ###### ###############

- ########(array)#######

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

- ##########(read-only memory)#######

  ```
  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 an another.

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.

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 manual 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 manual 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. [6]

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 `Makefile` s 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
```

---

[6] They do not use the `MAKEFILE` form as block capitals are often used for documentation files like `README` .

`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) in the ports collection.

This section is intended to be an introduction to using `gdb` and does not cover specialized 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 initialize 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 initialize 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`.

##

`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. [7] 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 customizable editor——indeed, it has been customized 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 summarize 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 customizable.
- 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.

---

[7] Some powerful, free IDEs now exist, such as KDevelop in the ports collection.

- 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.

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 you 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 to 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. Working with Emacs Lisp can be quite helpful if you want to go on and learn something like Common Lisp. Emacs Lisp has many features of Common Lisp, although it is considerably smaller (and thus easier to master).

The best way to learn Emacs Lisp is to download the Emacs Tutorial

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! [8]

---

[8] Many Emacs users set their `EDITOR` environment to `emacsclient` so this happens every time they need to edit a file.

2.1. A sample `.emacs` file

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

;; This file is designed to be re-evaled; 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 evaled")

;; 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)
(if (>= emacs-major-version 21)
 (setq show-trailing-whitespace t))

;; 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 color &optional bold)
  "Create a face from a color and optionally make it bold"
  (make-face face)
  (copy-face 'default face)
  (set-face-foreground face color)
  (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

For information about setting up a development environment for contributing fixes to FreeBSD itself, please see development(7).

- 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

3. Secure Programming

Contributed by Murray Stokely.

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.

`strcpy` (char *dest, const char *src)	May overflow the dest buffer
`strcat` (char *dest, const char *src)	May overflow the dest buffer
`getwd` (char *buf)	May overflow the buf buffer
`gets` (char *s)	May overflow the s buffer
`[vf]scanf` (const char *format, ...)	May overflow its arguments.
`realpath` (char *path, char resolved_path[])	May overflow the path buffer
`[v]sprintf` (char *str, const char *format, ...)	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 `strlcpy` 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 `strlcpy` 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:

> "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
- libparanoia

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 set up 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 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, mmaps, 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.

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 #### has been established. If you are an I18N/L10N developer, please send your comments, ideas, questions, and anything you deem related to it.

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
```

5. Source Tree Guidelines and Policies

Contributed by Poul-Henning Kamp.

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

5.1. `MAINTAINER` on Makefiles

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 `Makefile` s 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 # David O'Brien.

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 sendmail, 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.

##

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` `Makefile` s 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 `cvs add FREEBSD-upgrade ; cvs 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:
                cvs 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:
                cvs 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 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 decides per case if it should be commented out or not. The Core team can, of course, change their minds later on.
   c. The *Release Engineer* decides whether or not it goes into the release.
9. User-land files:
   a. The Core team decides if the code should be part of `make world`.
   b. The Release Engineer decides if it goes into the release.

5.4. Shared Libraries

Contributed by Satoshi Asami, Peter Wemm # David O'Brien.

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)`* .

##

`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 `Makefile` s “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.

6. Regression and Performance Testing

Regression tests are used to exercise a particular bit of the system to check that it works as expected, and to make sure that old bugs are not reintroduced.

The FreeBSD regression testing tools can be found in the FreeBSD source tree in the directory `src/tools/regression` .

6.1. Micro Benchmark Checklist

This section contains hints for doing proper micro-benchmarking on FreeBSD or of FreeBSD itself.

It is not possible to use all of the suggestions below every single time, but the more used, the better the benchmark's ability to test small differences will be.

- Disable APM and any other kind of clock fiddling (ACPI ?).
- Run in single user mode. E.g. cron(8), and and other daemons only add noise. The sshd(8) daemon can also cause problems. If ssh access is required during test either disable the SSHv1 key regeneration, or kill the parent `sshd` daemon during the tests.
- Do not run ntpd(8).
- If syslog(3) events are generated, run syslogd(8) with an empty `/etc/syslogd.conf` , otherwise, do not run it.
- Minimize disk-I/O, avoid it entirely if possible.
- Do not mount file systems that are not needed.
- Mount `/`, `/usr`, and any other file system as read-only if possible. This removes atime updates to disk (etc.) from the I/O picture.
- Reinitialize the read/write test file system with newfs(8) and populate it from a tar(1) or dump(8) file before every run. Unmount and mount it before starting the test. This results in a consistent file system layout. For a worldstone test this would apply to `/usr/obj` (just reinitialize with `newfs` and mount). To get 100% reproducibility, populate the file system from a dd(1) file (i.e.: `dd if=myimage of=/dev/ad0s1h bs=1m`)
- Use malloc backed or preloaded md(4) partitions.
- Reboot between individual iterations of the test, this gives a more consistent state.

- Remove all non-essential device drivers from the kernel. For instance if USB is not needed for the test, do not put USB in the kernel. Drivers which attach often have timeouts ticking away.

- Unconfigure hardware that are not in use. Detach disks with atacontrol(8) and camcontrol(8) if the disks are not used for the test.

- Do not configure the network unless it is being tested, or wait until after the test has been performed to ship the results off to another computer.

  If the system must be connected to a public network, watch out for spikes of broadcast traffic. Even though it is hardly noticeable, it will take up CPU cycles. Multicast has similar caveats.

- Put each file system on its own disk. This minimizes jitter from head-seek optimizations.

- Minimize output to serial or VGA consoles. Running output into files gives less jitter. (Serial consoles easily become a bottleneck.) Do not touch keyboard while the test is running, even space or back-space shows up in the numbers.

- Make sure the test is long enough, but not too long. If the test is too short, timestamping is a problem. If it is too long temperature changes and drift will affect the frequency of the quartz crystals in the computer. Rule of thumb: more than a minute, less than an hour.

- Try to keep the temperature as stable as possible around the machine. This affects both quartz crystals and disk drive algorithms. To get real stable clock, consider stabilized clock injection. E.g. get a OCXO + PLL, inject output into clock circuits instead of motherboard xtal. Contact Poul-Henning Kamp for more information about this.

- Run the test at least 3 times but it is better to run more than 20 times both for "before" and "after" code. Try to interleave if possible (i.e.: do not run 20 times before then 20 times after), this makes it possible to spot environmental effects. Do not interleave 1:1, but 3:3, this makes it possible to spot interaction effects.

  A good pattern is: `bababa{bbbaaa}*` . This gives hint after the first 1+1 runs (so it is possible to stop the test if it goes entirely the wrong way), a standard deviation after the first 3+3 (gives a good indication if it is going to be worth a long run) and trending and interaction numbers later on.

- Use `usr/src/tools/tools/ministat` to see if the numbers are significant. Consider buying "Cartoon guide to statistics" ISBN: 0062731025, highly recommended, if you have forgotten or never learned about standard deviation and Student's T.

- Do not use background fsck(8) unless the test is a benchmark of background `fsck`. Also, disable `background_fsck` in `/etc/rc.conf` unless the benchmark is not started at least 60+"`fsck` runtime" seconds after the boot, as rc(8) wakes up and checks if `fsck` needs to run on any file systems when background `fsck` is enabled. Likewise, make sure there are no snapshots lying around unless the benchmark is a test with snapshots.

- If the benchmark show unexpected bad performance, check for things like high interrupt volume from an unexpected source. Some versions of ACPI have been reported to "misbehave" and generate excess interrupts. To help diagnose odd test results, take a few snapshots of `vmstat -i` and look for anything unusual.
- Make sure to be careful about optimization parameters for kernel and userspace, likewise debugging. It is easy to let something slip through and realize later the test was not comparing the same thing.
- Do not ever benchmark with the `WITNESS` and `INVARIANTS` kernel options enabled unless the test is interested to benchmarking those features. `WITNESS` can cause 400%+ drops in performance. Likewise, userspace malloc(3) parameters default differently in -CURRENT from the way they ship in production releases.

II. Interprocess Communication(IPC)

####

7. Sockets

Contributed by G. Adam Stanislav.

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.

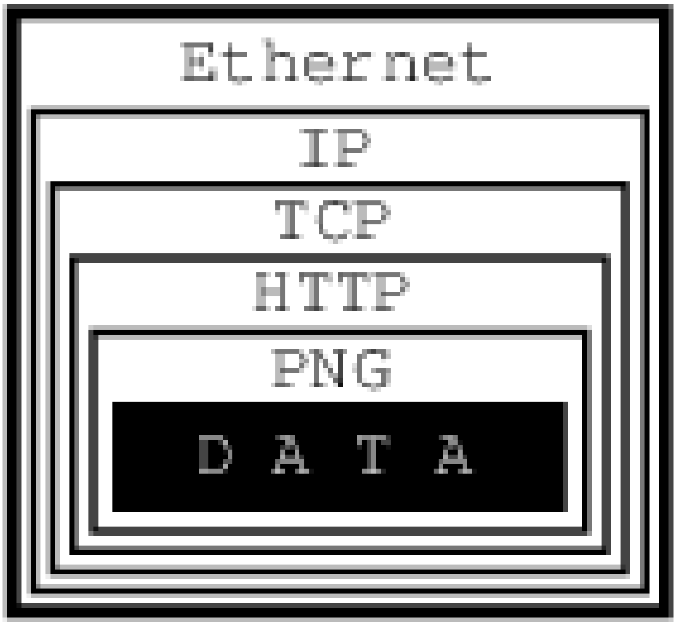
It is the same with computers: The same symbols may have different, even outright opposite meaning. Therefore, for two computers to understand each other, they must not only agree on the same *language*, but on the same *interpretation* of the language.

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...

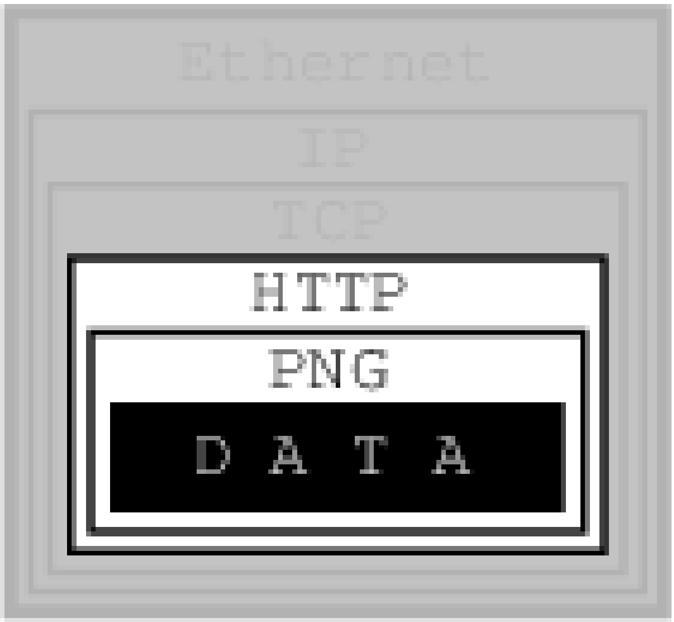
As a developer you should be asking by now, *“How am I supposed to handle it all?”*

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 {
 unsigned char sa_len;  /* total length */
 sa_family_t sa_family; /* address family */
 char  sa_data[14]; /* actually longer; address value */
};
#define SOCK_MAXADDRLEN 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_SLOW  33  /* 802.3ad slow protocol */
#define AF_SCLUSTER 34  /* Sitara cluster protocol */
#define AF_ARP  35
#define AF_BLUETOOTH 36  /* Bluetooth sockets */
#define AF_MAX  37
```

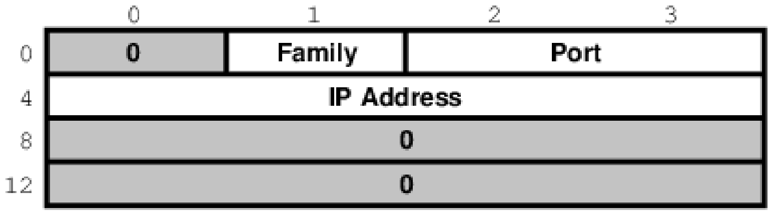
The one used for IP is AF_INET. It is a symbol for the constant 2.

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:

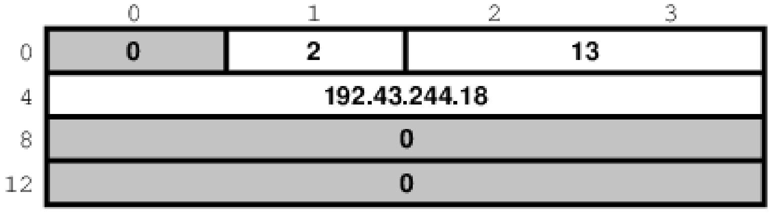
```
/*
 * Socket address, internet style.
 */
struct sockaddr_in {
 uint8_t  sin_len;
 sa_family_t sin_family;
 in_port_t sin_port;
 struct in_addr sin_addr;
 char sin_zero[8];
};
```

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.

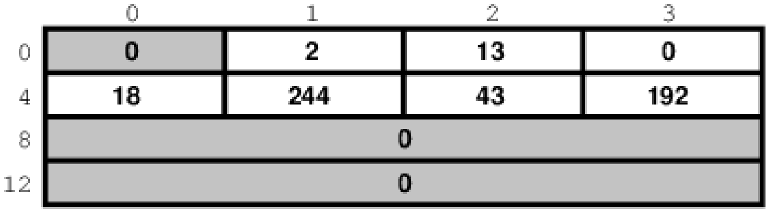
So far, we have viewed `sockaddr` as an abstraction. Our computer does not store `short` integers as a single 16-bit entity, but as a sequence of 2 bytes. Similarly, it stores 32-bit integers as a sequence of 4 bytes.

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;
```

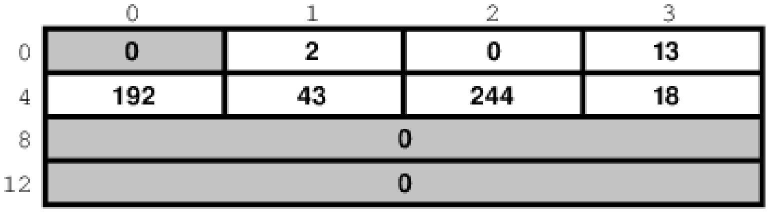
What would the result look like?

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



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

On a different system, it might look like this:



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

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.

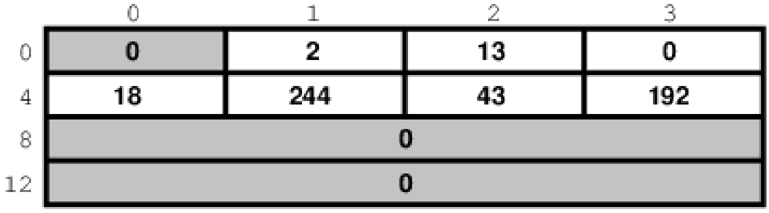
Similarly, we enter the IP address to tell everyone on the way where to send our data to. Sockets, again, only forwards it as data.

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*.

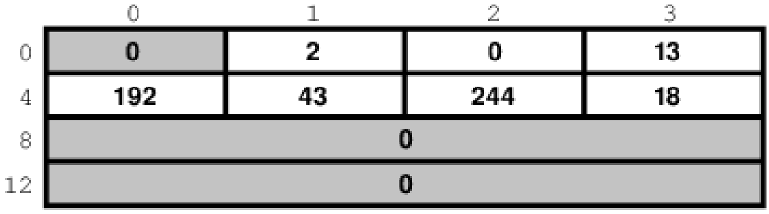
There is a convention of sending the multi-byte data over IP *MSB first*. This, we will refer to as the *network byte order*, or simply the *network order*.

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.

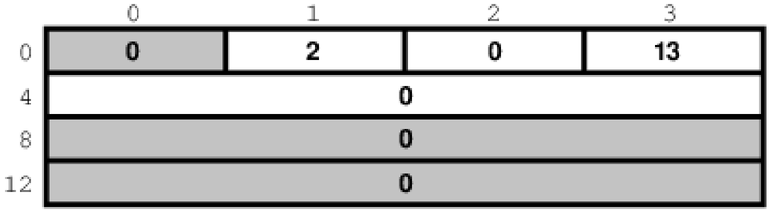
There are 65535 IP ports, but a server usually processes requests that come in on only one of them. It is like telling the phone room operator that we are now at work and available to answer the phone at a specific extension. We use bind(2) to tell sockets which port we want to serve.

```
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:



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.

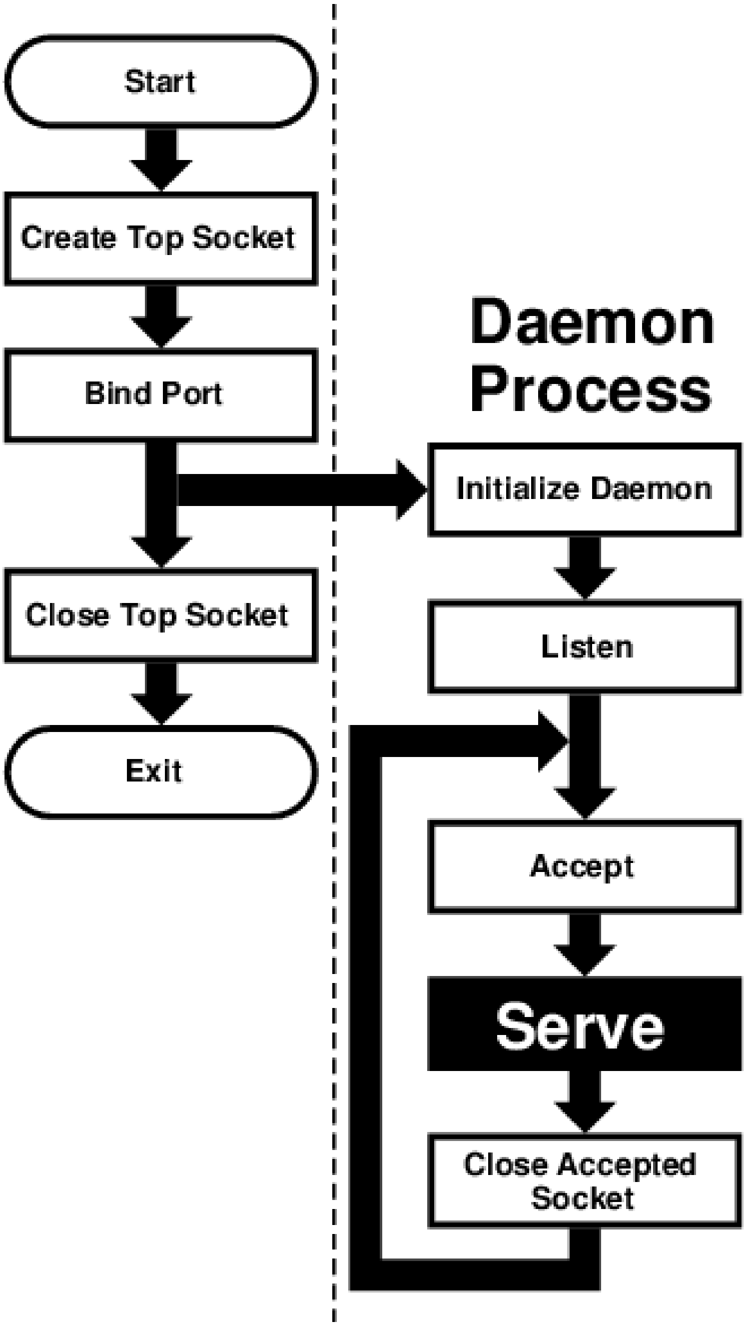
Finally, the daemon starts an endless loop, which performs the following steps:

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 `fork`s 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          ttyp0   Jun 19 16:59   (216.127.220.143)
xxx              ttyp1   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:

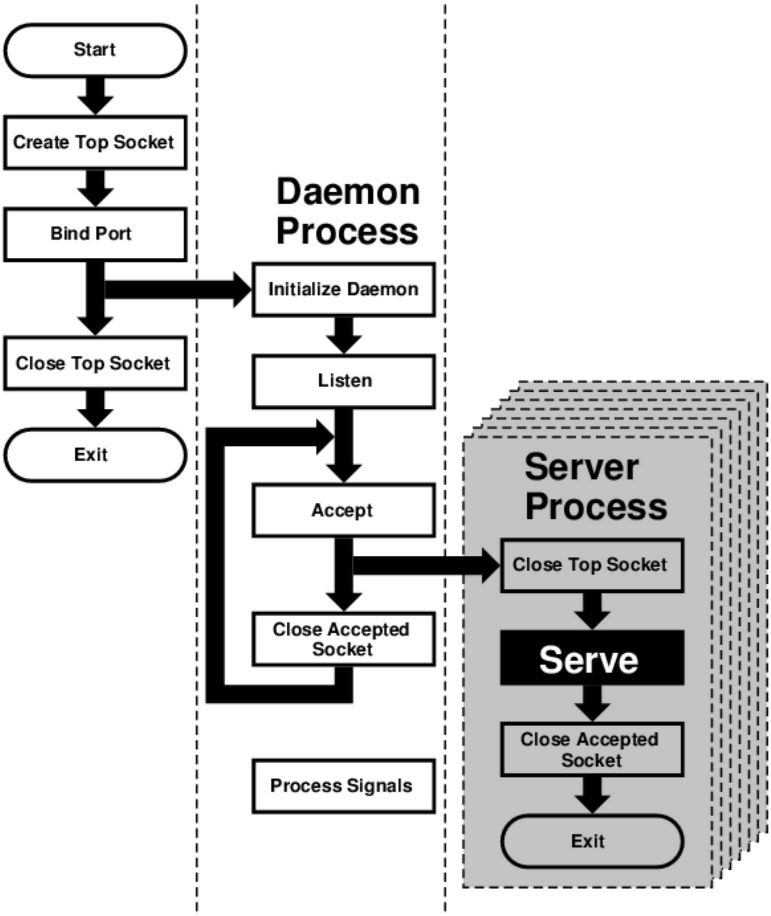
```
  struct servent *se;
  ...
  if ((se = getservbyname("daytime", "tcp")) == NULL {
    fprintf(stderr, "Cannot determine which port to use.\n");
    return 7;
  }
  sa.sin_port = se->s_port;
```

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 `waits` 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.

8. IPv6 Internals

8.1. IPv6/IPsec Implementation

Contributed by Yoshinobu Inoue.

This section should explain IPv6 and IPsec related implementation internals. These functionalities are derived from KAME project

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, manual 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/` . 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 ioctls (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, a last resort pseudo-random value, 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 *rtsol* command. rtsold(8) daemon is also available. rtsold(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 mistakingly 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 mistakingly 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 unreach, 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      (connection ↺
to ::ffff:10.1.1.1)
                socket gets IPv4 conn.)
                ---                     ---
FreeBSD 4.x     configurable            supported
                default: enabled
```

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 ####.

(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 set up 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 tunnelifp->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/). (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 as 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, 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               drop TOS bits on ↺
outer
                from inner to outer.            (use inner TOS bits ↺
as is)

ECN forbidden   copy TOS bits except for ECN    drop TOS bits on ↺
outer
                (masked with 0xfc) from inner   (use inner TOS bits ↺
as is)
                to outer.  set ECN bits to 0.

ECN allowed     copy TOS bits except for ECN    use inner TOS bits ↺
with some
                CE (masked with 0xfe) from      change.  if outer ↺
ECN CE bit
                inner to outer.                 is 1, enable ECN CE ↺
bit on
                set ECN CE bit to 0.            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, 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®, IIJ, Intel, Microsoft® Windows NT®, NIST (linux IPsec + plutoplus), Netscreen, OpenBSD, RedCreek, Routerware, SSH, Secure Computing, Soliton, Toshiba, VPNet, Yamaha RT100i

III. Kernel(##)

####

9. Kernel Debugging

Contributed by Paul Richards # Jörg Wunsch.

9.1. Obtaining a Kernel Crash Dump

When running a development kernel (eg: FreeBSD-CURRENT), such as a kernel under extreme conditions (eg: very high load averages, tens of thousands of connections, exceedingly high number of concurrent users, hundreds of jail(8)s, etc.), or using a new feature or device driver on FreeBSD-STABLE (eg: PAE), sometimes a kernel will panic. In the event that it does, this chapter will demonstrate how to extract useful information out of a crash.

A system reboot is inevitable once a kernel panics. Once a system is rebooted, the contents of a system's physical memory (RAM) is lost, as well as any bits that are on the swap device before the panic. To preserve the bits in physical memory, the kernel makes use of the swap device as a temporary place to store the bits that are in RAM across a reboot after a crash. In doing this, when FreeBSD boots after a crash, a kernel image can now be extracted and debugging can take place.

##

A swap device that has been configured as a dump device still acts as a swap device. Dumps to non-swap devices (such as tapes or CDRWs, for example) are not supported at this time. A “swap device” is synonymous with a “swap partition.”

To be able to extract a usable core, it is required that at least one swap partition be large enough to hold all of the bits in physical memory. When a kernel panics, before the system reboots, the kernel is smart enough to check to see if a swap device has been configured as a dump device. If there is a valid dump device, the kernel dumps the contents of what is in physical memory to the swap device.

9.1.1. Configuring the Dump Device

Before the kernel will dump the contents of its physical memory to a dump device, a dump device must be configured. A dump device is specified by using the dumpon(8) command to tell the kernel where to save kernel crash dumps. The dumpon(8) program must be called after the swap partition has been configured with swapon(8). This is normally handled by setting the `dumpdev` variable in rc.conf(5) to the path of the swap device (the recommended way to extract a kernel dump).

Alternatively, the dump device can be hard-coded via the `dump` clause in the config(5) line of a kernel configuration file. This approach is deprecated and should be used only if a kernel is crashing before dumpon(8) can be executed.

##

Check `/etc/fstab` or swapinfo(8) for a list of swap devices.

##

Make sure the `dumpdir` specified in rc.conf(5) exists before a kernel crash!

```
# mkdir /var/crash
# chmod 700 /var/crash
```

Also, remember that the contents of `/var/crash` is sensitive and very likely contains confidential information such as passwords.

9.1.2. Extracting a Kernel Dump

Once a dump has been written to a dump device, the dump must be extracted before the swap device is mounted. To extract a dump from a dump device, use the savecore(8) program. If `dumpdev` has been set in rc.conf(5), savecore(8) will be called automatically on the first multi-user boot after the crash and before the swap device is mounted. The location of the extracted core is placed in the rc.conf(5) value `dumpdir`, by default `/var/crash` and will be named `vmcore.0`.

In the event that there is already a file called `vmcore.0` in `/var/crash` (or whatever `dumpdir` is set to), the kernel will increment the trailing number for every crash to avoid overwriting an existing `vmcore` (eg: `vmcore.1`). While debugging, it is highly likely that you will want to use the highest version `vmcore` in `/var/crash` when searching for the right `vmcore`.

##

If you are testing a new kernel but need to boot a different one in order to get your system up and running again, boot it only into single user mode using the `-s` flag at the boot prompt, and then perform the following steps:

```
# fsck -p
# mount -a -t ufs        # make sure /var/crash is ↺
writable
# savecore /var/crash /dev/ad0s1b
# exit                    # exit to multi-user
```

This instructs savecore(8) to extract a kernel dump from `/dev/ad0s1b` and place the contents in `/var/crash`. Do not forget to make sure the destination directory `/var/crash` has enough space for the dump. Also, do not forget to specify the correct path to your swap device as it is likely different than `/dev/ad0s1b`!

The recommended, and certainly the easiest way to automate obtaining crash dumps is to use the `dumpdev` variable in rc.conf(5).

9.2. Debugging a Kernel Crash Dump with `kgdb`

##

This section covers kgdb(1) as found in FreeBSD 5.3 and later. In previous versions, one must use `gdb -k` to read a core dump file.

Once a dump has been obtained, getting useful information out of the dump is relatively easy for simple problems. Before launching into the internals of kgdb(1) to debug the crash dump, locate the debug version of your kernel (normally called `kernel.debug`) and the path to the source files used to build your kernel (normally `/usr/obj/usr/src/sys/KERNCONF`, where `KERNCONF` is the `ident` specified in a kernel config(5)). With those two pieces of info, let the debugging commence!

To enter into the debugger and begin getting information from the dump, the following steps are required at a minimum:

```
# cd /usr/obj/usr/src/sys/KERNCONF
# kgdb kernel.debug /var/crash/vmcore.0
```

You can debug the crash dump using the kernel sources just like you can for any other program.

This first dump is from a 5.2-BETA kernel and the crash comes from deep within the kernel. The output below has been modified to include line numbers on the left. This first trace inspects the instruction pointer and obtains a back trace. The address that is used on line 41 for the `list` command is the instruction pointer and can be found on line 17. Most developers will request having at least this information sent to them if you are unable to debug the problem yourself. If, however, you do solve the problem, make sure that your patch winds its way into the source tree via a problem report, mailing lists, or by being able to commit it!

```
 1:# cd /usr/obj/usr/src/sys/KERNCONF
 2:# kgdb kernel.debug /var/crash/vmcore.0
 3:GNU gdb 5.2.1 (FreeBSD)
 4:Copyright 2002 Free Software Foundation, Inc.
 5:GDB is free software, covered by the GNU General Public License, ↺
and you are
 6:welcome to change it and/or distribute copies of it under ↺
certain conditions.
 7:Type "show copying" to see the conditions.
 8:There is absolutely no warranty for GDB.  Type "show warranty" ↺
for details.
 9:This GDB was configured as "i386-undermydesk-freebsd"...
10:panic: page fault
11:panic messages:
12:---
13:Fatal trap 12: page fault while in kernel mode
14:cpuid = 0; apic id = 00
15:fault virtual address   = 0x300
16:fault code:             = supervisor read, page not present
17:instruction pointer     = 0x8:0xc0713860
18:stack pointer           = 0x10:0xdc1d0b70
19:frame pointer           = 0x10:0xdc1d0b7c
20:code segment            = base 0x0, limit 0xfffff, type 0x1b
21:                        = DPL 0, pres 1, def32 1, gran 1
22:processor eflags        = resume, IOPL = 0
23:current process         = 14394 (uname)
24:trap number             = 12
25:panic: page fault
26      cpuid = 0;
27:Stack backtrace:
28
29:syncing disks, buffers remaining... 2199 2199 panic: mi_switch: ↺
switch in a critical section
30:cpuid = 0;
31:Uptime: 2h43m19s
32:Dumping 255 MB
33: 16 32 48 64 80 96 112 128 144 160 176 192 208 224 240
34:---
35:Reading symbols from /boot/kernel/snd_maestro3.ko...done.
36:Loaded symbols for /boot/kernel/snd_maestro3.ko
37:Reading symbols from /boot/kernel/snd_pcm.ko...done.
38:Loaded symbols for /boot/kernel/snd_pcm.ko
39:#0  doadump () at /usr/src/sys/kern/kern_shutdown.c:240
```

```
240             dumping++;
(kgdb) list *0xc0713860
0xc0713860 is in lapic_ipi_wait (/usr/src/sys/i386/i386/
local_apic.c:663).
658                     incr = 0;
659                     delay = 1;
660             } else
661                     incr = 1;
662             for (x = 0; x < delay; x += incr) {
663                     if ((lapic->icr_lo & APIC_DELSTAT_MASK) ↺
== APIC_DELSTAT_IDLE)
664                             return (1);
665                     ia32_pause();
666             }
667             return (0);
(kgdb) backtrace
#0  doadump () at /usr/src/sys/kern/kern_shutdown.c:240
#1  0xc055fd9b in boot (howto=260) at /usr/src/sys/kern/
kern_shutdown.c:372
#2  0xc056019d in panic () at /usr/src/sys/kern/kern_shutdown.↺
c:550
#3  0xc0567ef5 in mi_switch () at /usr/src/sys/kern/kern_synch.↺
c:470
#4  0xc055fa87 in boot (howto=256) at /usr/src/sys/kern/
kern_shutdown.c:312
#5  0xc056019d in panic () at /usr/src/sys/kern/kern_shutdown.↺
c:550
#6  0xc0720c66 in trap_fatal (frame=0xdc1d0b30, eva=0)
    at /usr/src/sys/i386/i386/trap.c:821
#7  0xc07202b3 in trap (frame=
      {tf_fs = -1065484264, tf_es = -1065484272, tf_ds ↺
= -1065484272, tf_edi = 1, tf_esi = 0, tf_ebp = -602076292, tf_isp ↺
= -602076324, tf_ebx = 0, tf_edx = 0, tf_ecx = 1000000, tf_eax = ↺
243, tf_trapno = 12, tf_err = 0, tf_eip = -1066321824, tf_cs = 8, ↺
tf_eflags = 65671, tf_esp = 243, tf_ss = 0})
    at /usr/src/sys/i386/i386/trap.c:250
#8  0xc070c9f8 in calltrap () at {standard input}:94
#9  0xc07139f3 in lapic_ipi_vectored (vector=0, dest=0)
    at /usr/src/sys/i386/i386/local_apic.c:733
#10 0xc0718b23 in ipi_selected (cpus=1, ipi=1)
    at /usr/src/sys/i386/i386/mp_machdep.c:1115
#11 0xc057473e in kseq_notify (ke=0xcc05e360, cpu=0)
    at /usr/src/sys/kern/sched_ule.c:520
#12 0xc0575cad in sched_add (td=0xcbcf5c80)
    at /usr/src/sys/kern/sched_ule.c:1366
#13 0xc05666c6 in setrunqueue (td=0xcc05e360)
    at /usr/src/sys/kern/kern_switch.c:422
#14 0xc05752f4 in sched_wakeup (td=0xcbcf5c80)
    at /usr/src/sys/kern/sched_ule.c:999
#15 0xc056816c in setrunnable (td=0xcbcf5c80)
    at /usr/src/sys/kern/kern_synch.c:570
#16 0xc0567d53 in wakeup (ident=0xcbcf5c80)
    at /usr/src/sys/kern/kern_synch.c:411
```

```
82:#17 0xc05490a8 in exit1 (td=0xcbcf5b40, rv=0)
83:    at /usr/src/sys/kern/kern_exit.c:509
84:#18 0xc0548011 in sys_exit () at /usr/src/sys/kern/kern_exit.c:102
85:#19 0xc0720fd0 in syscall (frame=
86:      {tf_fs = 47, tf_es = 47, tf_ds = 47, tf_edi = 0, tf_esi =
 -1, tf_ebp = -1077940712, tf_isp = -602075788, tf_ebx = 672411944, ↺
tf_edx = 10, tf_ecx = 672411600, tf_eax = 1, tf_trapno = 12, tf_err ↺
= 2, tf_eip = 671899563, tf_cs = 31, tf_eflags = 642, tf_esp =
 -1077940740, tf_ss = 47})
87:    at /usr/src/sys/i386/i386/trap.c:1010
88:#20 0xc070ca4d in Xint0x80_syscall () at {standard input}:136
89:---Can't read userspace from dump, or kernel process---
90:(kgdb) quit
```

This next trace is an older dump from the FreeBSD 2 time frame, but is more involved and demonstrates more of the features of `gdb`. 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) backtrace
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_isp =
 -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 pcopen (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 *) 0x1bae
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_isp = -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
```

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.)

##

If your system is crashing regularly and you are running out of disk space, deleting old `vmcore` files in `/var/crash` could save a considerable amount of disk space!

9.3. 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.

9.4. 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, 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 with 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.

9.5. 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 for details on configuring the FreeBSD kernel).

> ##
>
> 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 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
```

##

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_symtab_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.

9.6. 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.

9.7. 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.

9.8. 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.

9.9. Debugging the Deadlocks

You may experience so called deadlocks, the situation where system stops doing useful work. To provide the helpful bug report in this situation, you shall use ddb as described above. Please, include the output of `ps` and `trace` for suspected processes in the report.

If possible, consider doing further investigation. Receipt below is especially useful if you suspect deadlock occurs in the VFS layer. Add the options

```
makeoptions  DEBUG=-g
 options  INVARIANTS
 options  INVARIANT_SUPPORT
 options  WITNESS
 options  DEBUG_LOCKS
 options  DEBUG_VFS_LOCKS
 options  DIAGNOSTIC
```

to the kernel config. When deadlock occurs, in addition to the output of the `ps` command, provide information from the `show allpcpu` , `show alllocks` , `show lockedvnods` and `show alltrace` .

For threaded processes, to obtain meaningful backtraces, use `thread thread-id` to switch to the thread stack, and do backtrace with `where`.

IV. Architectures(####)

####

10. x86 Assembly Language Programming

This chapter was written by G. Adam Stanislav.

10.1. 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; or if you prefer a printed book, take a look at Jeff Duntemann's Assembly Language Step-by-Step). However, once the chapter is finished, any assembly language programmer will be able to write programs for FreeBSD quickly and efficiently.

10.2. The Tools

10.2.1. 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.

10.2.2. 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.

10.3. System Calls

10.3.1. 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 `push`ing 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`.

10.3.2. 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
```

10.3.3. 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.

10.3.4. 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.

10.3.4.1. 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`.

##

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 `push`ed *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.

10.4. 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.

10.4.1. Man Pages

The traditional place to look for information about various system calls under UNIX® systems are the manual 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?

##

The information presented in the manual pages applies to C programs. The assembly language programmer needs additional information.

10.4.2. 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.

##

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.

##

If you cannot find the answer here or anywhere else, study libc source code and see how it interfaces with the kernel.

10.4.3. 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.

10.4.4. 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`.

10.5. 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.

10.5.1. 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
```

10.5.2. 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
```

10.5.3. 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.

10.5.4. 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.

10.5.5. 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.

##

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.

10.6. 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.

##

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.

10.6.1. 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.

10.6.1.1. 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.

##

If your system is not FreeBSD, you need to get nasm from its home page. 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!
%
```

10.7. 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.

##

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 %
```

##

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).

10.8. 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!

##

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.

10.8.1. How to Unread a Character

##

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").

10.9. 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 `push`es 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 `pop`ping 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.

##

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 `jecxz`. 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.

10.10. 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.

10.10.1. 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.

10.10.2. 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.

10.10.2.1. CGI: A Quick Overview

I have a detailed CGI 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.

##

While certain *environment variables* use standard names, others vary, depending on the web server. That makes webvars quite a useful diagnostic tool.

10.10.2.2. 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
; FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR ↺
CONSEQUENTIAL
; DAMAGES (INCLUDING, BUT NOT LIMITED TO, PROCUREMENT OF SUBSTITUTE ↺
GOODS
; OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS ↺
INTERRUPTION)
```

```
; HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN ↺
CONTRACT, STRICT
; LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ↺
ANY WAY
; OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE ↺
POSSIBILITY OF
; SUCH DAMAGE.
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;
; Version 1.0
;
; Started:  8-Dec-2000
; Updated:  8-Dec-2000
;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
%include 'system.inc'

section .data
http db 'Content-type: text/html', 0Ah, 0Ah
 db '<?xml version="1.0" encoding="utf-8"?>', 0Ah
 db '<!DOCTYPE html PUBLIC "-//W3C/DTD XHTML Strict//EN" '
 db '"DTD/xhtml1-strict.dtd">', 0Ah
 db '<html xmlns="http://www.w3.org/1999/xhtml" '
 db 'xml.lang="en" lang="en">', 0Ah
 db '<head>', 0Ah
 db '<title>Web Environment</title>', 0Ah
 db '<meta name="author" content="G. Adam Stanislav" />', 0Ah
 db '</head>', 0Ah, 0Ah
 db '<body bgcolor="#ffffff" text="#000000" link="#0000ff" '
 db 'vlink="#840084" alink="#0000ff">', 0Ah
 db '<div class="webvars">', 0Ah
 db '<h1>Web Environment</h1>', 0Ah
 db '<p>The following <b>environment variables</b> are defined '
 db 'on this web server:</p>', 0Ah, 0Ah
 db '<table align="center" width="80" border="0" cellpadding="10" '
 db 'cellspacing="0" class="webvars">', 0Ah
httplen equ $-http
left db '<tr>', 0Ah
 db '<td class="name"><tt>'
leftlen equ $-left
middle db '</tt></td>', 0Ah
 db '<td class="value"><tt><b>'
midlen equ $-middle
undef db '<i>(undefined)</i>'
undeflen equ $-undef
right db '</b></tt></td>', 0Ah
 db '</tr>', 0Ah
rightlen equ $-right
wrap db '</table>', 0Ah
 db '</div>', 0Ah
 db '</body>', 0Ah
 db '</html>', 0Ah, 0Ah
wraplen equ $-wrap
```

```
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 httplen
 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`** .

10.11. 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, 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).

10.11.1. 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 lf 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.

10.11.1.1. 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.

> ##
>
> 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.

10.11.1.2. 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.

10.11.2. 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.

10.11.3. 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 superseded 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 `push`ing 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:

##

For an in-depth treatment of `mmap`, see W. Richard Stevens' Unix Network Programming, Volume 2, Chapter 12.

10.11.4. 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.

10.11.5. 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.

10.11.6. 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
struc 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
```

##

Do not use this program on files stored on a disk formated 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.

10.12. 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.

10.12.1. 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.

The *`-t`* parameter declares what to replace the commas with. The `tab` is the default here. For example, *`-t;`* will replace all unquoted commas with semicolons.

I did not need the *`-c`* option, but it may come in handy in the future. It lets me declare that I want a character other than a comma replaced with something else. For example, *`-c@`* will replace all at signs (useful if you want to split a list of email addresses to their user names and domains).

The *`-p`* option preserves the first line, i.e., it does not delete it. By default, we delete the first line because in a CSV file it contains the field names rather than data.

The *`-i`* and *`-o`* options let me specify the input and the output files. Defaults are `stdin` and `stdout`, so this is a regular UNIX® filter.

I made sure that both *`-i filename`* and *`-ifilename`* are accepted. I also made sure that only one input and one output files may be specified.

To get the 11th field of each record, I can now do:

```
% csv '-t;' data.csv | awk '-F;' '{print $11}'
```

The code stores the options (except for the file descriptors) in `EDX`: The comma in `DH`, the new separator in `DL`, and the flag for the *-p* option in the highest bit of `EDX`, so a check for its sign will give us a quick decision what to do.

Here is the code:

```
;;;;;;; csv.↺
asm -;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;
; Convert a comma-separated file to a something-else separated file.
;
; Started: 31-May-2001
; Updated:  1-Jun-2001
;
; Copyright (c) 2001 G. Adam Stanislav
; All rights reserved.
;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

%include 'system.inc'

%define BUFSIZE 2048

section .data
fd.in dd stdin
fd.out dd stdout
usg db 'Usage: csv [-t<delim>] [-c<comma>] [-p] [-o <outfile>] [-i ↺
<infile>]', 0Ah
usglen equ $-usg
iemsg db "csv: Can't open input file", 0Ah
iemlen equ $-iemsg
oemsg db "csv: Can't create output file", 0Ah
oemlen equ $-oemsg

section .bss
ibuffer resb BUFSIZE
obuffer resb BUFSIZE

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.

10.12.1.1. 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.

10.13. 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.

10.13.1. 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 `fld`, `fild`, 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`.

10.13.1.1. 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*.

##

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 00 80
```

Remember that, or you will be pulling your hair out in desperation!

##

The book to read——if you can find it——is Richard Startz' 8087/80287/80387 for the IBM PC & Compatibles. 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.

10.13.2. 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.

10.13.2.1. 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*.

10.13.2.2. 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.

10.13.2.3. 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 * 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.

10.13.2.4. 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
```

10.13.2.5. 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.

10.13.2.6. 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.

10.13.3. Designing the Pinhole Software

We are now ready to decide what exactly we want our pinhole software to do.

10.13.3.1. 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.

10.13.3.2. 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`*.

10.13.3.3. 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.

##

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.

##

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 `shift`ing 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 f5.6. We will, therefore, calculate an *"f5.6 multiplier,"* i.e., by how much we need to multiply the exposure measured at f5.6 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`^{2} 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.

10.13.4. 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!*

##

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.

10.13.5. 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 skiptoeol
 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 `push`es 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 `pop`s 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 `call`ed `read`.

And since `getchar` never `push`ed anything before `call`ing `read`, the top of the stack now contains the return address to whatever or whoever `call`ed `getchar`. As far as that caller is concerned, he `call`ed `getchar`, which `ret`urned 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.

10.13.6. 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.

10.13.7. 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
%
```

10.14. 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.

10.14.1. 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.

10.14.2. 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.

> ##
>
> 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® form MS-DOS®. Of course, creative people often break rules, and it is OK as long as they know they are breaking them and why.

10.15. Acknowledgements

This tutorial would never have been possible without the help of many experienced FreeBSD programmers from the FreeBSD technical discussions ####, 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? 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.

V.

####

####

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##