

GNU/Linux Application Programming

WANG Xiaolin

`wx672ster+linux@gmail.com`

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Textbooks



MATTHEW N, STONES R. Beginning linux programming. 4th ed. John Wiley & Sons, 2008.



COOPER M. Advanced Bash Scripting Guide 5.3 Volume 1. Lulu.com, 2010.



RAYMOND E S. The art of Unix programming. Addison-Wesley, 2003.



STEVENS W R, RAGO S A. Advanced programming in the UNIX environment. Addison-Wesley, 2013.



LOVE R. Linux System Programming: Talking Directly to the Kernel and C Library. O'Reilly Media, Inc., 2007.



KERRISK M. The Linux Programming Interface: A Linux and UNIX System Programming Handbook. No Starch Press, 2010.



BRYANT R E, O'HALLARON D R. Computer Systems: A Programmer's Perspective. 2nd ed. Addison-Wesley, 2010.

Course Web Links

 <https://cs6.swfu.edu.cn/moodle>

 https://cs2.swfu.edu.cn/~wx672/lecture_notes/linux-app/slides/

 https://cs2.swfu.edu.cn/~wx672/lecture_notes/linux-app/src/

 <https://cs3.swfu.edu.cn/tech>

/etc/hosts

```
202.203.132.241  cs6.swfu.edu.cn
```

```
202.203.132.242  cs2.swfu.edu.cn
```

```
202.203.132.245  cs3.swfu.edu.cn
```

Homework

Weekly tech question

1. What was I trying to do?
2. How did I do it? (steps)
3. The expected output? The real output?
4. How did I try to solve it? (steps, books, web links)
5. How many hours did I struggle?

✉ wx672ster+linux@gmail.com

🇬🇧 Preferably in English

📖 in [stackoverflow](#) style

Or simply show me the tech questions you asked on any website

Getting Started

Linux Commands

Where to find them? /bin, /usr/bin, /usr/local/bin,
~/bin, ...

```
$ echo $PATH
```

How to find them? which, whereis, type

Command not found?

First double check your spelling

Then try:

```
④ aptitude search xxx
```

```
④ apt-cache search xxx
```

```
④ apt-file search xxx
```

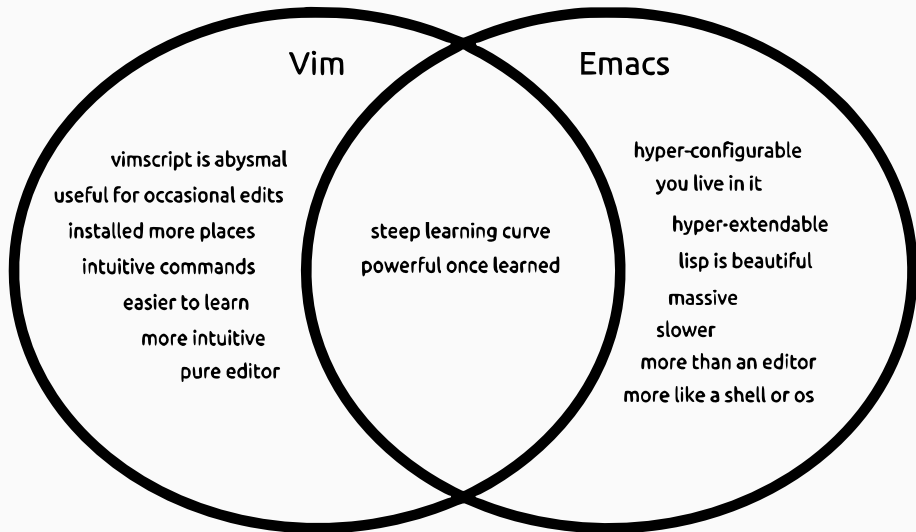
```
④ sudo apt install packagename
```

```
G Google "linux command xxx"
```

Text Editors



vs.



Help Your Editor

Suffix matters

\$ vim ✗

\$ vim hello ✗

\$ vim hello.c ✓

\$ vim hello.py ✓

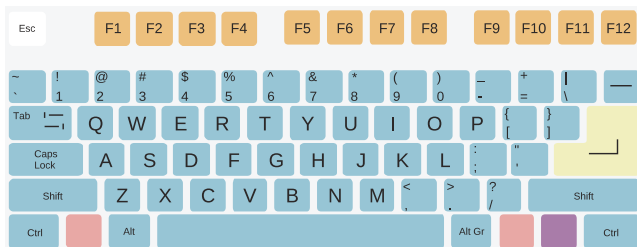
\$ emacs ✗

\$ emacs hello ✗

\$ emacsclient hello.c ✓

\$ emacsclient hello.py ✓

Keyboard



vimtutor

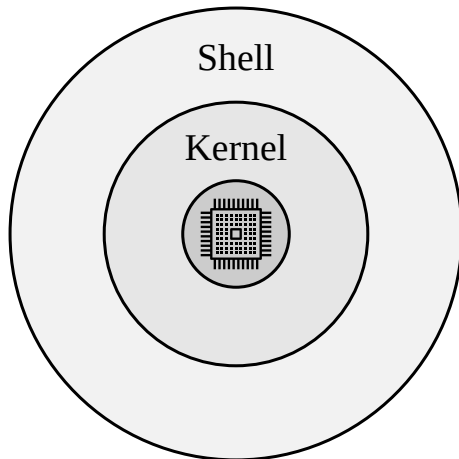


Ctrl + **h** **t**

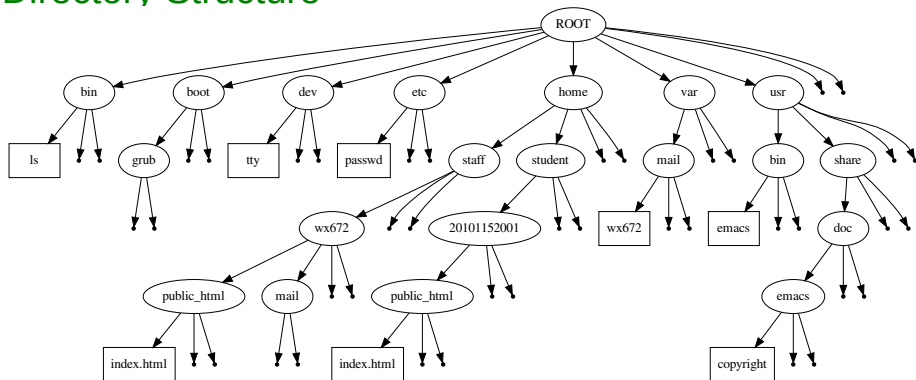
Shell Basics

Shell

- ▶ A command line interpreter
- ▶ A programming language



Directory Structure



Todo	How
Where am I?	<code>pwd</code>
What's in it?	<code>ls</code>
Move around?	<code>cd</code>
Disk usage?	<code>du</code> , <code>df</code>
USB drive?	<code>lsblk</code> , <code>mount</code>
New folder?	<code>mkdir</code>

File Operations

Ways to create a file

 Using an editor (vim, emacs, nano...), or

```
$ cat > filename
```

```
$ echo "hello, world" > filename
```

```
$ touch filename
```

More file operations:

Todo	How	Todo	How
Copy?	cp	Move/Rename?	mv
Delete?	rm	What's it?	file
Link?	ln	Permission?	chmod, chown
Count?	wc	Archive?	tar, gzip, 7z, ...
Sort?	sort, uniq	Search?	find, grep

Redirection

Redirecting output

```
$ ls -l > output.txt
```

```
$ ps aux >> output.txt
```

Redirecting input

```
$ more < output.txt
```

Process Operations

Todo	How	Todo	How
Kill?	kill, Ctrl-c	suspend?	Ctrl-z
background?	bg, &	foreground?	fg, jobs
status?	ps, top		

System Info

Todo	How	Todo	How
who?	w, who, whoami	how long?	uptime
software?	apt, aptitude, dpkg	kernel?	uname, lsmod
hardware?	lspci, lsusb, lscpu	memory?	free, lsmem

APT — package management

Todo	How
upgrading?	apt update && apt upgrade
install?	apt install xxx
remove?	apt purge xxx
search?	apt search xxx
details?	apt show xxx
friendly UI?	aptitude

CLI Shortcuts

Ctrl + **a** : beginning of line

Ctrl + **f** : forward

Ctrl + **n** : next

Ctrl + **r** : reverse search

Ctrl + **k** : kill (cut to end)

Ctrl + **d** : delete a character

Ctrl + **e** : end of line

Ctrl + **b** : backward

Ctrl + **p** : previous

Ctrl + **u** : cut to beginning

Ctrl + **y** : yank (paste)

 : completion

Tmux

Ctrl + **a** **c** : create window

Ctrl + **a** **n** : next window

Ctrl + **a** **-** : split window

Ctrl + **a** **j** : go down

Ctrl + **a** **l** : go right

Ctrl + **a** **Ctrl** + **a** : switch window

Ctrl + **a** **p** : previous window

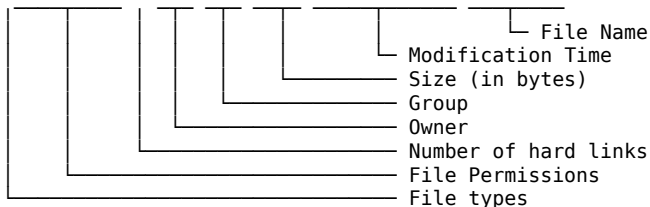
Ctrl + **a** **|** : split window

Ctrl + **a** **k** : go up

Ctrl + **a** **h** : go left

Understanding “ls -l”

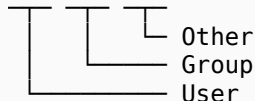
```
-rw----- 1 sam sam 57 Apr 17 1998 weather.txt
drwxr-xr-x 6 sam sam 102 Oct 9 1999 web_page
-rw-rw-r-- 1 sam sam 7648 Feb 11 20:41 web_site.tar
-rw----- 1 sam sam 574 Dec 16 1998 file.txt
```



d - directory
- - regular file
l - soft link
c - character device
b - block device
s - socket
p - named pipe (FIFO)

9-bit permission

```
7 5 5
111 101 101
rwx r-x r-x
```



```
$ chmod 755 foo      $ chmod 644 foo
$ chmod 000 foo      $ chmod 777 foo
$ chmod a-r foo      $ chmod u+x foo
$ chmod g+w foo      $ chmod go=rx foo
```

Wildcard Expansion

Character	Meaning	Example
?	any one	\$ ls ????.txt
*	zero or more	\$ ls *.c
[]	or	\$ ls *. [ch]
{}	and	\$ ls *.{c,h,cpp}

Example

```
$ touch {2,3,4,234}.{jpg,png} && ls
```

output:

2.jpg	234.jpg	3.jpg	4.jpg
2.png	234.png	3.png	4.png

```
$ rm [234].jpg
```

```
$ rm ?.jpg
```

```
$ rm {2,3,4,234}.jpg
```

```
$ rm ?.*
```

```
$ rm 2*
```

```
$ rm *
```

Everything Is A File

```
$ cat /dev/null > /var/log/messages # empty a file
```

```
  $ : > /var/log/messages # no new process
```

```
$ ls > /dev/null
```

```
$ dd if=/dev/zero of=/tmp/clean bs=1k count=1k
```

```
$ dd if=/dev/urandom of=/tmp/random bs=1k count=1k
```

/proc

Allow higher-level access to driver and kernel information

```
$ cat /proc/cpuinfo
```

```
$ cat /proc/meminfo
```

```
$ cat /proc/version
```

```
$ cat /proc/1/status
```

```
# echo 100000 > /proc/sys/kernel/pid_max
```

Pipe

Chain processes together

Unnamed pipe

```
$ ps aux | sort | less
```

Named pipe

1. `$ mkfifo mypipe`
2. `$ gzip -9 -c < mypipe > out.gz`
3. `$ cat file > mypipe`

Shell Programming

\$ — Give Me The Value Of ...

`$var` Give me the value of variable “var”

`$(echo hello)` Give me the value (output) of command “echo hello”

`$((1+1))` Give me the value (result) of “1+1”

`$$` Give me the value of special variable “\$”

`$?` Give me the value of special variable “?”

`$0` Give me the value of special variable “0”

`$@` Give me the value of special variable “@”

Variables

```
$ a=8; b=2
```

```
$ a=a+5; a=$a+5 ☹️
```

```
$ let a=a+5; let a+=5 😊
```

```
$ let b=b+a; let b+=a 😊
```

```
$ echo a; echo $a
```

```
$ (( a=5, b=6, a+=b )) 😊
```

```
$ (( b=a<5?8:9 )) 😊
```

```
$ r=$(( RANDOM%100 )) 😊
```

```
$ echo "$a" # partial quoting
```

```
$ echo '$a' # full quoting
```

```
$ a=$(ls -l); echo $a; echo "$a"
```

```
$ a=hello; b=world; let a+=b ☹️
```

Positional Parameters

\$0, \$1, \$2, ..., \$@, \$#

```
1  #!/bin/bash
2
3  echo "You said:"
4
5  echo -e "\t$@"
6  echo
7  echo -e "\targc = $#"
```

```
8  echo -e "\targv[0] = $0"
```

```
9
10 i=1
11 for arg in $@; do
12     echo -e "\targv[$i] = $arg"
13     let i++
14 done
```

```
1  #include <stdio.h>
2
3  int main(int argc, char *argv[])
4  {
5      int i;
6      printf("You said:\n\t");
7
8      for(i=1; i<argc; i++)
9          printf("%s ",argv[i]);
10
11     printf("\n\n\targc = %d\n", argc);
12
13     for(i=0; i<argc; i++)
14         printf("\targv[%d] = %s\n",i,argv[i]);
15
16     return 0;
17 }
```

Parameter Substitution

Default value

```
$ echo ${s:=abc}
```

```
$ echo ${v:-8}
```

```
$ echo ${s:=xyz}
```

```
$ echo ${v:-10}
```

Example

```
1  #!/bin/bash
2
3  echo -n Hello, ${1:-world}
4  echo !
```

Parameter Substitution

Substring removal

```
$ for f in *.pbm; do ppm2tiff $f ${f%.pbm}.tif; done
```

Substring replacement

```
$ for f in *.jpg; do mv $f ${f/.jpg/JPG}; done
```

Environmental Variables

Each process has an environment

\$PATH	\$PWD	\$HOME	\$UID	\$USER
\$GROUPS	\$SHELL	\$TERM	\$DISPLAY	\$TEMP
\$HOSTNAME	\$HOSTTYPE	\$IFS	\$EDITOR	\$BROWSER
\$HISTSIZE	\$FUNCNAME	\$TMOUT	...	

```
export HISTSIZE=2000
```

```
export BROWSER='/usr/bin/x-www-browser'
```

```
export EDITOR='vim'
```

```
export ALTERNATE_EDITOR="vim"
```

```
export PDFVIEWER='/usr/bin/zathura'
```

\$ env

\$ declare

Tests I

```
$ (( 5 < 6 )) && echo should be
```

```
$ [[ 1 < 2 ]] && echo of course
```

```
$ [[ $a -lt $b ]] && echo yes || echo no
```

```
$ if [[ $a -lt $b ]]; then echo yes; else echo no; fi
```

```
$ if test $a -lt $b; then echo of course; fi
```

```
$ if a = 5; then echo a=$a; fi # whitespace matters ❌
```

```
$ if a=5; then echo a=$a; fi 😞
```

```
$ if test a=5; then echo a=$a; fi 😞
```

```
$ if test a = 5; then echo a=$a; fi 😞
```

```
$ if test $a = 5; then echo a=$a; fi ✓
```

```
$ test $a = 5 && echo a=$a ✓
```

```
$ [[ $a = 5 ]] && echo a=$a ✓
```

Tests II

```
$ [[ cmp a b ]] && echo same file ✗
```

```
$ if test cmp a b; then echo same file; fi ✗
```

```
$ if cmp a b; then echo same file; fi ✓
```

```
$ [[ -f ~/.bash_aliases ]] && . ~/.bash_aliases
```

```
$ [[ -x /usr/bin/xterm ]] && /usr/bin/xterm -e tmux &
```

```
$ [[ "$pass" != "$MYPASS" ]] && echo 'Wrong password!' && exit  
1
```

```
$ help test
```

Tests III

```
1  #!/bin/bash
2
3  words=$@
4  string=linux
5  if echo "$words" | grep -q "$string"
6  then
7      echo "$string found in $words"
8  else
9      echo "$string not found in $words"
10 fi
```


Loops

```
for ARG in LIST; do COMMAND(s); done
```

```
$ for i in 1 2 3; do echo -n i="$i "; done
```

```
$ for i in {1..10}; do echo $i; done
```

```
$ for i in $(seq 10); do echo $i; done
```

```
$ for ((i=1; i<=10; i++)); do echo $i; done
```

```
$ for ((i=1, j=1; i<=10; i++, j++)); do
```

```
    echo $i-$j ☹️
```

```
    echo $((i-$j)) 😊
```

```
done
```

```
$ for ((i=1; i<=10; i++)) { echo $i; } # C style
```

```
$ for i in hello world; do echo -n "$i "; done
```

Loops

`while` `CONDITION`; `do` `COMMAND(s)`; `done`

`$ a=0; while [[a < 10]]; do echo $a; ((a++)); done` ☹️

`$ while [[$a < 10]]; do echo $a; ((a++)); done` ☹️

`$ while [[$a -lt 10]]; do echo $a; ((a++)); done` ✓

`$ while [$a -lt 10]; do echo $a; ((a++)); done` ✓

`$ while ((a < 10)); do echo $a; ((a++)); done` ✓

`$ until ((a = 10)); do echo $a; ((a++)); done` ☹️

`$ until ((a == 10)); do echo $a; ((a++)); done` ✓

`$ while read n; do n2 $n; done`

`$ while read n; do n2 $n; done < datafile`

`$ until ((n == 0)); do read n; n2 $n; done`

case

```

1  #!/bin/bash
2
3  [ -z "$1" ] && echo "Usage: `basename $0` [d|h] <number>" && exit 0;
4
5  case "$1" in
6      [dD]*)
7          NUM=$(echo $1 | cut -b 2-)
8          printf "\tDec\tHex\tBin\n"
9          printf "\t%d\t0x%02X\t%s\n" $NUM $NUM $(bc <<< "obase=2;$NUM")
10         ;;
11
12      [hH]*)
13          NUM=$(echo $1 | cut -b 2-)
14          NUM=$(echo $NUM | tr [:lower:] [:upper:])
15          printf "\tHex\t\tDec\t\tBin\n"
16          printf "\t0x%s\t\t%s\t\t%s\n" $NUM $(bc <<< "ibase=16;obase=A;$NUM") \
17              $(bc <<< "ibase=16;obase=2;$NUM")
18          ;;
19
20      0[xX]*)
21          NUM=$(echo $1 | cut -b 3-)
22          NUM=$(echo $NUM | tr [:lower:] [:upper:])
23          printf "\tHex\t\tDec\t\tBin\n"
24          printf "\t0x%s\t\t%s\t\t%s\n" $NUM $(bc <<< "ibase=16;obase=A;$NUM") \
25              $(bc <<< "ibase=16;obase=2;$NUM")
26          ;;
27
28      [bB]*)
29          NUM=$(echo $1 | cut -b 2-)
30          printf "\tBin\t\tHex\t\tDec\n"
31          printf "\t%s\t\t0x%s\t\t%s\n" $NUM $(bc <<< "ibase=2;obase=10000;$NUM") \
32              $(bc <<< "ibase=2;obase=1010;$NUM")
33          ;;
34
35      *)
36          printf "Dec\tHex\tBin\n"
37          printf "%d\t0x%08X\t%08d\n" $1 $1 $(bc <<< "obase=2;$1")
38          ;;
39
40  esac

```

select

```
1  #!/bin/bash
2
3  PS3='Your favorite OS? '
4
5  select OS in "Linux" "Mac OSX" "Windows"
6  do
7      [[ "$OS" = "Linux" ]] && echo wise guy.
8      [[ "$OS" = "Mac OSX" ]] && echo rich guy.
9      [[ "$OS" = "Windows" ]] && echo patient guy.
10     break
11 done
```

Functions

```
1  #!/bin/bash
2
3  function screencapture(){
4      ffmpeg -f x11grab -s 1920x1080 -r 30 -i :0.0 \
5          -c:v libx264 -crf 0 -preset ultrafast screen.mkv
6  }
7
8  w2pdf(){
9      libreoffice --convert-to pdf:writer_pdf_Export "$1"
10 }
11
12 rfc(){
13     [[ -n "$1" ]] || {
14         cat <<EOF
15         rfc - Command line RFC viewer
16         Usage: rfc <index>
17         EOF
18         return 1
19     }
20     find /usr/share/doc/RFC/ -type f -iname "rfc$1.*" | xargs less
21 }
```

Array

<https://www.tutorialspoint.com/unix/unix-using-arrays.htm>

C Programming Basics

Programming Environment

Program Languages

Machine code

The **binary numbers** that the CPUs can understand.

100111000011101111001111 ... and so on ...

Assembly language — friendly to humans

People don't think in numbers.

```
1  MOV A,47 ;1010 1111
2  ADD A,B   ;0011 0111
3  HALT      ;0111 0110
```

The ASM programs are translated to machine code by **assemblers**.

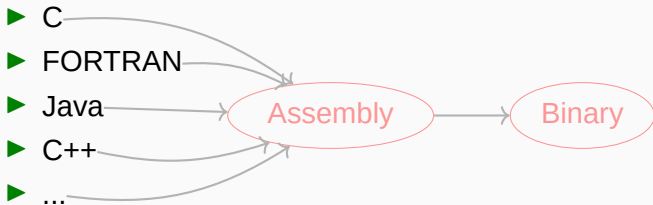
High level languages

Even easier to understand for humans. Examples:

- ▶ C
- ▶ FORTRAN
- ▶ Java
- ▶ C++
- ▶ ...

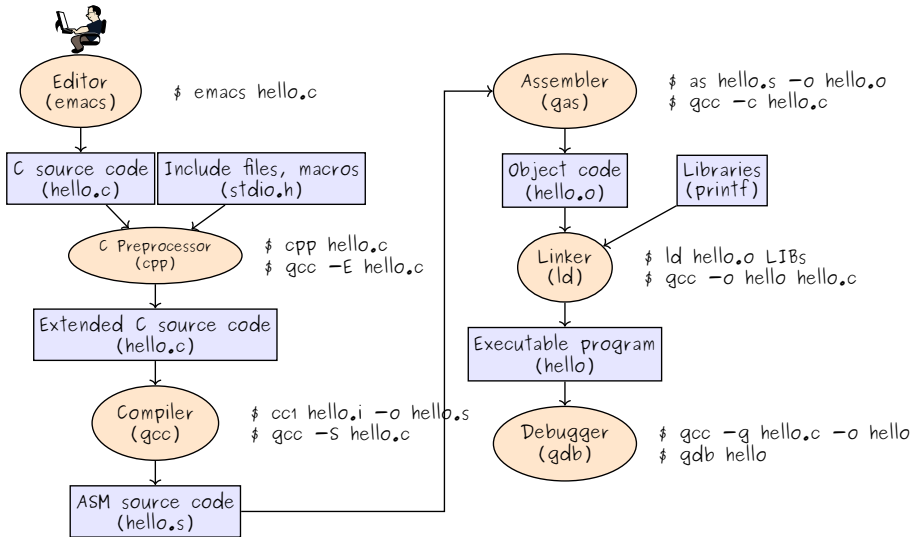
High level languages

Even easier to understand for humans. Examples:



Compilers do the translation work.

Compilation



Compiler vs. Interpreter

hello.c

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

```
int main()
```

```
{  
    printf("Hello, world!\n");  
    return 0;  
}
```

```
$ gcc -o hello hello.c
```

```
$ ./hello
```

hello.sh

```
#!/bin/bash
```

```
echo 'Hello, world!'
```

```
$ chmod +x hello.sh
```

```
$ ./hello.sh
```

hello.py

```
#!/usr/bin/python
```

```
print "Hello, world!"
```

```
$ chmod +x hello.py
```

```
$ ./hello.py
```

Header Files

Why?

```
#include "add.h"
```

```
int triple(int x)
{
    return add(x, add(x,x));
}
```

- ▶ Ensure everyone use the same code
- ▶ Easy to share, upgrade, reuse

Why not?

```
int add(int, int);
```

```
int triple(int x)
{
    return add(x, add(x, x));
}
```

In the header files...

- ▶ function declarations
- ▶ macro definitions
- ▶ constants
- ▶ system wide global variables

```
$ ls /usr/include/
```

Library Files

Static libraries `.a` files. Very old ones, but still alive.

```
$ find /usr/lib -name "*.a"
```

Shared libraries `.so` files. The preferred ones.

```
$ find /usr/lib -name "*.so.*"
```

Examples:

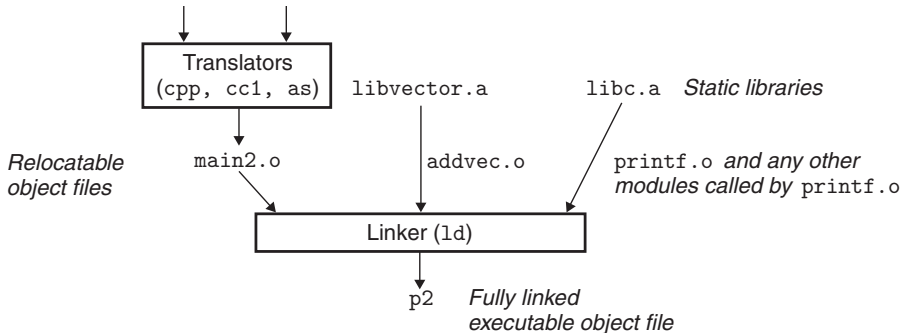
```
$ gcc -o hello hello.c /usr/lib/libm.a
```

```
$ gcc -o hello hello.c -lm
```

Static Linking

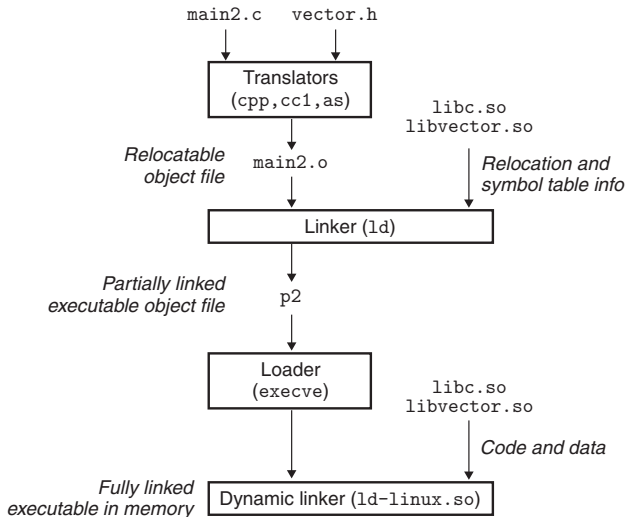
- ▶ The entire program and all data of a process must be in physical memory for the process to execute
- ▶ The size of a process is thus limited to the size of physical memory

Source files `main2.c` `vector.h`



Dynamic Linking

- ▶ Only one copy in memory
- ▶ Don't have to re-link after a library update



Build A Static Library

Source codes

main.c

```
1  #include "lib.h"
2
3  int main(int argc, char* argv[])
4  {
5      int i=1;
6
7      for (; i<argc; i++)
8      {
9          hello(argv[i]);
10         hi(argv[i]);
11     }
12     return 0;
13 }
```

lib.h

```
1  #include <stdio.h>
2
3  void hello(char *);
4  void hi(char *);
```

hello.c

```
1  #include <stdio.h>
2
3  void hello(char *arg)
4  {
5      printf("Hello, %s!\n", arg);
6  }
```

hi.c

```
1  #include <stdio.h>
2
3  void hi(char *arg)
4  {
5      printf("Hi, %s!\n", arg);
6  }
```

Build A Static Library

Step by step

1. Get `hello.o` and `hi.o`

```
$ gcc -c hello.c hi.c
```

2. Put `*.o` into `libhi.a`

```
$ ar crv libhi.a hello.o hi.o
```

3. Use `libhi.a`

```
$ gcc main.c libhi.a
```

Build A Static Library

Makefile

```
1  main: main.c lib.h libhi.a
2      gcc -Wall -o main main.c libhi.a
3
4  libhi.a: hello.o hi.o
5      ar crv libhi.a hello.o hi.o
6
7  hello.o: hello.c
8      gcc -Wall -c hello.c
9
10 hi.o: hi.c
11     gcc -Wall -c hi.c
12
13 clean:
14     rm -f *.o *.a main
```

Build A Shared Library

Source codes

hello.c

```
1  #include "hello.h"
2
3  int main(int argc, char *argv[])
4  {
5      if (argc != 2)
6          printf ("Usage: %s needs an argument.\n", argv[0]);
7      else
8          hi(argv[1]);
9      return 0;
10 }
```

hello.h

```
1  #include <stdio.h>
2  #include <stdlib.h>
3
4  int hi(char*);
```

hi.c

```
1  #include "hello.h"
2
3  int hi(char* s)
4  {
5      printf ("Hi, %s\n",s);
6      return 0;
7  }
```

Build A Shared Library

Step by step

1. Get `hi.o`

```
$ gcc -fPIC -c hi.c
```

2. Get `libhi.so`

```
$ gcc -shared -o libhi.so hi.o
```

3. Use `libhi.so`

```
$ gcc -L. -Wl,-rpath=. hello.c -lhi
```

4. Check it

```
$ ldd a.out
```

Build A Shared Library

Makefile

```
1  # http://www.cprogramming.com/tutorial/shared-libraries-linux-gcc.html
2  # http://tldp.org/HOWTO/Program-Library-HOWTO/shared-libraries.html
3  #
4  # gcc -fPIC -c hi.c
5  # gcc -shared -o libhi.so hi.o
6  # gcc -L/current/dir -Wl,option -Wall -o hello hello.c -lhi
7  #
8  # -L          - tells ld where to search libraries
9  # -Wl,option - pass option as an option to the linker (ld)
10 # -rpath=dir - Add a directory to the runtime library search path
11
12 hello: hello.c hello.h libhi.so
13         gcc -L. -Wl,-rpath=. -Wall -o hello hello.c -lhi
14 libhi.so: hi.o hello.h
15         gcc -shared -o libhi.so hi.o
16 hi.o: hi.c hello.h
17         gcc -fPIC -c hi.c
18 clean:
19         rm *.o *.so hello
```

GNU C Library

Linux API > POSIX API

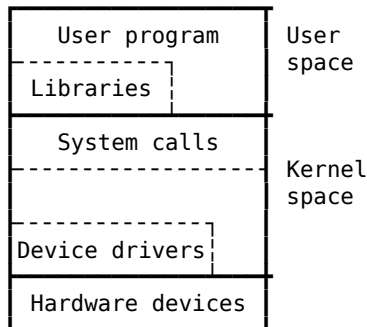
\$ man 7 libc

\$ man 3 intro

\$ man gcc

\$ info gcc

🌀 sudo apt install gcc-doc



errno.h

```
1  #include <stdio.h>
2  #include <stdlib.h>
3  #include <sys/stat.h>
4  #include <fcntl.h>
5
6  int main(int argc, char *argv[])
7  {
8      if ( open(argv[1], O_RDONLY) == -1 ){
9          perror("open");
10         exit(EXIT_FAILURE);
11     }
12     return 0;
13 }
```

\$ man errno

\$ man errno.h

\$ man perror

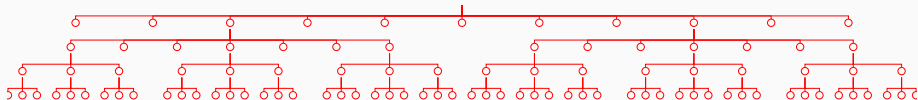
The Make Utility

To compile a single C program:

```
$ gcc hello.c -o hello
```

✓ OK. But...


What if you have a large project with 1000+ files?




Linux 4.9 source tree: 3799 directories, 55877 files

make: help you maintain your programs.

Makefile

```
1 target: dependencies
2 |  command
```

Example

```
1 hello: hello.c
2 |  gcc -o hello hello.c
```

\$ info make makefiles

Makefile

```
1  edit: main.o kbd.o command.o display.o \  
2      insert.o search.o files.o utils.o  
3      gcc -Wall -o edit main.o kbd.o command.o display.o \  
4      insert.o search.o files.o utils.o  
5  
6  main.o: main.c defs.h  
7      gcc -c -Wall main.c  
8  kbd.o : kbd.c defs.h command.h  
9      gcc -c -Wall kbd.c  
10 command.o: command.c defs.h command.h  
11      gcc -c -Wall command.c  
12 display.o : display.c defs.h buffer.h  
13      gcc -c -Wall display.c  
14 insert.o: insert.c defs.h buffer.h  
15      gcc -c -Wall insert.c  
16 search.o: search.c defs.h buffer.h  
17      gcc -c -Wall search.c  
18 files.o: files.c defs.h buffer.h command.h  
19      gcc -c -Wall files.c  
20 utils.o: utils.c defs.h  
21      gcc -c -Wall utils.c  
22  
23 clean:  
24     rm edit main.o kbd.o command.o display.o \  
25     insert.o search.o files.o utils.o
```

```
./  
├── command.c  
├── display.c  
├── files.c  
├── insert.c  
├── kbd.c  
├── main.c  
├── search.c  
├── utils.c  
├── buffer.h  
├── command.h  
├── defs.h  
└── Makefile
```

git

To create a new local git repo

In your source code directory, do:

```
$ git init
```

```
$ git add .
```

```
$ git commit -m "something to say..."
```

To clone a remote repo

Example:

```
$ git clone https://github.com/wx672/lecture-notes.git
```

```
$ git clone https://github.com/wx672/dotfile.git
```

Most commonly used git Commands

```
$ git add filename[s]
```

```
$ git rm filename[s]
```

```
$ git commit
```

```
$ git status
```

```
$ git log
```

```
$ git diff
```

```
$ git push
```

```
$ git pull
```

```
$ git help {add,rm,commit,...}
```

```
$ man gittutorial
```

```
$ man gittutorial-2
```

 `sudo apt install git`

 <https://github.com>

Man page

Layout

1 NAME

2 A one-line description of the command.

3 SYNOPSIS

4 A formal description of how to run it and what
5 command line options it takes.

6 DESCRIPTION

7 A description of the functioning of the command.

8 EXAMPLES

9 Some examples of common usage.

10 SEE ALSO

11 A list of related commands or functions.

12 BUGS

13 List known bugs.

14 AUTHOR

15 Specify your contact information.

16 COPYRIGHT

17 Specify your copyright information.

Man Page

Groff source code

```
1  .\" Text automatically generated by txt2man
2  .TH untitled "06 August 2019" "" ""
3  .SH NAME
4  \fBA one-line description of the command.
5  .SH SYNOPSIS
6  .nf
7  .fam C
8      \fBA formal description of how to run it and what command line options it takes.
9  .fam T
10 .fi
11 .fam T
12 .fi
13 .SH DESCRIPTION
14 \fBA description of the functioning of the command.
15 .SH EXAMPLES
16 Some examples of common usage.
17 .SH SEE ALSO
18 \fBA list of related commands or functions.
19 .SH BUGS
20 List known bugs.
21 .SH AUTHOR
22 Specify your contact information.
23 .SH COPYRIGHT
24 Specify your copyright information.
```

\$ man 7 groff

\$ man txt2man

\$ man a2x

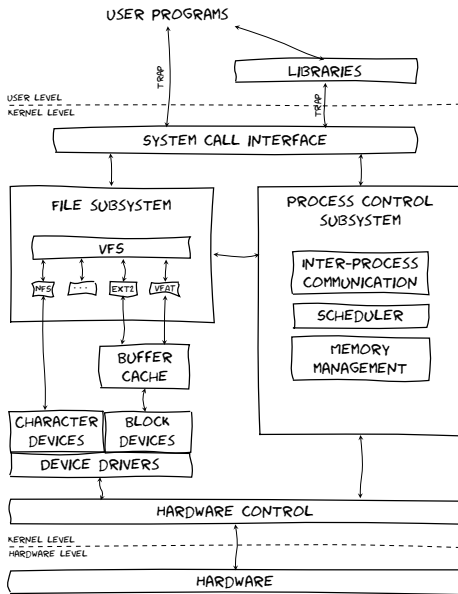
\$ ls /usr/share/man

How to “Do one thing, and do it well”?

```
$ apt source hello
```

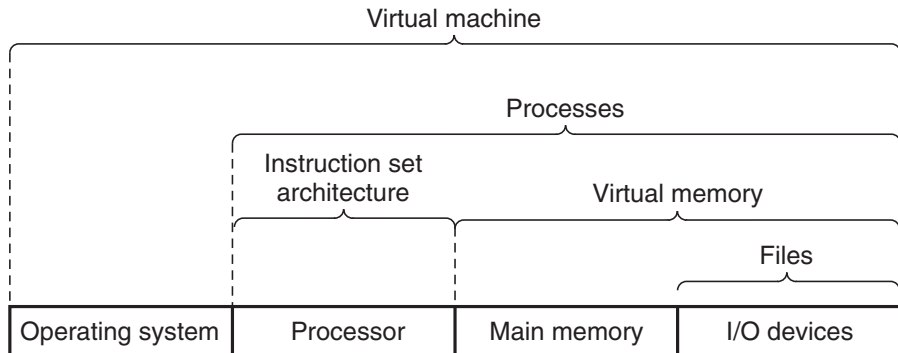
OS Basics

Operating System

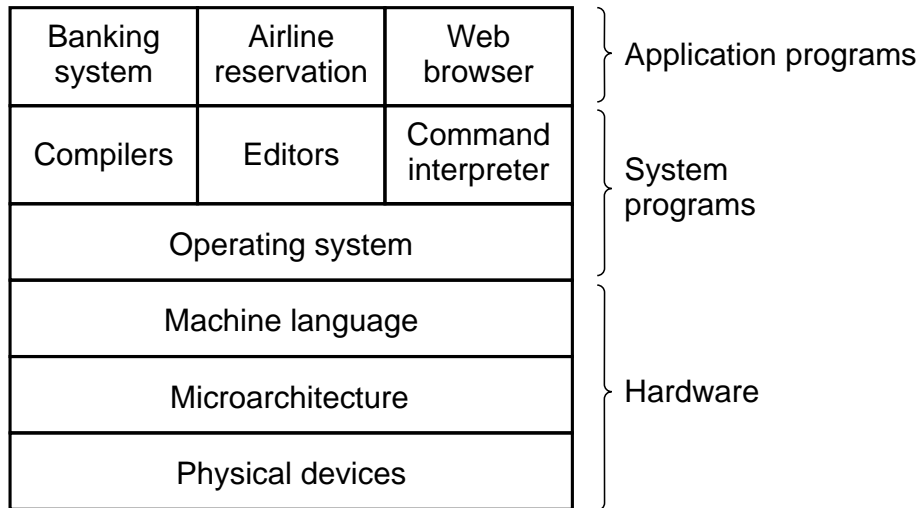


Abstractions

To hide the complexity of the actual implementations



A Computer System



CPU Working Cycle



1. Fetch the first instruction from memory
2. Decode it to determine its type and operands
3. execute it

Special CPU Registers

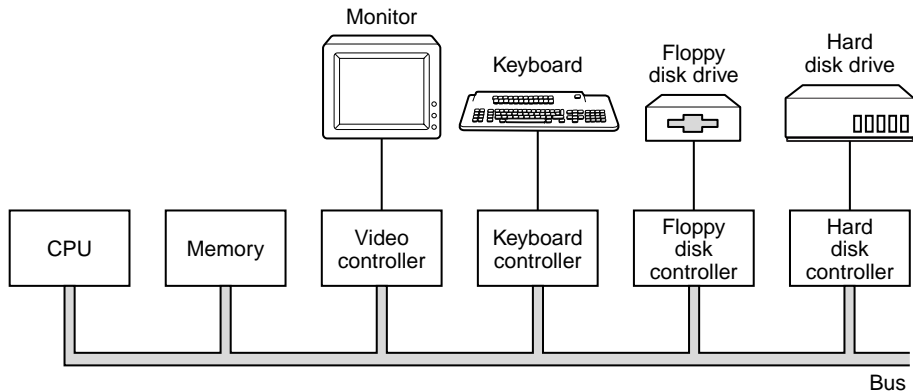
Program counter (PC): keeps the memory address of the next instruction to be fetched

Stack pointer (SP): ➡ the top of the current stack in memory

Program status (PS): holds

- condition code bits
- processor state

System Bus



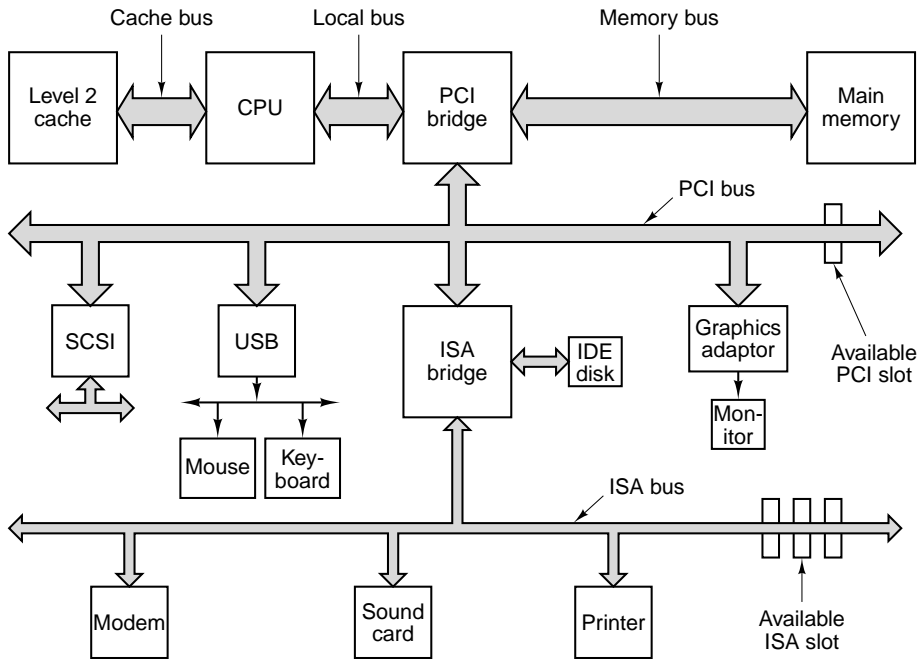
Address Bus: specifies the memory locations (addresses) for the data transfers

Data Bus: holds the data transferred. Bidirectional

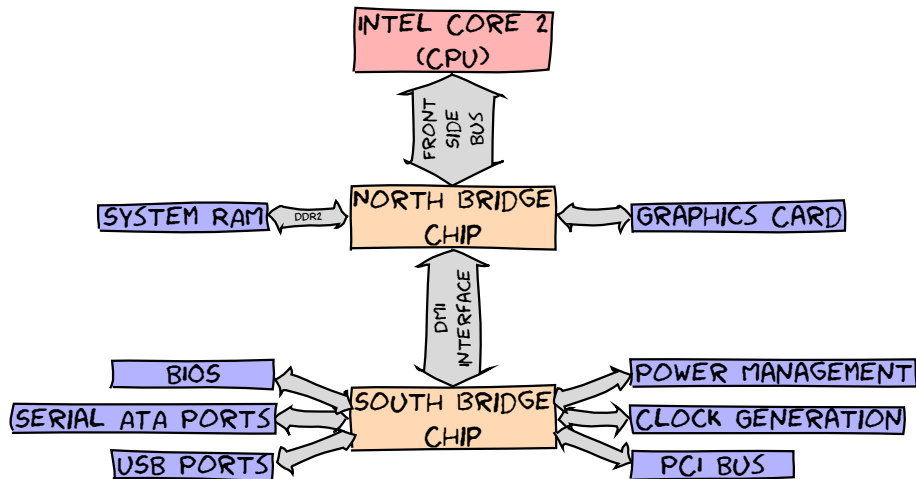
Control Bus: contains various lines used to route timing and control signals throughout the system

Controllers and Peripherals

- ▶ Peripherals are real devices controlled by controller chips
- ▶ Controllers are processors like the CPU itself, have control registers
- ▶ Device driver writes to the registers, thus control it
- ▶ Controllers are connected to the CPU and to each other by a variety of buses



Motherboard Chipsets



- ▶ The CPU doesn't know what it's connected to
 - CPU test bench? network router? toaster? brain implant?
- ▶ The CPU talks to the outside world through its pins
 - some pins to transmit the physical memory address
 - other pins to transmit the values
- ▶ The CPU's gateway to the world is the **front-side bus**

Intel Core 2 QX6600

- ▶ 33 pins to transmit the physical memory address
 - so there are 2^{33} choices of memory locations
- ▶ 64 pins to send or receive data
 - so data path is 64-bit wide, or 8-byte chunks

This allows the CPU to physically address 64GB of memory ($2^{33} \times 8B$)

Some physical memory addresses are mapped away!

- ▶ only the addresses, not the spaces
- ▶ Memory holes
 - 640 KiB ~ 1 MiB
 - `/proc/iomem`

Memory-mapped I/O

- ▶ BIOS ROM
- ▶ video cards
- ▶ PCI cards
- ▶ ...

This is why 32-bit OSes have problems using 4 GiB of RAM.

0xFFFFFFFF	Reset vector	0xFFFFFFFF	JUMP to 0xF0000	4GB
			Unaddressable memory, real mode is limited to 1MB.	4GB-16B
0x100000			System BIOS	1MB
0xF0000			Ext. System BIOS	960KB
0xE0000			Expansion Area (maps ROMs for old peripheral cards)	896KB
0xC0000			Legacy Video Card Memory Access	768KB
0xA0000			Accessible RAM (640KB is enough for anyone – old DOS area)	640KB
0				0

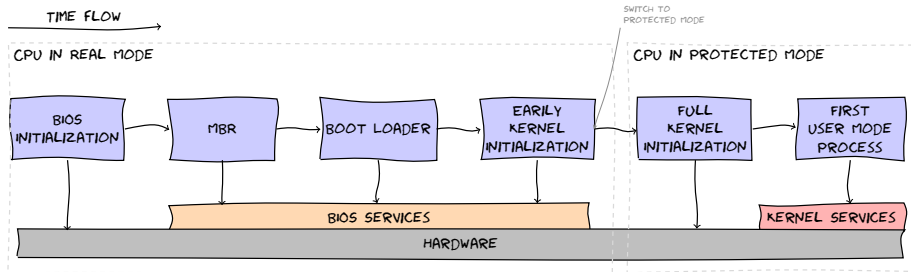
the northbridge

1. receives a physical memory request
2. decides where to route it
 - to RAM? to video card? to ...?
 - decision made via the [memory address map](#)

Bootstrapping

Can you pull yourself up by your own bootstraps?

A computer cannot run without first loading software but must be running before any software can be loaded.



Intel x86 Bootstrapping

1. BIOS (0xfffffff0)

➡ POST ➡ HW init ➡ Find a boot device (FD,CD,HD...) ➡ Copy **sector zero (MBR)** to RAM (0x00007c00)

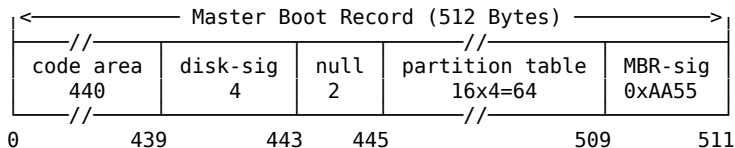
2. MBR – the first 512 bytes, contains

- ▶ Small code ($< 446\text{ B}$), e.g. GRUB stage 1, for loading GRUB stage 2
- ▶ the primary partition table ($16 \times 4 = 64\text{ B}$)
- ▶ its job is to load the second-stage boot loader.

3. GRUB stage 2 — load the OS kernel into RAM

4. startup

5. init — the first user-space process



```
$ sudo hd -n512 /dev/sda
```

Why Interrupt?

While a process is reading a disk file, can we do...

```
1 while(!done_reading_a_file())
2 {
3     let_CPU_wait();
4     // or...
5     lend_CPU_to_others();
6 }
7 operate_on_the_file();
```


Modern OS are Interrupt Driven

HW INT by sending a signal to CPU

SW INT by executing a **system call**

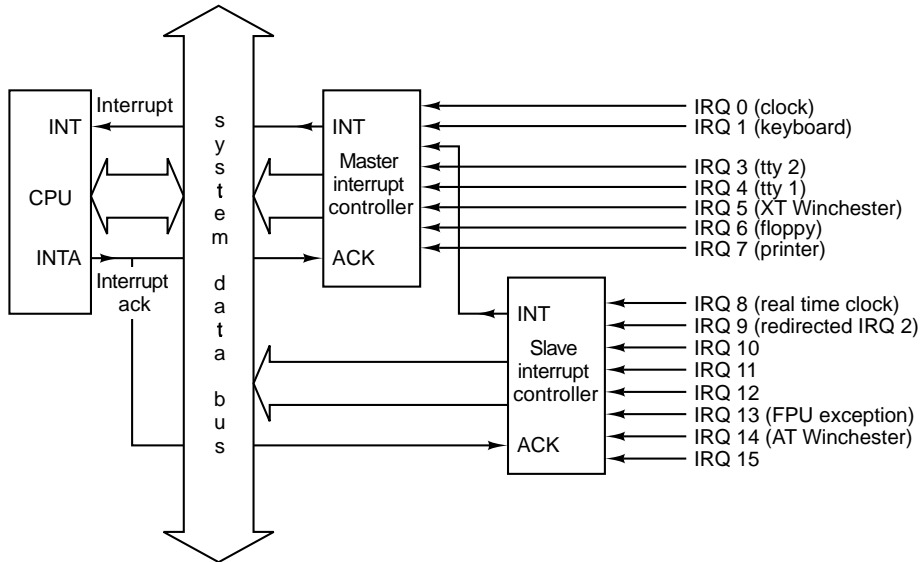
Trap (exception) is a software-generated INT caused by an error or by a specific request from an user program

Interrupt vector is an array of pointers ➡ the memory addresses of **interrupt handlers**. This array is indexed by a unique device number

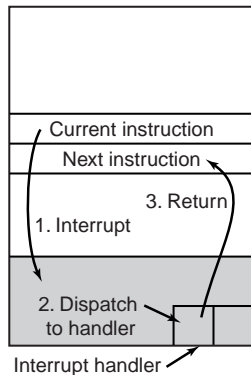
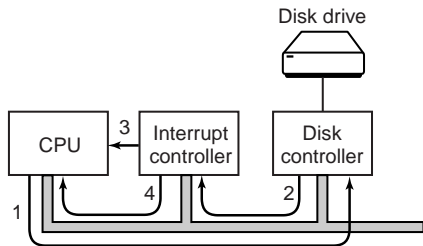
```
$ less /proc/devices
```

```
$ less /proc/interrupts
```

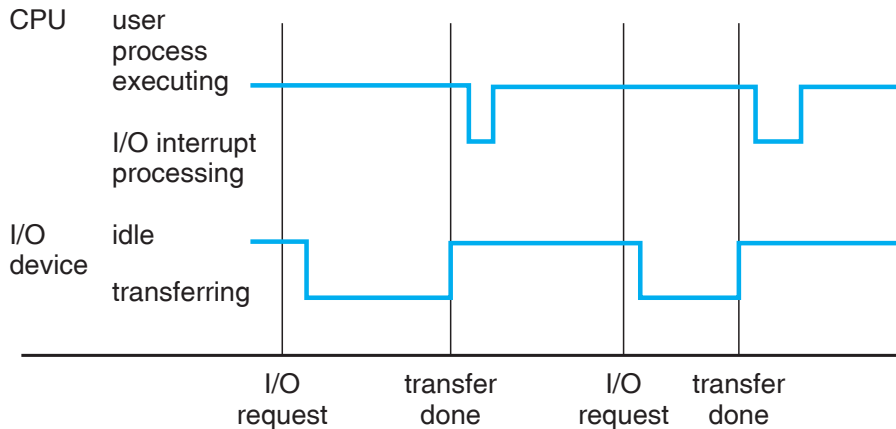
Programmable Interrupt Controllers



Interrupt Processing



Interrupt Timeline



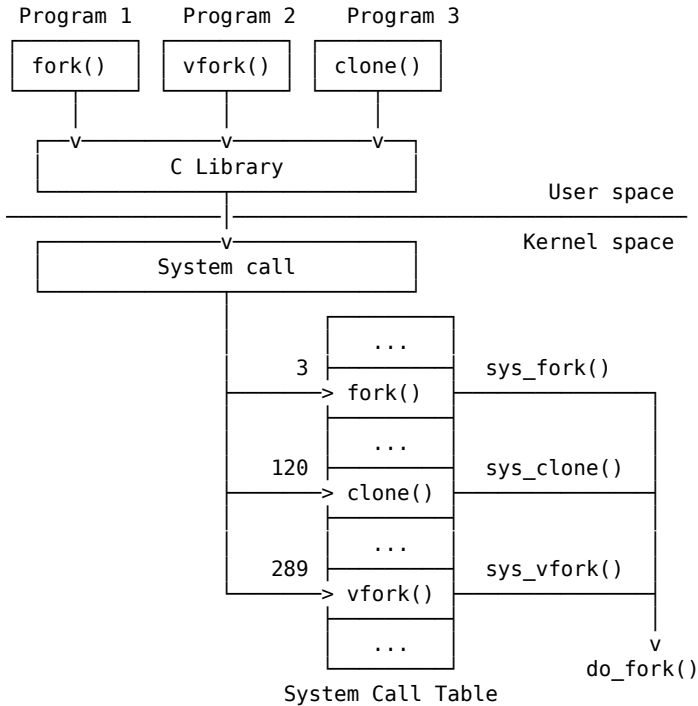
System Calls

A System Call

- ▶ is how a program requests a service from an OS kernel
- ▶ provides the interface between a process and the OS

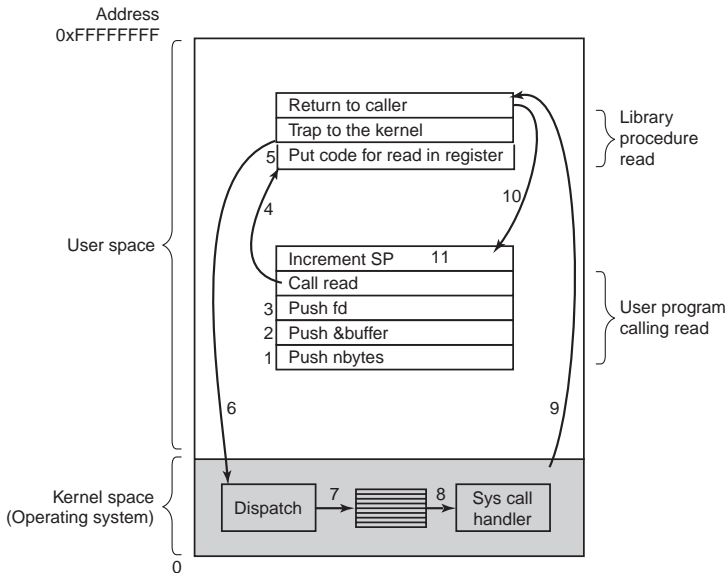
```
$ man 2 intro
```

```
$ man 2 syscalls
```



The 11 steps in making a system call

`read(fd,buffer,nbytes)`



Example

Linux INT 80h

Interrupt Vector Table: The very first 1KiB of x86 memory.

- ▶ 256 entries \times 4B = 1KiB
- ▶ Each entry is a complete memory address (segment:offset)
- ▶ It's populated by Linux and BIOS
- ▶ Slot 80h: address of the kernel services dispatcher (☛ sys-call table)

Example

```
1  Msg: db 'Hello, world'
2  MsgLen: equ $-Msg
3  mov eax,4          ; sys_write syscall = 4
4  mov ebx,1          ; 1 = STDOUT
5  mov ecx,Msg        ; offset of the message
6  mov edx,MsgLen     ; length of string
7  int 80h            ; call the kernel
```

```
$ nasm -f elf64 hello.asm -o hello.o
$ ld hello.o -o hello
$ ./hello
```

Process management

Call	Description
pid = fork()	Create a child process identical to the parent
pid = waitpid(pid, &statloc, options)	Wait for a child to terminate
s = execve(name, argv, environp)	Replace a process' core image
exit(status)	Terminate process execution and return status

File management

Call	Description
fd = open(file, how, ...)	Open a file for reading, writing or both
s = close(fd)	Close an open file
n = read(fd, buffer, nbytes)	Read data from a file into a buffer
n = write(fd, buffer, nbytes)	Write data from a buffer into a file
position = lseek(fd, offset, whence)	Move the file pointer
s = stat(name, &buf)	Get a file's status information

Directory and file system management

Call	Description
s = mkdir(name, mode)	Create a new directory
s = rmdir(name)	Remove an empty directory
s = link(name1, name2)	Create a new entry, name2, pointing to name1
s = unlink(name)	Remove a directory entry
s = mount(special, name, flag)	Mount a file system
s = umount(special)	Unmount a file system

Miscellaneous

Call	Description
s = chdir(dirname)	Change the working directory
s = chmod(name, mode)	Change a file's protection bits
s = kill(pid, signal)	Send a signal to a process
seconds = time(&seconds)	Get the elapsed time since Jan. 1, 1970

System Call Examples

fork()

```
1  #include <stdio.h>
2  #include <unistd.h>
3
4  int main()
5  {
6      printf("Hello World!\n");
7      fork();
8      printf("Goodbye Cruel World!\n");
9      return 0;
10 }
```

\$ man 2 fork

execve()

```
1  #include <stdio.h>
2  #include <unistd.h>
3
4  int main ()
5  {
6      printf("Hello World!\n");
7      if(fork() != 0 )
8          printf("I am the parent process.\n");
9      else {
10         printf("A child is listing the directory contents...\n");
11         execl("/bin/ls", "ls", "-al", NULL);
12     }
13     return 0;
14 }
```

\$ man 2 execve

\$ man 3 exec

The Linux Environment

Command Line Options

getopt.c

```
1  #include <stdio.h>
2  #include <unistd.h>
3
4  int main(int argc, char* argv[]) {
5      int opt;
6
7      while ((opt = getopt(argc, argv, "hf:l")) != -1) {
8          switch (opt) {
9              case 'h':
10                 printf("Usage: %s [-h] [-f file] [-l]\n", argv[0]);
11                 break;
12              case 'l':
13                 printf("option: %c\n", opt);
14                 break;
15              case 'f':
16                 printf("filename: %s\n", optarg);
17                 break;
18             }
19         }
20         return 0;
21     }
```

\$ man 3 getopt

Command Line Options

getopt.sh

```
1  #!/bin/bash
2
3  while getopts hf:l OPT; do
4      case $OPT in
5          h) echo "usage: `basename $0` [-h] [-f file] [-l]"
6              exit 1 ;;
7          l) echo "option: l" ;;
8          f) echo "filename: $OPTARG" ;;
9      esac
10  done
```

```
$ ./getopt.sh -h
```

```
$ ./getopt.sh -lf filename
```

```
$ ./getopt.sh -l -f filename
```

```
$ ./getopt.sh -f filename -l
```

Environment Variable

```
1  #include <stdlib.h>
2  #include <stdio.h>
3
4  extern char** environ;
5
6  int main() {
7      char** env = environ;          $ env
8                                      $ man 3 getenv
9      while (*env) {                 $ man 3 putenv
10         printf("%s\n", *env);
11         env++;
12     }
13
14     return 0;
15 }
```


Time and Date

```
1  #include <time.h>
2  #include <stdio.h>
3
4  int main(void)
5  {
6      time_t t = time(NULL); /* long int */
7
8      printf("epoch time:\t%ld\n",t);
9      printf("calendar time:\t%s", ctime(&t));
10
11     return 0;
12 }
```

► January 1 1970 — start of the Unix epoch

\$ man 3 time

\$ man 3 ctime

Temporary Files

mkstemp.c

```
1  #include <stdlib.h>
2  #include <unistd.h>
3  #define _GNU_SOURCE
4  #include <stdio.h>
5
6  int main(int argc, char *argv[])
7  {
8      char c, *f;
9
10     asprintf(&f, "%sXXXXXX", argv[1]);
11     int tmp = mkstemp(f);
12
13     while ( read(0, &c, 1) == 1)
14         write(tmp, &c, 1);
15
16     unlink(f);
17     free(f);
18     return 0;
19 }
```

mktemp.sh

```
1  #!/bin/bash
2
3  tmp=$(mktemp)
4
5  while read LINE; do
6      echo $LINE >> $tmp
7  done
8
9
```

\$ man 3 mkstemp

\$ man 3 tmpfile

\$ man 3 asprintf

Logging

syslog.c

```
1  #include <syslog.h>
2  #include <sys/stat.h>
3  #include <fcntl.h>
4
5  int main(int argc, char *argv[])
6  {
7      if ( open(argv[1], O_RDONLY) < 0 )
8          syslog(LOG_ERR | LOG_USER, "%s - %m\n", argv[1]);
9      else
10         syslog(LOG_INFO | LOG_USER, "%s - %m\n", argv[1]);
11     return 0;
12 }
```

logger.sh

```
1  #!/bin/bash
2
3  [[ -f "$1" ]] && logger "$1 exists." || logger "$1 not found."
```

Working With Files

File

File

A logical view of information storage

User's view

A file is the smallest storage unit on disk.

- ▶ Data cannot be written to disk unless they are within a file

UNIX view

Each file is a sequence of 8-bit bytes

- ▶ It's up to the application program to interpret this byte stream.

File

What is stored in a file?

Source code, object files, executable files, shell scripts, PostScript...

Different type of files have different structure

- ▶ UNIX looks at contents to determine type

Shell scripts start with “#!”

PDF start with “%PDF . . .”

Executables start with magic number

- ▶ Windows uses file naming conventions

executables end with “.exe” and “.com”

MS-Word end with “.doc”

MS-Excel end with “.xls”

File Types

Regular files: ASCII, binary

Directories: Maintaining the structure of the FS

In UNIX, everything is a file

Character special files: I/O related, such as terminals, printers ...

Block special files: Devices that can contain file systems, i.e. disks

Disks — logically, linear collections of blocks; disk driver translates them into physical block addresses

File Operations

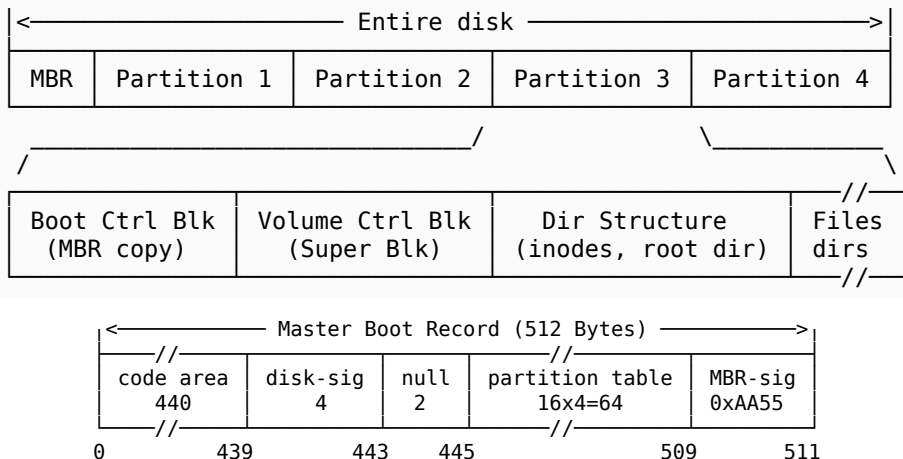
POSIX file system calls

```
creat(name, mode)
open(name, flags)
close(fd)
link(oldname, newname)
unlink(name)
truncate(name, size)
ftruncate(fd, size)
stat(name, buffer)
fstat(fd, buffer)
```

```
read(fd, buffer, byte_count)
write(fd, buffer, byte_count)
lseek(fd, offset, whence)
chown(name, owner, group)
fchown(fd, owner, group)
chmod(name, mode)
fchmod(fd, mode)
utimes(name, times)
```

File System Implementation

A typical file system layout



On-Disk Information Structure

Boot block a MBR copy

Superblock Contains volume details

number of blocks	size of blocks
free-block count	free-block pointers
free FCB count	free FCB pointers

I-node Organizes the files **FCB (File Control Block)**, contains file details (metadata).

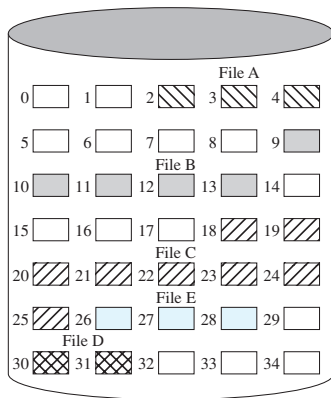
Superblock

Keeps information about the file system

- ▶ Type — ext2, ext3, ext4...
- ▶ Size
- ▶ Status — how it's mounted, free blocks, free inodes, ...
- ▶ Information about other metadata structures

```
$ sudo dumpe2fs /dev/sda1 | less
```

Implementing Files



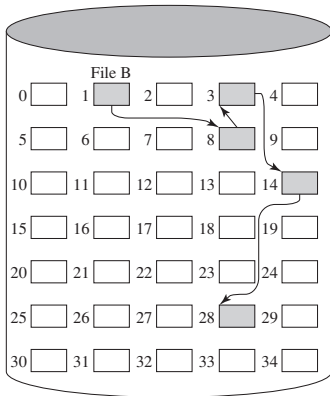
File Allocation Table

File Name	Start Block	Length
File A	2	3
File B	9	5
File C	18	8
File D	30	2
File E	26	3

Contiguous Allocation

- 😊 simple
- 😊 good for read only

😞 fragmentation



File Allocation Table

File Name	Start Block	Length
• • • File B • • •	• • • 1 • • •	• • • 5 • • •

Linked List (Chained) Allocation

A pointer in each disk block



no waste block

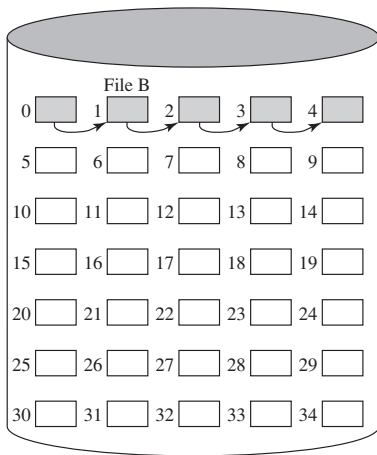


slow random access



not 2^n

Linked List (Chained) Allocation Though there is no external fragmentation, consolidation is still preferred.



File Allocation Table

File Name	Start Block	Length
• • • File B • • •	• • • 0 • • •	• • • 5 • • •

FAT: Linked list allocation with a table in RAM

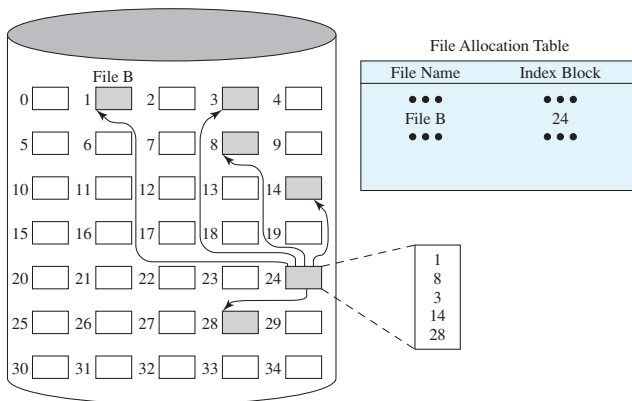
- ▶ Taking the pointer out of each disk block, and putting it into a table in memory
- ▶ fast random access (chain is in RAM)
- ▶ is 2^n
- ▶ the entire table must be in RAM

$disk \nearrow \Rightarrow FAT \nearrow \Rightarrow RAM_{used} \nearrow$

Physical
block

0		
1		
2	10	
3	11	
4	7	← File A starts here
5		
6	3	← File B starts here
7	2	
8		
9		
10	12	
11	14	
12	-1	
13		
14	-1	
15		← Unused block

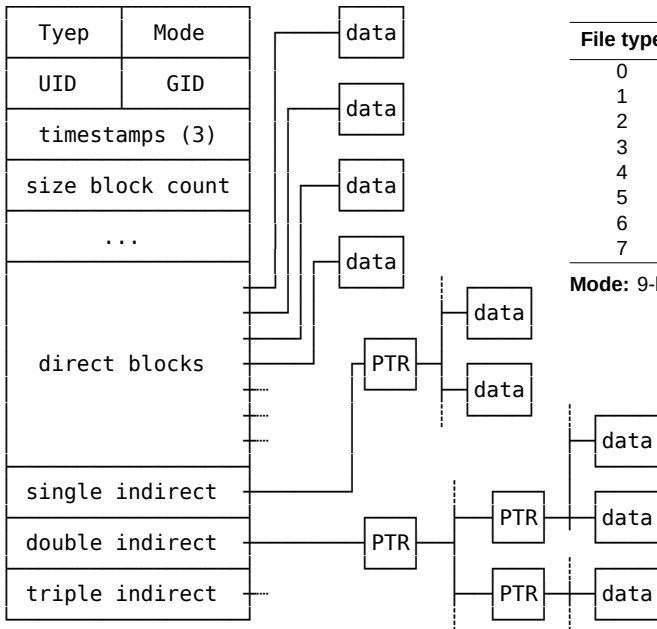
Indexed Allocation



I-node A data structure for each file. An i-node is in memory *only* if the file is open

$$files_{opened} \nearrow \Rightarrow RAM_{used} \nearrow$$

I-node



File type	Description
0	Unknown
1	Regular file
2	Directory
3	Character device
4	Block device
5	Named pipe
6	Socket
7	Symbolic link

Mode: 9-bit pattern

UNIX Treats a Directory as a File

.	2
..	2
bin	11116545
boot	2
cdrom	12
dev	3
:	:

Directory inode (128B)

Type	Mode
User ID	Group ID
File size	# blocks
# links	Flags
Timestamps (x3)	
Direct blocks (x12)	
Single indirect	
Double indirect	
Triple indirect	

Directory block

.	inode #
..	inode #
passwd	inode #
fstab	inode #
...	...

Indirect block

Direct blocks (x512)

File inode (128B)

Type	Mode
User ID	Group ID
File size	# blocks
# links	Flags
Timestamps (x3)	
Direct blocks (x12)	
Single indirect	
Double indirect	
Triple indirect	

File data block

Data

Block # of
block with
512 double
indirect
entries

Block # of
block with
512 single
indirect
entries

Block #s of
more
directory
blocks

open()

Why? To avoid constant searching

- ▶ Without open(), every file operation involves searching the directory for the file.

The steps in looking up /usr/ast/mbox

Root directory

1	.
1	..
4	bin
7	dev
14	lib
9	etc
6	usr
8	tmp

Looking up
usr yields
i-node 6

I-node 6
is for /usr

Mode size times
132

I-node 6
says that
/usr is in
block 132

Block 132
is /usr
directory

6	.
1	..
19	dick
30	erik
51	jim
26	ast
45	bal

/usr/ast
is i-node
26

I-node 26
is for
/usr/ast

Mode size times
406

I-node 26
says that
/usr/ast is in
block 406

Block 406
is /usr/ast
directory

26	.
6	..
64	grants
92	books
60	mbox
81	minix
17	src

/usr/ast/mbox
is i-node
60

```
fd open(pathname, flags)
```

A per-process **open-file table** is kept in the OS

- ▶ upon a successful `open()` syscall, a new entry is added into this table
- ▶ indexed by **file descriptor (fd)**
- ▶ `close()` to remove an entry from the table

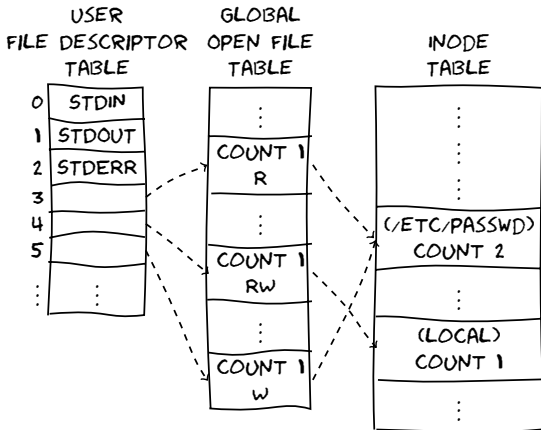
To see files opened by a process, e.g. `init`

```
$ lsof -p 1
```

```
$ man 2 open
```

A process executes the following code:

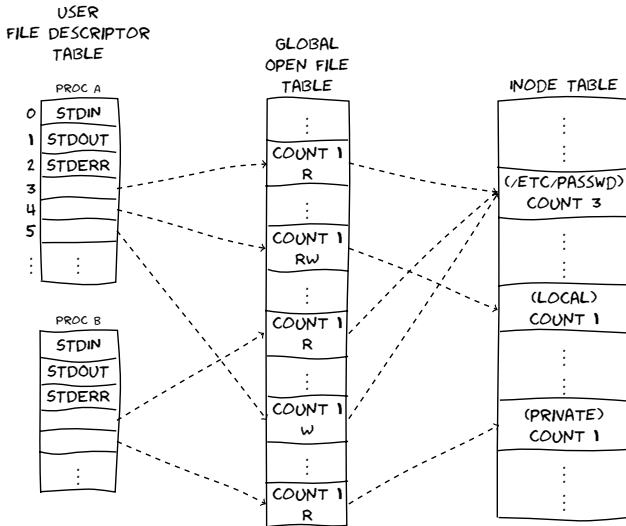
```
fd1 = open("/etc/passwd", O_RDONLY);  
fd2 = open("local", O_RDWR);  
fd3 = open("/etc/passwd", O_WRONLY);
```



One more process B:

```
fd1 = open("/etc/passwd", O_RDONLY);
```

```
fd2 = open("private", O_RDONLY);
```



write()

```
1  #include <unistd.h>
2
3  int main(void)
4  {
5      write(1, "Hello, world!\n", 14);
6
7      return 0;
8  }
```

\$ man 2 write

\$ man 3 write

read()

```
1  #include <unistd.h>
2
3  int main(void)
4  {
5      char buffer[10];
6
7      read(0, buffer, 10);
8
9      write(1, buffer, 10);
10
11     return 0;
12 }
```

\$ man 2 read

\$ man 3 read

cp

```
1  #include <sys/types.h>    /* include necessary header files */
2  #include <fcntl.h>
3  #include <stdlib.h>
4  #include <unistd.h>
5
6  #define BUF_SIZE 4096      /* use a buffer size of 4096 bytes */
7  #define OUTPUT_MODE 0700 /* protection bits for output file */
8
9  int main(int argc, char *argv[])
10 {
11     int in, out, rbytes, wbytes;
12     char buf[BUF_SIZE];
13
14     if (argc != 3) exit(1);
15
16     if ( (in = open(argv[1], O_RDONLY)) < 0 ) exit(2); /* open source file */
17
18     if ( (out = creat(argv[2], OUTPUT_MODE)) < 0 ) exit(3); /* create destination file */
19
20     while (1) { /* Copy loop */
21         if ( (rbytes = read(in, buf, BUF_SIZE)) <= 0 ) break; /* read a block of data */
22         if ( (wbytes = write(out, buf, rbytes)) <= 0 ) exit(4); /* write data */
23     }
24
25     close(in);
26     close(out);
27     if (rbytes == 0) exit(0); /* no error on last read */
28     else exit(5);           /* error on last read */
29 }
```

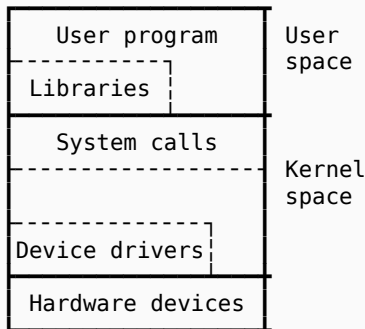
stdio — The Standard I/O Library

System calls: `open()`, `read()`, `write()`, `close()`...

Library functions: `fopen()`, `fread()`, `fwrite`, `fclose()`...

Avoid calling syscalls directly as much as you can

- ▶ Portability
- ▶ Buffered I/O



open() vs. fopen()

open()

```
1  #include <unistd.h>
2  #include <sys/stat.h>
3  #include <fcntl.h>
4  #include <stdio.h>
5
6  int main()
7  {
8      char c;
9      int in;
10     in = open("/tmp/1m.test", O_RDONLY);
11
12     while (read(in, &c, 1) == 1);
13
14     return 0;
15 }
```

```
$ strace -c ./open
```

```
$ dd if=/dev/zero of=/tmp/1m.test bs=1k count=1024
```

fopen() — Buffered I/O

```
1  #include <stdio.h>
2
3  int main(void)
4  {
5      FILE *stream;
6
7      stream = fopen("/tmp/1m.test", "r");
8
9      while ( fgetc(stream) != EOF );
10
11     fclose(stream);
12
13     return 0;
14 }
```

```
$ strace -c ./fopen
```

cp — With stdio

```
1  #include <stdio.h>
2  #include <stdlib.h>
3
4  int main(int argc, char *argv[])
5  {
6      FILE *in, *out;
7      int c=0;
8
9      if (argc != 3) exit(1);
10
11     in = fopen(argv[1], "r");
12     out = fopen(argv[2], "w");
13
14     while ( (c = fgetc(in)) != EOF )
15         fputc(c, out);
16
17     return 0;
18 }
```

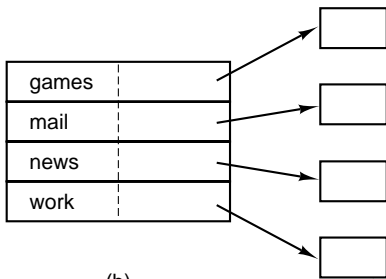
Homework: Try fread()/fwrite() instead.

Directory

Implementing Directories

games	attributes
mail	attributes
news	attributes
work	attributes

(a)



(b)

Data structure
containing the
attributes

(a) A simple directory (Windows)

- ▶ fixed size entries
- ▶ disk addresses and attributes in directory entry

(b) Directory in which each entry just refers to an i-node (UNIX)

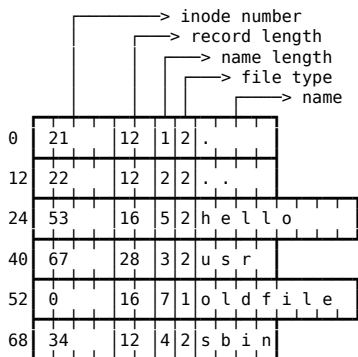
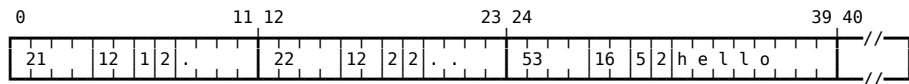
Directory entry in `glibc`

```
1  struct dirent {
2      ino_t      d_ino;          /* Inode number */
3      off_t      d_off;          /* Not an offset; see below */
4      unsigned short d_reclen;    /* Length of this record */
5      unsigned char d_type;       /* Type of file; not supported
6                                   by all filesystem types */
7      char       d_name[256];    /* Null-terminated filename */
8  };
```

\$ man readdir

\$ view /usr/include/x86_64-linux-gnu/bits/dirent.h

Ext2 Directories



- ▶ Directories are special files
- ▶ "." and ".." first
- ▶ Padding to $4 \times$
- ▶ inode number is 0 — deleted file

ls

```
1  #include <sys/types.h>
2  #include <dirent.h>
3  #include <stddef.h>
4  #include <stdio.h>
5
6  int main(int argc, char *argv[])
7  {
8      DIR *dp;
9      struct dirent *entry;
10
11     dp = opendir(argv[1]);
12
13     while ( (entry = readdir(dp)) != NULL ){
14         printf("%s\n", entry->d_name);
15     }
16
17     closedir(dp);
18
19     return 0;
20 }
```

The real ls.c?

116 A4 pages
5308 lines

Do one thing, and do
it really well.

\$ apt source coreutils

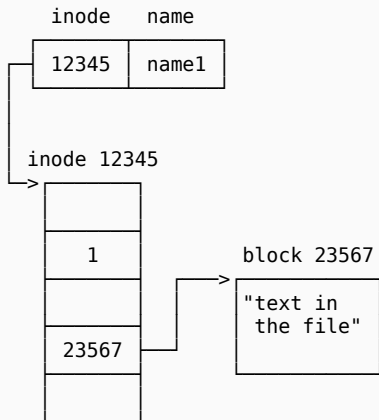
mkdir(), chdir(), rmdir(), getcwd()

```
1  #include <sys/stat.h>
2  #include <sys/types.h>
3  #include <unistd.h>
4  #include <stdio.h>
5
6  int main(int argc, char *argv[])
7  {
8      char s[100];
9      if ( mkdir(argv[1], S_IRUSR|S_IXUSR) == 0 )
10         chdir(argv[1]);
11     printf("PWD = %s\n", getcwd(s,100));
12     rmdir(argv[1]);
13     return 0;
14 }
```

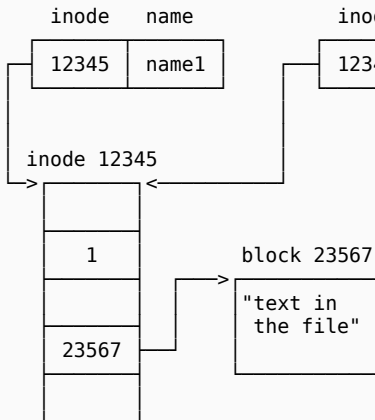
Hard Links

Hard links → the same inode

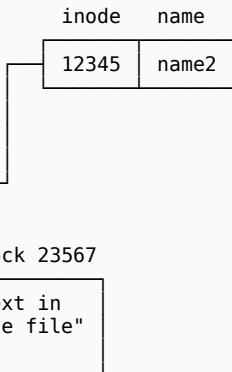
directory entry in /dirA



dir entry in /dirA

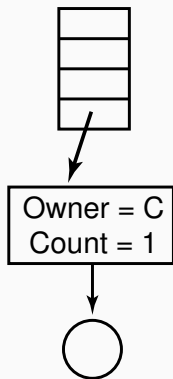


dir entry in /dirB



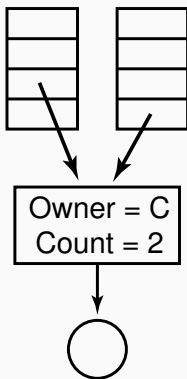
Drawback

C's directory



(a)

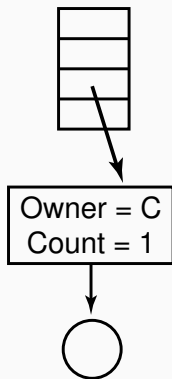
B's directory



(b)

C's directory

B's directory



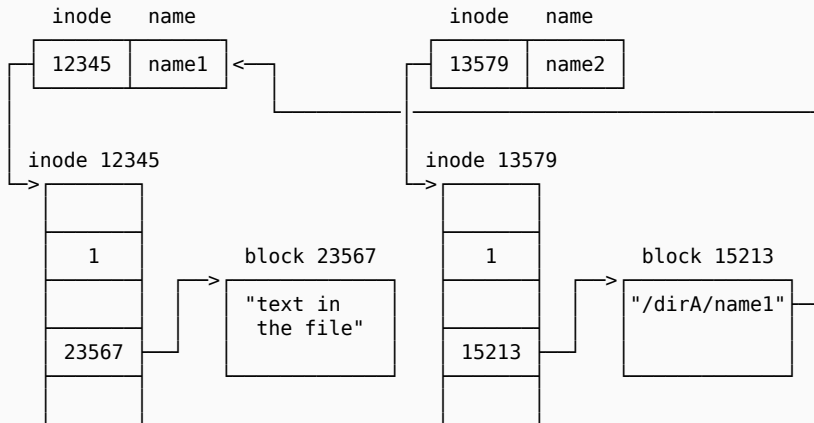
(c)

Symbolic Links

A symbolic link has its own inode → a directory entry

directory entry in /dirA

directory entry in /dirB



Fast symbolic link: Short path name (< 60 *chars*) needs no data block.
Can be stored in the 15 pointer fields

link(), unlink(), symlink()

```
1  #include <unistd.h>
2  #include <stdio.h>
3
4  int main(int argc, char *argv[])
5  {
6      link(argv[1], argv[2]);
7      perror(argv[0]);
8      return 0;
9  }
10
11  /* symlink(argv[1], argv[2]); */
12  /* unlink(argv[1]); */
```

Processes and Threads

Process

Process

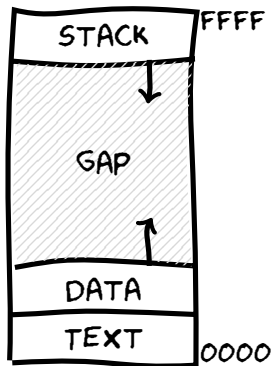
A **process** is an instance of a program in execution

Processes are like human beings:

- ➡ they are generated
- ➡ they have a life
- ➡ they optionally generate one or more child processes, and
- ➡ eventually they die

A small difference:

- ▶ sex is not really common among processes
- ▶ each process has just one parent



Process Control Block (PCB)

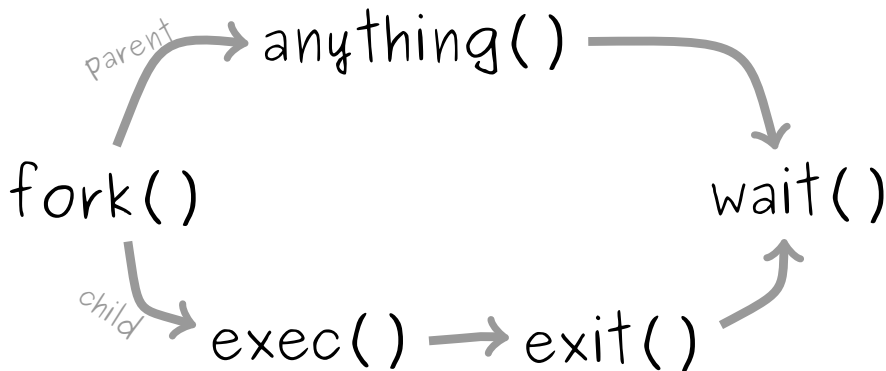
Implementation

A process is **the collection of data structures** that fully describes how far the execution of the program has progressed.

- ▶ Each process is represented by a **PCB**
- ▶ `task_struct` in 

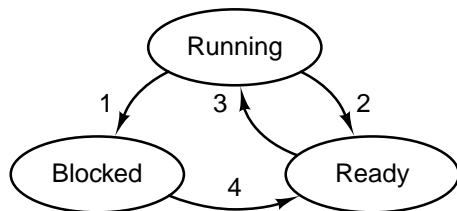
process state
PID
program counter
registers
memory limits
list of open files
...

Process Creation



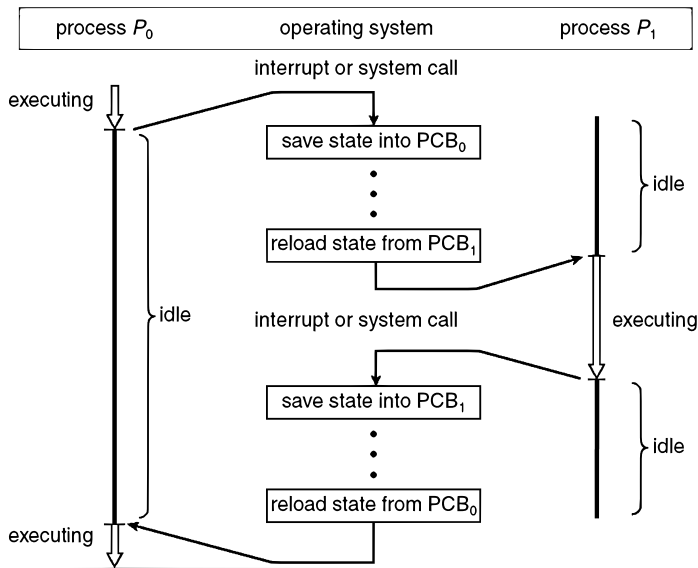
- ▶ When a process is created, it is almost identical to its parent
 - ▶ It receives a (logical) copy of the parent's address space, and
 - ▶ executes the same code as the parent
- ▶ The parent and child have separate copies of the data (stack and heap)

Process State Transition



1. Process blocks for input
2. Scheduler picks another process
3. Scheduler picks this process
4. Input becomes available

CPU Switch From Process To Process



Forking in C

```
1  #include <stdio.h>
2  #include <unistd.h>
3
4  int main()
5  {
6      printf("Hello World!\n");
7      fork();
8      printf("Goodbye Cruel World!\n");
9      return 0;
10 }
```

exec()

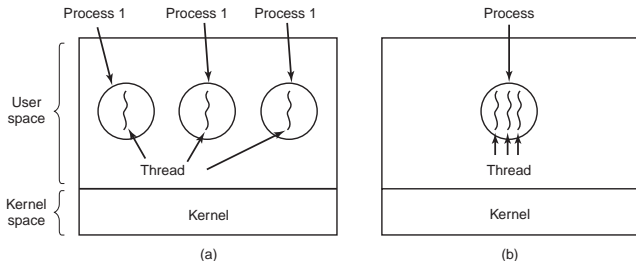
```
1  int main()
2  {
3      pid_t pid;
4      /* fork another process */
5      pid = fork();
6      if (pid < 0) { /* error occurred */
7          fprintf(stderr, "Fork Failed");
8          exit(-1);
9      }
10     else if (pid == 0) { /* child process */
11         execlp("/bin/ls", "ls", NULL);
12     }
13     else { /* parent process */
14         /* wait for the child to complete */
15         wait(NULL);
16         printf ("Child Complete");
17         exit(0);
18     }
19     return 0;
20 }
```

Thread

Process vs. Thread

a single-threaded process = resource + execution

a multi-threaded process = resource + executions



A process = a unit of resource ownership, used to group resources together;

A thread = a unit of scheduling, scheduled for execution on the CPU.

Threads

code, data, open files, signals...		
thread ID	thread ID	thread ID
program counter	program counter	program counter
register set	register set	register set
stack	stack	stack

POSIX Threads

IEEE 1003.1c The standard for writing portable threaded programs. The threads package it defines is called **Pthreads**, including over 60 function calls, supported by most UNIX systems.

Some of the Pthreads function calls

Thread call	Description
<code>pthread_create</code>	Create a new thread
<code>pthread_exit</code>	Terminate the calling thread
<code>pthread_join</code>	Wait for a specific thread to exit
<code>pthread_yield</code>	Release the CPU to let another thread run
<code>pthread_attr_init</code>	Create and initialize a thread's attribute structure
<code>pthread_attr_destroy</code>	Remove a thread's attribute structure

Pthreads

Example 1

```
1  #include <pthread.h>
2  #include <stdlib.h>
3  #include <unistd.h>
4  #include <stdio.h>
5
6  void *thread_function(void *arg){
7      int i;
8      for( i=0; i<20; i++ ){
9          printf("Thread says hi!\n");
10         sleep(1);
11     }
12     return NULL;
13 }
14
15 int main(void){
16     pthread_t mythread;
17     if(pthread_create(&mythread, NULL, thread_function, NULL)){
18         printf("error creating thread.");
19         abort();
20     }
21
22     if(pthread_join(mythread, NULL)){
23         printf("error joining thread.");
24         abort();
25     }
26     exit(0);
27 }
```

Pthreads

`pthread_t` defined in `pthread.h`, is often called a "thread id" (`tid`);
`pthread_create()` returns zero on success and a non-zero value on failure;
`pthread_join()` returns zero on success and a non-zero value on failure;

How to use pthread?

```
► #include<pthread.h>
$ gcc thread1.c -o thread1 -pthread
$ ./thread1
```

Pthreads

Example 2

```
1  #include <pthread.h>
2  #include <stdio.h>
3  #include <stdlib.h>
4
5  #define NUMBER_OF_THREADS 10
6
7  void *print_hello_world(void *tid)
8  {
9      /* prints the thread's identifier, then exits.*/
10     printf ("Thread %d: Hello World!\n", tid);
11     pthread_exit(NULL);
12 }
13
14 int main(int argc, char *argv[])
15 {
16     pthread_t threads[NUMBER_OF_THREADS];
17     int status, i;
18     for (i=0; i<NUMBER_OF_THREADS; i++)
19     {
20         printf ("Main: creating thread %d\n",i);
21         status = pthread_create(&threads[i], NULL, print_hello_world, (void *)i);
22
23         if(status != 0){
24             printf ("Oops. pthread_create returned error code %d\n",status);
25             exit(-1);
26         }
27     }
28     exit(NULL);
29 }
```

Linux Threads

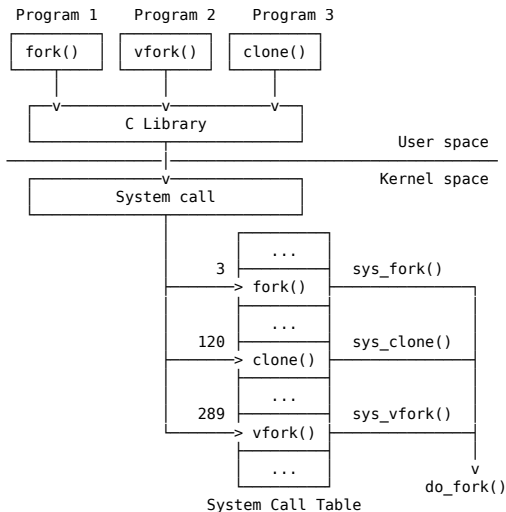
To the Linux kernel, there is no concept of a thread

- ▶ Linux implements all threads as standard processes
- ▶ To Linux, a thread is merely a process that shares certain resources with other processes
- ▶ Some OS (MS Windows, Sun Solaris) have cheap threads and expensive processes.
- ▶ Linux processes are already quite lightweight

On a 75MHz Pentium thread: $1.7\mu\text{s}$
 fork: $1.8\mu\text{s}$

Linux Threads


`clone()` creates a separate process that shares the address space of the calling process. The cloned task behaves *much like* a separate thread.



clone()

```
1 | #include <sched.h>
2 | int clone(int (*fn) (void *), void *child_stack,
3 |          int flags, void *arg, ...);
```

arg 1 the function to be executed, i.e. `fn(arg)`, which returns an `int`;

arg 2 a pointer  a (usually malloced) memory space to be used as the stack for the new thread;

arg 3 a set of flags used to indicate how much the calling process is to be shared. In fact,

`clone(0) == fork()`

arg 4 the arguments passed to the function.

It returns the PID of the child process or -1 on failure.

\$ `man clone`

The `clone()` System Call

Some flags:

flag	Shared
<code>CLONE_FS</code>	File-system info
<code>CLONE_VM</code>	Same memory space
<code>CLONE_SIGHAND</code>	Signal handlers
<code>CLONE_FILES</code>	The set of open files

In practice, one should try to avoid calling `clone()` directly

Instead, use a threading library (such as `pthread`) which use `clone()` when starting a thread (such as during a call to `pthread_create()`)

clone() Example

```
1  #include <unistd.h>    16  int main(void)
2  #include <sched.h>      17  {
3  #include <sys/types.h>  18      void *child_stack;
4  #include <stdlib.h>     19      variable = 9;
5  #include <string.h>     20
6  #include <stdio.h>      21      child_stack = (void *) malloc(16384);
7  #include <fcntl.h>      22      printf("The variable was %d\n", variable);
8                          23
9  int variable;           24      clone(do_something, child_stack,
10                          25          CLONE_FS | CLONE_VM | CLONE_FILES, NULL);
11  int do_something()      26      sleep(1);
12  {                        27
13      variable = 42;      28      printf("The variable is now %d\n", variable);
14      _exit(0);           29      return 0;
15  }                       30  }
```

clone() Example

```
1  #include <unistd.h>    16  int main(void)
2  #include <sched.h>      17  {
3  #include <sys/types.h>  18      void *child_stack;
4  #include <stdlib.h>     19      variable = 9;
5  #include <string.h>     20
6  #include <stdio.h>      21      child_stack = (void *) malloc(16384);
7  #include <fcntl.h>      22      printf("The variable was %d\n", variable);
8                          23
9  int variable;           24      clone(do_something, child_stack,
10                          25          CLONE_FS | CLONE_VM | CLONE_FILES, NULL);
11  int do_something()      26      sleep(1);
12  {                       27
13      variable = 42;      28      printf("The variable is now %d\n", variable);
14      _exit(0);           29      return 0;
15  }                       30  }
```



Stack Grows Downwards

```
child_stack = (void**)malloc(8192) + 8192/sizeof(*child_stack);
```



Signals

Signals

- ▶ Signals are software interrupts
- ▶ Every signal has a name (SIGXXXX)
- ▶ One process can send a signal to another process

Sending signals

```
$ [Ctrl]+[c], [Ctrl]+[z], ...
```

```
$ kill -signal <pid>
```

Trapping signals

```
#! trap <command> <signals>
```

Trap

```
1  #!/bin/bash
2
3  sigint(){
4      echo -e "Why Ctrl-c?\n-> "
5  }
6
7  trap sigint SIGINT
8
9  echo -n "-> "
10
11 while read CMD; do
12     $CMD
13     echo -n "-> "
14 done
```

```
#! trap "rm -rf $tmpfiles" EXIT
```


Example

SIGINT

```
8      #define MAXLINE 4096
9
10     void sig_int(int signo)
11     {
12         printf("Why Ctrl-c?\n-> ");
13     }
14
15     int main(void)
16     {
17         char buf[MAXLINE];
18         pid_t pid;
19         int status;
20
21         if (signal(SIGINT, sig_int) == SIG_ERR)
22             perror("signal");
23
24         printf("-> ");
25         while (fgets(buf, MAXLINE, stdin) != NULL) {
26             buf[strlen(buf) - 1] = '\0'; /* null */
27
28             if ( (pid = fork()) == 0 ) { /* child */
29                 execlp(buf, buf, (char *)0);
30                 perror("execlp");
31                 exit(127);
32             }
33
34             if ((pid = waitpid(pid, &status, 0)) < 0)
35                 perror("waitpid");
36             printf("-> ");
37         }
38         exit(0);
39     }
```

Example

SIGUSR1

```
1  #include <signal.h>
2  #include <stdio.h>
3  #include <unistd.h>
4
5  void sig_usr(int);
6
7  int main(void)
8  {
9      printf("PID = %d\n", getpid());
10
11     if (signal(SIGUSR1, sig_usr) == SIG_ERR)
12         perror("signal<SIGUSR1>");
13
14     for ( ; ; )
15         pause();
16 }
17
18 void sig_usr(int signo)
19 {
20     if (signo == SIGUSR1)
21         printf("received SIGUSR1\n");
22     else
23         perror("sig_usr");
24 }
```

\$ kill -USR1 <PID>

Example

SIGALRM

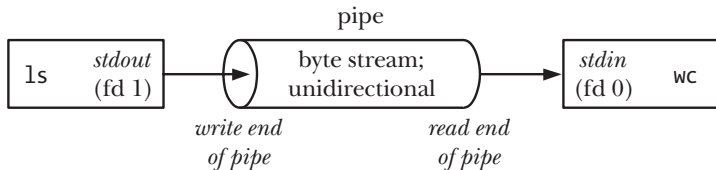
```
1  #include <signal.h>
2  #include <stdio.h>
3  #include <unistd.h>
4  #include <stdlib.h>
5
6  void cry(int sig)
7  {
8      puts("C: I'm crying...");
9      kill(getppid(),sig);
10 }
11
12 void complain(int sig)
13 {
14     puts("P: You're noisy.");
15 }
16
17 int main()
18 {
19     if ( fork() == 0 ){
20         signal(SIGALRM, cry);
21         alarm(2);
22         pause();
23     }
24
25     signal(SIGALRM, complain);
26     pause();
27     exit(0);
28 }
```

IPC

Pipes and FIFOs

Pipe

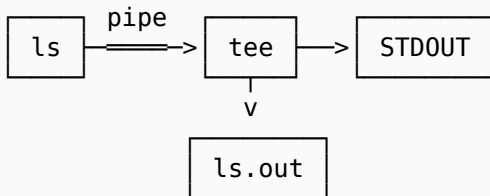
```
$ ls | wc -l
```

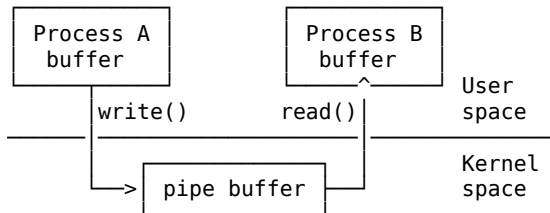


- ▶ A pipe is a byte stream
- ▶ Unidirectional
- ▶ `read()` would be blocked if nothing written at the other end

tee

```
$ ls | tee ls.out
```

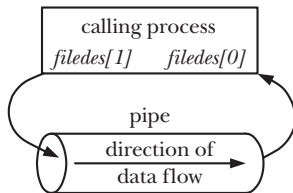




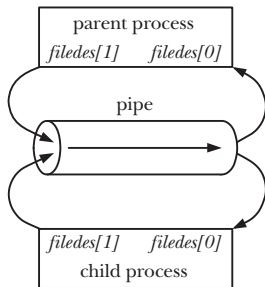
- ▶ No direct link between A and B
- ▶ A pipe is simply a buffer maintained in kernel memory
 - \$ `cat /proc/sys/fs/pipe-max-size`
- ▶ Need system calls

pipe()

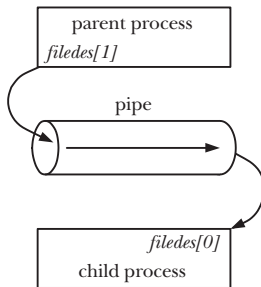
```
1  #include <unistd.h>
2
3  int pipe(int fd[2]);
```



pipe() + fork()



a) After *fork()*



b) After closing unused descriptors


```

9  int main(int argc, char *argv[]) /* Over-simplified! */
10 {
11     int pfd[2]; /* Pipe file descriptors */
12     char buf[BUF_SIZE];
13     ssize_t numRead;
14
15     pipe(pfd); /* Create the pipe */
16
17     switch (fork()) {
18     case 0: /* Child - reads from pipe */
19         close(pfd[1]); /* Write end is unused */
20
21         for (;;) { /* Read data from pipe, echo on stdout */
22             if ( (numRead = read(pfd[0], buf, BUF_SIZE)) == 0)
23                 break; /* End-of-file */
24             if (write(1, buf, numRead) != numRead)
25                 perror("child - partial/failed write");
26         }
27         puts(""); /* newline */
28
29         close(pfd[0]);
30
31         _exit(EXIT_SUCCESS);
32
33     default: /* Parent - writes to pipe */
34         close(pfd[0]); /* Read end is unused */
35
36         if (write(pfd[1], argv[1], strlen(argv[1])) != strlen(argv[1]))
37             perror("parent - partial/failed write");
38
39         close(pfd[1]); /* Child will see EOF */
40
41         wait(NULL); /* Wait for child to finish */
42         exit(EXIT_SUCCESS);
43     }
44 }

```

popen()

[Advanced programming in the UNIX environment, Sec. 15.3]

Named Pipe (FIFO)

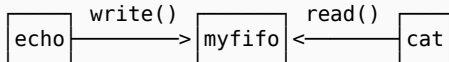
PIPEs pass data between related processes.

FIFOs pass data between any processes.

```
$ mkfifo myfifo
```

```
$ echo hello > myfifo
```

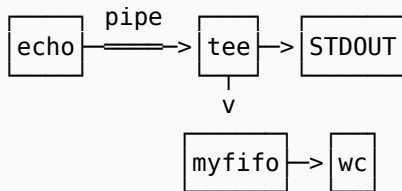
```
$ cat myfifo
```



tee

```
$ echo hello | tee myfifo
```

```
$ wc myfifo
```



IPC With FIFO

```
int main(int argc, char *argv[])
{
    int fd, i, mode = 0;
    char c;

    if (argc < 2) {}

    for(i = 1; i < argc; i++) {}

    if (access(FIFO_NAME, F_OK) == -1) mkfifo(FIFO_NAME, 0777);

    printf("Process %d: FIFO(fd %d, mode %d) opened.\n",
           getpid(), fd = open(FIFO_NAME, mode), mode);

    if( (mode == 0) | (mode == 2048) )
        while( read(fd,&c,1) == 1 ) putchar(c);

    if( (mode == 1) | (mode == 2049) )
        while( (c = getchar()) != EOF ) write(fd,&c,1);

    exit(EXIT_SUCCESS);
}
```

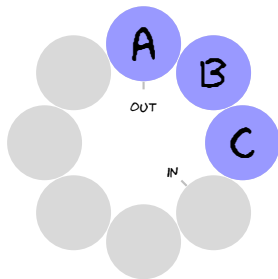
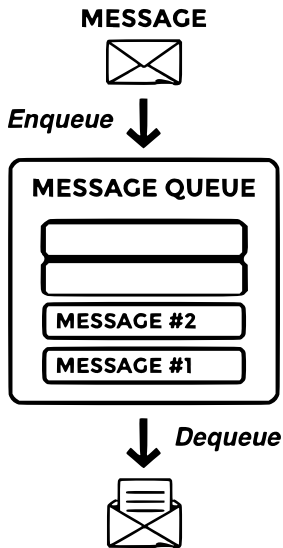
```
$ watch 'lsof -n.1 /tmp/myfifo'
$ ./a.out O_RDONLY
$ ./a.out O_WRONLY
$ ./a.out O_RDONLY O_NONBLOCK
$ ./a.out O_WRONLY O_NONBLOCK
```

O_NONBLOCK

- ▶ A read()/write() will wait on an empty blocking FIFO
- ▶ A read() on an empty nonblocking FIFO will return 0 bytes
- ▶ `open(const char *path, O_WRONLY | O_NONBLOCK);`
 - ▶ Returns an error (-1) if FIFO not open
 - ▶ Okay if someone's reading the FIFO
- ▶ If opened with `O_RDWR`, the result is undefined

Message Queues

Message Queues



Producer-Consumer Problem

- ▶ Consumers don't try to remove objects from Buffer when it is empty.
- ▶ Producers don't try to add objects to the Buffer when it is full.

```
1 while(TRUE){  
2     while(FULL);  
3     item = produceItem();  
4     insertItem(item);  
5 }
```

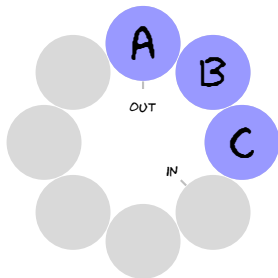
```
1 while(TRUE){  
2     while(EMPTY);  
3     item = removeItem();  
4     consumeItem(item);  
5 }
```

How to define full/empty?

Bounded-Buffer Problem (Circular Array)

Front(out): the first full position

Rear(in): the next free position



Full or empty when “*front == rear*”?

Common solution:

Full: when `“(in + 1)%BUFFER_SIZE == out”`

Actually, this is `“full - 1”`

Empty: when `“in == out”`

Can only use `“BUFFER_SIZE - 1”` elements

Shared data:

```
1  #define BUFFER_SIZE 6
2  typedef struct {
3      ...
4  } item;
5  item buffer[BUFFER_SIZE];
6  int in = 0; //the next free position
7  int out = 0; //the first full position
```

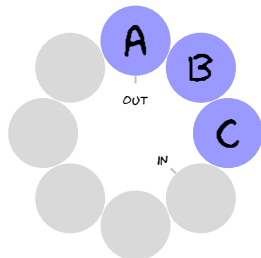
Bounded-Buffer Problem

Producer:

```
1  while (true) {  
2      /* do nothing -- no free buffers */  
3      while (((in + 1) % BUFFER_SIZE) == out);  
4  
5      produce(buffer[in]);  
6  
7      in = (in + 1) % BUFFER_SIZE;  
8  }
```

Consumer:

```
1  while (true) {  
2      while (in == out); /* do nothing */  
3  
4      consume(buffer[out]);  
5  
6      out = (out + 1) % BUFFER_SIZE;  
7  }
```



Message Queues

Send

```
int main(int argc, char **argv)
{
    mqd_t queue;
    struct mq_attr attrs;
    size_t msg_len;

    if (argc < 3){}

    queue = mq_open(argv[1], O_WRONLY | O_CREAT, S_IRUSR | S_IWUSR, NULL);
    if (queue == (mqd_t)-1){}

    if (mq_getattr(queue, &attrs) == -1){}

    msg_len = strlen(argv[2]);
    if (msg_len > LONG_MAX || (long)msg_len > attrs.mq_msgsize){}

    if (mq_send(queue, argv[2], strlen(argv[2]), 0) == -1){}

    return 0;
}
```

Message Queues

Receive

```
int main(int argc, char **argv)
{
    mqd_t queue;
    struct mq_attr attrs;
    char *msg_ptr;
    ssize_t recvd;
    size_t i;

    if (argc < 2){}

    queue = mq_open(argv[1], O_RDONLY | O_CREAT, S_IRUSR | S_IWUSR, NULL);
    if (queue == (mqd_t)-1){}

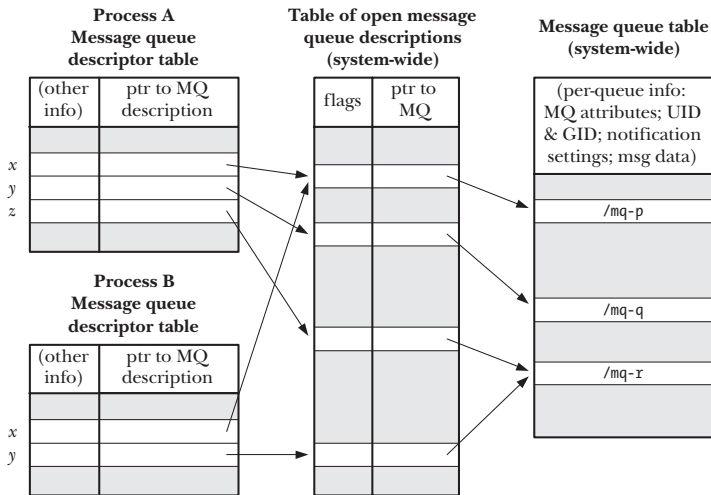
    if (mq_getattr(queue, &attrs) == -1){}

    msg_ptr = calloc(1, attrs.mq_msgsize);
    if (msg_ptr == NULL){}

    recvd = mq_receive(queue, msg_ptr, attrs.mq_msgsize, NULL);
    if (recvd == -1){}

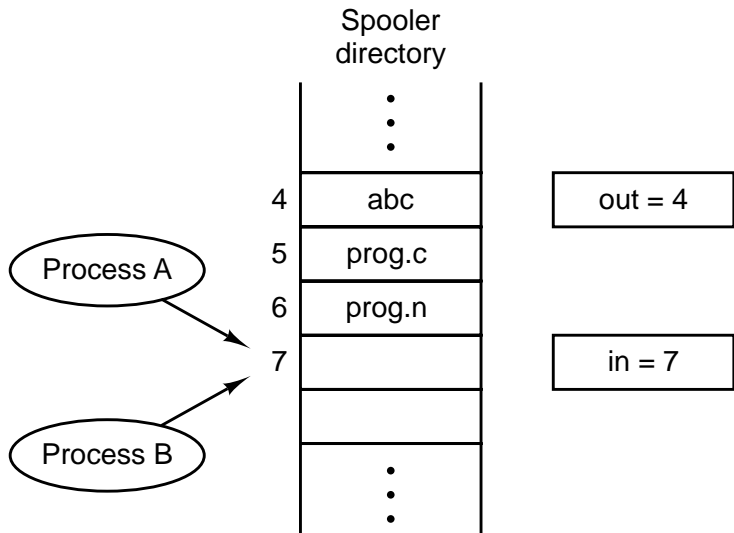
    printf("Message: ");
    for (i = 0; i < (size_t)recvd; i++)
        putchar(msg_ptr[i]);
    puts("");
}
```

Relationship Between Kernel Data Structures



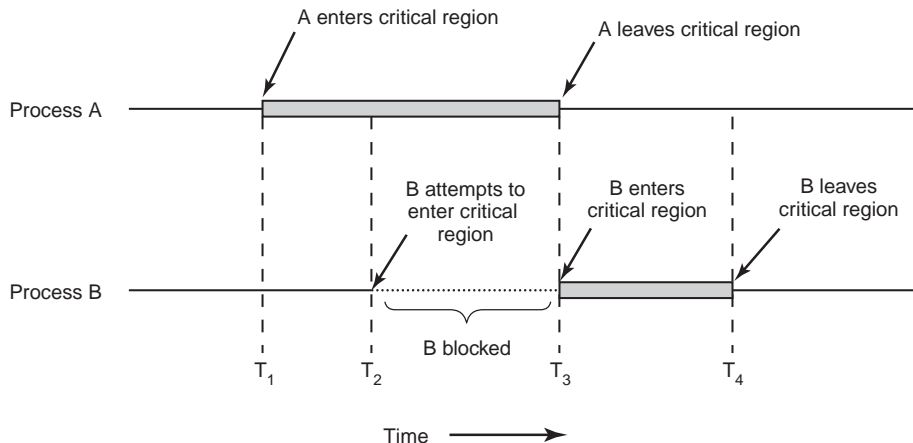
Semaphores

Race Conditions



Mutual Exclusion

Critical Region is a piece of code accessing a common resource.



A solution to the critical region problem must satisfy three conditions

Mutual Exclusion: No two processes may be simultaneously inside their critical regions.

Progress: No process running outside its critical region may block other processes.

Bounded Waiting: No process should have to wait forever to enter its critical region.

Mutual Exclusion With Busy Waiting

Strict Alternation

```
1 while(TRUE){  
2     while(turn != 0);  
3     critical_region();  
4     turn = 1;  
5     noncritical_region();  
6 }
```

```
1 while(TRUE){  
2     while(turn != 1);  
3     critical_region();  
4     turn = 0;  
5     noncritical_region();  
6 }
```

☹ One process can be blocked by another not in its critical region

Mutual Exclusion With Busy Waiting

Peterson's Solution

```
1 | int interest[0] = 0;  
2 | int interest[1] = 0;  
3 | int turn;
```

P0

```
1 | interest[0] = 1;  
2 | turn = 1;  
3 | while(interest[1] == 1  
4 |         && turn == 1);  
5 | critical_section();  
6 | interest[0] = 0;
```

P1

```
1 | interest[1] = 1;  
2 | turn = 0;  
3 | while(interest[0] == 1  
4 |         && turn == 0);  
5 | critical_section();  
6 | interest[1] = 0;
```



[Wikipedia](#). Peterson's algorithm — Wikipedia, The Free Encyclopedia. 2015.

Mutual Exclusion With Busy Waiting

Lock file

```
7  const char *mylock = "/tmp/LCK.test2";
8
9  int main() {
10     int fd;
11
12     for(;;){
13         while( (fd = open(mylock, O_RDWR | O_CREAT | O_EXCL, 0444)) != -1 ) {
14             printf("Process(%d) - Working in critical region...\n", getpid());
15             sleep(2);           /* working */
16             close(fd);
17             if ( unlink(mylock) == 0 ) puts("Done.\nResource unlocked.");
18             sleep(3);           /* non-critical region */
19         }
20         printf("Process(%d) - Waiting for lock...\n", getpid());
21     }
22
23     exit(EXIT_SUCCESS);
24 }
```

☹ Lock file could be left in system after **Ctrl**+**C**



```
10 void sigint(int signo){
11     if ( unlink(mylock) == 0 ) puts("Quit. Lock released.");
12     exit(EXIT_SUCCESS);
13 }
14
15 int main() {
16     int fd;
17
18     signal(SIGINT,sigint);
19
20     for(;;){
21         while( (fd = open(mylock, O_RDWR | O_CREAT | O_EXCL, 0444)) != -1 ) {
22             printf("Process(%d) - Working in critical region...\n", getpid());
23             sleep(2);           /* working */
24             close(fd);
25             if ( unlink(mylock) == 0 ) puts("Done.\nResource unlocked.");
26             sleep(3);           /* non-critical region */
27         }
28         printf("Process(%d) - Waiting for lock...\n", getpid());
29     }
30
31     exit(EXIT_SUCCESS);
32 }
```

What is a Semaphore?

- ▶ A locking mechanism
- ▶ An integer or ADT

```
1 down(S){  
2   while(S<=0);  
3   S--;  
4 }
```

```
1 up(S){  
2   S++;  
3 }
```

<i>Atomic Operations</i>	
P()	V()
Wait()	Signal()
Down()	Up()
Decrement()	Increment()
...	...

More meaningful names:

- ▶ `increment_and_wake_a_waiting_process_if_any()`
- ▶ `decrement_and_block_if_the_result_is_negative()`

Using Semaphore For Signaling

- ▶ One thread sends a signal to another to indicate that something has happened
- ▶ It solves the serialization problem

Signaling makes it possible to guarantee that a section of code in one thread will run before that in another

1		statement a1	1		sem.wait()
2		sem.signal()	2		statement b1

What's the initial value of `sem`?

Example

```
void *func(void *arg);
sem_t sem;

#define BUFSIZE 1024
char buf[BUFSIZE];

int main() {
    pthread_t t;

    if( sem_init(&sem, 0, 0) != 0 ) {}

    if( pthread_create(&t, NULL, func, NULL) != 0 ) {}

    puts("Please input some text. Ctrl-d to quit.");

    while( fgets(buf, BUFSIZE, stdin) )
        sem_post(&sem);

    sem_post(&sem);           /* in case of Ctrl-d */

    if( pthread_join(t, NULL) != 0 ) {}

    sem_destroy(&sem);

    exit(EXIT_SUCCESS);
}

void *func(void *arg) {
    sem_wait(&sem);
    while( buf[0] != '\0' ) {
        printf("You input %ld characters\n", strlen(buf)-1);
        buf[0] = '\0';       /* in case of Ctrl-d */
        sem_wait(&sem);
    }
    pthread_exit(NULL);
}
```

i++ can go wrong!

```
static int glob = 0;

static void *threadFunc(void *arg) /* loop 'arg' times */
{
    int j;

    for (j = 0; j < *((int *) arg); j++)
        glob++; /* not atomic! */

    return NULL;
}

int main(int argc, char *argv[])
{
    pthread_t t1, t2;
    int loops;

    loops = (argc > 1) ? atoi(argv[1]) : 10000000;

    if( pthread_create(&t1, NULL, threadFunc, &loops) != 0 ){}

    if( pthread_create(&t2, NULL, threadFunc, &loops) != 0 ){}

    if( pthread_join(t1, NULL) != 0 ){}

    if( pthread_join(t2, NULL) != 0 ){}

    printf("glob = %d\n", glob);
    exit(EXIT_SUCCESS);
}
```

Atomic

i++ is not atomic in assembly language

```
1  LOAD    [i], r0    ;load the value of 'i' into
2                      ;a register from memory
3  ADD     r0, 1       ;increment the value
4                      ;in the register
5  STORE   r0, [i]     ;write the updated
6                      ;value back to memory
```

Interrupts might occur in between. So, i++ needs to be protected with a mutex.

Mutex A semaphore that is initialized to 1. In case of:

1: A thread may proceed and access the shared variable

0: It has to wait for another thread to release the mutex

```
1 | mutex.wait()  
2 |     i++  
3 | mutex.signal()
```

```
1 | mutex.wait()  
2 |     i++  
3 | mutex.signal()
```

```

static int glob = 0;
static pthread_mutex_t mtx = PTHREAD_MUTEX_INITIALIZER;

static void *threadFunc(void *arg)
{
    int j;

    for (j = 0; j < *((int *) arg); j++) {
        if ( pthread_mutex_lock(&mtx) != 0 ){}
        glob++;
        if ( pthread_mutex_unlock(&mtx) != 0 ){}
    }

    return NULL;
}

int main(int argc, char *argv[])
{
    pthread_t t1, t2;
    int loops;

    loops = (argc > 1) ? atoi(argv[1]) : 10000000;

    if( pthread_create(&t1, NULL, threadFunc, &loops) != 0 ){}

    if( pthread_create(&t2, NULL, threadFunc, &loops) != 0 ){}

    if( pthread_join(t1, NULL) != 0 ){}

    if( pthread_join(t2, NULL) != 0 ){}

    printf("glob = %d\n", glob);
    exit(EXIT_SUCCESS);
}

```

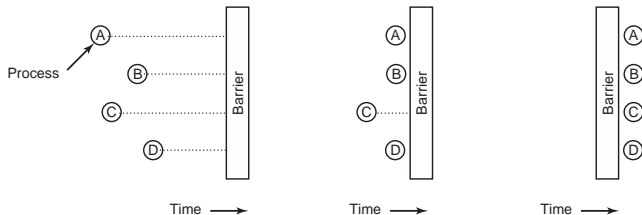
```
static int glob = 0;
static sem_t sem;

static void *threadFunc(void *arg)
{
    int j;

    for (j = 0; j < *((int *) arg); j++) {
        if (sem_wait(&sem) == -1) {}
        glob++;
        if (sem_post(&sem) == -1) {}
    }

    return NULL;
}
```

Barrier



1. Processes approaching a barrier
2. All processes but one blocked at the barrier
3. When the last process arrives at the barrier, all of them are let through

Synchronization requirement:

```
specific_task()  
critical_point()
```

No thread executes `critical_point()` until after all threads have executed `specific_task()`.

Barrier Solution

```
1  n = the number of threads
2  count = 0
3  mutex = Semaphore(1)
4  barrier = Semaphore(0)
```

count: keeps track of how many threads have arrived

mutex: provides exclusive access to count

barrier: is locked (≤ 0) until all threads arrive

When `barrier.value < 0`,

`barrier.value == Number of queueing processes`

```
1  specific_task();
2  mutex.wait();
3      count++;
4  mutex.signal();
5  if (count < n)
6      barrier.wait();
7  barrier.signal();
8  critical_point();
```

```
1  specific_task();
2  mutex.wait();
3      count++;
4  mutex.signal();
5  if (count == n)
6      barrier.signal();
7  barrier.wait();
8  critical_point();
```


Barrier Solution

```
1 n = the number of threads
2 count = 0
3 mutex = Semaphore(1)
4 barrier = Semaphore(0)
```

count: keeps track of how many threads have arrived

mutex: provides exclusive access to count

barrier: is locked (≤ 0) until all threads arrive

When `barrier.value < 0`,

`barrier.value == Number of queueing processes`

```
1 specific_task();
2 mutex.wait();
3   count++;
4 mutex.signal();
5 if (count < n)
6   barrier.wait();
7 barrier.signal();
8 critical_point();
```

```
1 specific_task();
2 mutex.wait();
3   count++;
4 mutex.signal();
5 if (count == n)
6   barrier.signal();
7 barrier.wait();
8 critical_point();
```

Only one thread can pass the barrier!

Barrier Solution

```
1  specific_task();
2
3  mutex.wait();
4      count++;
5  mutex.signal();
6
7  if (count == n)
8      barrier.signal();
9
10 barrier.wait();
11 barrier.signal();
12
13 critical_point();
```

```
1  specific_task();
2
3  mutex.wait();
4      count++;
5
6      if (count == n)
7          barrier.signal();
8
9          barrier.wait();
10         barrier.signal();
11 mutex.signal();
12
13 critical_point();
```

Barrier Solution

```
1  specific_task();
2
3  mutex.wait();
4      count++;
5  mutex.signal();
6
7  if (count == n)
8      barrier.signal();
9
10 barrier.wait();
11 barrier.signal();
12
13 critical_point();
```

```
1  specific_task();
2
3  mutex.wait();
4      count++;
5
6      if (count == n)
7          barrier.signal();
8
9      barrier.wait();
10     barrier.signal();
11     mutex.signal();
12
13     critical_point();
```

💀 Blocking on a semaphore while holding a mutex! 💀

```
barrier.wait();  
barrier.signal();
```

Turnstile

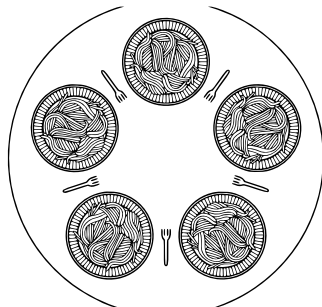
This pattern, a `wait` and a `signal` in rapid succession, occurs often enough that it has a name called a *turnstile*, because

- ▶ it allows one thread to pass at a time, and
- ▶ it can be locked to bar all threads

Classical IPC Problems

The Dining Philosophers Problem

```
1 while True:
2     think()
3     get_forks()
4     eat()
5     put_forks()
```



How to implement `get_forks()` and `put_forks()` to ensure

1. No deadlock
2. No starvation
3. Allow more than one philosopher to eat at the same time

The Dining Philosophers Problem

Deadlock

```
#define N 5                                /* number of philosophers */

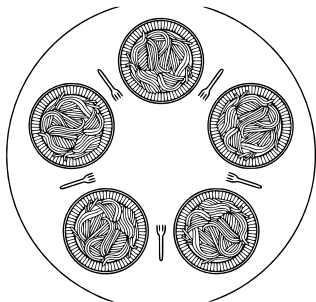
void philosopher(int i)                    /* i: philosopher number, from 0 to 4 */
{
    while (TRUE) {
        think();                          /* philosopher is thinking */
        take_fork(i);                     /* take left fork */
        take_fork((i+1) % N);              /* take right fork; % is modulo operator */
        eat();                             /* yum-yum, spaghetti */
        put_fork(i);                       /* put left fork back on the table */
        put_fork((i+1) % N);               /* put right fork back on the table */
    }
}
```

- Put down the left fork and wait for a while if the right one is not available? Similar to CSMA/CD — Starvation

The Dining Philosophers Problem

With One Mutex

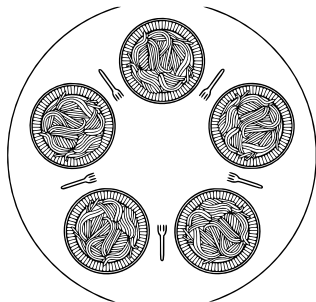
```
1  #define N 5
2  semaphore mutex=1;
3
4  void philosopher(int i)
5  {
6      while (TRUE) {
7          think();
8          wait(&mutex);
9              take_fork(i);
10             take_fork((i+1) % N);
11             eat();
12             put_fork(i);
13             put_fork((i+1) % N);
14             signal(&mutex);
15         }
16     }
```



The Dining Philosophers Problem

With One Mutex

```
1  #define N 5
2  semaphore mutex=1;
3
4  void philosopher(int i)
5  {
6      while (TRUE) {
7          think();
8          wait(&mutex);
9          take_fork(i);
10         take_fork((i+1) % N);
11         eat();
12         put_fork(i);
13         put_fork((i+1) % N);
14         signal(&mutex);
15     }
16 }
```



- ▶ Only one philosopher can eat at a time.
- ▶ How about 2 mutexes? 5 mutexes?

The Dining Philosophers Problem

AST Solution (Part 1)

A philosopher may only move into eating state if neither neighbor is eating

```
1  #define N 5                /* number of philosophers */
2  #define LEFT (i+N-1)%N    /* number of i's left neighbor */
3  #define RIGHT (i+1)%N     /* number of i's right neighbor */
4  #define THINKING 0        /* philosopher is thinking */
5  #define HUNGRY 1          /* philosopher is trying to get forks */
6  #define EATING 2          /* philosopher is eating */
7  typedef int semaphore;
8  int state[N];              /* state of everyone */
9  semaphore mutex = 1;       /* for critical regions */
10 semaphore s[N];            /* one semaphore per philosopher */
11
12 void philosopher(int i)    /* i: philosopher number, from 0 to N-1 */
13 {
14     while (TRUE) {
15         think( );
16         take_forks(i); /* acquire two forks or block */
17         eat( );
18         put_forks(i); /* put both forks back on table */
19     }
20 }
```

The Dining Philosophers Problem

AST Solution (Part 2)

```
1 void take_forks(int i)           /* i: philosopher number, from 0 to N-1 */
2 {
3     down(&mutex);                /* enter critical region */
4     state[i] = HUNGRY;           /* record fact that philosopher i is hungry */
5     test(i);                    /* try to acquire 2 forks */
6     up(&mutex);                 /* exit critical region */
7     down(&s[i]);                /* block if forks were not acquired */
8 }
9 void put_forks(i)               /* i: philosopher number, from 0 to N-1 */
10 {
11     down(&mutex);              /* enter critical region */
12     state[i] = THINKING;       /* philosopher has finished eating */
13     test(LEFT);               /* see if left neighbor can now eat */
14     test(RIGHT);              /* see if right neighbor can now eat */
15     up(&mutex);               /* exit critical region */
16 }
17 void test(i)                   /* i: philosopher number, from 0 to N-1 */
18 {
19     if (state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING) {
20         state[i] = EATING;
21         up(&s[i]);
22     }
23 }
```

The Dining Philosophers Problem

AST Solution (Part 2)

```
1 void take_forks(int i)           /* i: philosopher number, from 0 to N-1 */
2 {
3     down(&mutex);                /* enter critical region */
4     state[i] = HUNGRY;           /* record fact that philosopher i is hungry */
5     test(i);                     /* try to acquire 2 forks */
6     up(&mutex);                  /* exit critical region */
7     down(&s[i]);                 /* block if forks were not acquired */
8 }
9 void put_forks(i)               /* i: philosopher number, from 0 to N-1 */
10 {
11     down(&mutex);                /* enter critical region */
12     state[i] = THINKING;         /* philosopher has finished eating */
13     test(LEFT);                  /* see if left neighbor can now eat */
14     test(RIGHT);                 /* see if right neighbor can now eat */
15     up(&mutex);                  /* exit critical region */
16 }
17 void test(i)                    /* i: philosopher number, from 0 to N-1 */
18 {
19     if (state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING) {
20         state[i] = EATING;
21         up(&s[i]);
22     }
23 }
```

The Dining Philosophers Problem

More Solutions

- ▶ If there is at least one leftie and at least one rightie, then deadlock is not possible
- ▶ [Wikipedia: Dining philosophers problem](#)

The Readers-Writers Problem

Constraint: no process may access the shared data for reading or writing while another process is writing to it.

```
1 semaphore mutex = 1;
2 semaphore noOther = 1;
3 int readers = 0;
4
5 void writer(void)
6 {
7     while (TRUE) {
8         wait(&noOther);
9         writing();
10        signal(&noOther);
11    }
12 }
```

```
1 void reader(void)
2 {
3     while (TRUE) {
4         wait(&mutex);
5         readers++;
6         if (readers == 1)
7             wait(&noOther);
8         signal(&mutex);
9         reading();
10        wait(&mutex);
11        readers--;
12        if (readers == 0)
13            signal(&noOther);
14        signal(&mutex);
15        anything();
16    }
17 }
```

The Readers-Writers Problem

Constraint: no process may access the shared data for reading or writing while another process is writing to it.

```
1 semaphore mutex = 1;
2 semaphore noOther = 1;
3 int readers = 0;
4
5 void writer(void)
6 {
7     while (TRUE) {
8         wait(&noOther);
9         writing();
10        signal(&noOther);
11    }
12 }
```

```
1 void reader(void)
2 {
3     while (TRUE) {
4         wait(&mutex);
5         readers++;
6         if (readers == 1)
7             wait(&noOther);
8         signal(&mutex);
9         reading();
10        wait(&mutex);
11        readers--;
12        if (readers == 0)
13            signal(&noOther);
14        signal(&mutex);
15        anything();
16    }
17 }
```

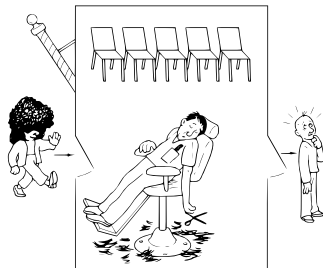
The Readers-Writers Problem

No starvation

```
1 semaphore mutex = 1;
2 semaphore noOther = 1;
3 semaphore turnstile = 1;
4 int readers = 0;
5
6 void writer(void)
7 {
8     while (TRUE) {
9         turnstile.wait();
10        wait(&noOther);
11        writing();
12        signal(&noOther);
13        turnstile.signal();
14    }
15 }
```

```
1 void reader(void)
2 {
3     while (TRUE) {
4         turnstile.wait();
5         turnstile.signal();
6
7         wait(&mutex);
8         readers++;
9         if (readers == 1)
10             wait(&noOther);
11         signal(&mutex);
12         reading();
13         wait(&mutex);
14         readers--;
15         if (readers == 0)
16             signal(&noOther);
17         signal(&mutex);
18         anything();
19     }
20 }
```


The Sleeping Barber Problem



Where's the problem?

- ▶ the barber saw an empty room right before a customer arrives the waiting room;
- ▶ Several customer could race for a single chair;

Solution

```
1  #define CHAIRS 5
2  semaphore customers = 0; // any customers or not?
3  semaphore bber = 0;      // barber is busy
4  semaphore mutex = 1;
5  int waiting = 0;         // queueing customers
```

```
1  void barber(void)
2  {
3      while (TRUE) {
4          wait(&customers);
5          wait(&mutex);
6          waiting--;
7          signal(&mutex);
8          cutHair();
9          signal(&bber);
10 }
11 }
```

```
1  void customer(void)
2  {
3      if(waiting == CHAIRS)
4          goHome();
5      else {
6          wait(&mutex);
7          waiting++;
8          signal(&mutex);
9          signal(&customers);
10         wait(&bber);
11         getHairCut();
12     }
13 }
```

Solution2

```
1  #define CHAIRS 5
2  semaphore customers = 0;
3  semaphore bber = ?;
4  semaphore mutex = 1;
5  int waiting = 0;
6
7  void barber(void)
8  {
9      while (TRUE) {
10         wait(&customers);
11         cutHair();
12     }
13 }
```

```
1  void customer(void)
2  {
3      if (waiting == CHAIRS)
4         goHome();
5      else {
6         wait(&mutex);
7         waiting++;
8         signal(&mutex);
9         signal(&customers);
10        wait(&bber);
11        getHairCut();
12        signal(&bber);
13        wait(&mutex);
14        waiting--;
15        signal(&mutex);
16    }
17 }
```

User Interface

Dialog, Zenity

Ncurses

GTK+

Qt

Terminal

IDE