# GNU/Linux
# Application Programming

Lecture Handouts

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## Contents

# References


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[16] Wikipedia. *Dynamic linker — Wikipedia, The Free Encyclopedia*. 2012. http://en.wikipedia.org/w/index.php?title=Dynamic_linker&oldid=517400345.

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### 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
```

**System Programming** https://github.com/angrave/SystemProgramming/wiki
**Beej's Guides** http://beej.us/guide/
**BLP4e** http://www.wrox.com/WileyCDA/WroxTitle/productCd-0470147628,descCd-DOWNLOAD.html
**TLPI** http://www.man7.org/tlpi/

### 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*
𝔼 Preferably in English
in stackoverflow style
OR simply show me the tech questions you asked on any website

☠ Oversimplifed programs ahead!

# 1 Getting Started

**Linux Commands**
**Where to find them?** `/bin`, `/usr/bin`, `/usr/local/bin`, `~/bin`, …

    $ echo $PATH

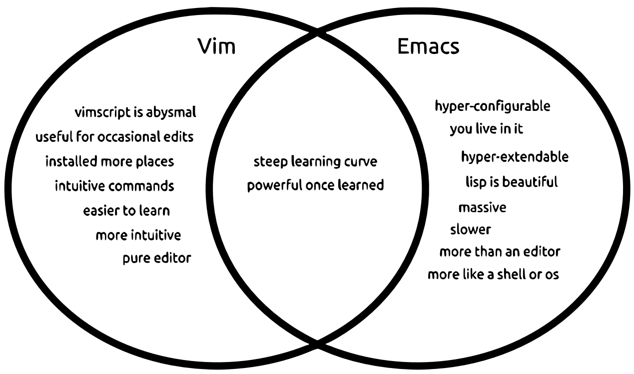
**How to find them?** `which`, `whereis`, `type`

**Command not found?**
**First** double check your spelling
**Then** try:

- `aptitude search xxx`
- `apt-cache search xxx`
- `apt-file search xxx`
- `sudo apt install packagename`
- Google `"linux command xxx"`

**Text Editors**

vs.

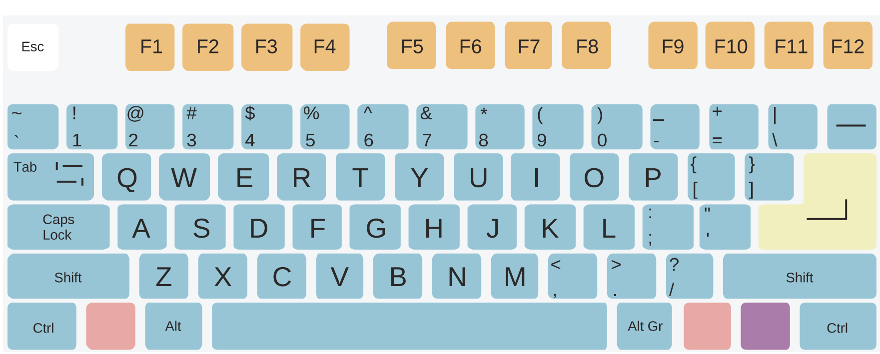



**Help Your Editor**

**Suffix matters**

```
$ vim ✘
$ vim hello ✘
$ vim hello.c ✔
$ vim hello.py ✔
$ emacs ✘
$ emacs hello ✘
$ emacsclient hello.c ✔
$ emacsclient hello.py ✔
```

**Keyboard**



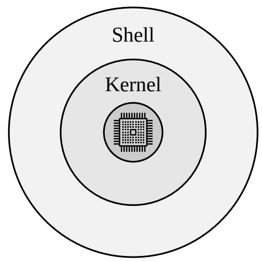
vimtutor

Ctrl + h t

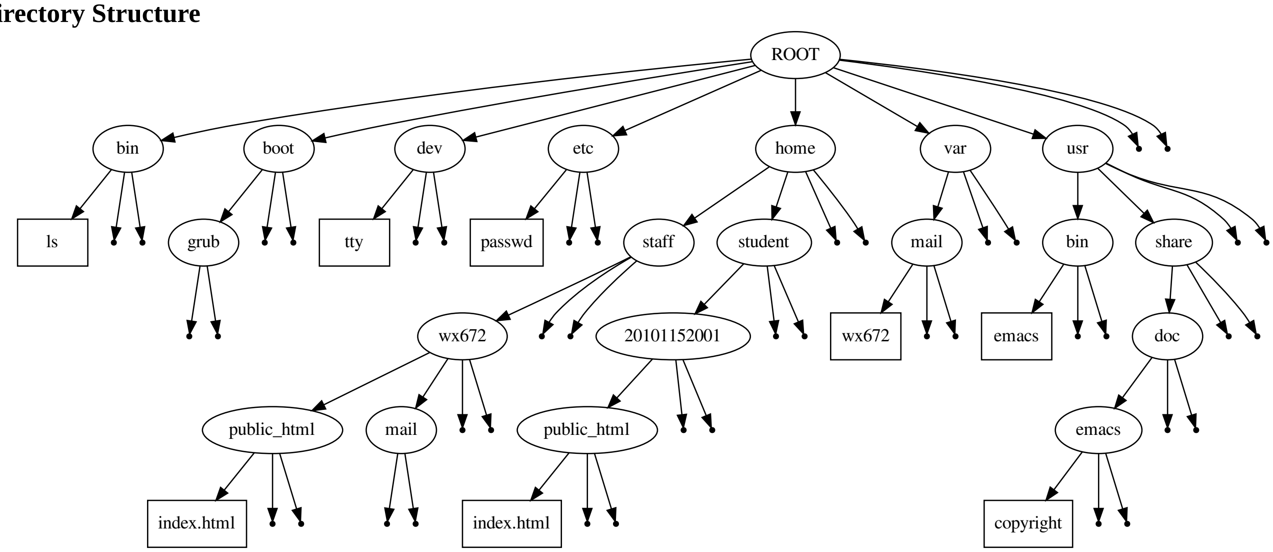
# 2 Shell Basics

### Shell

- A command line interpreter
- A programming language




### Directory Structure




| Todo | How |
|---:|---|
| Where am I? | `pwd` |
| What's in it? | `ls` |
| Move around? | `cd` |
| Disk usage? | `du, df` |
| USB drive? | `lsblk, mount` |
| New folder? | `mkdir` |

### 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, &` | forground? | `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+e : | end of line |
| Ctrl+f : | forward | Ctrl+b : | backward |
| Ctrl+n : | next | Ctrl+p : | previous |
| Ctrl+r : | reverse search | Ctrl+u : | cut to beginning |
| Ctrl+k : | kill (cut to end) | Ctrl+y : | yank (paste) |
| Ctrl+d : | delete a character | ↹ : | completion |

## Tmux

| | | | |
|---|---|---|---|
| Ctrl+a c : | create window | Ctrl+a Ctrl+a : | switch window |
| Ctrl+a n : | next window | Ctrl+a p : | previous window |
| Ctrl+a - : | split window | Ctrl+a \| : | split widnow |
| Ctrl+a j : | go down | Ctrl+a k : | go up |
| Ctrl+a l : | go right | 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
|_________ | ___ ___ ____ ____________ _________
|    |     |  |   |    |        |          └ File Name
|    |     |  |   |    |        └─────── Modification Time
|    |     |  |   |    └──────────────── Size (in bytes)
|    |     |  |   └───────────────────── Group
|    |     |  └───────────────────────── Owner
|    |     └──────────────────────────── Number of hard links
|    └────────────────────────────────── File Permissions
└─────────────────────────────────────── File types
```

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
___ ___ ___
 |   |   └ Other
 |   └──── Group
 └──────── User
```

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

```
$ rm ?.jpg
$ rm ?.*
$ 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

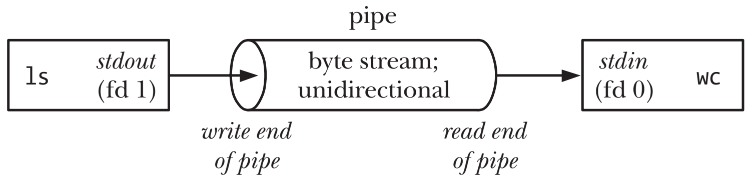
Allow higher-level access to driver and kernel information

```
$ cat /proc/cpuinfo
$ cat /proc/meminfo
$ cat /proc/version
$ cat /proc/1/status
# echo 100000 > /proc/sys/kernel/pid_max
```

**Pipe**

*Chain processes together*

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




**Unnamed pipe**

```
$ unicode skull | head -1 | cut -f1 -d' ' | sm -
```

**Named pipe**

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

- https://en.wikipedia.org/wiki/Named_pipe

## 3 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, …, $@, $#`*

```bash
#!/bin/bash

echo "You said:"

echo -e "\t$@"
echo
echo -e "\targc = $#"
echo -e "\targv[0] = $0"

i=1
for arg in $@; do
  echo -e "\targv[$i] = $arg"
  let i++
done
```

```c
#include <stdio.h>

int main(int argc, char *argv[])
{
  int i;
  printf("You said:\n\t");

  for(i=1; i<argc; i++)
    printf("%s ",argv[i]);

  printf("\n\n\targc = %d\n", argc);

  for(i=0; i<argc; i++)
    printf("\targv[%d] = %s\n",i,argv[i]);

  return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra isay.c -o isay" */
/* End: */
```

### Parameter Substitution

#### Default value

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

```
$ echo ${v:-8}
$ echo ${v:-10}
```

#### Example

```bash
#!/bin/bash

echo -n Hello, ${1:-world}
echo !
```

Re-write it in C

`$ sudo apt install abs-guide`

- file:///usr/share/doc/abs-guide/html/parameter-substitution.html

### 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

```
$ (( 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 ✔
$ [[ 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
```

```bash
#!/bin/bash

words=$@
string=linux
if echo "$words" | grep -q "$string"
then
  echo "$string found in $words"
else
  echo "$string not found in $words"
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

```
#!/bin/bash

[ -z "$1" ] && echo "Usage: `basename $0` [dhb]<number>" && exit 0;

case "$1" in
        [dD]*)
                NUM=$(echo $1 | cut -b 2-)
                printf "\tDec\tHex\tBin\n"
                printf "\t%d\t0x%02X\t%s\n" $NUM $NUM $(bc <<< "obase=2;$NUM")
                ;;
        [hH]*)
                NUM=$(echo $1 | cut -b 2-)
                NUM=$(echo $NUM | tr [:lower:] [:upper:])
                printf "\tHex\t\tDec\t\tBin\n"
                printf "\t0x%s\t\t%s\t\t%s\n" $NUM $(bc <<< "ibase=16;obase=A;$NUM") \
                        $(bc <<< "ibase=16;obase=2;$NUM")
                ;;
        0[xX]*)
                NUM=$(echo $1 | cut -b 3-)
                NUM=$(echo $NUM | tr [:lower:] [:upper:])
                printf "\tHex\t\tDec\t\tBin\n"
                printf "\t0x%s\t\t%s\t\t%s\n" $NUM $(bc <<< "ibase=16;obase=A;$NUM") \
                        $(bc <<< "ibase=16;obase=2;$NUM")
                ;;
        [bB]*)
                NUM=$(echo $1 | cut -b 2-)
                printf "\tBin\t\tHex\t\tDec\n"
                printf "\t%s\t\t0x%s\t\t%s\n" $NUM $(bc <<< "ibase=2;obase=10000;$NUM") \
                        $(bc <<< "ibase=2;obase=1010;$NUM")
                ;;
            *)
                printf "Dec\tHex\tBin\n"
                printf "%d\t0x%08X\t%08d\n" $1 $1 $(bc <<< "obase=2;$1")
                ;;
esac
```

### select

```
#!/bin/bash

PS3='Your favorite OS? '

select OS in "Linux" "Mac OSX" "Windows"
do
  [[ "$OS" = "Linux" ]] && echo wise guy.
  [[ "$OS" = "Mac OSX" ]] && echo rich guy.
  [[ "$OS" = "Windows" ]] && echo patient guy.
  break
done
```

## Functions

```bash
#!/bin/bash

function screencapture(){
  ffmpeg -f x11grab -s 1920x1080 -r 30 -i :0.0 \
         -c:v libx264 -crf 0 -preset ultrafast screen.mkv
}

w2pdf(){
  libreoffice --convert-to pdf:writer_pdf_Export "$1"
}

rfc(){
    [[ -n "$1" ]] || {
                cat <<EOF
  rfc - Command line RFC viewer
  Usage: rfc <index>
EOF
                return 1
        }
        find /usr/share/doc/RFC/ -type f -iname "rfc$1.*" | xargs less
}
```

### Array

```bash
#!/bin/bash

IMGDIR="$HOME/Pics/2009Summer/wallpapers/2009summer-1280x768"

files=($IMGDIR/*.jpg)

# get the length of array ${files[@]}
n=${#files[@]}

# get a random array element
wallpaper="${files[RANDOM % n]}"

# set it as wallpaper
qiv -z $wallpaper
```

Change wallpaper every 5 mins?

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

# 4 C Programming Basics

## 4.1 Programming Environment

### Program Languages

#### Machine code

The *binary numbers* that the CPUs can understand.

```
100111000011101111001111 ... and so on ...
```

People don't think in numbers.

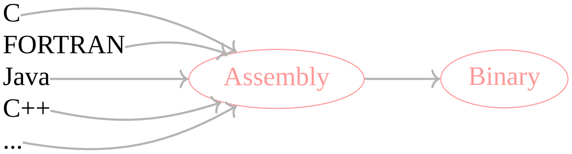
#### Assembly language — friendly to humans

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

**Assemblers** translate the ASM programs to machine code

**High level languages**
Even easier to understand by humans. Examples:

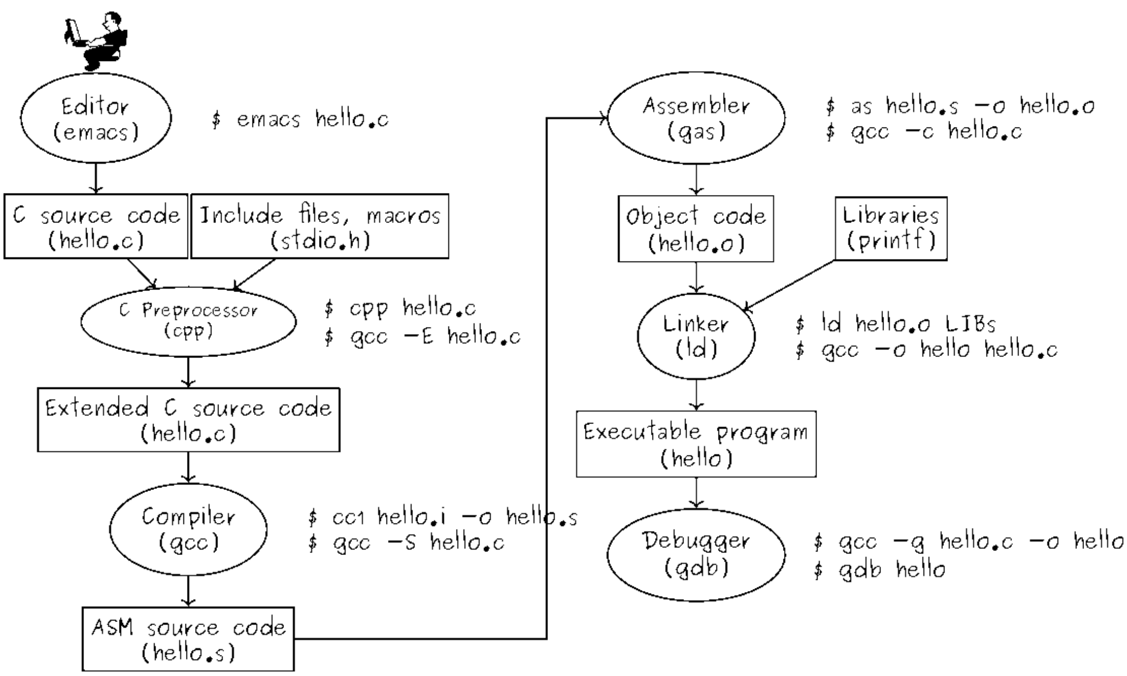
- C
- FORTRAN
- Java
- C++
- ...




**Compilers** do the translation work

### 4.1.1 The Tool Chain

**Compilation**




**Source code** written by programmer in high-level language, in our case in `C`. We write c source code with a *text editor*, such as `emacs`, `vim`, etc.

**Preprocessing** is the first pass of any C compilation. It processes `include-files`, `conditional compilation instructions` and `macros`.

**cpp** The GNU C preprocessor

```
$ gcc -E hello.c
```

**Compilation** is the second pass. It takes the output of the preprocessor, and the `source code`, and generates `assembly source code`.

**gcc/g++** GNU C/C++ compiler

```
$ gcc -S hello.c
```

**Assembly** is the third stage of compilation. It takes the assembly source code and produces an assembly listing with offsets. The assembler output is stored in an `object file`.

**as** the portable GNU assembler

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

**Linking** is the final stage of compilation. It combines object code with predefined routines from `libraries` and produces the `executable program`.

**ld** The GNU linker

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

**Wrapper** The whole compilation process is usually not done ‘by hand’, but using a `wrapper` program that combines the functions of preprocessor(cpp), compiler(gcc/g++), assembler(as) and linker(ld).

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

**Compiler vs. Interpreter**

hello.c
```c
#include <stdio.h>
int main()
{
  printf("Hello, world!\n");
  return 0;
}
```

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

hello.sh
```bash
#!/bin/bash
echo 'Hello, world!'
```

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

hello.py
```python
#!/usr/bin/python
print "Hello, world!"
```

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

### 4.1.2 Header Files

**Header Files**

**Why?**

```c
#include "add.h"

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

**Why not?**

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

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

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

**In the header files…**

- function declarations
- macro definitions
- contants
- system wide global variables

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

### 4.1.3 Library Files

**Library Files**

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

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

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

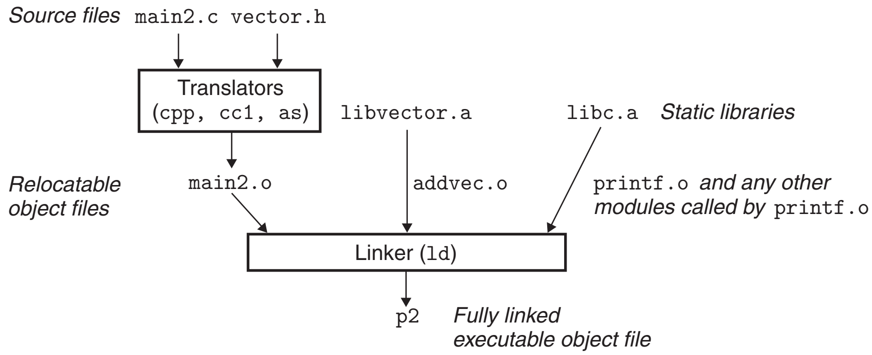
```
$ find /usr/lib -name "*.so.*"
```

Examples:

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

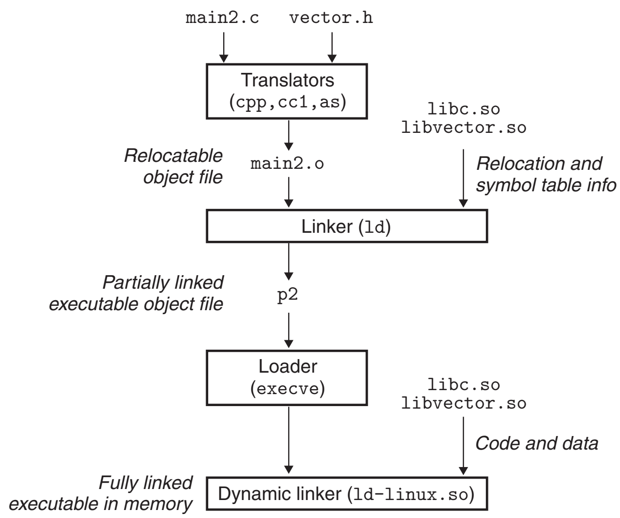
**Static Linking**

- 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




**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**

```c
#include "lib.h"

int main(int argc, char* argv[])
{
  int i=1;

  for (; i<argc; i++)
    {
      hello(argv[i]);
      hi(argv[i]);
    }
  return 0;
}
```

**lib.h**

```c
#include <stdio.h>

void hello(char *);
void hi(char *);
```

**hello.c**

```c
#include <stdio.h>

void hello(char *arg)
{
  printf("Hello, %s!\n", arg);
}
```

**hi.c**

```c
#include <stdio.h>

void hi(char *arg)
{
  printf("Hi, %s!\n", arg);
}
```

**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*

```makefile
main: main.c lib.h libhi.a
	gcc -Wall -o main main.c libhi.a

libhi.a: hello.o hi.o
	ar crv libhi.a hello.o hi.o

hello.o: hello.c
	gcc -Wall -c hello.c

hi.o: hi.c
	gcc -Wall -c hi.c

clean:
	rm -f *.o *.a main
```

**Build A Shared Library**
*Source codes*

**hello.c**

```c
#include "hello.h"

int main(int argc, char *argv[])
```

```c
{
  if (argc != 2)
    printf ("Usage: %s needs an argument.\n", argv[0]);
  else
    hi(argv[1]);
  return 0;
}
```

**hello.h**

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

int hi(char*);
```

**hi.c**

```c
#include "hello.h"

int hi(char* s)
{
  printf ("Hi, %s\n",s);
  return 0;
}
```

**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**

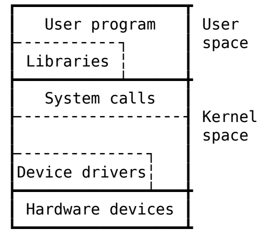
*Makefile*

```makefile
# http://www.cprogramming.com/tutorial/shared-libraries-linux-gcc.html
# http://tldp.org/HOWTO/Program-Library-HOWTO/shared-libraries.html
#
# gcc -fPIC -c hi.c
# gcc -shared -o libhi.so hi.o
# gcc -L/current/dir -Wl,option -Wall -o hello hello.c -lhi
#
# -L          - tells ld where to search libraries
# -Wl,option - pass option as an option to the linker (ld)
# -rpath=dir - Add a directory to the runtime library search path

hello: hello.c hello.h libhi.so
	gcc -L. -Wl,-rpath=. -Wall -o hello hello.c -lhi
libhi.so: hi.o hello.h
	gcc -shared -o libhi.so hi.o
hi.o: hi.c hello.h
	gcc -fPIC -c hi.c
clean:
	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
```




### 4.1.4 Error Handling

**errno.h**

```c
#include <stdio.h>
#include <stdlib.h>
#include <sys/stat.h>
#include <fcntl.h>

int main(int argc, char *argv[])
{
  if( open(argv[1], O_RDONLY) == -1 ){
    perror("open");
    exit(EXIT_FAILURE);
  }
  return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra perror.c -o perror" */
/* End: */
```

```
$ man errno
$ man errno.h
$ man perror
```

- [*Advanced programming in the UNIX environment*, Sec. 1.7]
- https://stackoverflow.com/questions/30078281/raise-error-in-a-bash-script

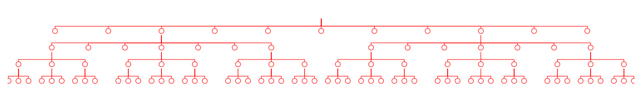
### 4.1.5 The Make Utility

**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**

```make
target: dependencies
	command
```

**Example**

```make
hello: hello.c
	gcc -o hello hello.c
```

```
$ info make makefiles
```

**Makefile**

```
edit: main.o kbd.o command.o display.o \
                insert.o search.o files.o utils.o
        gcc -Wall -o edit main.o kbd.o command.o display.o \
                insert.o search.o files.o utils.o

main.o: main.c defs.h
        gcc -c -Wall main.c

kbd.o : kbd.c defs.h command.h
        gcc -c -Wall kbd.c

command.o: command.c defs.h command.h
        gcc -c -Wall command.c

display.o : display.c defs.h buffer.h
        gcc -c -Wall display.c

insert.o: insert.c defs.h buffer.h
        gcc -c -Wall insert.c

search.o: search.c defs.h buffer.h
        gcc -c -Wall search.c

files.o: files.c defs.h buffer.h command.h
        gcc -c -Wall files.c

utils.o: utils.c defs.h
        gcc -c -Wall utils.c


clean:
        rm edit main.o kbd.o command.o display.o \
           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
```

### 4.1.6 Version Control

**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

### 4.1.7 Manual Pages

**Man page**
*Layout*

```
NAME
    A one-line description of the command.
SYNOPSIS
    A formal description of how to run it and what
    command line options it takes.
DESCRIPTION
    A description of the functioning of the command.
EXAMPLES
    Some examples of common usage.
SEE ALSO
    A list of related commands or functions.
BUGS
    List known bugs.
AUTHOR
   Specify your contact information.
COPYRIGHT
    Specify your copyright information.
```

**Man Page**
*Groff source code*

```
.\" Text automatically generated by txt2man
.TH untitled  "06 August 2019" "" ""
.SH NAME
\fBA one-line description of the command.
.SH SYNOPSIS
.nf
.fam C
  \fBA formal description of how to run it and what command line options it takes.
.fam T
.fi
.fam T
.fi
.SH DESCRIPTION
\fBA description of the functioning of the command.
.SH EXAMPLES
Some examples of common usage.
.SH SEE ALSO
\fBA list of related commands or functions.
.SH BUGS
List known bugs.
.SH AUTHOR
Specify your contact information.
.SH COPYRIGHT
Specify your copyright information.
```

```
$ man 7 groff
$ man txt2man
$ man a2x
$ ls /usr/share/man
```

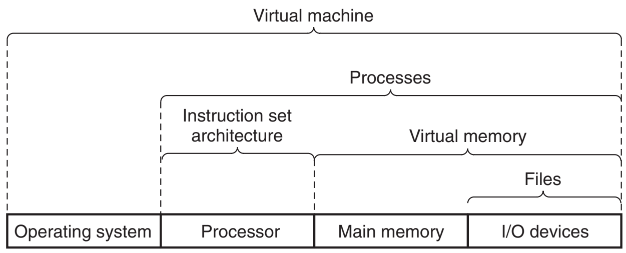
### 4.1.8 A Sample GNU Package

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

```
$ apt source hello
```

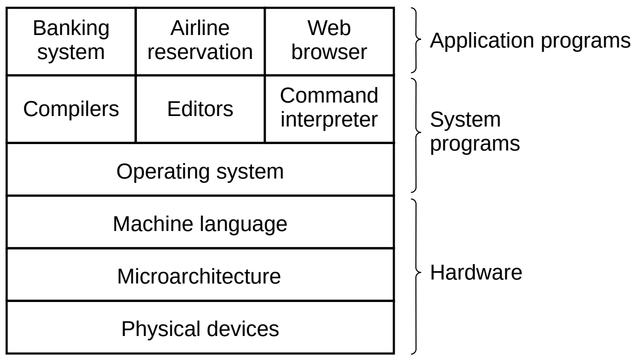
## 4.2 OS Basics

**Abstractions**
*To hide the complexity of the actual implementations*




See also: [*Computer Systems: A Programmer's Perspective*, Sec. 1.9.2, *The Importance of Abstractions in Computer Systems*].

**A Computer System**



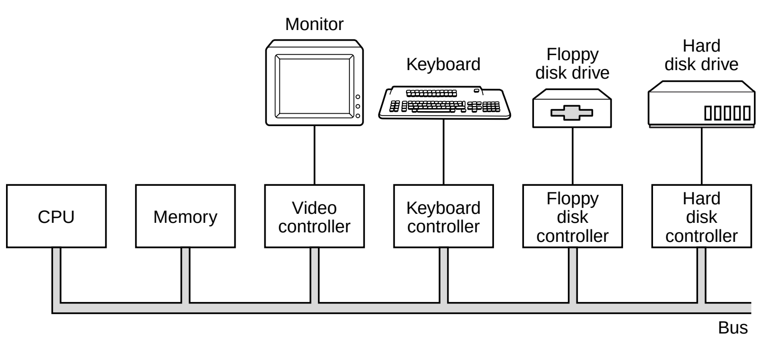

### 4.2.1 Hardware

**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

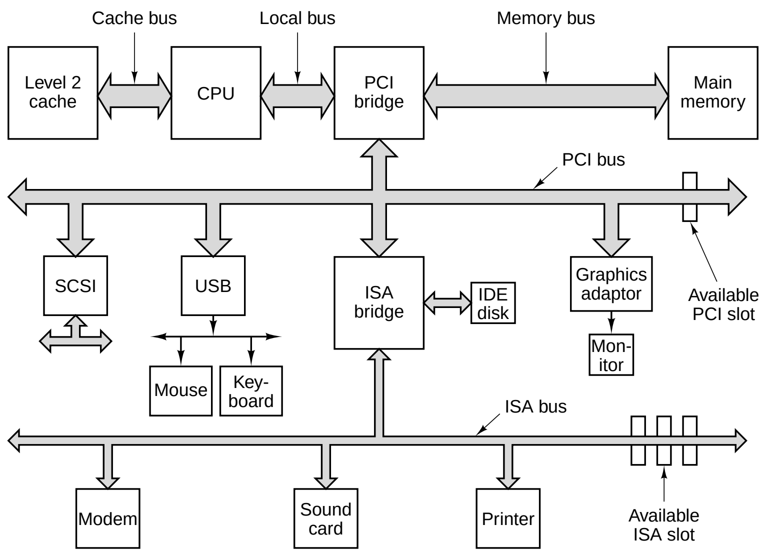
**System Bus**



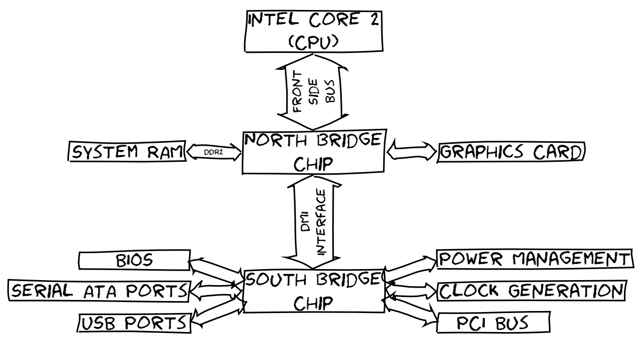

**Address Bus:** specifies the memory locations (addresses) for the data transfers
**Data Bus:** holds the data transfered. Bidirectional
**Control Bus:** contains various lines used to route timing and control signals throughout the system

**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**




See also: *Motherboard Chipsets And The Memory Map* [1].

- 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 ($2^{33} \times 8B$)

[1] http://duartes.org/gustavo/blog/post/motherboard-chipsets-memory-map

See also: *Datasheet for Intel Core 2 Quad-Core Q6000 Sequence* [2].

**Some physical memory addresses are mapped away!**

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

```
0xFFFFFFFF  +--------------------+ 4GB
Reset vector|  JUMP to 0xF0000   |
0xFFFFFFF0  +--------------------+ 4GB-16B
            |  Unaddressable     |
            |  memory, real mode |
            |  is limited to 1MB.|
0x100000    +--------------------+ 1MB
            |    System BIOS     |
0xF0000     +--------------------+ 960KB
            |  Ext. System BIOS  |
0xE0000     +--------------------+ 896KB
            |  Expansion Area    |
            | (maps ROMs for old |
            |  peripheral cards) |
0xC0000     +--------------------+ 768KB
            | Legacy Video Card  |
            |   Memory Access    |
0xA0000     +--------------------+ 640KB
            |  Accessible RAM    |
            | (640KB is enough   |
            | for anyone - old   |
            |    DOS area)       |
0           +--------------------+ 0
```

**Memory-mapped I/O**

- BIOS ROM
- video cards
- PCI cards
- …

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

**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*

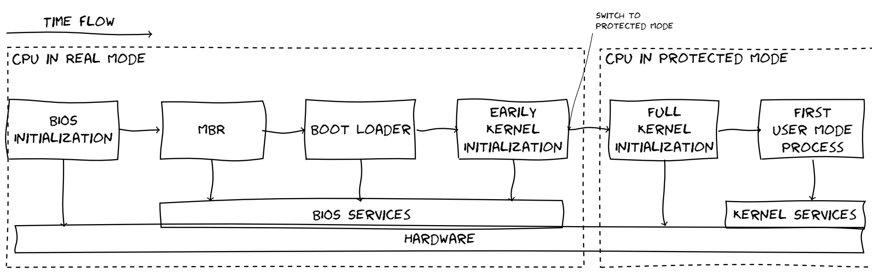
- When is the memory address map built? `setup()`.

### 4.2.2 Bootstrapping

**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 ($< 446\,B$), e.g. GRUB stage 1, for loading GRUB stage 2
   - the primary partition table ($16 \times 4 = 64\,B$)
   - 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

```
|<---------- Master Boot Record (512 Bytes) ---------->|
+-----//-----+---------+------+-------//-------+--------+
| code area  | disk-sig| null | partition table| MBR-sig|
|    440     |    4    |  2   |    16x4=64     | 0xAA55 |
+-----//-----+---------+------+-------//-------+--------+
0          439       443    445              509      511
```

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

- https://en.wikipedia.org/wiki/Unified_Extensible_Firmware_Interface

[2] http://download.intel.com/design/processor/datashts/31559205.pdf

### 4.2.3 Interrupt

**Why Interrupt?**

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

```
while(!done_reading_a_file())
{
  let_CPU_wait();
  // or...
  lend_CPU_to_others();
}
operate_on_the_file();
```

**Modern OS are Interrupt Driven**

**HW INT** by sending a signal to CPU

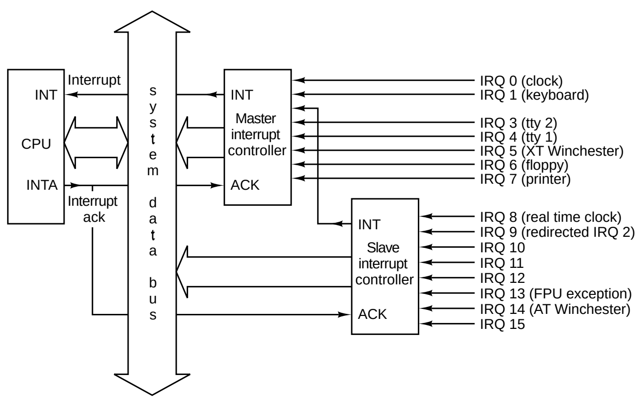
**SW INT** by executing a *system call*

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

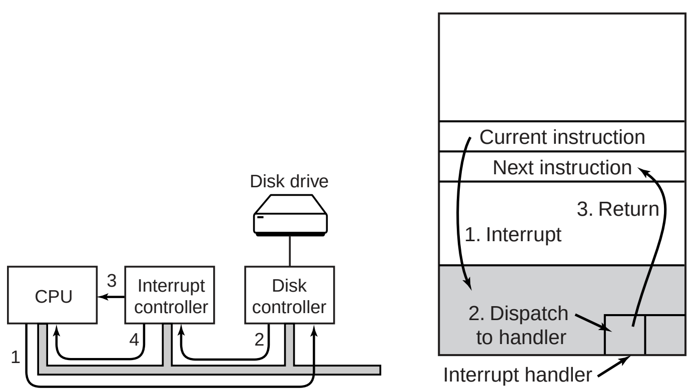
**Interrupt vector** is an array of pointers ☛ the memory addresses of *interrupt handlers*. This array is indexed by a unique device number

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

**Programmable Interrupt Controllers**

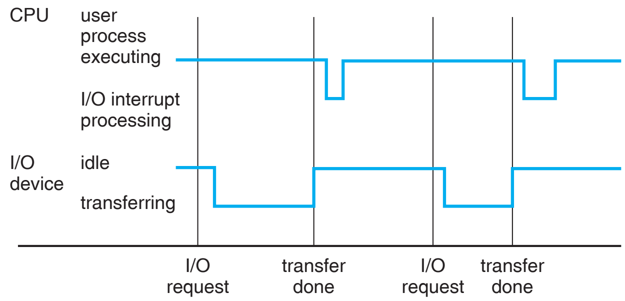



**Interrupt Processing**




- [*Modern Operating Systems*, Sec. 1.3.5, *I/O Devices*]

**Interrupt Timeline**



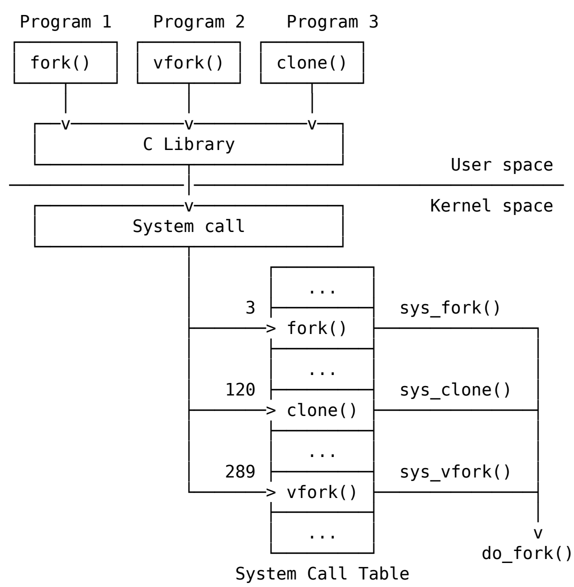

### 4.2.4 System Calls

**System Calls**

**A System Call**

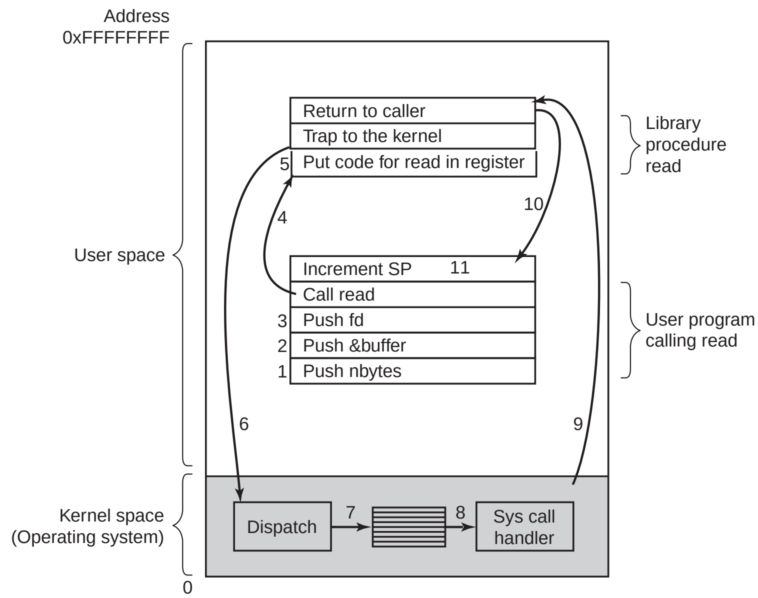
- is how a program requests a service from an OS kernel
- provides the interface between a process and the OS

```
$ 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**

```
Msg: db 'Hello, world'
MsgLen: equ $-Msg
mov eax,4       ; sys_write syscall = 4
mov ebx,1       ; 1 = STDOUT
mov ecx,Msg     ; offset of the message
mov edx,MsgLen  ; length of string
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 |

Fig. 1-18. Some of the major POSIX system calls. The return code *s* is −1 if an error has occurred. The return codes are as follows: *pid* is a process id, *fd* is a file descriptor, *n* is a byte count, *position* is an offset within the file, and *seconds* is the elapsed time. The parameters are explained in the text.

### System Call Examples

`fork()`

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

int main ()
{
  printf("Hello World!\n");
  fork();
  printf("Goodbye Cruel World!\n");
  return 0;
}
```

```
$ man 2 fork
```

`execve()`

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

int main()
{
  printf("Hello World!\n");
  if( fork() != 0 )
    printf("I am the parent process.\n");
  else {
    printf("A child is listing the directory contents...\n");
    execl("/bin/ls", "ls", "-al", NULL);
  }
  return 0;
}
```

```
$ man 2 execve
$ man 3 exec
```

Quoted from stackoverflow: What is the difference between the functions of the *exec* family of system calls:

> There is no *exec* system call — this is usually used to refer to all the *execXX* calls as a group. They all do essentially the same thing: loading a new program into the current process, and provide it with arguments and environment variables. The differences are in how the program is found, how the arguments are specified, and where the environment comes from.
>
> - The calls with *v* in the name take an array parameter to specify the `argv[]` array (*vector*) of the new program.
> - The calls with *l* in the name take the arguments of the new program as a variable-length argument *list* to the function itself.
> - The calls with *e* in the name take an extra argument to provide the *environment* of the new program; otherwise, the program inherits the current process's environment.
> - The calls with *p* in the name search the *PATH* environment variable to find the program if it doesn't have a directory in it (i.e. it doesn't contain a / character). Otherwise, the program name is always treated as a path to the executable.

# 5 The Linux Environment

**Command Line Options**

*getopt.c*

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

int main(int argc, char* argv[]) {
  int opt;

  while ((opt = getopt(argc, argv, "hf:l")) != -1) {
    switch (opt) {
    case 'h':
      printf("Usage: %s [-h] [-f file] [-l]\n", argv[0]);
      break;
    case 'l':
      printf("option: %c\n", opt);
      break;
    case 'f':
      printf("filename: %s\n", optarg);
      break;
    }
  }
  return 0;
```

```
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra getopt.c -o getopt" */
/* End: */
```

```
$ man 3 getopt
```

**Command Line Options**

*getopt.sh*

```
#!/bin/bash

while getopts hf:l OPT; do
  case $OPT in
    h) echo "usage: `basename $0` [-h] [-f file] [-l]"
       exit 1 ;;
    l) echo "option: l" ;;
    f) echo "filename: $OPTARG" ;;
  esac
done
```

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

**Environment Variable**

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

extern char** environ;

int main() {
  char** env = environ;

  while (*env) {
    printf("%s\n", *env);
    env++;
  }

  return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra env.c
↪  -o env" */
/* End: */
```

```
$ env
$ man 3 getenv
$ man 3 putenv
```

[*Beginning linux programming*, p.147, Sec. The `environ` Variable]

**Time and Date**

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

int main(void)
{
  time_t t = time(NULL); /* long int */

  printf("epoch time:\t%ld\n",t);
  printf("calendar time:\t%s", ctime(&t));

  return 0;
}
```

- January 1 1970 — start of the Unix epoch

```
$ man 3 time
$ man 3 ctime
```

### Temporary Files

**mkstemp.c**

```c
#define _GNU_SOURCE
#include <stdlib.h>
#include <unistd.h>
#include <stdio.h>

int main(int argc, char *argv[])
{
  char c, *f;

  asprintf(&f, "%sXXXXXX", argv[1]);
  int tmp = mkstemp(f);

  while ( read(0, &c, 1) == 1)
    write(tmp, &c, 1);

  unlink(f);
  free(f);
  return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra mkstemp.c -o
↪  mkstemp" */
/* End: */
```

**mktemp.sh**

```bash
#!/bin/bash

tmp=$(mktemp)

while read LINE; do
  echo $LINE >> $tmp
done
```

```
$ man 3 mkstemp
$ man 3 tmpfile
$ man 3 asprintf
```

### Logging

**syslog.c**

```c
#include <syslog.h>
#include <sys/stat.h>
#include <fcntl.h>

int main(int argc, char *argv[])
{
  if( open(argv[1], O_RDONLY) < 0 )
    syslog(LOG_ERR | LOG_USER, "%s - %m\n", argv[1]);
  else
    syslog(LOG_INFO | LOG_USER, "%s - %m\n", argv[1]);
```

```
  return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra syslog.c -o syslog" */
/* End: */
```

`logger.sh`

```
#!/bin/bash

[[ -f "$1" ]] && logger "$1 exists." || logger "$1 not found."
```

# 6 Working With Files

## 6.1 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**

```
|<--------------------- Entire disk --------------------->|
+-----+-------------+-------------+-------------+-------------+
| MBR | Partition 1 | Partition 2 | Partition 3 | Partition 4 |
+-----+-------------+-------------+-------------+-------------+
  ______________________________/              \____________
 /                                                          \
+---------------+-----------------+-------------------+--//--+
| Boot Ctrl Blk | Volume Ctrl Blk |   Dir Structure   | Files|
|  (MBR copy)   |   (Super Blk)   | (inodes, root dir)| dirs |
+---------------+-----------------+-------------------+--//--+

|<------------ Master Boot Record (512 Bytes) ------------>|
+----//-----+-----------+-------+-------//-------+----------+
| code area | disk-sig  | null  | partition table | MBR-sig  |
|    440    |     4     |   2   |     16x4=64     | 0xAA55   |
+----//-----+-----------+-------+-------//-------+----------+
0          439         443     445               509       511
```

**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).

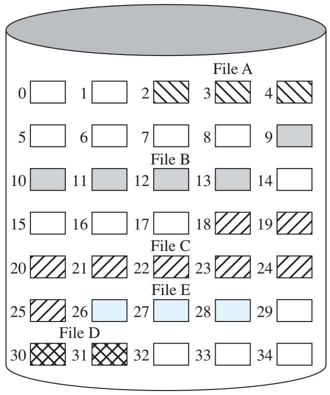
**Superblock**

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**

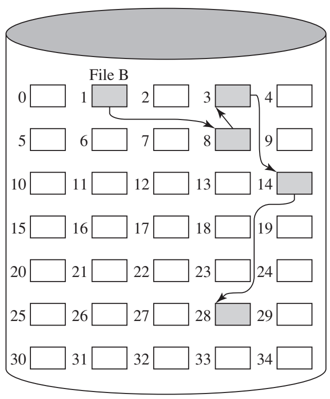



File Allocation Table

| 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



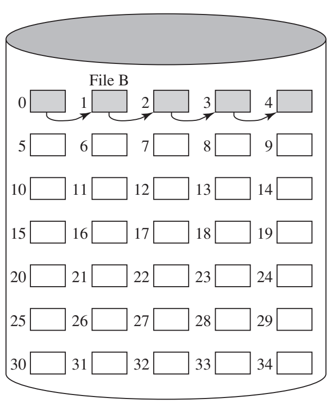

File Allocation Table

| 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.



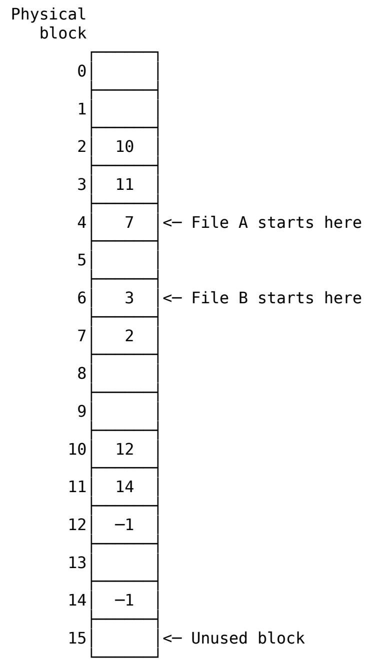

File Allocation Table

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

FAT: Linked list allocation with a table in RAM

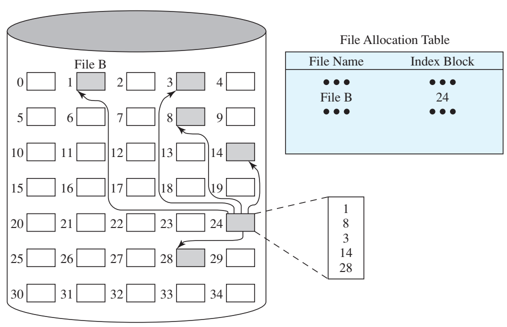
- Taking the pointer out of each disk block, and putting it into a table in memory
- fast random access (chain is in RAM)
- is $2^n$
- the entire table must be in RAM

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




See also: [*File Allocation Table — Wikipedia, The Free Encyclopedia*, *Wikipedia:FAT*].

### Indexed Allocation

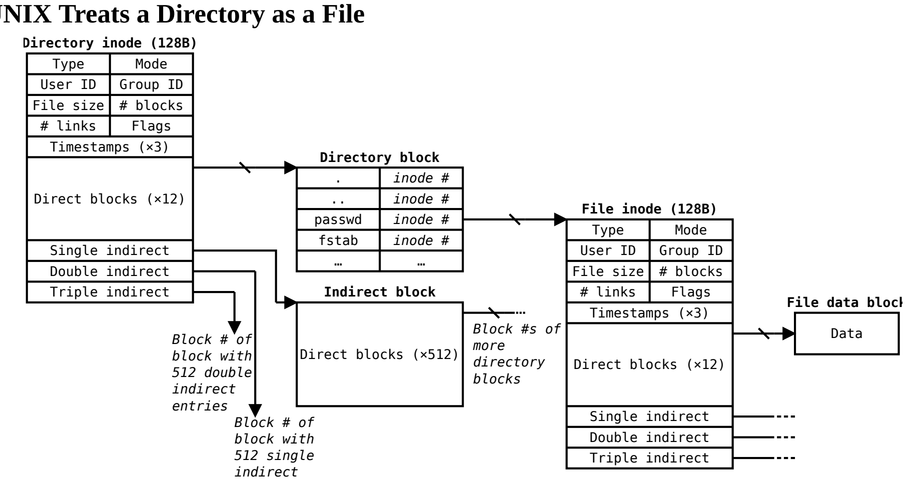



**I-node** A data structure for each file. An i-node is in memory *only if* the file is open

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

See also: [*Inode — Wikipedia, The Free Encyclopedia*, *Wikipedia:inode*].

### UNIX Treats a Directory as a File

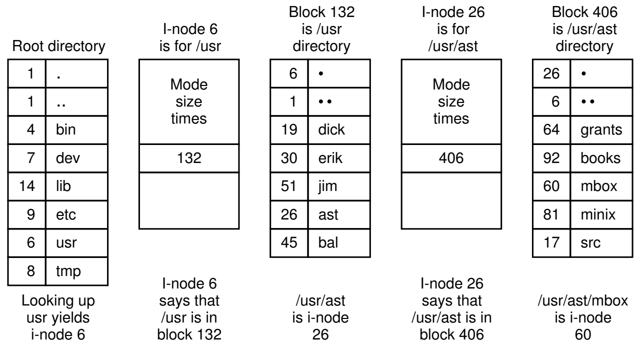


`open()`

**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`




**`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

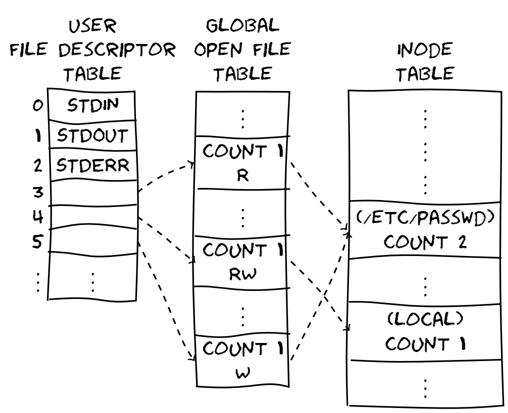
To see files opened by a process, e.g. `init`

```
$ lsof -p 1
```

```
$ man 2 open
```

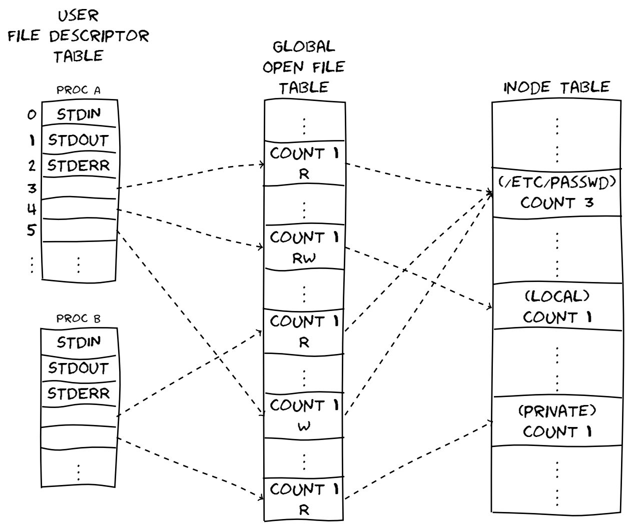
**A process executes the following code:**

```
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()

```c
#include <unistd.h>

int main(void)
{
  write(1, "Hello, world!\n", 14);

  return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra write.c -o
↪  write" */
/* End: */
```

```
$ man 2 write
$ man 3 write
```

### read()

```c
#include <unistd.h>

int main(void)
{
  char buffer[10];

  read(0, buffer, 10);

  write(1, buffer, 10);

  return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall
↪  -Wextra read.c -o read" */
/* End: */
```

```
$ man 2 read
$ man 3 read
```

### cp

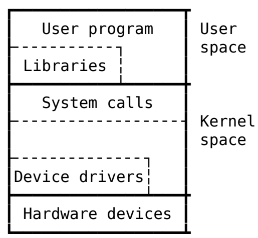
```c
#include <sys/types.h>   /* include necessary header files */
#include <fcntl.h>
#include <stdlib.h>
#include <unistd.h>

#define BUF_SIZE 4096
#define OUTPUT_MODE 0700

int main(int argc, char *argv[])
{
  int in, out, rbytes, wbytes;
  char buf[BUF_SIZE];

  if (argc != 3) exit(1);

  if ( (in = open(argv[1], O_RDONLY)) < 0 ) exit(2);

```

```c
  if ( (out = creat(argv[2], OUTPUT_MODE)) < 0 ) exit(3);

  while (1) { /* Copy loop */
    if ( (rbytes = read(in, buf, BUF_SIZE)) <= 0 ) break;
    if ( (wbytes = write(out, buf, rbytes)) <= 0 ) exit(4);
  }

  close(in); close(out);
  if (rbytes == 0) exit(0); /* no error on last read */
  else exit(5);             /* error on last read */
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra cp-syscall.c -o cp-syscall" */
/* End: */
```

**`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()`

```c
#include <unistd.h>
#include <sys/stat.h>
#include <fcntl.h>
#include <stdio.h>

int main()
{
  char c;
  int in;
  in = open("/tmp/1m.test", O_RDONLY);

  while (read(in, &c, 1) == 1);

  return 0;
}


/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra
↪  open.c -o open" */
/* End: */
```

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

`fopen()` — Buffered I/O

```c
#include <stdio.h>

int main(void)
{
  FILE *stream;

  stream = fopen("/tmp/1m.test", "r");

  while ( fgetc(stream) != EOF );

  fclose(stream);

  return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra
↪  fopen.c -o fopen" */
/* End: */
```

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

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

- https://stackoverflow.com/questions/1658476/c-fopen-vs-open

**cp — With stdio**

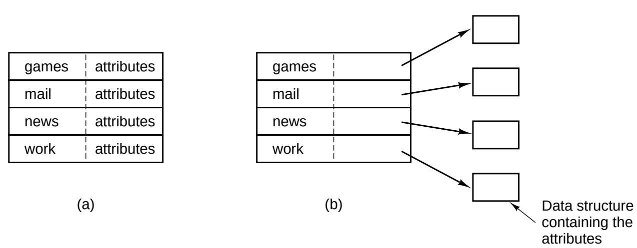
```c
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char *argv[])
{
  FILE *in, *out;
  int c=0;

  if (argc != 3) exit(1);

  in = fopen(argv[1], "r");
  out = fopen(argv[2], "w");

  while( (c = fgetc(in)) != EOF )
    fputc(c, out);

  return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra cp-libc.c -o cp-libc" */
/* End: */
```

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

- https://stackoverflow.com/questions/32742430/is-getc-a-macro-or-a-function
- https://stackoverflow.com/questions/9104568/macro-vs-function-in-c

## 6.2 Directory

### Implementing Directories




(a) A simple directory (Windows)
   - fixed size entries
   - disk addresses and attributes in directory entry

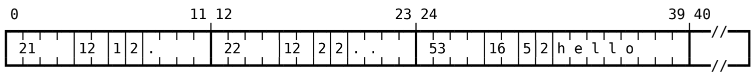
(b) Directory in which each entry just refers to an i-node (UNIX)

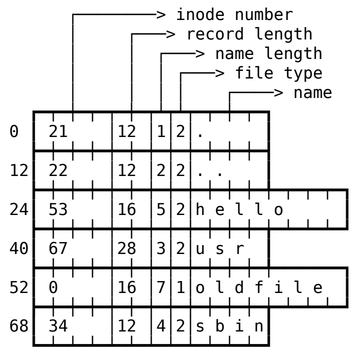
### Directory entry in `glibc`

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

```
$ 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`

```c
#include <sys/types.h>
#include <dirent.h>
#include <stddef.h>
#include <stdio.h>

int main(int argc, char *argv[])
{
  DIR *dp;
  struct dirent *entry;

  dp = opendir(argv[1]);

  while ( (entry = readdir(dp)) != NULL ){
    printf("%s\n", entry->d_name);
  }

  closedir(dp);

  return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra ls.c -o ls" */
/* End: */
```

**The real `ls.c`?**

- 116 A4 pages
- 5308 lines

Do one thing, and do it really well.

`$ apt source coreutils`

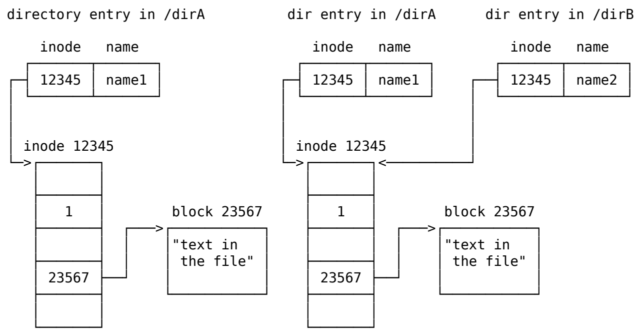
### `mkdir(), chdir(), rmdir(), getcwd()`

```c
#include <sys/stat.h>
#include <sys/types.h>
#include <unistd.h>
#include <stdio.h>

int main(int argc, char *argv[])
{
  char s[100];
  if ( mkdir(argv[1], S_IRUSR|S_IXUSR) == 0 )
    chdir(argv[1]);
  printf("PWD = %s\n", getcwd(s,100));
  rmdir(argv[1]);
  return 0;
}
```

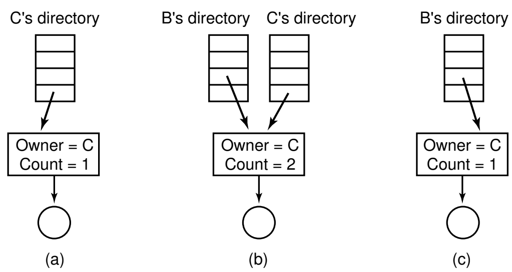
```
/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra mkdir.c -o mkdir" */
/* End: */
```

### Hard Links

### Hard links ☛ the same inode

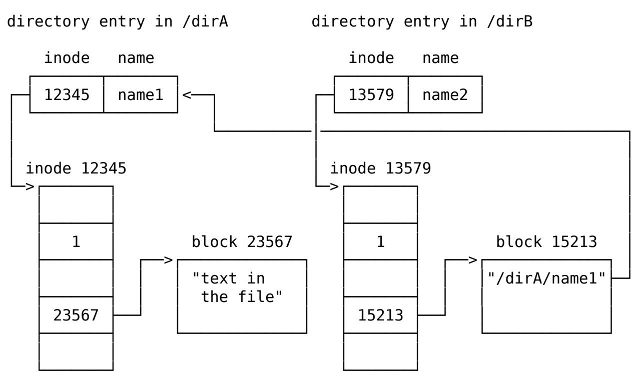



### Drawback




### Symbolic Links

### A symbolic link has its own inode ☛ a directory entry




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

### `link()`, `unlink()`, `symlink()`

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

int main(int argc, char *argv[])
{
  /* link(argv[1], argv[2]); */
  /* symlink(argv[1], argv[2]); */
```

```
  unlink(argv[1]);
  perror(argv[0]);
  return 0;
}


/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra link.c -o ln" */
/* End: */
```

# 7 Processes and Threads

## 7.1 Virtual Memory

**Programs**

A program is a file sitting in your hard disk. Two forms:

- Source code, e.g. `hello.c`, human readable
- Executable code, e.g. `a.out`, machine readable

  **Binary format identification** Usually ELF

  **Machine-language instructions** Program algorithm

  **Entry-point address** Where to find `main()`?

  **Data** Initialized variables

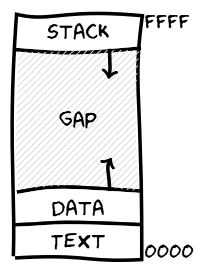
  **Symbol and relocation tables** Address of variables, functions...

  **Shared-library** Where to find `printf()`?

  **More** ...

**Process**

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



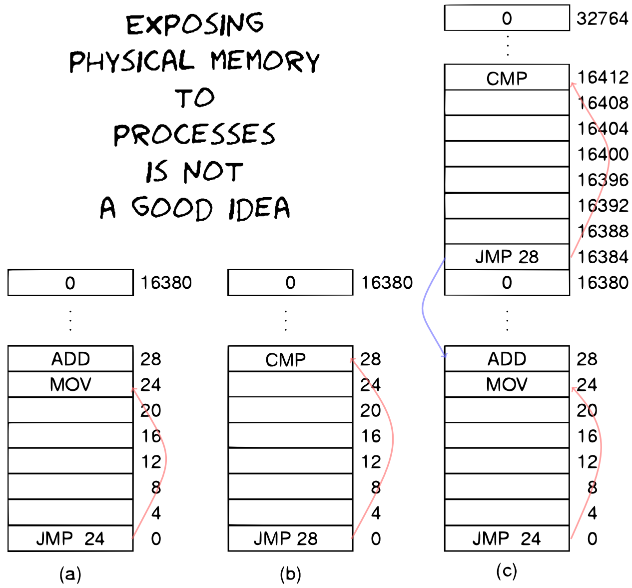

**Processes are like human beings:**

➠ 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

**Problem With Real Mode**




**Protected mode**

We need

- Protect the OS from access by user programs
- Protect user programs from one another

**Protected mode** is an operational mode of x86-compatible CPU.

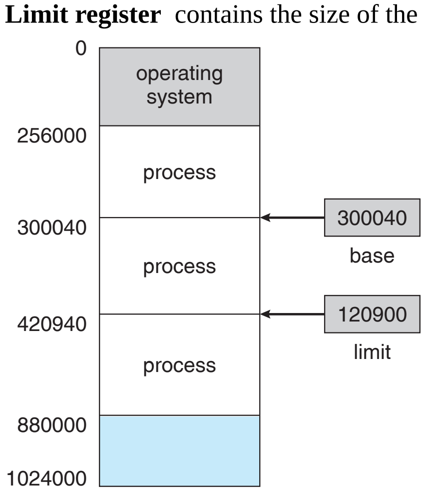
- The purpose is to protect everyone else (including the OS) from your program.

**Memory Protection**

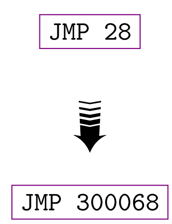
*Logical Address Space*

**Base register** holds the smallest legal physical memory address

**Limit register** contains the size of the range

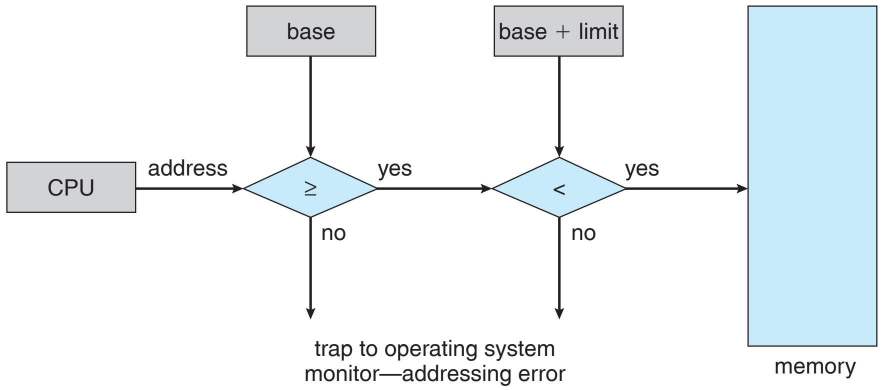



A pair of `base` and `limit` registers define the logical address space




**Memory Protection**

*Base and limit registers*




**UNIX View of a Process' Memory**

```
max
        +-----------------+
        |      Stack      |  Stack segment
        +-----------------+
        |        |        |
        |        v        |
        |                 |
        |        ^        |
        |        |        |
        +-----------------+
        | Dynamic storage |  Heap
        |(from new, malloc)|
        +-----------------+
        |Static variables |
        | (uninitialized, |  BSS  segment
        |  initialized)   |  Data segment
        +-----------------+
        |      Code       |  Text segment
  0     +-----------------+
```

THE SIZE OF A PROCESS (TEXT + DATA + BSS) IS ESTABLISHED AT COMPILE TIME

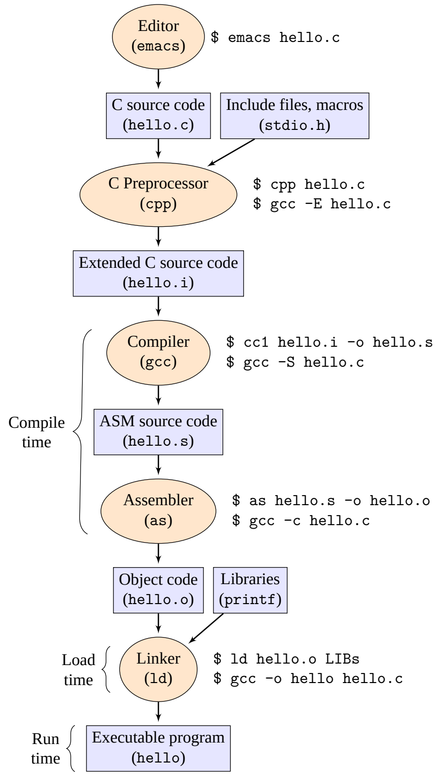
text: program code
data: initialized global and static data
bss: uninitialized global and static data
heap: dynamically allocated with `malloc, new`
stack: local variables

**Stack vs. Heap**

| **Stack** | **Heap** |
|---|---|
| compile-time allocation | run-time allocation |
| auto clean-up | you clean-up |
| inflexible | flexible |
| smaller | bigger |
| quicker | slower |

**How large is the ...**
**stack:** `ulimit -s`
**heap:** could be as large as your virtual memory
**text|data|bss:** `size a.out`

**Multi-step Processing of a User Program**
*When is space allocated?*




**Static:** before program start running

- Compile time
- Load time

**Dynamic:** as program runs

- Execution time

**Compiler** The name ”compiler” is primarily used for programs that translate source code from a high-level programming language to a lower level language (e.g., assembly language or machine code)[*Compiler — Wikipedia, The Free Encyclopedia*].

**Assembler** An assembler creates object code by translating assembly instruction mnemonics into opcodes, and by resolving symbolic names for memory locations and other entities[*Assembly language — Wikipedia, The Free Encyclopedia*].

**Linker** Computer programs typically comprise several parts or modules; all these parts/modules need not be contained within a single object file, and in such case refer to each other by means of symbols[*Linker (computing) — Wikipedia, The Free Encyclopedia*].

When a program comprises multiple object files, the linker combines these files into a unified executable program, resolving the symbols as it goes along.

Linkers can take objects from a collection called a library. Some linkers do not include the whole library in the output; they only include its symbols that are referenced from other object files or libraries. Libraries exist for diverse purposes, and one or more system libraries are usually linked in by default.

The linker also takes care of arranging the objects in a program's address space. This may involve relocating code that assumes a specific base address to another base. Since a compiler seldom knows where an object will reside, it often assumes a fixed base location (for example,zero).

**Loader** An assembler creates object code by translating assembly instruction mnemonics into opcodes, and by resolving symbolic names for memory locations and other entities. ... Loading a program involves reading the contents of executable file, the file containing the program text, into memory, and then carrying out other required preparatory tasks to prepare the executable for running. Once loading is complete, the operating system starts the program by passing control to the loaded program code[*Loader (computing) — Wikipedia, The Free Encyclopedia*]

**Dynamic linker** A dynamic linker is the part of an operating system (OS) that loads (copies from persistent storage to RAM) and links (fills jump tables and relocates pointers) the shared libraries needed by an executable at run time, that is, when it is executed. The specific operating system and executable format determine how the dynamic linker functions and how it is implemented. Linking is often referred to as a process that is performed at compile time of the executable while a dynamic linker is in actuality a special loader that loads external shared libraries into a running process and then binds those shared libraries dynamically to the running process. The specifics of how a dynamic linker functions is operating-system dependent[*Dynamic linker — Wikipedia, The Free Encyclopedia*]

Linkers and Loaders allow programs to be built from modules rather than as one big monolith.
See also:

- [*Computer Systems: A Programmer's Perspective*, Chap. 7, *Linking*].
- COMPILER, ASSEMBLER, LINKER AND LOADER: A BRIEF STORY[3].
- Linkers and Loaders[4].
- [*Linkers and Loaders*, *Links and loaders*].
- Linux Journal: Linkers and Loaders[5]. Discussing how compilers, links and loaders work and the benefits of shared libraries.

**Address Binding**
*Who assigns memory to segments?*

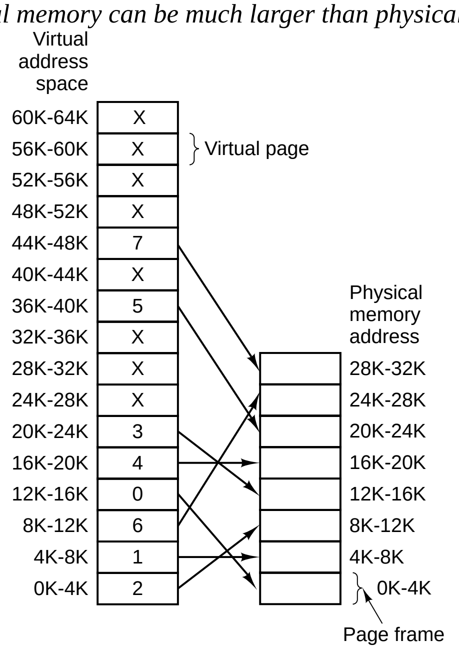
**Static-binding: before a program starts running**
**Compile time:** *Compiler* and *assembler* generate an object file for each source file
**Load time:**

- *Linker* combines all the object files into a single executable object file
- *Loader* (part of OS) loads an executable object file into memory at location(s) determined by the OS
  - invoked via the `execve` system call

**Dynamic-binding: as program runs**

- Execution time:
  – uses `new` and `malloc` to dynamically allocate memory
  – gets space on stack during function calls
- Address binding has nothing to do with physical memory (RAM). It determines the addresses of objects in the address space (virtual memory) of a process.

**Virtual Memory**
*Logical memory can be much larger than physical memory*




**Address translation**

$$\begin{matrix} virtual \\ address \end{matrix} \xrightarrow{page\,table} \begin{matrix} physical \\ address \end{matrix}$$

$$Page\ 0 \xrightarrow{map\,to} Frame\ 2$$

$$0_{virtual} \xrightarrow{map\,to} 8192_{physical}$$

$$\begin{matrix} 20500_{vir} \\ (20k+20)_{vir} \end{matrix} \xrightarrow{map\,to} \begin{matrix} 12308_{phy} \\ (12k+20)_{phy} \end{matrix}$$

**Paging**
*Address Translation Scheme*

**Address generated by CPU is divided into:**
**Page number(p):** an index into a page table

[3] http://www.tenouk.com/ModuleW.html
[4] http://www.iecc.com/linker/
[5] http://www.linuxjournal.com/article/6463

**Page offset(d):** to be copied into memory

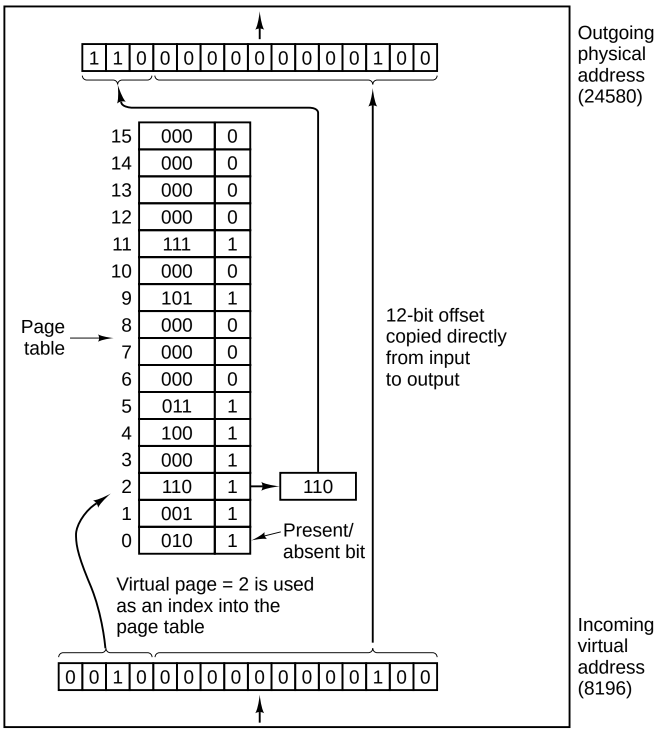
Given *logical address space* ($2^m$) and *page size* ($2^n$),

$$\text{number of pages} = \frac{2^m}{2^n} = 2^{m-n}$$

**Example: addressing to** 0010000000000100

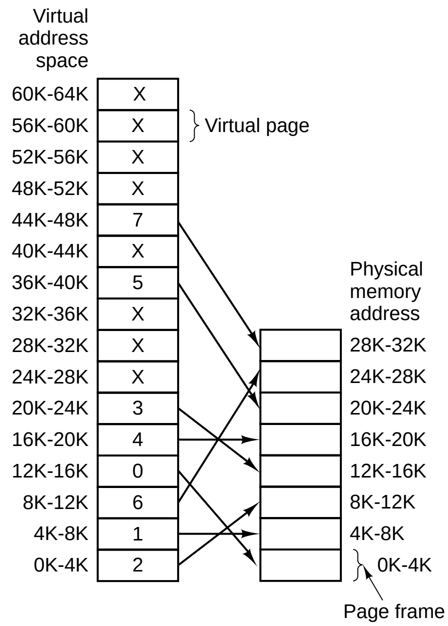
$$\underbrace{\overbrace{0\,0\,1\,0}^{m-n=4}\ \overbrace{0\,0\,0\,0\,0\,0\,0\,0\,0\,1\,0\,0}^{n=12}}_{m=16}$$

$$\text{page number} = 0010 = 2, \quad \text{page offset} = 000000000100$$




| | |
|---|---|
| Virtual pages: | 16 |
| Page size: | 4k |
| Virtual memory: | 64K |
| Physical frames: | 8 |
| Physical memory: | 32K |

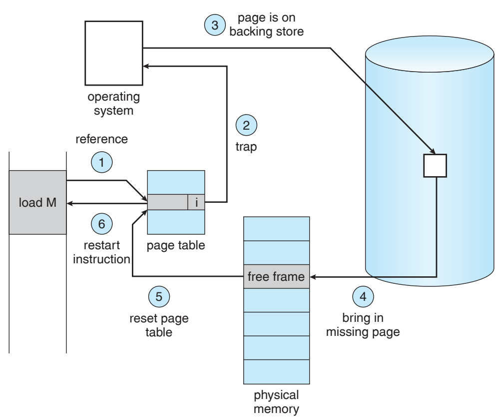
**Page Fault**



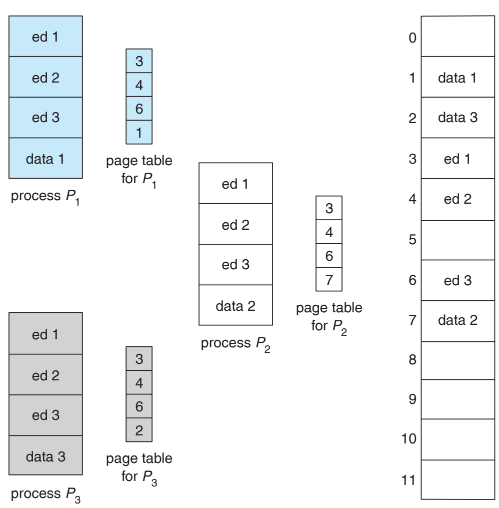

MOV REG, 32780?

➠ Page fault & swapping

**Page Fault Handling**




**Shared Pages**



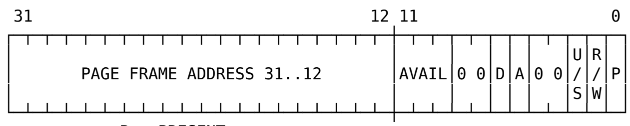
**Page Table Entry**

*Intel i386 Page Table Entry*

- Commonly 4 bytes (32 bits) long
- Page size is usually 4k ($2^{12}$ bytes). OS dependent

  `$ getconf PAGESIZE`
- Could have $2^{32-12} = 2^{20} = 1M$ pages

  Could address $1M \times 4KB = 4GB$ memory



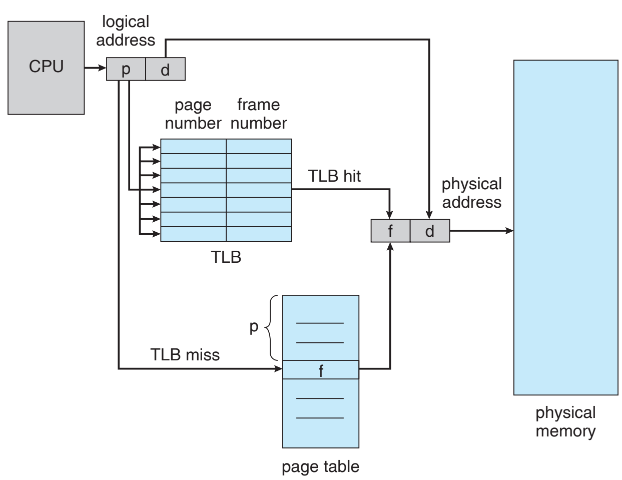

```
      P - PRESENT
    R/W - READ/WRITE
    U/S - USER/SUPERVISOR
      A - ACCESSED
      D - DIRTY
  AVAIL - AVAILABLE FOR SYSTEMS PROGRAMMER USE

  NOTE: 0 INDICATES INTEL RESERVED. DO NOT DEFINE.
```

**Page Table**

- Page table is kept in main memory
- Usually one page table for each process
- *Page-table base register (PTBR):* A pointer to the page table is stored in PCB
- *Page-table length register (PRLR):* indicates size of the page table
- Slow
  - Requires two memory accesses. One for the page table and one for the data/instruction.
- TLB

**Translation Lookaside Buffer (TLB)**

**80-20 rule** Only a small fraction of the PTEs are heavily read; the rest are barely used at all




**Multilevel Page Tables**

- a $1M$-entry page table eats $4M$ memory
- while 100 processes running, $400M$ memory is gone for page tables
- avoid keeping all the page tables in memory all the time

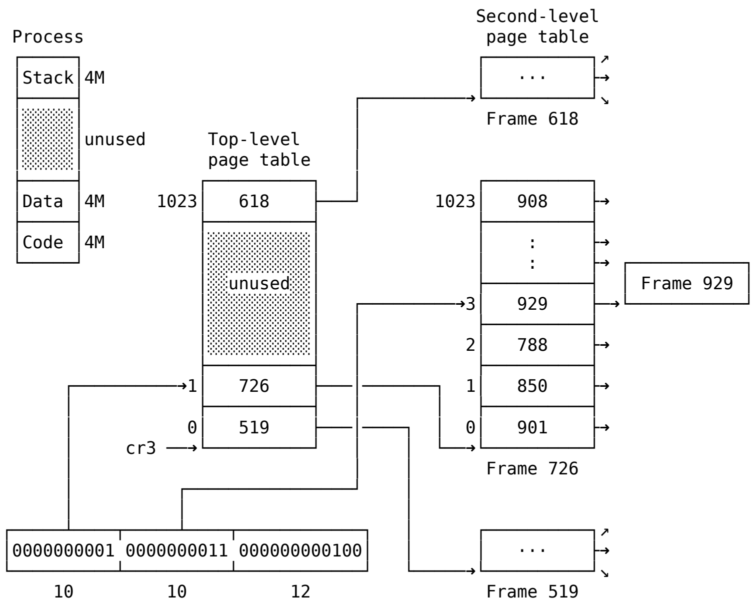
**A two-level scheme**

```
      page number        page offset
  +-----------+-----------+-----------+
  |    p1     |    p2     |     d     |
  +-----------+-----------+-----------+
      10          10          12
      |           |
      |           └─> pointing to 1k frames
      └─> pointing to 1k page tables
```

**p1:** is an index into the outer page table
**p2:** is the displacement within the page of the outer page table

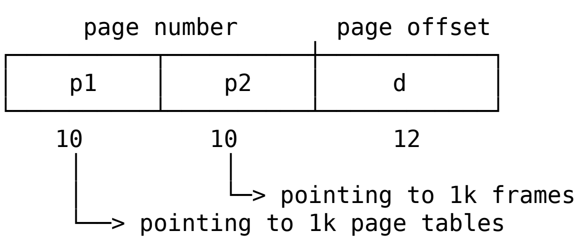
- Split one huge page table into 1k small page tables
  - i.e. the huge page table has 1k entries.
  - Each entry keeps a page frame number of a small page table.
- Each small page table has 1k entries
  - Each entry keeps a page frame number of a physical frame.

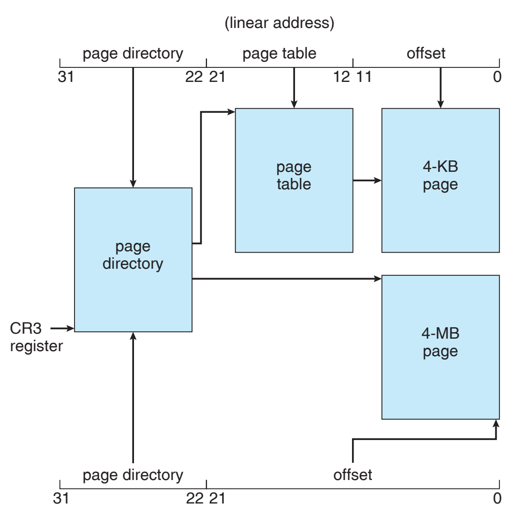
**Two-Level Page Tables**
*Example*




**Pentium Paging**
*Linear Address ⇒ Physical Address*

Two page size in Pentium:
4K: 2-level paging
4M: 1-level paging




**Problem With 64-bit Systems**
**Given:**

- virtual address space $= 64\,bits$
- page size $= 4\,KB = 2^{12}\,B$

**?** How much space would a simple single-level page table take?
if Each page table entry takes $4\,Bytes$

then The whole page table ($2^{64-12}$ entries) will take

$$2^{64-12} \times 4\,B = 2^{54}\,B = 16\,PB \quad {\scriptstyle (peta \Rightarrow tera \Rightarrow giga)!}$$

And this is for ONE process!

**Multi-level?**

if $10\,bits$ for each level

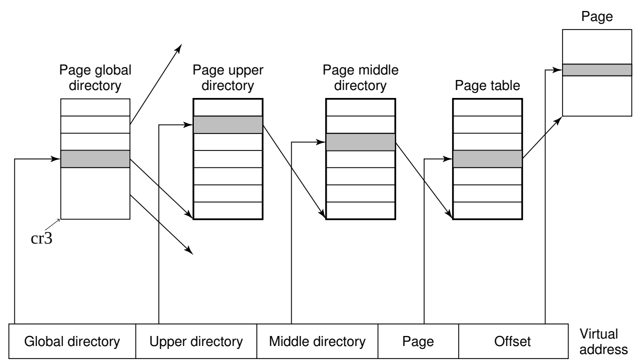
then $\frac{64-12}{10} = 5$ levels are required

5 memory accress for each address translation!

- The CR3 register ☛ the top level page table for the current process.

**Paging In Linux**

*4-level paging for both 32-bit and 64-bit*




**4-level paging for both 32-bit and 64-bit**

- *64-bit: four-level paging*
  1. Page Global Directory
  2. Page Upper Directory
  3. Page Middle Directory
  4. Page Table
- *32-bit: two-level paging*
  1. Page Global Directory
  2. Page Upper Directory — 0 bits; 1 entry
  3. Page Middle Directory — 0 bits; 1 entry
  4. Page Table

*The same code can work on 32-bit and 64-bit architectures*

| Arch | Page size | Address bits | Paging levels | Address splitting |
|---|---|---|---|---|
| x86 | 4KB(12bits) | 32 | 2 | $10+0+0+10+12$ |
| x86-PAE | 4KB(12bits) | 32 | 3 | $2+0+9+\ \ 9+12$ |
| x86-64 | 4KB(12bits) | 48 | 4 | $9+9+9+\ \ 9+12$ |

## 7.2 Process

**From kernel's point of view**

A process consists of

**User-space memory** program code, variable...

**Kernel data structures** keep the state of the process

**Process Control Block (PCB)**

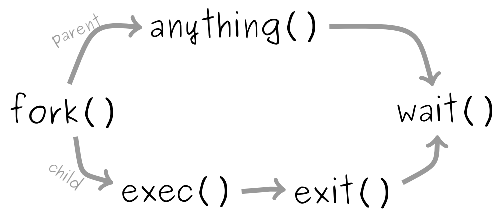
| |
|---|
| process state |
| PID |
| program counter |
| registers |
| memory limits |
| list of open files |
| ... |

**Implementation**

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

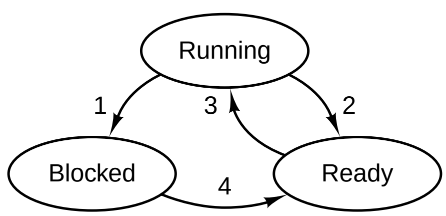
- Each process is represented by a *PCB*
- `task_struct` in 🐧

**Process Creation**



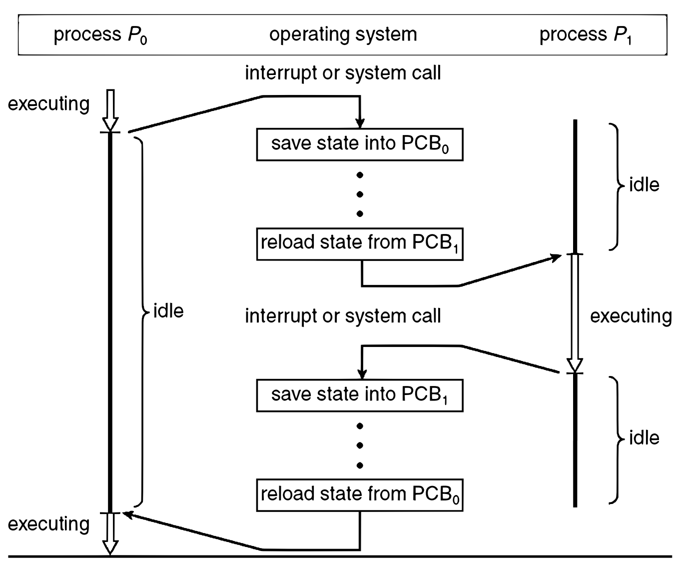

- When a process is created, it is almost identical to its parent
  - It receives a (logical) copy of the parent's address space, and
  - executes the same code as the parent
- The parent and child have separate copies of the data (stack and heap)

**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**

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

int main ()
{
  printf("Hello World!\n");
  fork();
  printf("Goodbye Cruel World!\n");
  return 0;
}
```

`exec()`

```c
int main()
{
  pid_t pid;
  /* fork another process */
  pid = fork();
  if (pid < 0) { /* error occurred */
    fprintf(stderr, "Fork Failed");
    exit(-1);
  }
  else if (pid == 0) { /* child process */
    execlp("/bin/ls", "ls", NULL);
  }
  else { /* parent process */
    /* wait for the child to complete */
    wait(NULL);
    printf ("Child Complete");
    exit(0);
  }
  return 0;
}
```

**More about `argv[0]`** `int execve(const char *pathname, char *const argv[], char *const envp[]);`

- `pathname` should be the binary image of a program. Or it can be a script (`man 2 execve`);
- `argv[0]` is the new process name, usually the same as the basename of `pathname`, though it can be any other string. It can even be NULL (see Figure 3 for example).
  The fact that `argv[0]` contains the name used to invoke the program can be employed to perform a useful trick. We can create multiple links to (i.e., names for) the same program, and then have the program look at `argv[0]` and take different actions depending on the name used to invoke it. An example of this technique is provided by the *gzip(1)*, *gunzip(1)*, and *zcat(1)* commands, all of which are links to the same executable file. [*The Linux Programming Interface: A Linux and UNIX System Programming Handbook*, Sec. 6.6]
- https://stackoverflow.com/questions/2794150/when-can-argv0-have-null
- https://stackoverflow.com/questions/36673765/why-can-the-execve-system-call-run-bin-sh-without-any-argv-arguments-but-not

## 7.3 Thread

**Process vs. Thread**

| | | |
|---|---|---|
| a single-threaded process | = | resource + execution |
| a multi-threaded process | = | resource + executions |

```c
#include <unistd.h>

int main(void) {
  char *argv[] = {NULL};
  char *envp[] = {NULL};
  execve("callee.out", argv, envp);
}
```

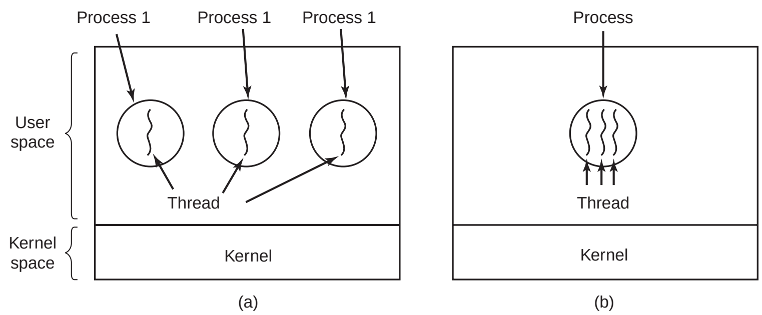
**Fig. 1:** `caller.c`

```c
#include <stdio.h>

int main(int argc, char **argv) {
  if (argc == 0 && argv[0] == NULL)
      puts("yup");
}
```

**Fig. 2:** `callee.c`

```
$ gcc -Wall caller.c -o caller.out
$ gcc -Wall callee.c -o callee.out
$ ./caller.out ./callee.out
```

**Fig. 3:** `argv[0]` can be NULL




**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 |
|---|---|
| `pthread_create` | Create a new thread |
| `pthread_exit` | Terminate the calling thread |
| `pthread_join` | Wait for a specific thread to exit |
| `pthread_yield` | Release the CPU to let another thread run |
| `pthread_attr_init` | Create and initialize a thread's attribute structure |
| `pthread_attr_destroy` | Remove a thread's attribute structure |

**Pthreads**
*Example 1*

```
#include <pthread.h>
#include <stdlib.h>
#include <unistd.h>
#include <stdio.h>

void *thread_function(void *arg) {
  int i;
  for ( i=0; i<10; i++ ) {
    printf("Thread says hi!, %d\n",i);
    sleep(1);
  }
  return NULL;
}

int main(void) {

  pthread_t mythread;

  if ( pthread_create(&mythread, NULL, thread_function, NULL) ) {
    printf("error creating thread.");
    abort();
  }
  printf("Can you see my thread working?\n");

 if ( pthread_join ( mythread, NULL ) ) {
    printf("error joining thread.");
    abort();
  }
  exit(0);
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra thread1.c -o thread1 -pthread" */
/* End: */
```

**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*

```c
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>

#define NUMBER_OF_THREADS 10

void *print_hello_world(void *tid)
{
  /* prints the thread's identifier, then exits.*/
  printf ("Thread %d: Hello World!\n", tid);
  pthread_exit(NULL);
}

int main(int argc, char *argv[])
{
  pthread_t threads[NUMBER_OF_THREADS];
  int status, i;
  for (i=0; i<NUMBER_OF_THREADS; i++)
    {
      printf ("Main: creating thread %d\n",i);
      status = pthread_create(&threads[i], NULL, print_hello_world, (void *)i);

      if(status != 0){
        printf ("Oops. pthread_create returned error code %d\n",status);
        exit(-1);
      }
    }
  exit(NULL);
}
```

### Linux Threads

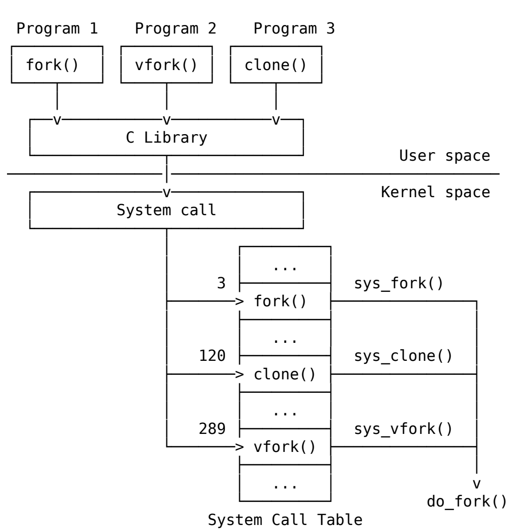
**To the Linux kernel, there is no concept of a thread**

- 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: $1.7\mu s$
fork: $1.8\mu s$

### 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()`

```c
#include <sched.h>
int clone(int (*fn) (void *), void *child_stack,
          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 |
|---|---|
| `CLONE_FS` | File-system info |
| `CLONE_VM` | Same memory space |
| `CLONE_SIGHAND` | Signal handlers |
| `CLONE_FILES` | The set of open files |

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

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

### `clone()` Example

```c
#include <unistd.h>
#include <sched.h>
#include <sys/types.h>
#include <stdlib.h>
#include <string.h>
#include <stdio.h>
#include <fcntl.h>

int variable;

int do_something()
{
  variable = 42;
  _exit(0);
}

int main(void)
{
  void *child_stack;
  variable = 9;

  child_stack = (void *) malloc(16384);
  printf("The variable was %d\n", variable);

  clone(do_something, child_stack,
        CLONE_FS | CLONE_VM | CLONE_FILES, NULL);
  sleep(1);

  printf("The variable is now %d\n", variable);
  return 0;
}
```

#### Stack Grows Downwards

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

## 7.4 Signals

- Singals are software interrupts. Every signal has a name (SIGXXXX). Signals are classic examples of asynchronous events. They occur at what appear to be random times to the process. The process can't simply test a variable (such as `errno`) to see whether a signal has occurred; instead, the process has to tell the kernel "if and when this signal occurs, do the following." [*Advanced programming in the UNIX environment*, chap. 10]
- Signals are software interrupts sent to a program to indicate that an important event has occurred. The events can vary from user requests to illegal memory access errors. Some signals, such as the interrupt signal, indicate that a user has asked the program to do something that is not in the usual flow of control. (https://www.tutorialspoint.com/unix/unix-signals-traps)
- Signals are similar to interrupts, the difference being that interrupts are mediated by the processor and handled by the kernel while signals are mediated by the kernel (possibly via system calls) and handled by processes. The kernel may pass an interrupt as a signal to the process that caused it (typical examples are SIGSEGV, SIGBUS, SIGILL and SIGFPE). (https://en.wikipedia.org/wiki/Signal_(IPC))
- signal(7)

```
$ trap -l
```

#### Signals

- Singals 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

```
#!/bin/bash

sigint(){
  echo -e "Why Ctrl-c?\n-> "
}

trap sigint SIGINT

echo -n "-> "

while read CMD; do
  $CMD
  echo -n "-> "
done
```

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

#### Example

*SIGINT*

```
#include <stdio.h>
#include <string.h>              /* for strlen() */
#include <stdlib.h>
#include <unistd.h>              /* for fork() */
```

```c
#include <sys/wait.h>           /* for waitpid() */
#include <signal.h>

#define MAXLINE 4096

void sig_int(int signo)
{
    printf("Why Ctrl-c?\n-> ");
}

int main(void)
{
    char  buf[MAXLINE];
    pid_t pid;
    int   status;

    if (signal(SIGINT, sig_int) == SIG_ERR)
        perror("signal");

    printf("-> ");
    while (fgets(buf, MAXLINE, stdin) != NULL) {
        buf[strlen(buf) - 1] = '\0'; /* null */

        if ( (pid = fork()) == 0 ) { /* child */
            execlp(buf, buf, (char *)0);
            perror("execlp");
            exit(127);
        }

        if ((pid = waitpid(pid, &status, 0)) < 0)
            perror("waitpid");
        printf("-> ");
    }
    exit(0);
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra shell2.c -o shell2" */
/* End: */
```

- https://stackoverflow.com/questions/840501/how-do-function-pointers-in-c-work

**Example**
*SIGUSR1*

```c
#include <signal.h>
#include <stdio.h>
#include <unistd.h>

void sig_usr(int);

int main(void)
{
  printf("PID = %d\n", getpid());

  if (signal(SIGUSR1, sig_usr) == SIG_ERR)
    perror("signal<SIGUSR1>");

  for ( ; ; )
    pause();
}

void sig_usr(int signo)
{
  if (signo == SIGUSR1)
    printf("received SIGUSR1\n");
  else
    perror("sig_usr");
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra sigusr.c -o sigusr" */
/* End: */
```

```
$ kill -USR1 <PID>
```

**Example**
*SIGALRM*

```c
#include <signal.h>
#include <stdio.h>
#include <unistd.h>
#include <stdlib.h>

void cry(int sig)
{
  puts("C: I'm crying...");
  kill(getppid(),sig);
}

void complain(int sig)
{
  puts("P: You're noisy.");
}

int main()
{
  if ( fork() == 0 ){
    signal(SIGALRM, cry);
    alarm(2);
    pause();
  }

  signal(SIGALRM, complain);
  pause();
  exit(0);
}
```

```

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra alarm.c -o alarm" */
/* End: */
```

# 8 IPC

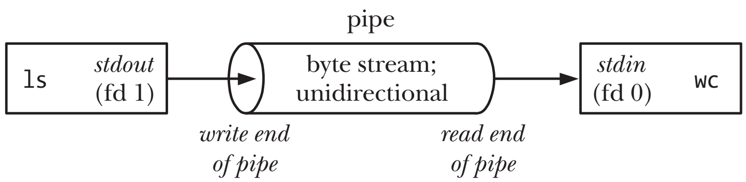
- https://stackoverflow.com/questions/2281204/which-linux-ipc-technique-to-use
- https://stackoverflow.com/questions/404604/comparing-unix-linux-ipc
- https://www.thegeekstuff.com/2010/08/ipcs-command-examples/

## 8.1 Pipes and FIFOs

- [*The Linux Programming Interface: A Linux and UNIX System Programming Handbook*, chap. 44]

**Pipe**

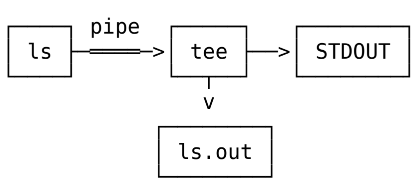
```
$ ls | wc -l
```



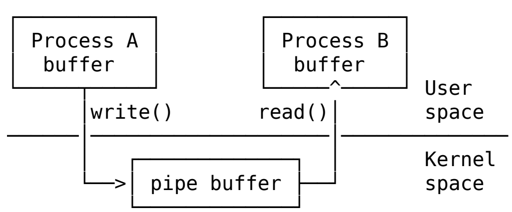

- A pipe is a byte stream
- Unidirectional
- `read()` would be blocked if nothing written at the other end

`tee`

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



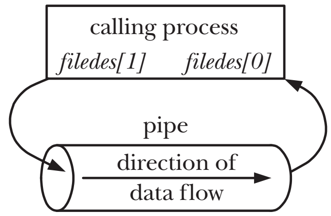

- When we say that a pipe is a byte stream, we mean that there is no concept of messages or message boundaries when using a pipe. The process reading from a pipe can read blocks of data of any size, regardless of the size of blocks written by the writing process. Furthermore, the data passes through the pipe sequentially — bytes are read from a pipe in exactly the order they were written. It is not possible to randomly access the data in a pipe using `lseek()`. [*The Linux Programming Interface: A Linux and UNIX System Programming Handbook*, chap. 44]



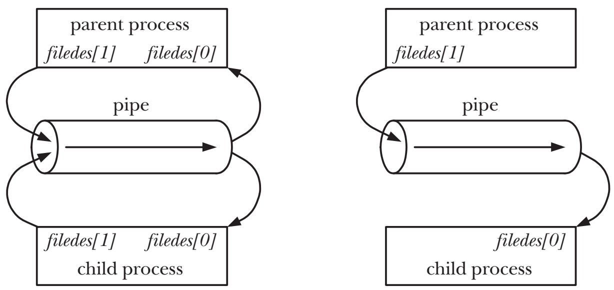

- No direct link between A and B
- A pipe is simply a buffer maintained in kernel memory
  ```
  $ cat /proc/sys/fs/pipe-max-size
  ```
- Need system calls

**pipe()**

```c
#include <unistd.h>

int pipe(int fd[2]);
```




**pipe() + fork()**




**a) After *fork()*** **b) After closing unused descriptors**

- Pipes must have a reader and a writer. If a process tries to write to a pipe that has no reader, it will be sent the SIGPIPE signal from the kernel. This is imperative when more than two processes are involved in a pipeline. (http://www.tldp.org/LDP/lpg/node20.html)
- While it is possible for the parent and child to both read from and write to the pipe, this is not usual. Therefore, immediately after the `fork()`, one process closes its descriptor for the write end of the pipe, and the other closes its descriptor for the read end. For example, if the parent is to send data to the child, then it would close its read descriptor for the pipe, `filedes[0]`, while the child would close its write descriptor for the pipe, `filedes[1]`. One reason that it is not usual to have both the parent and child reading from a single pipe is that if two processes try to simultaneously read from a pipe, we can't be sure which process will be the first to succeed—the two processes race for data. Preventing such races would require the use of some synchronization mechanism. However, if we require bidirectional communication, there is a simpler way: just create two pipes, one for sending data in each direction between the two processes. (If employing this technique, then we need to be wary of deadlocks that may occur if both processes block while trying to read from empty pipes or while trying to write to pipes that are already full.) [*The Linux Programming Interface: A Linux and UNIX System Programming Handbook*, chap. 44, p. 893]
- Pipes can be used for communication between any two (or more) related processes, as long as the pipe was created by a common ancestor before the series of `fork()` calls that led to the existence of the processes. For example, a pipe could be used for communication between a process and its grandchild. The first process creates the pipe, and then forks a child that in turn forks to yield the grandchild. A common scenario is that a pipe is used for communication between two siblings — their parent creates the pipe, and then creates the two children. This is what the shell does when building a pipeline.
- **Closing unused pipe file descriptors**. The process reading from the pipe closes its write descriptor for the pipe, so that, when the other process completes its output and closes its write descriptor, the reader sees end-of-file (once it has read any outstanding data in the pipe). If the reading process doesn't close the write end of the pipe, then, after the other process closes its write descriptor, the reader won't see end-of-file, even after it has read all data from the pipe. Instead, a `read()` would block waiting for data, because the kernel knows that there is still at least one write descriptor open for the pipe. That this descriptor is held open by the reading process itself is irrelevant; in theory, that process could still write to the pipe, even if it is blocked trying to read. For example, the `read()` might be interrupted by a signal handler that writes data to the pipe.
  The writing process closes its read descriptor for the pipe for a different reason. When a process tries to write to a pipe for which no process has an open read descriptor, the kernel sends the SIGPIPE signal to the writing process. By default, this signal kills a process. A process can instead arrange to catch or ignore this signal, in which case the `write()` on the pipe fails with the error EPIPE (broken pipe). Receiving the SIGPIPE signal or getting the EPIPE error is a useful indication about the status of the pipe, and this is why unused read descriptors for the pipe should be closed.

If the writing process doesn't close the read end of the pipe, then, even after the other process closes the read end of the pipe, the writing process will still be able to write to the pipe. Eventually, the writing process will fill the pipe, and a further attempt to write will block indefinitely.

One final reason for closing unused file descriptors is that it is only after all file descriptors in all processes that refer to a pipe are closed that the pipe is destroyed and its resources released for reuse by other processes. At this point, any unread data in the pipe is lost.

```c
#include <sys/wait.h>
#include <unistd.h>
#include <string.h>
#include <stdlib.h>
#include <stdio.h>

#define BUF_SIZE 10

int main(int argc, char *argv[]) /* Over-simplified! */
{
  int pfd[2]; /* Pipe file descriptors */
  char buf[BUF_SIZE];
  ssize_t numRead;

  pipe(pfd); /* Create the pipe */

  switch (fork()) {
  case 0: /* Child - reads from pipe */
    close(pfd[1]); /* Write end is unused */

    for (;;) { /* Read data from pipe, echo on stdout */
      if ( (numRead = read(pfd[0], buf, BUF_SIZE)) == 0)
        break;  /* End-of-file */
      if (write(1, buf, numRead) != numRead)
        perror("child - partial/failed write");
    }
    puts(""); /* newline */

    close(pfd[0]);

    _exit(EXIT_SUCCESS);

  default: /* Parent - writes to pipe */
    close(pfd[0]); /* Read end is unused */

    if( (size_t)write(pfd[1], argv[1], strlen(argv[1])) != strlen(argv[1]) )
      perror("parent - partial/failed write");

    close(pfd[1]); /* Child will see EOF */

    wait(NULL); /* Wait for child to finish */
    exit(EXIT_SUCCESS);
  }
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra simple_pipe.c -o simple-pipe" */
/* End: */
```

- https://stackoverflow.com/questions/5422831/what-is-the-difference-between-using-exit-exit-in-a-conventional-linux-fo
- `_exit(2)`

**`popen()`**

```
fp = popen(cmd, "r");           fp = popen(cmd, "w");
+-----+     +--------+          +-----+     +--------+
|   fp|<----|stdout  |          |   fp|---->|stdin   |
+-----+     +--------+          +-----+     +--------+
parent      child (cmd)         parent      child (cmd)
```

**`popen()`** does a `fork()` and `exec()` to execute the `cmd` and returns STD I/O file pointer.

r `fp` is readable (stdout)

w `fp` is writable (stdin)

- [*Advanced programming in the UNIX environment*, Sec. 15.3]
- [*Beginning linux programming*, Sec. 13.2]

### Example

```c
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

int main()
{
  FILE *fp;
  char buf[1025];
  int rc;

  memset(buf, '\0', sizeof(buf));

  if( (fp = popen("ps ax", "r")) != NULL ) {
    rc = fread(buf, sizeof(char), 1024, fp);
    while (rc > 0) {
      buf[rc - 1] = '\0';
      printf("Reading %d:-\n %s\n", 1024, buf);
      rc = fread(buf, sizeof(char), 1024, fp);
    }
    pclose(fp);
    exit(EXIT_SUCCESS);
  }
  exit(EXIT_FAILURE);
}


/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra popen3.c -o popen3" */
/* End: */
```

```
$ ps ax | cat
```

### Example

```c
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

int main(int argc, char *argv[])
{
  FILE *fp;
  char buf[BUFSIZ + 1];

```

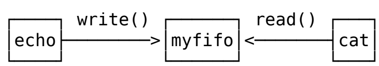
```c
  sprintf(buf, argv[1]);

  if( (fp = popen("od -c", "w")) != NULL ) {
    fwrite(buf, sizeof(char), strlen(buf), fp);
    pclose(fp);
    exit(EXIT_SUCCESS);
  }
  exit(EXIT_FAILURE);
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra popen2.c -o popen2" */
/* End: */
```

```
$ echo -n hello | od -c
```

**Named Pipe (FIFO)**
**PIPEs** pass data between related processes.
**FIFOs** pass data between any processes.

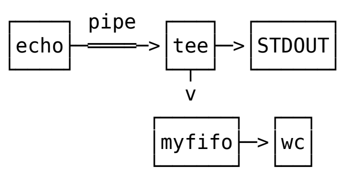
```
$ mkfifo myfifo
```

```
$ echo hello > myfifo
$ cat myfifo
```




`tee`

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




- https://en.wikipedia.org/wiki/Named_pipe

**IPC With FIFO**

```c
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include <fcntl.h>
#include <sys/types.h>
#include <sys/stat.h>

#define FIFO_NAME "/tmp/myfifo"

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

  if (argc < 2) {
    fprintf(stderr, "Usage: %s <O_RDONLY | O_WRONLY | O_NONBLOCK>\n", argv[0]);
    exit(EXIT_FAILURE);
  }

  for(i = 1; i < argc; i++) {
    if (strncmp(*++argv, "O_RDONLY", 8) == 0)  mode |= O_RDONLY;
    if (strncmp(*argv, "O_WRONLY", 8) == 0)    mode |= O_WRONLY;
    if (strncmp(*argv, "O_NONBLOCK", 10) == 0) mode |= O_NONBLOCK;
  }
```

```

  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);
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra fifo2.c -o fifo2" */
/* End: */
```

```
$ 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**

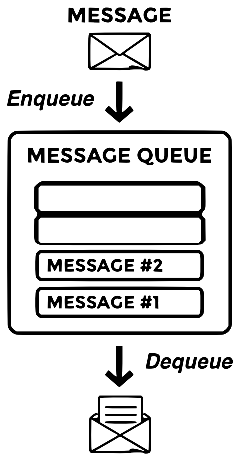
- A `read()`/`write()` will wait on an empty blocking FIFO
- A `read()` on an empty nonblocking FIFO will return 0 bytes
- `open(const char *path, O_WRONLY | O_NONBLOCK);`
  - Returns an error (-1) if FIFO not open
  - Okay if someone's reading the FIFO
- If opened with `O_RDWR`, the result is undefined

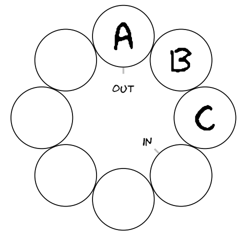
- If opened with `O_RDWR`, the result is undefined. If you do want to pass data in both directions, it's much better to use a pair of FIFOs or pipes, one for each direction.
- There are four legal combinations of `O_RDONLY`, `O_WRONLY`, and the `O_NONBLOCK` flag.

```
open(const char *path, O_RDONLY);
/* In this case, the open call will block; it will not return until a process opens the
   same FIFO for writing. */

open(const char *path, O_RDONLY | O_NONBLOCK);
/* The open call will now succeed and return immediately, even if the FIFO has not been
   opened for writing by any process. */

open(const char *path, O_WRONLY);
/* In this case, the open call will block until a process opens the same FIFO for
   reading. */

open(const char *path, O_WRONLY | O_NONBLOCK);
/* This will always return immediately, but if no process has the FIFO open for reading,
   open will return an error, -1, and the FIFO won't be opened. If a process does have the
   FIFO open for reading, the file descriptor returned can be used for writing to the
   FIFO. */
```

## 8.2 Message Queues

**Message Queues**




**Producer-Consumer Problem**

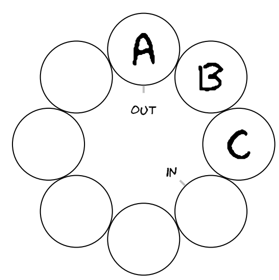
- Consumers don't try to remove objects from Buffer when it is empty.
- Producers don't try to add objects to the Buffer when it is full.

```
while(TRUE){
    while(FULL);
    item = produceItem();
    insertItem(item);
}
```

```
while(TRUE){
    while(EMPTY);
    item = removeItem();
    consumeItem(item);
}
```

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 "$(\texttt{in}+1)\%\texttt{BUFFER\_SIZE} == \texttt{out}$"
Actually, this is "$\texttt{full} - 1$"
**Empty:** when "$\texttt{in} == \texttt{out}$"
Can only use "$\texttt{BUFFER\_SIZE} - 1$" elements

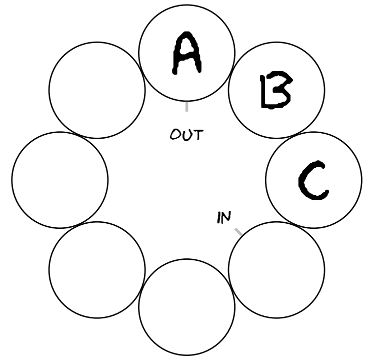
**Shared data:**

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

### Bounded-Buffer Problem

**Producer:**

```
while (true) {
  /* do nothing -- no free buffers */
  while (((in + 1) % BUFFER_SIZE) == out);

  produce(buffer[in]);

  in = (in + 1) % BUFFER_SIZE;
}
```




**Consumer:**

```
while (true) {
  while (in == out); /* do nothing */

  consume(buffer[out]);

  out = (out + 1) % BUFFER_SIZE;
}
```

- [*The Linux Programming Interface: A Linux and UNIX System Programming Handbook*, Sec. 52.3]
- `mq_overview(7)`
- `sem_overview(7)`
- `shm_overview(7)`
- https://www.uninformativ.de/blog/postings/2016-05-16/0/POSTING-en.html

### Message Queues

*Send*

```c
#include <fcntl.h>
#include <limits.h>
#include <mqueue.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <sys/stat.h>

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

  if (argc < 3){
    fprintf(stderr, "Usage: %s <queuename> <message>\n", argv[0]);
    return 1;
  }

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

  if (mq_getattr(queue, &attrs) == -1){
    perror("mq_getattr");
    mq_close(queue);
```

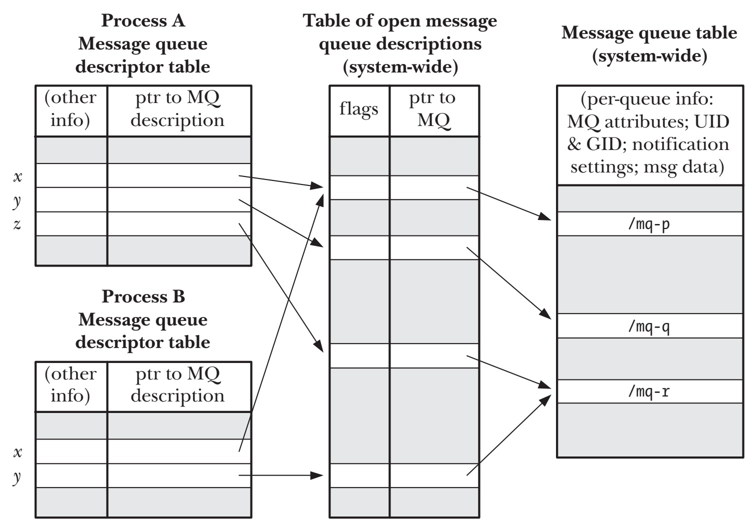
```
    return 1;
  }

  msg_len = strlen(argv[2]);
  if (msg_len > LONG_MAX || (long)msg_len > attrs.mq_msgsize){
    fprintf(stderr, "Your message is too long for the queue.\n");
    mq_close(queue);
    return 1;
  }

  if (mq_send(queue, argv[2], strlen(argv[2]), 0) == -1){
    perror("mq_send");
    mq_close(queue);
    return 1;
  }

  return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra mq-send.c -o mq-send -lrt" */
/* End: */
```

**Message Queues**
*Receive*

```
#include <fcntl.h>
#include <mqueue.h>
#include <stdio.h>
#include <stdlib.h>
#include <sys/stat.h>

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){
    fprintf(stderr, "Usage: %s <queuename>\n", argv[0]);
    return 1;
  }

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

  if (mq_getattr(queue, &attrs) == -1){
    perror("mq_getattr");
    mq_close(queue);
    return 1;
  }

  msg_ptr = calloc(1, attrs.mq_msgsize);
  if (msg_ptr == NULL){
    perror("calloc for msg_ptr");
    mq_close(queue);
```

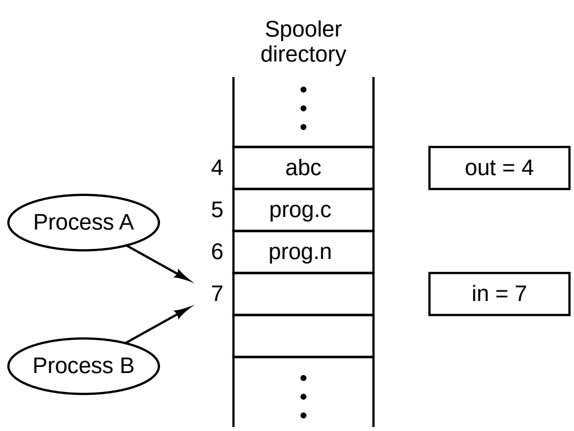
```
    return 1;
  }

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

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

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra mq-recv.c -o mq-recv -lrt" */
/* End: */
```

**Relationship Between Kernel Data Structures**



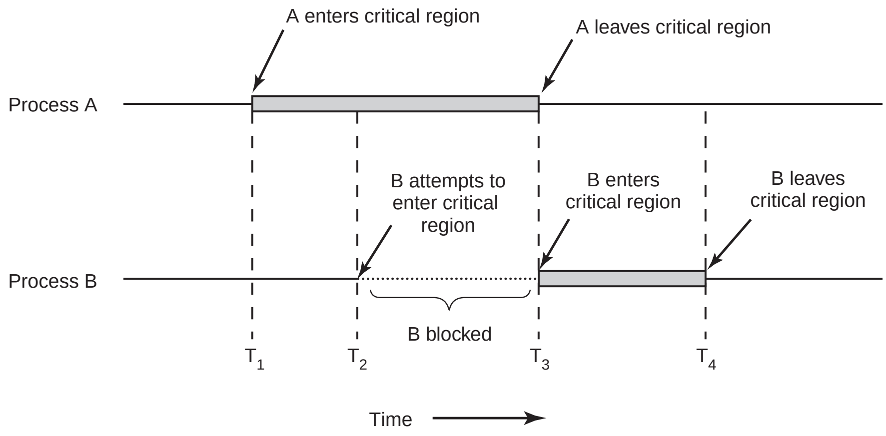

## 8.3 Semaphores

**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*

```
while(TRUE){
  while(turn != 0);
  critical_region();
  turn = 1;
  noncritical_region();
}
```

```
while(TRUE){
  while(turn != 1);
  critical_region();
  turn = 0;
  noncritical_region();
}
```

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

### Mutual Exclusion With Busy Waiting

*Peterson's Solution*

```
int interest[0] = 0;
int interest[1] = 0;
int turn;
```

**P0**

```
interest[0] = 1;
turn = 1;
while(interest[1] == 1
          && turn == 1);
critical_section();
interest[0] = 0;
```

**P1**

```
interest[1] = 1;
turn = 0;
while(interest[0] == 1
          && turn == 0);
critical_section();
interest[1] = 0;
```

[1] Wikipedia. *Peterson's algorithm — Wikipedia, The Free Encyclopedia*. 2015.

### Mutual Exclusion With Busy Waiting

*Lock file*

```
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <fcntl.h>
#include <errno.h>
```

```c

const char *mylock = "/tmp/LCK.test2";

int main() {
  int fd;

  for(;;){
    while( (fd = open(mylock, O_RDWR | O_CREAT | O_EXCL, 0444)) != -1 ) {
      printf("Process(%d) - Working in critical region...\n", getpid());
      sleep(2);           /* working */
      close(fd);
      if ( unlink(mylock) == 0 ) puts("Done.\nResource unlocked.");
      sleep(3);               /* non-critical region */
    }
    printf("Process(%d) - Waiting for lock...\n", getpid());
  }

  exit(EXIT_SUCCESS);
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra lock2.c -o lock2" */
/* End: */
```

☹ Lock file could be left in system after Ctrl+c

✘

```c
#include <unistd.h>
#include <stdlib.h>
#include <stdio.h>
#include <fcntl.h>
#include <errno.h>
#include <signal.h>

const char *mylock = "/tmp/LCK.test2";

void sigint(int signo){
  if ( unlink(mylock) == 0 ) puts("Quit. Lock released.");
  exit(EXIT_SUCCESS);
}

int main() {
  int fd;

  signal(SIGINT,sigint);

  for(;;){
    while( (fd = open(mylock, O_RDWR | O_CREAT | O_EXCL, 0444)) != -1 ) {
      printf("Process(%d) - Working in critical region...\n", getpid());
      sleep(2);           /* working */
      close(fd);
      if ( unlink(mylock) == 0 ) puts("Done.\nResource unlocked.");
      sleep(3);               /* non-critical region */
    }
    printf("Process(%d) - Waiting for lock...\n", getpid());
  }

  exit(EXIT_SUCCESS);
}

```

```
/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra lock2-sigint.c -o lock2-sigint" */
/* End: */
```

- The `sigint()` function is too crude to be reliable. Need a more sophisticated design.

### What is a Semaphore?

- A locking mechanism
- An integer or ADT

```
down(S){
  while(S<=0);
  S--;
}
```

```
up(S){
  S++;
}
```

| *Atomic* Operations | |
|---|---|
| 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

```
statement a1
sem.signal()
```

```
sem.wait()
statement b1
```

What's the initial value of `sem`?

### Example

```
#include <stdio.h>
#include <unistd.h>
#include <stdlib.h>
#include <string.h>
#include <pthread.h>
#include <semaphore.h>

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 ) {
    perror("Semaphore initialization failed");
    exit(EXIT_FAILURE);
  }

```

```
  if( pthread_create(&t, NULL, func, NULL) != 0 ) {
    perror("Thread creation failed");
    exit(EXIT_FAILURE);
  }

  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) {
    perror("Thread join failed");
    exit(EXIT_FAILURE);
  }

  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);
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra thread3.c -o thread3 -pthread" */
/* End: */
```

- [*Beginning linux programming*, Sec. 12.5]
- https://stackoverflow.com/questions/368322/differences-between-system-v-and-posix-semaphores

**i++ can go wrong!**

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

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 ){
          perror("pthread_create 1");
  }

  if( pthread_create(&t2, NULL, threadFunc, &loops) != 0 ){
    perror("pthread_create 2");
  }

  if( pthread_join(t1, NULL) != 0 ){
    perror("pthread_join 1");
  }

  if( pthread_join(t2, NULL) != 0 ){
    perror("pthread_join 2");
  }

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

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra atomic-non.c -o atomic-non -pthread" */
/* End: */
```

### Atomic

#### `i++` is not atomic in assembly language

```
LOAD    [i], r0   ;load the value of 'i' into
                  ;a register from memory
ADD     r0, 1     ;increment the value
                  ;in the register
STORE   r0, [i]   ;write the updated
                  ;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

```
mutex.wait()
    i++
mutex.signal()
```

```
mutex.wait()
    i++
mutex.signal()
```

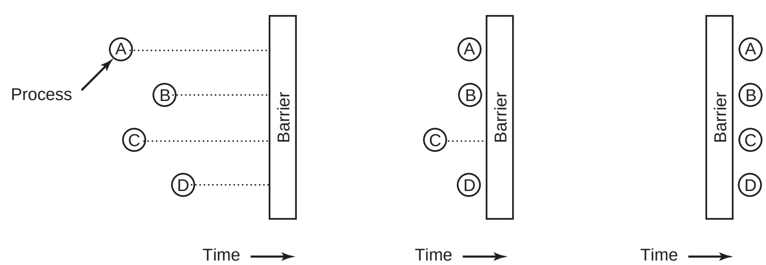
```
#include <pthread.h>
#include <stdlib.h>
#include <stdio.h>

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 ){
```

```c
        perror("pthread_mutex_lock");
    }
    glob++;
    if ( pthread_mutex_unlock(&mtx) != 0){
        perror("pthread_mutex_unlock");
    }
  }

  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 ){
      perror("pthread_create");
  }

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

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

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

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

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra atomic-mutex.c -o atomic-mutex -pthread" */
/* End: */
```

```c
#include <semaphore.h>
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>

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){
      perror("sem_wait");
    }
    glob++;
    if (sem_post(&sem) == -1){
      perror("sem_post");
    }
```

```c
  }

  return NULL;
}

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

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

  if( sem_init(&sem, 0, 1) == -1 ){
      perror("sem_init");
  }

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

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

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

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

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

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra mutex.c -o mutex -pthread" */
/* End: */
```

**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**

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

**count:** keeps track of how many threads have arrived
**mutex:** provides exclusive access to `count`
**barrier:** is locked ($\leq 0$) until all threads arrive
When `barrier.value < 0`,

```
barrier.value == Number of queueing processes
```

```
#define CHAIRS 5
semaphore customers = 0;
semaphore bber = ?;
semaphore mutex = 1;
int waiting = 0;

void barber(void)
{
  while (TRUE) {
    wait(&customers);
    cutHair();
  }
}
```

```
void customer(void)
{
  if (waiting == CHAIRS)
    goHome();
  else {
    wait(&mutex);
    waiting++;
    signal(&mutex);
    signal(&customers);
    wait(&bber);
    getHairCut();
    signal(&bber);
    wait(&mutex);
      waiting--;
    signal(&mutex);
  }
}
```

*Only one thread can pass the barrier!*

**Barrier Solution**

```
specific_task();

mutex.wait();
   count++;
mutex.signal();

if (count == n)
   barrier.signal();

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

critical_point();
```

```
specific_task();

mutex.wait();
   count++;

   if (count == n)
      barrier.signal();

   barrier.wait();
   barrier.signal();
mutex.signal();

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

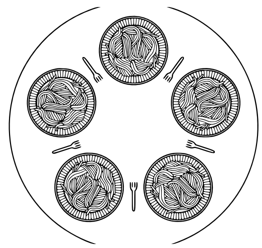
- it allows one thread to pass at a time, and
- it can be locked to bar all threads

## 8.4 Classical IPC Problems

### 8.4.1 The Dining Philosophers Problem

**The Dining Philosophers Problem**

```
while True:
    think()
    get_forks()
    eat()
    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

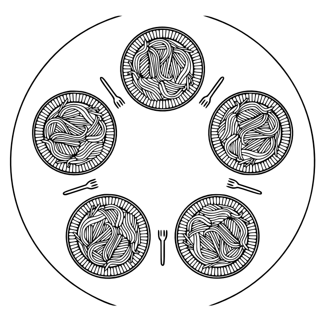
**The Dining Philosophers Problem**
*Deadlock*

```
#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*

```
#define N 5
semaphore mutex=1;

void philosopher(int i)
{
    while (TRUE) {
      think();
      wait(&mutex);
         take_fork(i);
         take_fork((i+1) % N);
         eat();
         put_fork(i);
         put_fork((i+1) % N);
      signal(&mutex);
    }
}
```



- 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**

```
#define N 5              /* number of philosophers */
#define LEFT (i+N-1)%N   /* number of i's left neighbor */
#define RIGHT (i+1)%N    /* number of i's right neighbor */
#define THINKING 0       /* philosopher is thinking */
#define HUNGRY 1         /* philosopher is trying to get forks */
#define EATING 2         /* philosopher is eating */
typedef int semaphore;
int state[N];            /* state of everyone */
semaphore mutex = 1;     /* for critical regions */
semaphore s[N];          /* one semaphore per philosopher */

void philosopher(int i)  /* i: philosopher number, from 0 to N-1 */
{
     while (TRUE) {
          think( );
          take_forks(i); /* acquire two forks or block */
          eat( );
          put_forks(i);  /* put both forks back on table */
     }
}
```

**The Dining Philosophers Problem**
*AST Solution (Part 2)*

```
void take_forks(int i)             /* i: philosopher number, from 0 to N-1 */
{
    down(&mutex);                  /* enter critical region */
    state[i] = HUNGRY;             /* record fact that philosopher i is hungry */
    test(i);                       /* try to acquire 2 forks */
    up(&mutex);                    /* exit critical region */
    down(&s[i]);                   /* block if forks were not acquired */
}
void put_forks(i)                  /* i: philosopher number, from 0 to N-1 */
{
    down(&mutex);                  /* enter critical region */
    state[i] = THINKING;           /* philosopher has finished eating */
    test(LEFT);                    /* see if left neighbor can now eat */
    test(RIGHT);                   /* see if right neighbor can now eat */
    up(&mutex);                    /* exit critical region */
}
void test(i)                       /* i: philosopher number, from 0 to N-1 */
{
    if (state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING) {
          state[i] = EATING;
          up(&s[i]);
    }
}
```

Starvation can happen!

**Step by step**

1. If 5 philosophers `take_forks(i)` at the same time, only one can get `mutex`.
2. The one who gets `mutex` sets his `state` to `HUNGRY`. And then,
3. `test(i);` try to get 2 forks.
   If his `LEFT` and `RIGHT` are not `EATING`, success to get 2 forks.
      i. sets his `state` to `EATING`
      ii. `up(&s[i]);` The initial value of `s(i)` is 0.
   Now, his `LEFT` and `RIGHT` will fail to get 2 forks, even if they could grab `mutex`.
   If either `LEFT` or `RIGHT` are `EATING`, fail to get 2 forks.
4. release `mutex`
5. `down(&s[i]);`
   (a) block if forks are not acquired
   (b) `eat()` if 2 forks are acquired
6. After `eat()`ing, the philosopher doing `put_forks(i)` has to get `mutex` first.
   - because `state[i]` can be changed by more than one philosopher.
7. After getting `mutex`, set his `state` to `THINKING`
8. `test(LEFT);` see if `LEFT` can now eat?
   If `LEFT` is `HUNGRY`, and `LEFT`'s `LEFT` is not `EATING`, and `LEFT`'s `RIGHT` (me) is not `EATING`
      i. set `LEFT`'s `state` to `EATING`
      ii. `up(&s[LEFT]);`
   If `LEFT` is not `HUNGRY`, or `LEFT`'s `LEFT` is `EATING`, or `LEFT`'s `RIGHT` (me) is `EATING`, `LEFT` fails to get 2 forks.
9. `test(RIGHT);` see if `RIGHT` can now eat?
10. release `mutex`

**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

### 8.4.2 The Readers-Writers Problem

**The Readers-Writers Problem**

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

```
semaphore mutex = 1;
semaphore noOther = 1;
int readers = 0;

void writer(void)
{
  while (TRUE) {
    wait(&noOther);
      writing();
    signal(&noOther);
  }
}
```

```
void reader(void)
{
  while (TRUE) {
    wait(&mutex);
      readers++;
      if (readers == 1)
          wait(&noOther);
    signal(&mutex);
    reading();
    wait(&mutex);
      readers--;
      if (readers == 0)
        signal(&noOther);
    signal(&mutex);
    anything();
  }
}
```

**Starvation** The writer could be blocked forever if there are always someone reading.

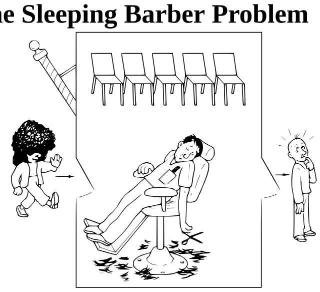
**The Readers-Writers Problem**
*No starvation*

```c
semaphore mutex = 1;
semaphore noOther = 1;
semaphore turnstile = 1;
int readers = 0;

void writer(void)
{
  while (TRUE) {
    turnstile.wait();
      wait(&noOther);
        writing();
      signal(&noOther);
    turnstile.signal();
  }
}
```

```c
void reader(void)
{
  while (TRUE) {
    turnstile.wait();
    turnstile.signal();

    wait(&mutex);
      readers++;
      if (readers == 1)
         wait(&noOther);
    signal(&mutex);
    reading();
    wait(&mutex);
      readers--;
      if (readers == 0)
        signal(&noOther);
    signal(&mutex);
    anything();
  }
}
```

### 8.4.3 The Sleeping Barber Problem

**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**

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

```c
void barber(void)
{
  while (TRUE) {
    wait(&customers);
    wait(&mutex);
       waiting--;
    signal(&mutex);
    cutHair();
    signal(&bber);
  }
}
```

```c
void customer(void)
{
  if(waiting == CHAIRS)
    goHome();
  else {
    wait(&mutex);
    waiting++;
    signal(&mutex);
    signal(&customers);
    wait(&bber);
    getHairCut();
  }
}
```

**Solution2**

```
#define CHAIRS 5
semaphore customers = 0;
semaphore bber = ???;
semaphore mutex = 1;
int waiting = 0;

void barber(void)
{
  while (TRUE) {
    wait(&customers);
    cutHair();
  }
}
```

```
void customer(void)
{
  wait(&mutex);
  if (waiting == CHAIRS){
      signal(&mutex);
      goHome();
  } else {
      waiting++;
      signal(&customers);
      signal(&mutex);
      wait(&bber);
      getHairCut();
      wait(&mutex);
         waiting--;
      signal(&mutex);
      signal(&bber);
  }
}
```

## 8.5 Shared Memory

### Write

```
int main(int argc, char *argv[])
{
  int fd;
  size_t len;                 /* Size of shared memory object */
  char *addr;

  if (argc != 3 || strcmp(argv[1], "--help") == 0){
      printf("%s shm-name string\n", argv[0]);
  }

  if ( (fd = shm_open(argv[1], O_RDWR | O_CREAT, S_IRUSR | S_IWUSR)) == -1 ){
      perror("shm_open");
  }

  len = strlen(argv[2]);
  if (ftruncate(fd, len) == -1){ /* Resize object to hold string */
      perror("ftruncate");
  }
  printf("Resized to %ld bytes\n", (long)len);

  addr = mmap(NULL, len, PROT_READ | PROT_WRITE, MAP_SHARED, fd, 0);
  if (addr == MAP_FAILED) perror("mmap");

  if (close(fd) == -1) perror("close");

  printf("copying %ld bytes\n", (long) len);
  memcpy(addr, argv[2], len);             /* Copy string to shared memory */
  exit(EXIT_SUCCESS);
}
```

### Read

```
int main(int argc, char *argv[])
{
  int fd;
  char *addr;
  struct stat sb;

  if (argc != 2 || strcmp(argv[1], "--help") == 0){
    printf("%s shm-name\n", argv[0]);
  }

  if ( (fd = shm_open(argv[1], O_RDONLY, 0)) == -1 ){
    perror("shm_open");
  }

  if (fstat(fd, &sb) == -1) perror("fstat"); /* Get object size */

  addr = mmap(NULL, sb.st_size, PROT_READ, MAP_SHARED, fd, 0);
  if (addr == MAP_FAILED) perror("mmap");

  if (close(fd) == -1) perror("close");

  write(STDOUT_FILENO, addr, sb.st_size);
  printf("\n");
  exit(EXIT_SUCCESS);
}
```

## 8.6 Sockets

**Message Passing**

**Problem with semaphores**

- Too low level
- Not suitable for distributed systems

**Message passing**

- No conflicts, easier to implement
- Uses two primitives, `send()` and `receive()` system calls:
  - `send(destination, &message);`
  - `receive(source,  &message);`

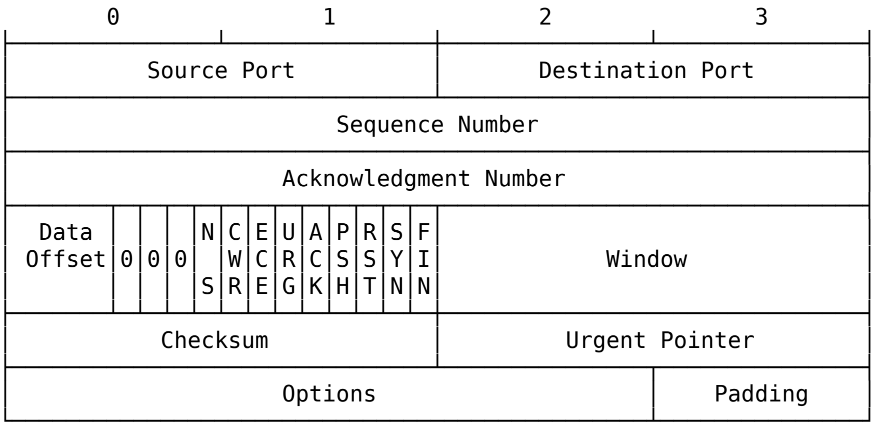
**Message Passing**

**Design issues**

- Message can be lost by network; — `ACK`
- What if the ACK is lost? — `SEQ`
- What if two processes have the same name? — `socket`
- Am I talking with the right guy? Or maybe a MIM? — `authentication`
- What if the sender and the receiver on the same machine? — Copying messages is always slower than doing a semaphore operation.

**Message Passing**

*TCP Header Format*




**Message Passing**

*The producer-consumer problem*

```c
#define N 100  /* number of slots in the buffer */
void producer(void)
{
    int item;
    message m;                      /* message buffer */
    while (TRUE) {
        item = produce_item();     /* generate something to put in buffer */
        receive(consumer, &m);     /* wait for an empty to arrive */
        build_message(&m, item);   /* construct a message to send */
        send(consumer, &m);        /* send item to consumer */
    }
}

void consumer(void)
{
    int item, i;
    message m;
    for (i=0; i<N; i++) send(producer, &m);  /* send N empties */
    while (TRUE) {
        receive(producer, &m);     /* get message containing item */
        item = extract_item(&m);   /* extract item from message */
        send(producer, &m);        /* send back empty reply */
        consume_item(item);        /* do something with the item */
    }
}
```

**A TCP Connection**

```
wx672@cs3:~$ netstat -at | grep http | grep ESTAB
tcp   0   0 cs3.swfu.edu.cn:http    220.163.96.3:47179    ESTABLISHED
```

address port address port

socket socket

a pair of sockets form a TCP connection

**Port numbers**

**Port range:** 0 ~ 65535

**Well-known ports:** 0 ~ 1023

| | | | | | |
|---|---|---|---|---|---|
| FTP | 20/21 | SSH | 22 | Telnet | 23 |
| SMTP | 25 | DNS | 53 | DHCP | 67/68 |
| HTTP | 80 | POP3 | 110 | HTTPS | 443 |
| IMAP4 | 143 | | | | |

**Sockets**

To create a socket:

```
fd = socket(domain, type, protocol)
```

**Domain** Determines address format and the range of communication (local or remote). The most commonly used domains are:

| Domain | Addr structure | Addr format |
|---|---|---|
| AF_UNIX | sockaddr_un | /path/name |
| AF_INET | sockaddr_in | ip:port |
| AF_INET6 | sockaddr_in6 | ip6:port |

**Type** SOCK_STREAM(☎), SOCK_DGRAM (🖂)
**Protocol** always 0

**Address Structure**

- Different socket domain, different address format, different structure type
- One set of socket syscalls supports all socket domains

```
struct sockaddr {
  sa_family_t sa_family;   /* Address family (AF_* constant) */
  char        sa_data[14]; /* Socket address (size varies
                              according to socket domain) */
};
```

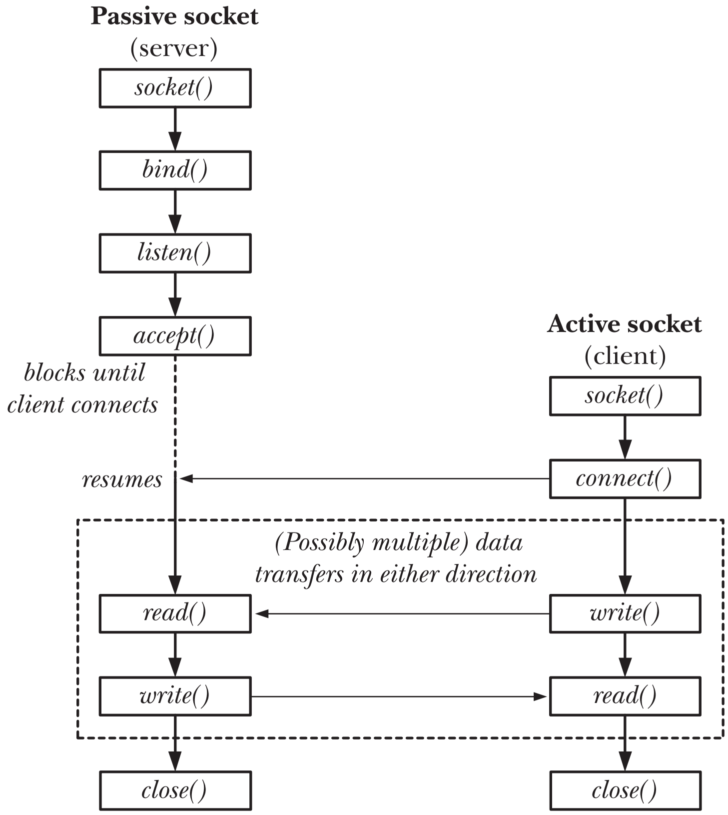
**Example**

```
struct sockaddr_un addr;
```
✔ `bind(sfd, (struct sockaddr *)&addr, sizeof(struct sockaddr_un));`
✘ `bind(sfd, &addr, sizeof(struct sockaddr_un));`

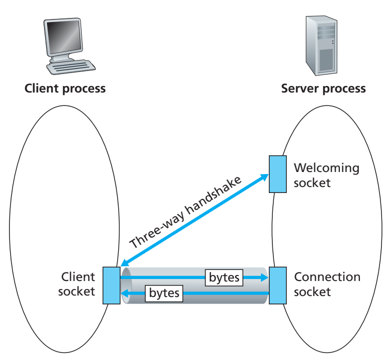
- Why does a cast from sockaddr_in to sockaddr work? sockaddr is defined the way it is to maintain size-compatibility with sockaddr_in, which is 16 bytes, and is what sockaddr used to be in the days when AF_INET was the only address family. But newer families are NOT limited to 14 bytes of data. For instance, sockaddr_in6 has 26 bytes (the sin6_addr field alone is 16 bytes). The ONLY requirement is ALL sockaddr_* types MUST start with a 2-byte family member, whose value dictates the size of the remaining data.
  Presumably, the bind function knows what kind of socket descriptor it has as the address family is part of the socket's internal info. bind() (and connect()) validates the passed in sockaddr matches the socket's address family, and converts the struct sockaddr * back to a struct sockaddr_in *. (For AF_INET) after checking that the passed sockaddr is the correct family AND byte size (which is why bind(), connect(), and accept() have a parameter to receive the size of the sockaddr). If a mismatch occurs, bind() (and connect() and accept()) fails. https://stackoverflow.com/questions/51287930/why-does-a-cast-from-sockaddr-in-to-sockaddr-work
- Why do we cast sockaddr_in to sockaddr when calling bind()? https://stackoverflow.com/questions/21099041/why-do-we-cast-sockaddr-in-to-sockaddr-when-calling-bind
- sa_data is an array of 14 bytes that contains the transport address data. The SOCKADDR structure is large enough to contain a transport address for most address families. A WSK application typically does not access the sa_data member directly. Instead, a pointer to a SOCKADDR structure is normally cast to a pointer to the specific SOCKADDR structure type that corresponds to a particular address family. (https://docs.microsoft.com/en-us/windows/win32/api/ws2def/ns-ws2def-sockaddr)

### 8.6.1 Stream Sockets

**Stream Sockets**




**Two Sockets at the Server**




**Socket System Calls**

**`socket()`** creates a new socket
**`bind()`** binds a socket to an address (usually a well-known address on server side)
**`listen()`** waits for incoming connection requests
**`connect()`** sends a connection request to peer
**`accept()`** accepts a connection request
**`send()/recv()`** data transfer

[*The Linux Programming Interface: A Linux and UNIX System Programming Handbook*, Sec. 56.5]

**`int listen(int sockfd, int backlog);`** To understand the purpose of the `backlog` argument, we first observe that the client may call `connect()` before the server calls `accept()`. This could happen, for example, because the server is busy handling some other client(s). This results in a pending connection. The kernel must record some information about each pending connection request so that a subsequent `accept()` can be processed. The `backlog` argument allows us to limit the number of such pending connections. Connection requests up to this limit succeed immediately. Further connection requests block until a pending connection is accepted (via `accept()`), and thus removed from the queue of pending connections.

**int accept(int sockfd, struct sockaddr *addr, socklen_t *addrlen);** If there are no pending connections when `accept()` is called, the call blocks until a connection request arrives. The key point to understand about `accept()` is that it creates a new socket, and it is this new socket that is connected to the peer socket that performed the `connect()`. A file descriptor for the connected socket is returned as the function result of the `accept()` call. The listening socket (`sockfd`) remains open, and can be used to accept further connections. A typical server application creates one listening socket, binds it to a well-known address, and then handles all client requests by accepting connections via that socket.

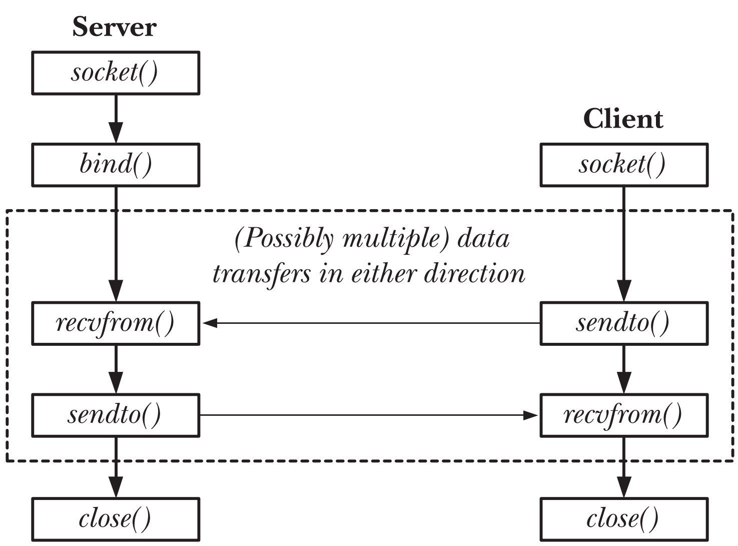
The remaining arguments to `accept()` return the address of the peer socket. The `addr` argument points to a structure that is used to return the socket address. The type of this argument depends on the socket domain (as for `bind()`).

The `addrlen` argument is a value-result argument. It points to an integer that, prior to the call, must be initialized to the size of the buffer pointed to by `addr`, so that the kernel knows how much space is available to return the socket address. Upon return from `accept()`, this integer is set to indicate the number of bytes of data actually copied into the buffer.

If we are not interested in the address of the peer socket, then addr and addrlen should be specified as `NULL` and 0, respectively.

### 8.6.2 Datagram Sockets

**Datagram Sockets**




### 8.6.3 Unix Domain Sockets

**Unix Domain Sockets**

```
struct sockaddr_un {
  sa_family_t sun_family; /* Always AF_UNIX */
  char sun_path[108];     /* Null-terminated socket pathname */
};
```

**Stream server**

```
#include <sys/un.h>
#include <sys/socket.h>
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

#define SV_SOCK_PATH "/tmp/us_xfr"
#define BUF_SIZE 100
#define BACKLOG 5
```

```c

int main(void)
{
  struct sockaddr_un addr;
  int sfd, cfd;
  ssize_t numRead;
  char buf[BUF_SIZE];

  if( (sfd = socket(AF_UNIX, SOCK_STREAM, 0)) == -1 ){
      perror("socket");
          exit(EXIT_FAILURE);
  }

  memset(&addr, 0, sizeof(struct sockaddr_un));
  addr.sun_family = AF_UNIX;
  strncpy(addr.sun_path, SV_SOCK_PATH, sizeof(addr.sun_path) - 1);

  if( bind(sfd, (struct sockaddr *)&addr, sizeof(struct sockaddr_un)) == -1 ){
      perror("bind");
          exit(EXIT_FAILURE);
  }

  if(listen(sfd, BACKLOG) == -1){
      perror("listen");
          exit(EXIT_FAILURE);
  }

  for(;;) {
      if( (cfd = accept(sfd, NULL, NULL)) == -1 ){
                  perror("accept");
                  exit(EXIT_FAILURE);
                }

      while((numRead = read(cfd, buf, BUF_SIZE)) > 0)
          if(write(STDOUT_FILENO, buf, numRead) != numRead){
              perror("partial/failed write");
                          exit(EXIT_FAILURE);
                        }

      if(numRead == -1){
                  perror("read");
                  exit(EXIT_FAILURE);
          }

      if(close(cfd) == -1){
                  perror("close");
                  exit(EXIT_FAILURE);
          }
  }
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra us_xfr_sv.c -o us-xfr-sv" */
/* End: */
```

**Stream client**

```c
#include <sys/un.h>
#include <sys/socket.h>
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
```

```c

#define SV_SOCK_PATH "/tmp/us_xfr"
#define BUF_SIZE 100

int main(void)
{
  struct sockaddr_un addr;
  int sfd;
  ssize_t numRead;
  char buf[BUF_SIZE];

  if( (sfd = socket(AF_UNIX, SOCK_STREAM, 0)) == -1 ){
      perror("socket");
      exit(EXIT_FAILURE);
  }

  memset(&addr, 0, sizeof(struct sockaddr_un));
  addr.sun_family = AF_UNIX;
  strncpy(addr.sun_path, SV_SOCK_PATH, sizeof(addr.sun_path) - 1);

  if (connect(sfd, (struct sockaddr *) &addr, sizeof(struct sockaddr_un)) == -1){
      perror("connect");
                exit(EXIT_FAILURE);
  }

  while ((numRead = read(STDIN_FILENO, buf, BUF_SIZE)) > 0)
      if (write(sfd, buf, numRead) != numRead){
          perror("partial/failed write");
                        exit(EXIT_FAILURE);
                }

  if (numRead == -1){
      perror("read");
                exit(EXIT_FAILURE);
  }

  exit(EXIT_SUCCESS); /* Closes our socket; server sees EOF */
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra us_xfr_cl.c -o us-xfr-cl" */
/* End: */
```

**Datagram server**
**Datagram client**

### 8.6.4 Internet Sockets

**Network Byte Order**
**Big endian** The most significant byte comes first
**Little endian** The least significant byte comes first

```
Big endian
            0x100 0x101 0x102 0x103
      ... | 01  | 23  | 45  | 67  | ...
              int i = 0x01234567;

Little endian
            0x100 0x101 0x102 0x103
      ... | 67  | 45  | 23  | 01  | ...
```

**Network byte order** is big endian
**Host byte order** Most architectures are big endian. x86 is an exception.

**Convert `int` between host and network byte order**

```
#include <arpa/inet.h>
uint32_t htonl(uint32_t hostlong);
uint16_t htons(uint16_t hostshort);
uint32_t ntohl(uint32_t netlong);
uint16_t ntohs(uint16_t netshort);
```

Strictly speaking, the use of these four functions is necessary only on systems where the host byte order differs from network byte order. However, these functions should always be used, so that programs are portable to different hardware architectures. On systems where the host byte order is the same as network byte order, these functions simply return their arguments unchanged. [*The Linux Programming Interface: A Linux and UNIX System Programming Handbook*, Sec. 59.2]

### Socket Addresses

#### IPv4

```
struct in_addr {               /* IPv4 4-byte address */
    in_addr_t s_addr;          /* Unsigned 32-bit integer */
};

struct sockaddr_in {           /* IPv4 socket address */
    sa_family_t    sin_family; /* Address family (AF_INET) */
    in_port_t      sin_port;   /* Port number */
    struct in_addr sin_addr;   /* IPv4 address */
    unsigned char  __pad[X];   /* Pad to size of sockaddr (16 bytes) */
};
```

#### IPv6

```
struct in6_addr {               /* IPv6 address structure */
    uint8_t s6_addr[16];        /* 16 bytes == 128 bits */
};

struct sockaddr_in6 {           /* IPv6 socket address */
    sa_family_t sin6_family;    /* Address family (AF_INET6) */
    in_port_t   sin6_port;      /* Port number */
    uint32_t    sin6_flowinfo;  /* IPv6 flow information */
    struct in6_addr sin6_addr;  /* IPv6 address */
    uint32_t    sin6__scope_id; /* Scope ID (new in kernel 2.4) */
};
```

# 9 User Interface

## 9.1 Dialog, Zenity

## 9.2 Ncurses

## 9.3 GTK+

## 9.4 Qt

# 10 Terminal

- chap 62 of [*The Linux Programming Interface: A Linux and UNIX System Programming Handbook*]
- http://tldp.org/HOWTO/Text-Terminal-HOWTO-16.html
- http://pubs.opengroup.org/onlinepubs/9699919799/

```
$ man infocmp
```

# 11 IDE

Makefile, git