GNU/Linux
Application Programming

Lecture Handouts

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Contents

References

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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 on it?

- *wx672ster+linux@gmail.com*
- Preferably in English
- in stackoverflow style

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

Oversimplifed programs ahead!

Part I
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?

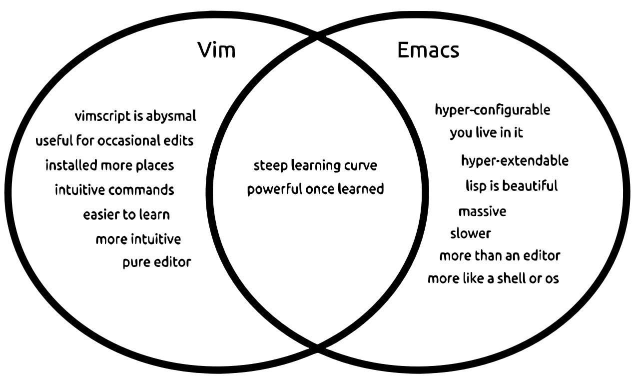
First double check your spelling

Then try:

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

Text Editors

vs.



uemacs Linus Torvalds' editor

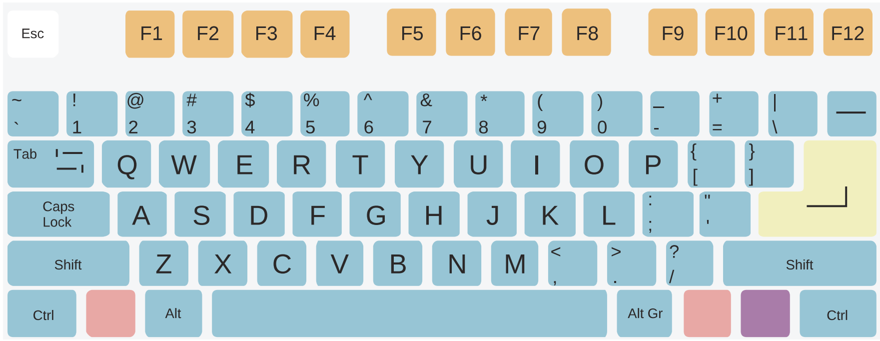
https://github.com/torvalds/uemacs

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

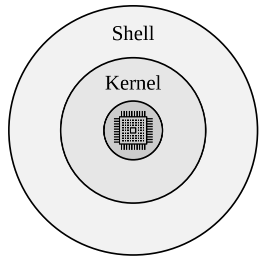
Ctrl+h t

Part II
Shell Basics

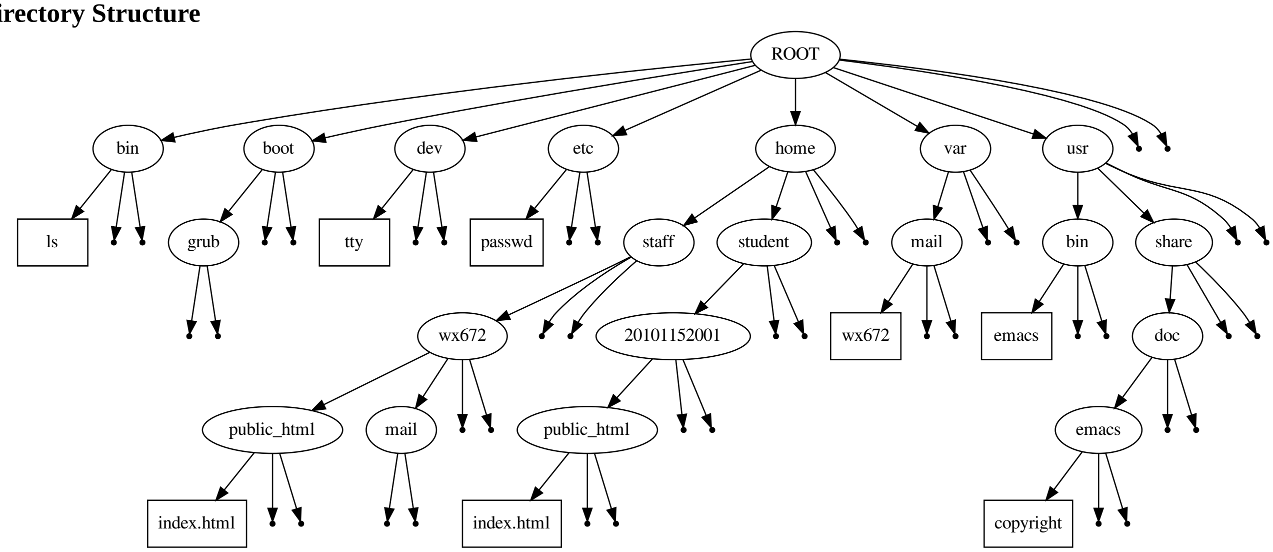
1 Shell Basics

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

Everything Is A File

```
$ cat /dev/null > /var/log/messages # empty a file
    $ : > /var/log/messages # no new process
$ ls > /dev/null
$ dd if=/dev/zero of=/tmp/clean bs=1k count=1k
$ dd if=/dev/urandom of=/tmp/random bs=1k count=1k
```

Generating random numbers

```
$ echo $RANDOM # 0 ~ 32767; pseudorandom!
$ r=$((RANDOM % 100)) # 0 ~ 100
$ RANDOM=8; for i in $(seq 10); do echo $RANDOM; done
$ od -A n -N1 -t d /dev/urandom
```

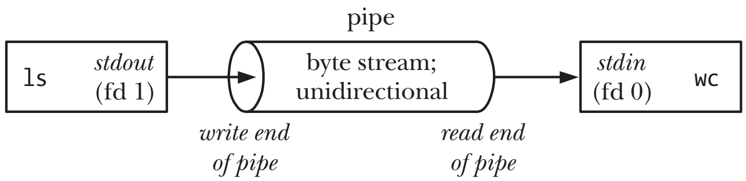
`/proc`

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

2 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; a=$((a+5)) ☺
$ let b=b+a; let b+=a; b=$((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;
  puts("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 /tmp/isay" */
/* End: */
```

Parameter Substitution

Default value

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

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

Example

```bash
#!/bin/bash

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

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 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 ls,cd,…
$ if a = 5; then echo a=$a; fi ✘ # whitespace matters
$ if a=5; then echo a=$a; fi 😐
$ test $a = 5 && echo a=$a ✔
$ [[ $a = 5 ]] && echo a=$a ✔
$ if cmp a b; then echo same file; fi ✔
$ [[ cmp a b ]] && echo same file ✘
$ if test 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)) ☺
  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 -lt 10 ]]; do echo $a; ((a++)); done ✔
$ while  [ $a -lt 10 ] ; do echo $a; ((a++)); done ✔
$ while [[  a < 10 ]]; do echo $a; ((a++)); done ✘
$ while [[ $a < 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

```
#!/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

```
#!/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

Subshells

```
$ read first second
  hello world
$ echo $first $second

$ read first second <<<'hello world'
$ echo $first $second
```

`Subshell examples`

```
$ echo hello world | (read f s; echo $f $s)
$ echo $f $s

$ x=out; (x=in; echo $x)
```

- file:///usr/share/doc/abs-guide/html/subshells.html
- file:///usr/share/doc/abs-guide/html/process-sub.html

Part III
Linux Programming Environment

3 C Programming Environment

Program Languages

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

```
10011100001110111100111 ... 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

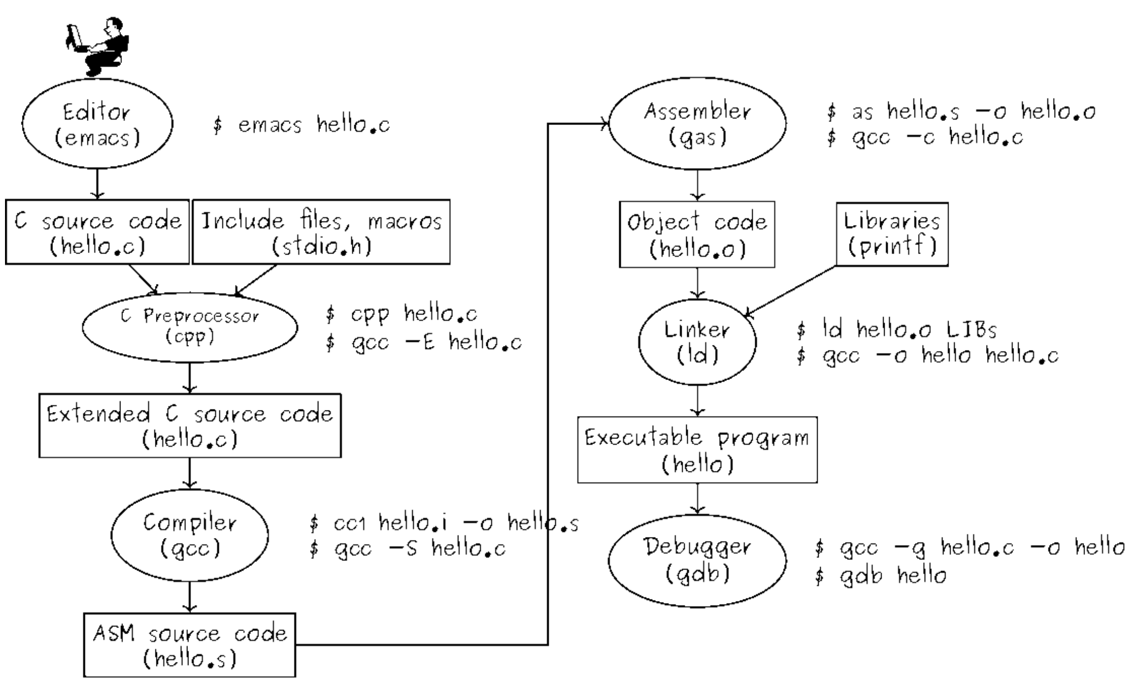
High level languages
Even easier to understand by humans. Examples:

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

Compilers do the translation work

3.1 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(void)
{
  puts("Hello, world!");
  return 0;
}

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

```
$ 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
```

3.2 Header Files And Macros

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, e.g.:

  `int myfunc(int fd, void *buf, int nbyte);`
- macro definitions, e.g.:

  `#define SQR(x) ((x) * (x))`
- constants
- system wide global variables

The `#include` Instruction

```c
#include <stdio.h>
#include "defs.h"
```

Standard header files: define data structures, macros, and function prototypes used by library routines, e.g. `printf()`.

`$ ls /usr/include`

Local include files: self-defined data structures, macros, and function prototypes.

`$ gcc -E hello.c`

The `#define` Instruction

Always put *{ }* around all multi-statement macros!

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

#define DIE \
    printf("Fatal Error! Abort\n"); exit(8);

int main(void)
{
    int i = 1;
    if (i<0) DIE
    printf("Still alive!\n");
    return 0;
}
```

```c
#define DIE \
    {printf("Fatal error! Abort\n"); exit(8);}
```

Why? `gcc -E`

Always put *( )* around the parameters of a macro!

```c
#include<stdio.h>

#define SQR(x) (x * x)
#define N 5

int main(void)
{
    int i = 0;

    for (i = 0; i < N; ++i) {
        printf("x = %d, SQR(x) = %d\n", i+1, SQR(i+1));
    }

    return 0;
}
```

✔ *#define SQR(x) ((x) * (x))*

`$ gcc -E`

3.2.1 A small software project

Makefile

```
triple: triple.o add3.o
        gcc $(CFLAGS) -Wall triple.o
        ↪  add3.o -o triple

triple.o: triple.c add.h
        gcc $(CFLAGS) -Wall -c triple.c

add3.o: add3.c add.h
        gcc $(CFLAGS) -Wall -c add3.c

clean:
        rm -f triple *.o
```

triple.c

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

int main(int argc, char *argv[])
{
    if (argc < 2) {
        fprintf(stderr, "Usage: %s
        ↪  number\n", argv[0]);
        exit(EXIT_FAILURE);
    }

    int i = atoi(argv[1]);

    printf("triple of %d is %d.\n", i,
    ↪  triple(i));
    return 0;
}
```

add.h

```
#define add(x,y) ((x)+(y))

/* int add(int,int); */
int triple(int);
```

add3.c

```
/* add() is defined as a macro in add.h
 *
 * int add(int x, int y)
 * {
 *         return x+y;
 * }
 */

#include "add.h"

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

`triple.c` — the main source file.
`add.h` — macros and function prototypes. Like `stdio.h`, can be used by anyone.
`add3.c` — function implementations. It's like a black box. Any changes made inside a block box are transparent to the calling functions.
`Makefile` — managing the project.

3.3 Library Files

Library Files
A library is a collection of pre-compiled object files which can be linked into programs.
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.*"
```

Example

calc.c

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

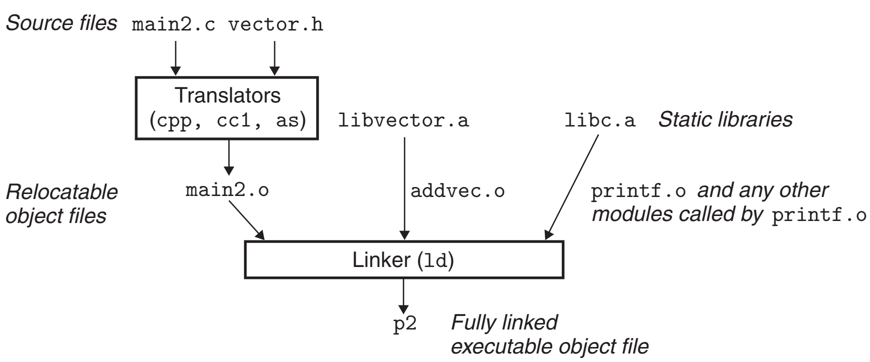
```c

int main (void)
{
  double x = sqrt (2.0);
  printf ("The square root of 2.0 is %f\n", x);
  return 0;
}

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

```
$ gcc -o calc calc.c $(find /usr/lib -name libm.a) ✔
$ gcc -o calc calc.c -lm ✔
$ gcc -o calc -lm calc.c ☹
```

- https://www.linuxtopia.org/online_books/an_introduction_to_gcc/gccintro_18.html

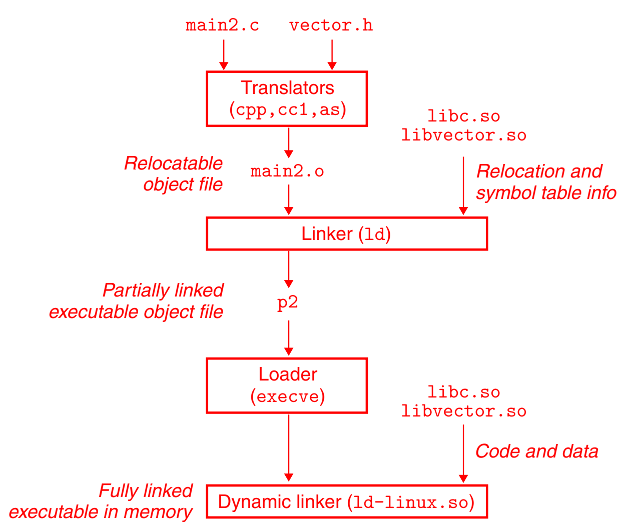
Static Linking

- 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[])
```

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

hello.h

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

int hi(char*);
```

hi.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

```
# 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
```

Position Independent Code (PIC) Unlike executables, when shared libraries are being built, the linker can't assume a known load address for their code. When translated to x86 assembly, this will involve lots of `mov` instruction to pull the value of some variable from its location in memory into a register. `mov` requires an absolute address - so how does the linker know which address to place in it? The answer is - it doesn't. As I mentioned above, shared libraries have no pre-defined load address - it will be decided at runtime.

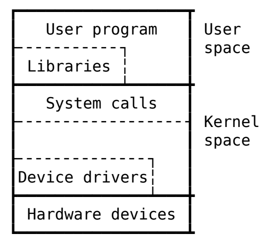
In Linux, the dynamic loader is a piece of code responsible for preparing programs for running. One of its tasks is to load shared libraries from disk into memory, when the running executable requests them. When a shared library is loaded into memory, it is then adjusted for its newly determined load location. It is the job of the dynamic loader to solve the problem presented in the previous paragraph.
The idea behind PIC is simple - add an additional level of indirection to all global data and function references in the code. By cleverly utilizing some artifacts of the linking and loading processes, it's possible to make the text section of the shared library truly *position independent*, in the sense that it can be easily mapped into different memory addresses without needing to change one bit.

- https://eli.thegreenplace.net/2011/08/25/load-time-relocation-of-shared-libraries/
- https://eli.thegreenplace.net/2011/11/03/position-independent-code-pic-in-shared-libraries/
- https://en.wikipedia.org/wiki/Position-independent_code
- https://en.wikipedia.org/wiki/Relocation_(computing)#Load-time
- https://stackoverflow.com/questions/813980/why-isnt-all-code-compiled-position-independent
- https://eklitzke.org/position-independent-executables
- http://davidad.github.io/blog/2014/02/19/relocatable-vs-position-independent-code-or/
- https://www.codeproject.com/Articles/1032231/What-is-the-Symbol-Table-and-What-is-the-Global-Of
- https://www.technovelty.org/linux/plt-and-got-the-key-to-code-sharing-and-dynamic-libraries.html

GNU C Library

Linux API > POSIX API

```
$ man 7 libc
$ man 3 intro
$ man gcc
$ info gcc
sudo apt install gcc-doc
```



3.4 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 /tmp/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

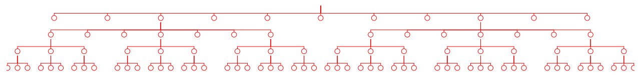
3.5 The Make Utility

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

```
target: dependencies
	command
```

Example

```
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
```

3.6 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

3.7 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
```

3.8 A Sample GNU Package

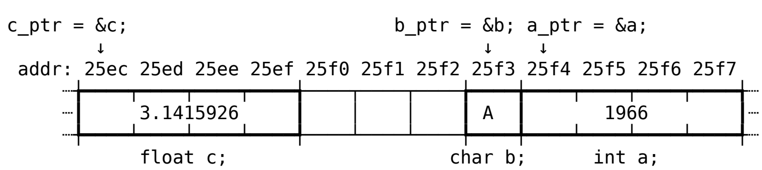
How to “Do one thing, and do it well”?

```
$ apt source hello
```

3.9 Pointers in C

Pointers

```c
#include<stdio.h>

int main(void)
{
  int   a = 1966;
  char  b = 'A';
  float c = 3.1415926;
  int   *a_ptr = &a; /* a pointer to an integer */
  char  *b_ptr = &b; /* a pointer to a  char    */
  float *c_ptr = &c; /* a pointer to a  float   */

  printf("&a = %p, sizeof(a) = %ld\n", a_ptr, sizeof(a));
  printf("&b = %p, sizeof(b) = %ld\n", b_ptr, sizeof(b));
  printf("&c = %p, sizeof(c) = %ld\n", c_ptr, sizeof(c));
  return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra ptr1-code.c -o /tmp/ptr1-code" */
/* End: */
```



Pointer Operators

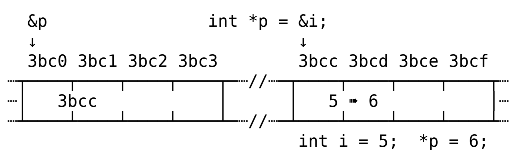
- & returns the *address* of a thing
- ∗ return the *object (thing)* to which a pointer points at

```
int thing; int *thing_ptr;
```

C Code	Description
`thing`	the variable named ‘thing’
`&thing`	address of ‘thing’ (a pointer)
`*thing`	✘ `thing` is not a pointer
`thing_ptr`	pointer to an int
`*thing_ptr`	the int variable at the address `thing_ptr` points to
`&thing_ptr`	odd, a pointer to a pointer

Example

```c
#include<stdio.h>

int main(void)
{
  int i = 5;
  int *p;
  p = &i; /* now p pointing to i */
  *p = 6; /* i = 6 */

  printf("&i = %p, i = %d, *p = %d\n", &i, i, *p);
  printf("&p = %p, p = %p\n", &p, p);
  return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra ptr2-code.c -o /tmp/ptr2-code" */
/* End: */
```



Invalid operation

```c
#include<stdio.h>

int main(void)
{
  int i = 5;
  /* int *i = (int *)5; */ /* segfault */
  printf("*i = %d\n", *i); /* Wrong! */

  return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra ptr2-wrong1.c -o /tmp/ptr2-wrong1" */
/* End: */
```

In the `printf()` statement, it’s trying to treat `i` as a pointer.

Invalid memory access

```c
#include<stdio.h>

int main(void)
{
    int *p = 5; /* should be (int *)5 */

    printf(" p = %p\n",  p); /*  p = 0x5 */
    printf("&p = %p\n", &p); /* &p = 0x7ffda48a2068 */
    printf("*p = %c\n", *p); /* Invalid memory access */
    return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra ptr2-wrong2.c -o /tmp/ptr2-wrong2" */
/* End: */
```

This is trying to treat the value of `p` as a memory address. But the memory address `5` is not accessible by this program.

Call By Value

```c
#include <stdio.h>

void inc_count(int count){
  ++count;
  printf("inc_count: &count = %p\n", &count);
  printf("inc_count: count = %d\n", count);
}

int main(){
  int count = 0;
  printf("main: &count = %p\n", &count);

  inc_count(count);
  printf("main: count = %d\n", count);

  return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall ptr4-wrong.c -o ptr4-wrong -o /tmp/ptr4-wrong" */
/* End: */
```

Call by value: only the *value* of '`count`' is handed to the function `inc_count()`

Solution 1: return

```c
#include <stdio.h>

int inc_count(int count)
{
    return ++count;
}

int main()
{
    int count = 0;

        count = inc_count(count);
        printf("%d\n", count);

```

```
    return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra ptr4-ok.c -o /tmp/ptr4-ok" */
/* End: */
```

1. read the *value* of `count`, and pass it to `inc_count()`;
2. `inc_count()` uses the *value* of `count` to do the calculations;
3. return the result to `main()`.

Solution 2: Call by reference

```
#include <stdio.h>

void inc_count(int *count_ptr)
{
    ++(*count_ptr);
}

int main()
{
    int count = 0;

        inc_count(&count);
        printf("%d\n", count);

    return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra ptr4.c -o /tmp/ptr4" */
/* End: */
```

1. pass the address of `count` to `inc_count()`;
2. `inc_count()` operates directly on `count`.

More efficient than solution 1 Imagining you are operating on a large data structure rather than an `int`

3.10 Pointers and Arrays

```
int main(void)
{
  int a[] = {9,8,0,1};
  int i = 0;

  while (a[i] != 0)
    ++i;

  printf("ZERO at a[%d].\n", i);

  return 0;
}
```

```
int main(void)
{
  int a[] = {9,8,0,1};
  int *pa = a;

  while ((*pa) != 0)
    ++pa;

  printf("ZERO at a[%ld].\n", pa - a);
  printf("pa = %p; a = %p\n",pa,a);
  return 0;
}
```

C automatically scales pointer arithmetic so that it works correctly, by incrementing/ decrementing by the correct number of bytes. For example, in above program, the value of `pa` (`&a[2]`) is `1008`, and the value of `a` (`&a[0]`) is `1000`. But the result of “`pa - a`” is `2` rather than `8`. This means `pa` is *two ints* ahead of `a`.

```
       &a                                                  &pa
       ↓                                                   ↓
addr:  1000 1004 1008 1012 ... ... ... ... ...             3456 3460 3464 3468 ...
     |  9  |  8  |  0  |  1  | // | 0→2 | // | 1000 | 1004 | 1008 | 1012 |
       a[0] a[1] a[2] a[3]           int i;          pa   pa+1  pa+2  pa+3

      int a[] = {9,8,0,1};                              int *pa = a;
```

Passing Arrays to Functions

When passing an array to a function, C will automatically change the array into a pointer.

```c
#include <stdio.h>

#define MAX 5
void init_array_1(int*);
void init_array_2(int*);

int main(void)
{
  int a[MAX], i;

  init_array_1(a);
  printf("init_array_1: ");
  for(i=0; i<MAX; i++)
    printf("a[%d]=%d, ", i, a[i]);
  puts("");

  init_array_2(a);
  printf("init_array_2: ");
  for(i=0; i<MAX; i++)
    printf("a[%d]=%d, ", i, a[i]);
  puts("");

  return 0;
}

void init_array_1(int a[])
{
  int i;

  for (i=0; i<MAX; ++i)
      a[i] = 0;
}

void init_array_2(int *ptr)
{
  int i;

  for (i=0; i<MAX; ++i)
      *(ptr + i) = i;
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra array3.c -o /tmp/array3" */
/* End: */
```

Strings — Arrays Of Characters

Strings are *character arrays* with the additional special character "`\0`" (`NUL`) at the end, e.g.:

```c
char system[] = "Linux";
```

L	i	n	u	x	\0

The most common string functions

```
strcpy(string1, string2) /* copy string2 into string1 */
strcat(string1, string2) /* concatenate string2 onto
                            the end of string1 */
length = strlen(string)  /* get the length of a string */
strcmp(string1, string2) /* 0 if string1 equals string2,
                            otherwise nonzero */
```

Arrays Of Pointers

```
#include<stdio.h>

void print_msg(char *ptr_a[], int n)
{
  int i;
  for (i = 0; i < n; i++)
    printf(" %s", ptr_a[i]);

  puts(".");
}

int main()
{
  char *message[9] =
    {"Dennis", "Ritchie", "designed",
         "the",        "C", "language",
          "in",      "the",     "1970s"};
  print_msg(message, 9);
  return 0;
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra array4.c -o /tmp/array4" */
/* End: */
```

Once you've declared an array, you can't reassign it. Why? Consider an assignment like

```
char *my_str = "foo"; // Declare and initialize a char pointer.
my_str = "bar"; // Change its value.
```

The first line declares a char pointer and "aims" it at the first letter in `foo`. Since `foo` is a string constant, it resides somewhere in memory with all the other constants. When you reassign the pointer, you're assigning a new value to it: the address of `bar`. But the original string, `foo`, remains unchanged. You've moved the pointer, but haven't altered the data.

When you declare an array, however, you aren't declaring a pointer at all. You're reserving a certain amount of memory and giving it a name. So the line

```
char c[5] = "data";
```

starts with the string constant `data`, then allocates 5 new bytes, calls them `c`, and copies the string into them. You can access the elements of the array exactly as if you'd declared a pointer to them; arrays and pointers are (for most purposes) interchangeable in that way.

But since arrays are not pointers, you cannot reassign them. You can't make `c` "point" anywhere else, because it's not a pointer; it's the name of an area of memory. For example,

```
char c[5] = "data";
char b[5] = "beta";
b = c; /* Wrong! 'b[]' cannot be reassigned (pointing to elsewhere). */
```

- https://stackoverflow.com/questions/17077505/string-pointer-and-array-of-chars-in-c

4 The Linux Environment

Command Line Options

```c
#include <stdio.h>

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

  for(arg = 0; arg < argc; arg++) {
    if(argv[arg][0] == '-')
      printf("option: %s\n", argv[arg]);
    else
      printf("argv[%d]: %s\n", arg, argv[arg]);
  }
  return 0;
}

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

```
$ ./a.out -a -bc hello 'holy world'
```

getopt — The Standard Way

```
$ man 3 getopt
```

```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 /tmp/getopt" */
/* End: */
```

```
$ ./a.out -h -l -fhello
```

```
$ help getopts
```

```bash
#!/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 <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 /tmp/env" */
/* End: */
```

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

[*Beginning linux programming*, p.147, Sec 4.2 The `environ` Variable]

Time and Date

```
#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;
}

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

- 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
↪  /tmp/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 /tmp/syslog" */
/* End: */
```

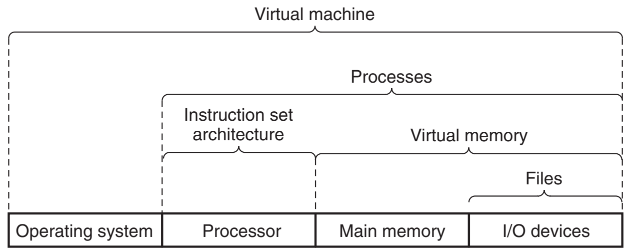
logger.sh

```bash
#!/bin/bash

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

5 OS Basics

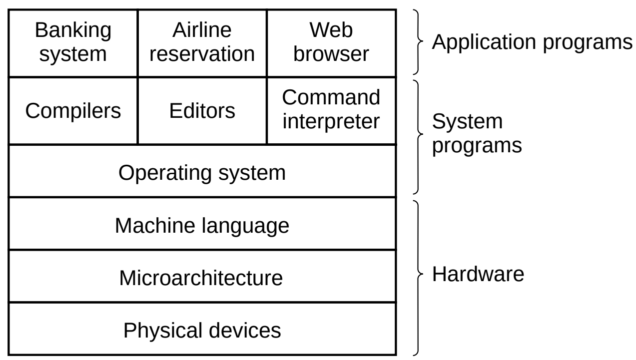
Abstractions

To hide the complexity of the actual implementations



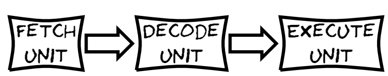
See also: [*Computer Systems: A Programmer's Perspective*, Sec. 1.9.2, *The Importance of Abstractions in Computer Systems*].

A Computer System



5.1 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

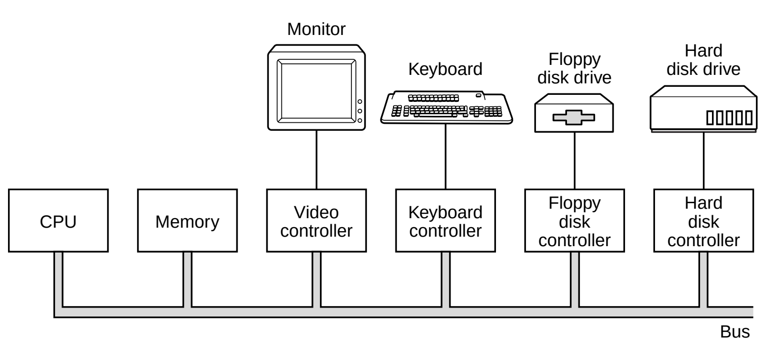
Program counter (PC): keeps the memory address of the next instruction to be fetched

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

Program status (PS): holds

- condition code bits
- processor state

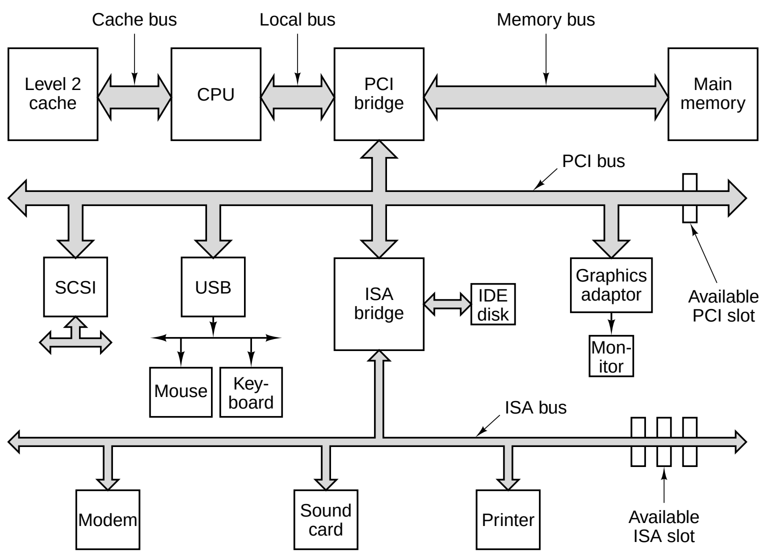
System Bus



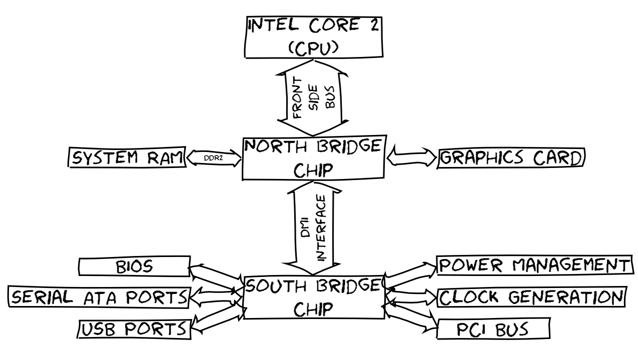
Address Bus: specifies the memory locations (addresses) for the data transfers
Data Bus: holds the data transfered. Bidirectional
Control Bus: contains various lines used to route timing and control signals throughout the system

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

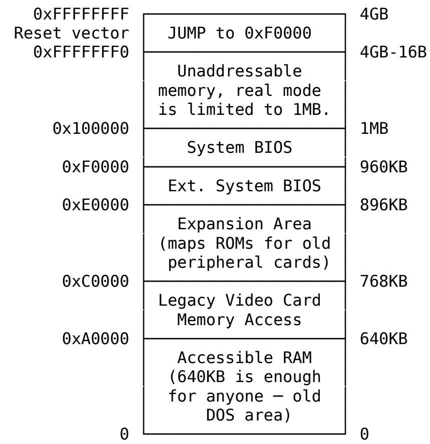
[1] http://duartes.org/gustavo/blog/post/motherboard-chipsets-memory-map

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

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`



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*

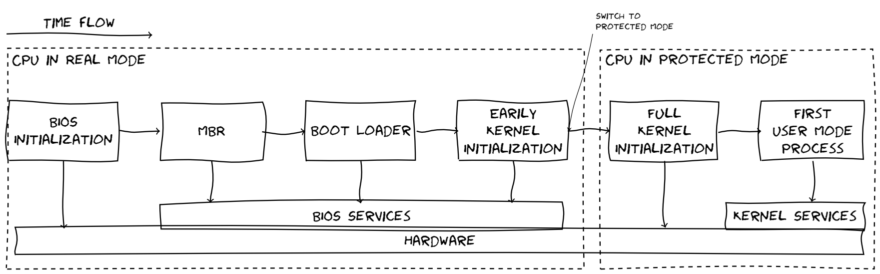
- When is the memory address map built? `setup()`.

5.2 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

5.3 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

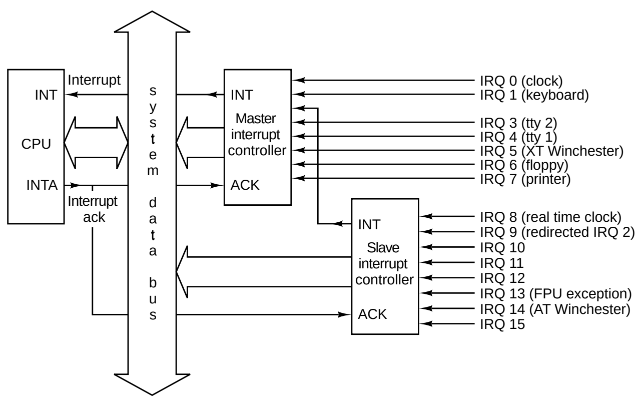
SW INT by executing a *system call*

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

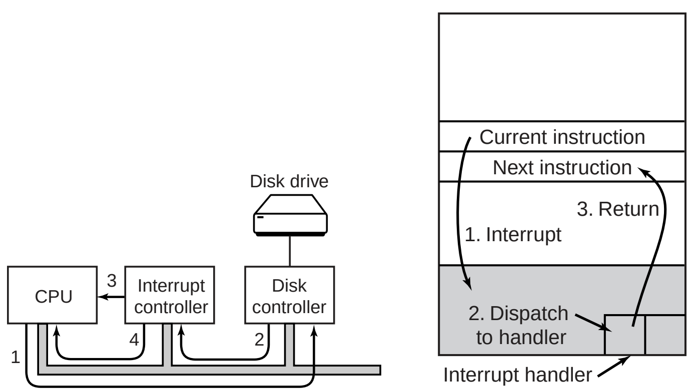
Interrupt vector is an array of pointers ☛ the memory addresses of *interrupt handlers*. This array is indexed by a unique device number

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

Programmable Interrupt Controllers

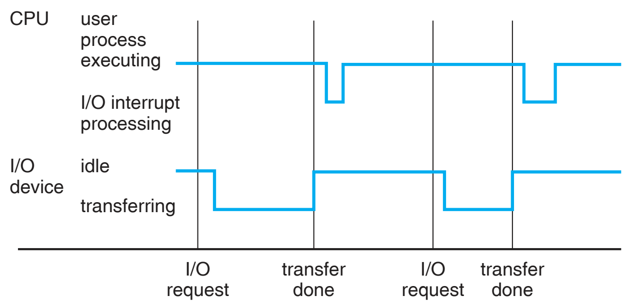


Interrupt Processing



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

Interrupt Timeline



5.4 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
```

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

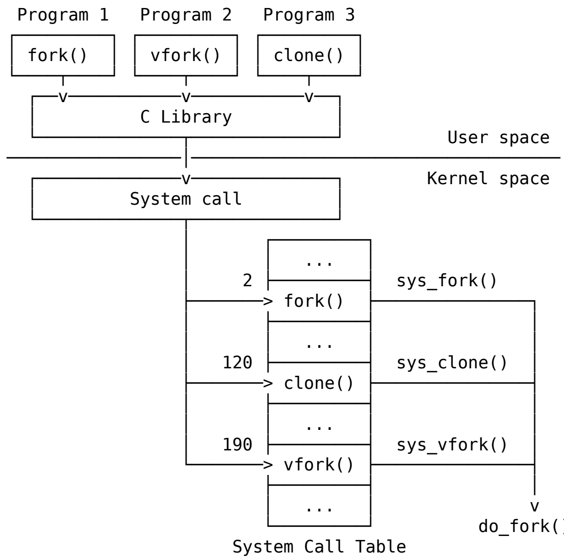
Directory and file system management

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

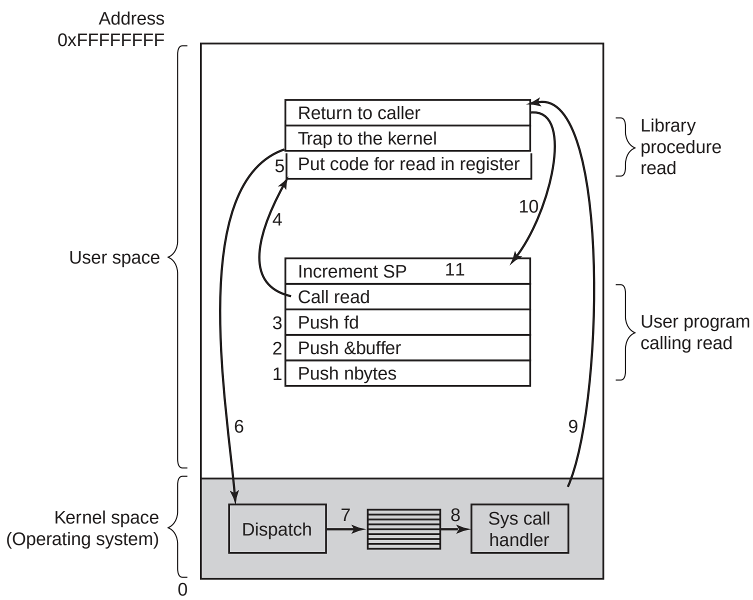
Call	Description
s = chdir(dirname)	Change the working directory
s = chmod(name, mode)	Change a file's protection bits
s = kill(pid, signal)	Send a signal to a process
seconds = time(&seconds)	Get the elapsed time since Jan. 1, 1970

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.



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 × 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

```
        ; https://www.devdungeon.com/content/hello-world-nasm-assembler
        ; Compile: nasm -f elf hello32.asm -o hello.o
        ;    Link: ld hello.o -o hello -m elf_i386
        ;     Run: ./hello
        ;
        ; strace issue:
```

```
                ; https://github.com/strace/strace/issues/103 (need kernel 5.3+)
                ; https://stackoverflow.com/questions/57850588/
                ↪  confused-by-strace-output-of-a-simple-helloworld-nasm-program/
                ↪  57884132#57884132
        ;

SECTION .DATA
Msg:     db 'Hello, world!',10  ; 10 = ascii for LF
MsgLen:  equ $-Msg

SECTION .TEXT
GLOBAL _start

_start:
        mov eax, 4       ; write(
        mov ebx, 1       ;   STDOUT_FILENO,
        mov ecx, Msg     ;   "Hello, world!\n",
        mov edx, MsgLen  ;   sizeof("Hello, world!\n")
        int 80h          ; );

        mov eax, 1       ; exit(
        mov ebx, 0       ;   EXIT_SUCCESS
        int 80h          ; );
```

```
$ nasm -f elf64 hello.asm -o hello.o
$ ld hello.o -o hello
$ less /usr/include/asm/unistd_32.h
$ less /usr/include/asm/unistd_64.h
```

64-bits version:

```
        ; https://jameshfisher.com/2018/03/10/linux-assembly-hello-world/
        ;
        ; $ nasm -f elf64 -o hello64.o hello64.s
        ; $ ld -o hello64 hello64.o
        ; $ ./hello64

global _start

section .text

_start:
  mov rax, 1        ; write(
  mov rdi, 1        ;   STDOUT_FILENO,
  mov rsi, msg      ;   "Hello, world!\n",
  mov rdx, msglen   ;   sizeof("Hello, world!\n")
  syscall           ; );

  mov rax, 60       ; exit(
  mov rdi, 0        ;   EXIT_SUCCESS
  syscall           ; );

section .rodata
  msg: db "Hello, world!", 10
  msglen: equ $ - msg
```

System Call Examples

```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 /
↪  tmp/write" */
/* End: */
```

- Actually, write() is a wrapper function in glibc.

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

Don't invoke syscall directly whenever possible

```c
/* Calling sys_write using inline assembly code */
/* https://jameshfisher.com/2018/02/20/c-inline-assembly-hello-world/ */
int main(void) {
  register char* arg2 asm("rsi") = "hello, world!\n";

  /* rax: sys_write; rdi: STDOUT; */
  asm("mov $1, %rax; mov $1, %rdi; mov $14, %rdx; syscall;");

  return 0;
}

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

- https://jameshfisher.com/2018/02/20/c-inline-assembly-hello-world/
- https://cs.lmu.edu/~ray/notes/gasexamples/
- https://montcs.bloomu.edu/Information/LowLevel/Assembly/assembly-tutorial.html

System Call Examples

```
$ man 2 fork
```

```c
/* Basically, the fork() call, inside a process, creates an exact copy of that process somewhere
   else in the memory (meaning it'll copy variable values, etc...), and runs the copy from the
↪  point
   the call was made (for the assembly kids : it means that the relative value of the next
   instruction pointer is also copied)  */

/* When we launch this program, it first goes through the first puts(). Then, the fork() makes a
   copy of this program. Finally, each one of this program and its copy goes through the second
   puts().  */

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

int main ()
{
  puts("Hello World!");
  fork();
  puts("Goodbye Cruel World!");
  return 0;
}
/* Local Variables: */
/* compile-command: "gcc -Wall fork.c -o /tmp/fork" */
/* End: */
```

`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.

Part IV
Working With Files

6 Files

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)`	`read(fd, buffer, byte_count)`
`open(name, flags)`	`write(fd, buffer, byte_count)`
`close(fd)`	`lseek(fd, offset, whence)`
`link(oldname, newname)`	`chown(name, owner, group`
`unlink(name)`	`fchown(fd, owner, group)`
`truncate(name, size)`	`chmod(name, mode`
`ftruncate(fd, size)`	`fchmod(fd, mode)`
`stat(name, buffer)`	`utimes(name, times)`
`fstat(fd, buffer)`	

`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 /tmp/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 /tmp/read" */
/* End: */
```

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

- No need to `open()` `STDIN`, `STDOUT`, and `STDERR`

`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);

  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);
  }
```

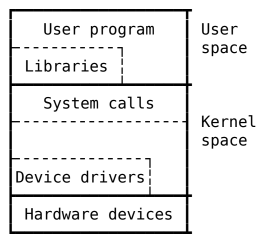
```
  close(in); close(out);
  if (rbytes == 0) exit(0); /* no error on last read */
  else exit(5);             /* error on last read */
}

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

```
#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 /tmp/open" */
/* End: */
```

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

`fopen()` — Buffered I/O

```
#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 /tmp/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`

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

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

```c
{
  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 /tmp/cp-libc" */
/* End: */
```

☐ 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

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    |--//--
|  (MBR copy)   |   (Super Blk)   | (inodes, root dir) | Files
|               |                 |                    | 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

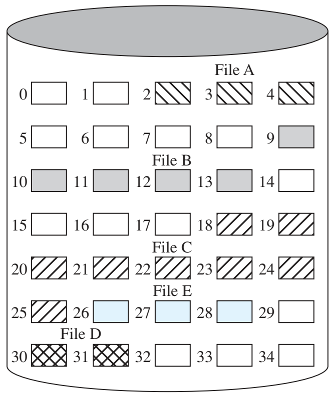
I-node Organizes the files *FCB (File Control Block)*, contains file details (metadata).

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

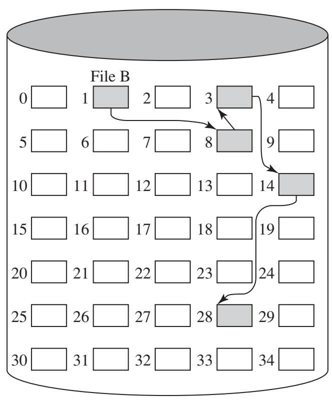


File Allocation Table

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



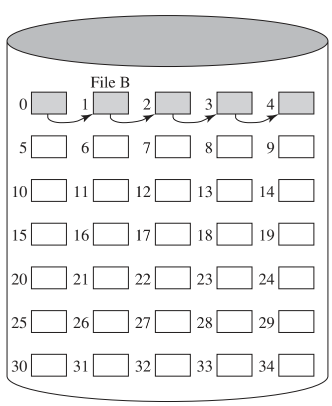
File Allocation Table

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

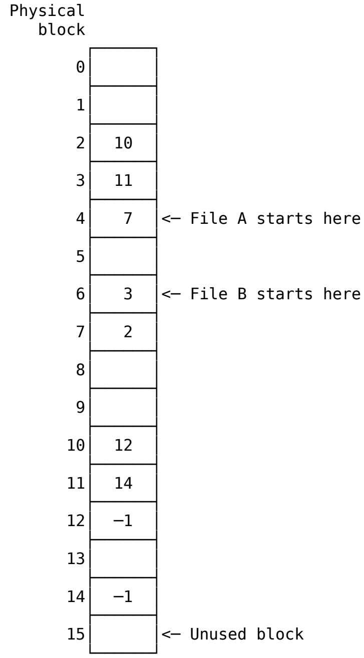
Linked List (Chained) Allocation Though there is no external fragmentation, consolidation is still preferred.



File Allocation Table

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

FAT: Linked list allocation with a table in RAM

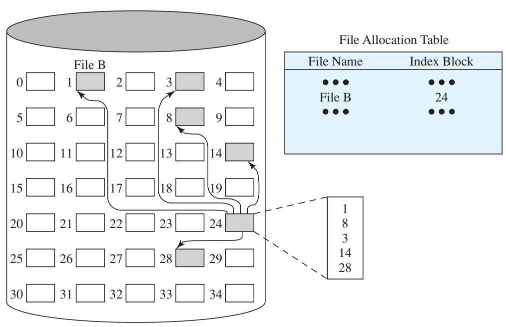


- Taking the pointer out of each disk block, and putting it into a table in memory
- fast random access (chain is in RAM)
- is 2^n
- the entire table must be in RAM

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

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

Indexed Allocation

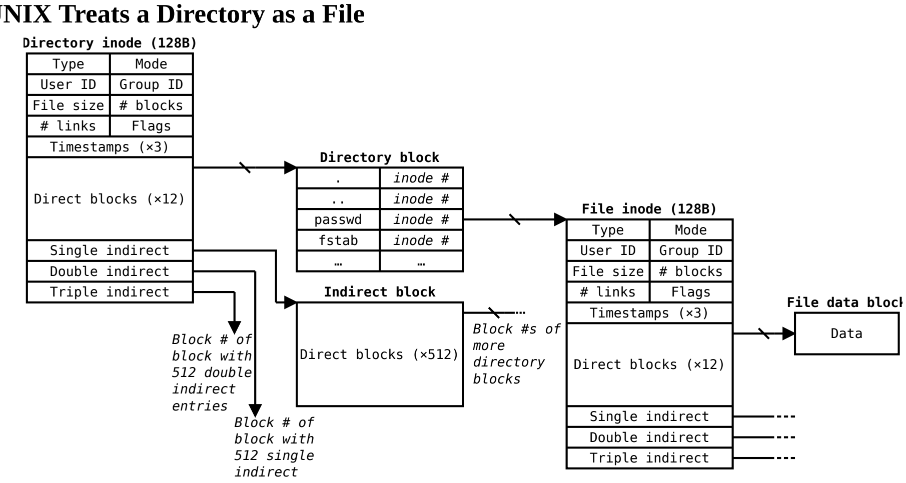


I-node A data structure for each file. An i-node is in memory *only if* the file is open

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

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

UNIX Treats a Directory as a File

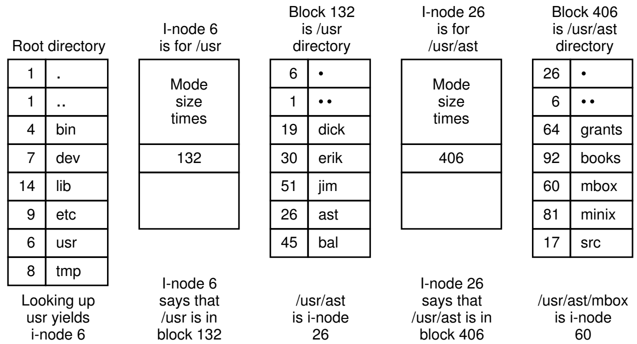


`open()`

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

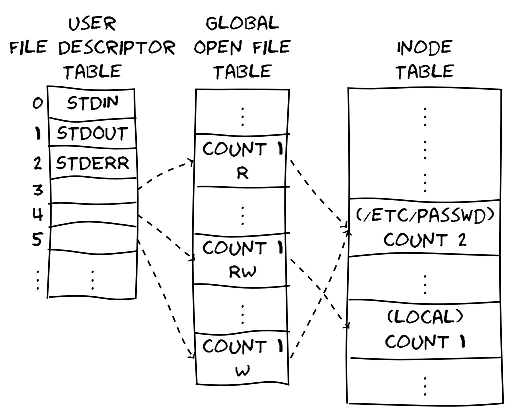
To see files opened by a process, e.g. `init`

```
$ lsof -p 1
```

```
$ man 2 open
```

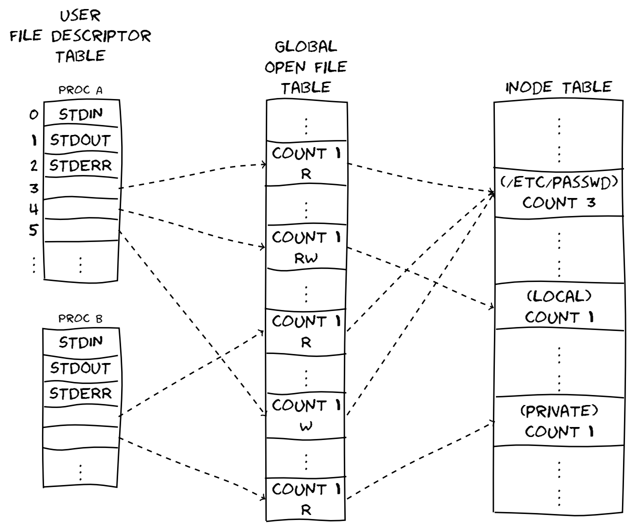
A process executes the following code:

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



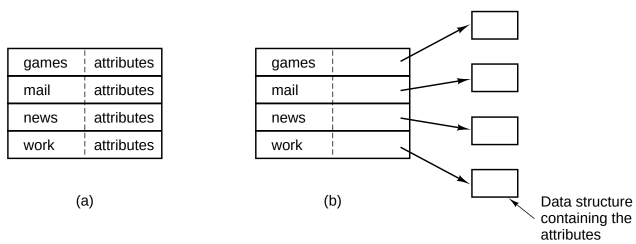
One more process B:

```
fd1 = open("/etc/passwd", O_RDONLY);
fd2 = open("private", O_RDONLY);
```



7 Directories

Implementing Directories



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

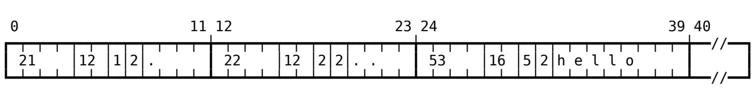
(b) Directory in which each entry just refers to an i-node (UNIX)

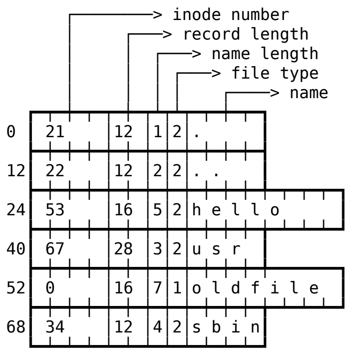
Directory entry in `glibc`

```
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 /tmp/ls" */
/* End: */
```

The real `ls.c`?

- 116 A4 pages
- 5308 lines

Do one thing, and do it really well.

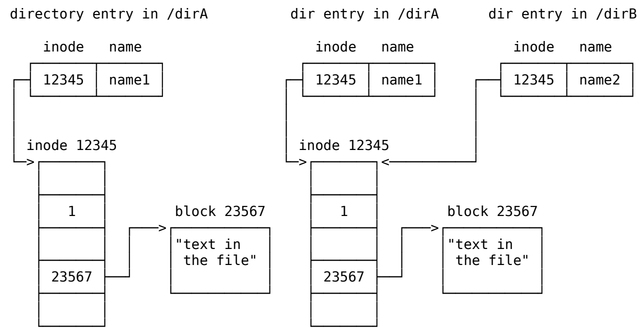
`$ apt source coreutils`

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

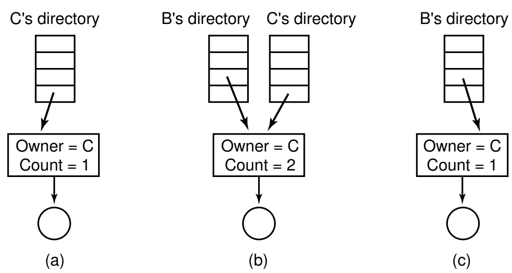
```c
#include <sys/stat.h>
#include <sys/types.h>
#include <unistd.h>
#include <stdio.h>

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 /tmp/mkdir" */
/* End: */
```

Hard Links

Hard links ☛ the same inode

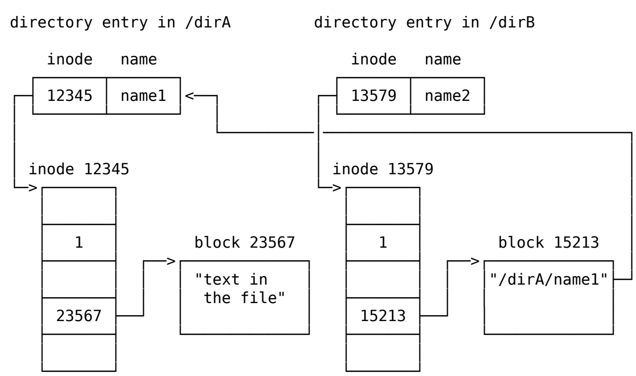


Drawback



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()`

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

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

  perror(argv[0]);
  return 0;
```

```
}


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

Part V
Processes and Threads

8 Virtual Memory

Programs

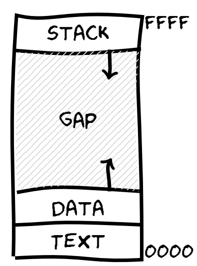
A program is a file sitting in your hard disk. Two forms:

- 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



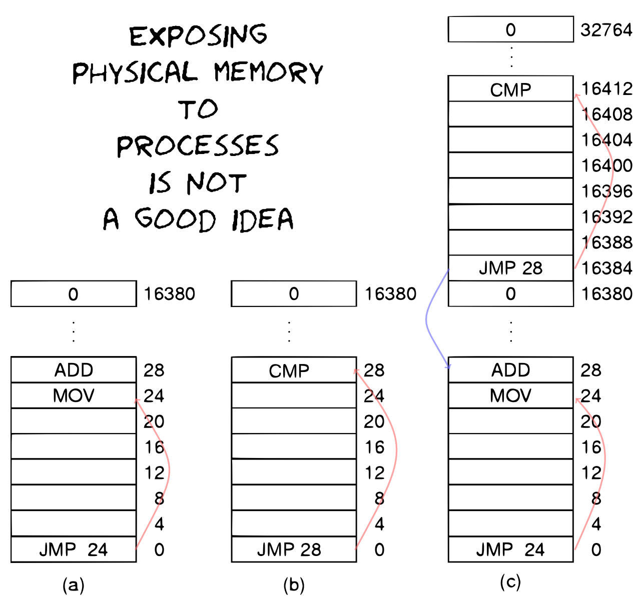
Processes are like human beings:

- ➠ 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

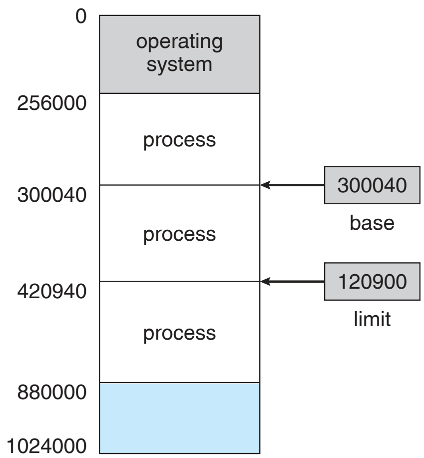
We need

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

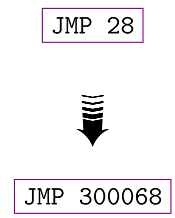
Protected mode is an operational mode of x86-compatible CPU.

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

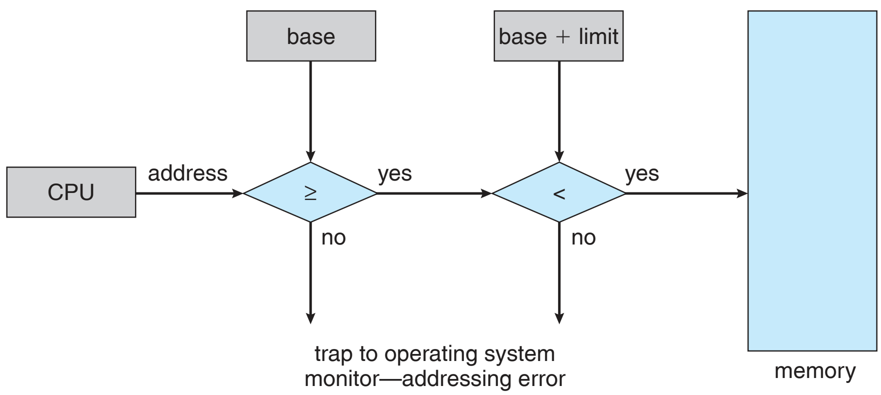
Memory Protection
Logical Address Space
Base register holds the smallest legal physical memory address
Limit register contains the size of the range



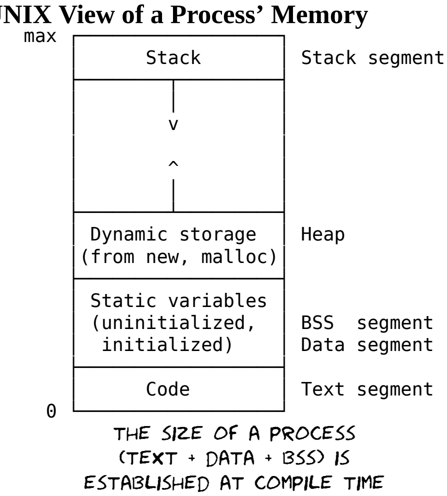
A pair of `base` and `limit` registers define the logical address space



Memory Protection
Base and limit registers



UNIX View of a Process' Memory



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

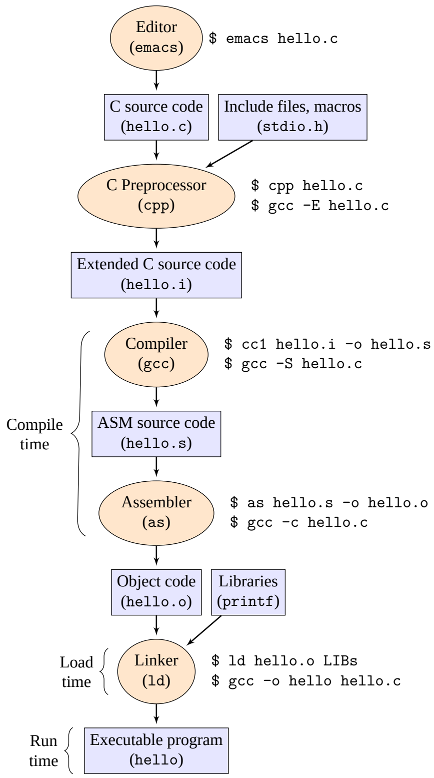
Stack vs. Heap

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:

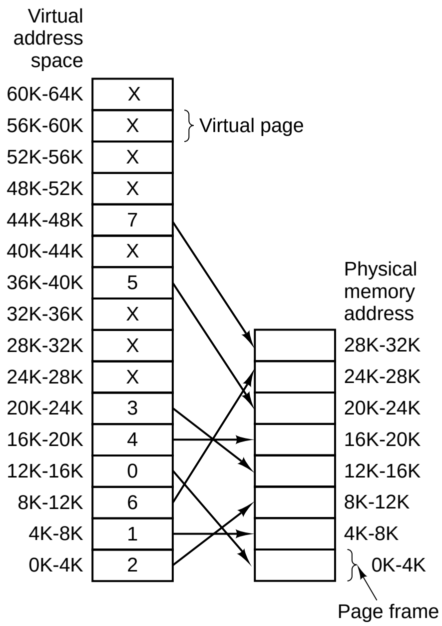
- *Linker* combines all the object files into a single executable object file
- *Loader* (part of OS) loads an executable object file into memory at location(s) determined by the OS
  - invoked via the `execve` system call

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

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



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
Page offset(d): to be copied into memory

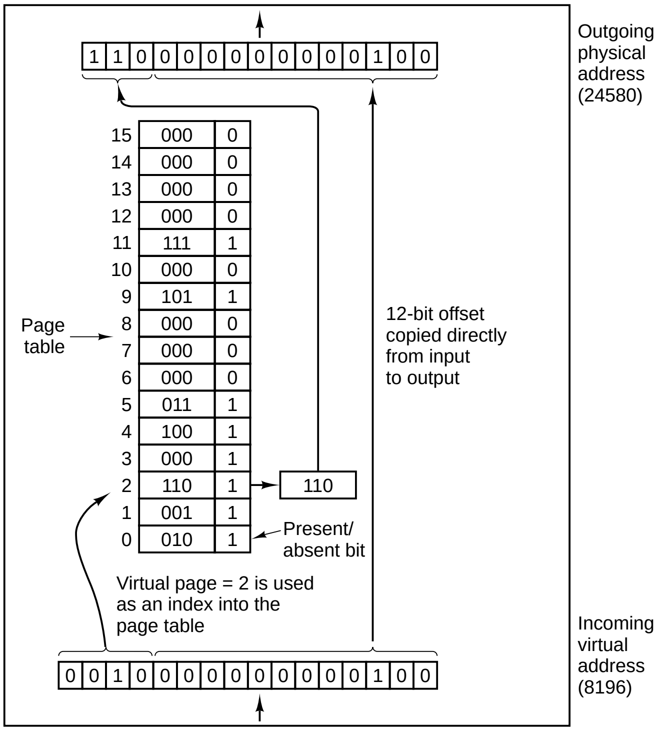
Given *logical address space* (2^m) and *page size* (2^n),

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

Example: addressing to 0010000000000100

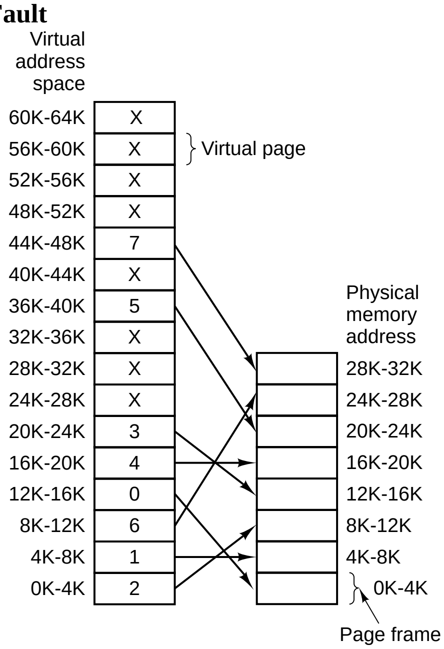
$$\underbrace{\overbrace{0\,0\,1\,0}^{m-n=4}\ \overbrace{0\,0\,0\,0\,0\,0\,0\,0\,0\,1\,0\,0}^{n=12}}_{m=16}$$

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



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

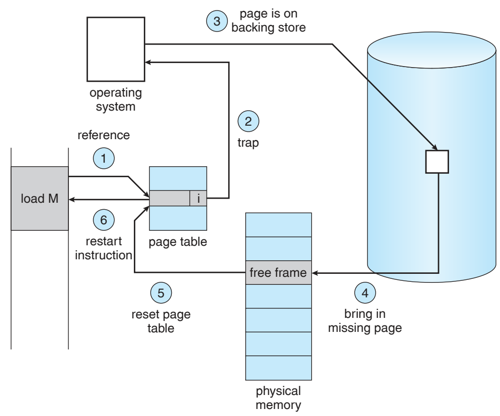
Page Fault



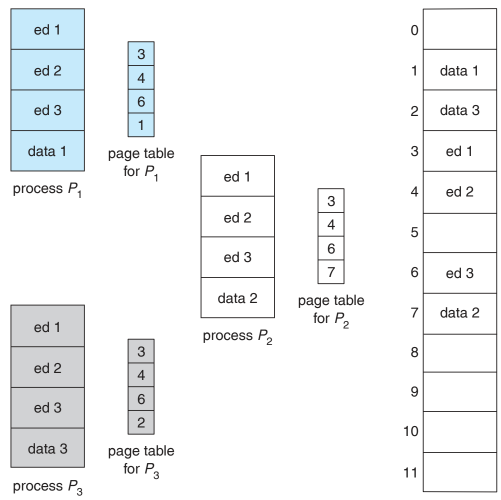
`MOV REG, 32780`?

➠ Page fault & swapping

Page Fault Handling



Shared Pages



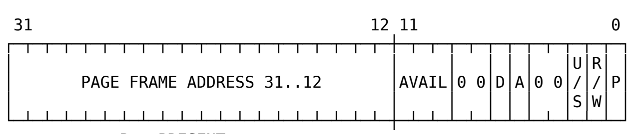
Page Table Entry

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.
```

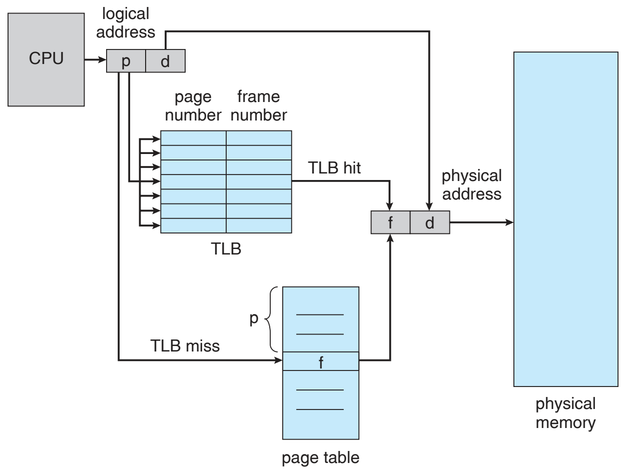
Page Table

- 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

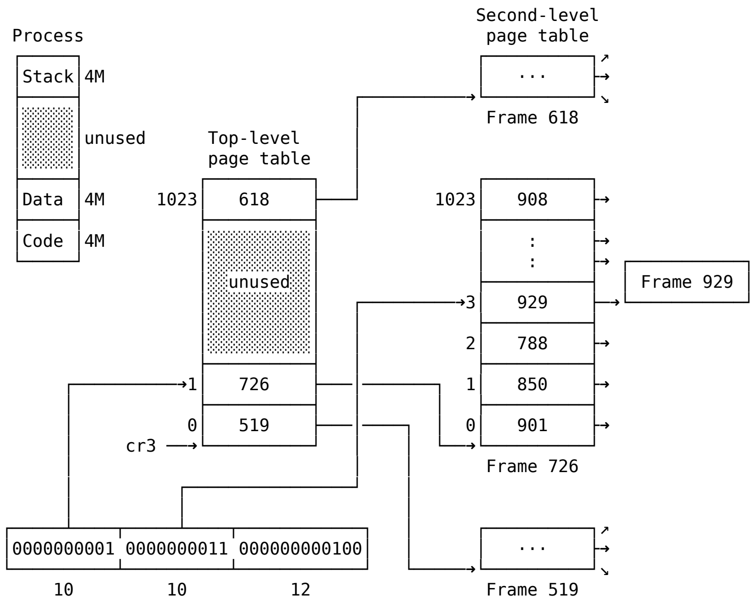
A two-level scheme

```
     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

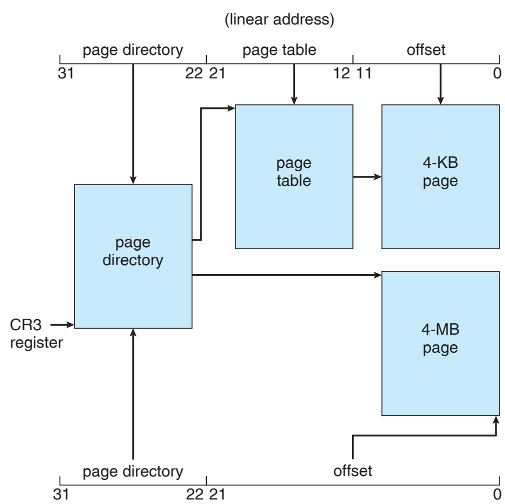
- Split one huge page table into 1k small page tables
  – i.e. the huge page table has 1k entries.
  – Each entry keeps a page frame number of a small page table.
- Each small page table has 1k entries
  – Each entry keeps a page frame number of a physical frame.

Two-Level Page Tables
Example

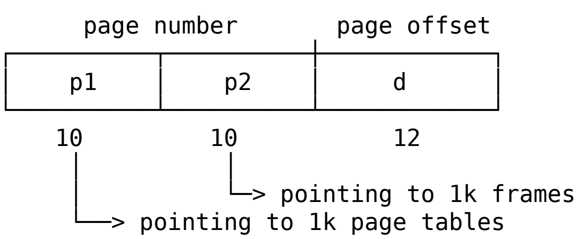


Pentium Paging

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

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

And this is for ONE process!

Multi-level?

if $10\, bits$ for each level

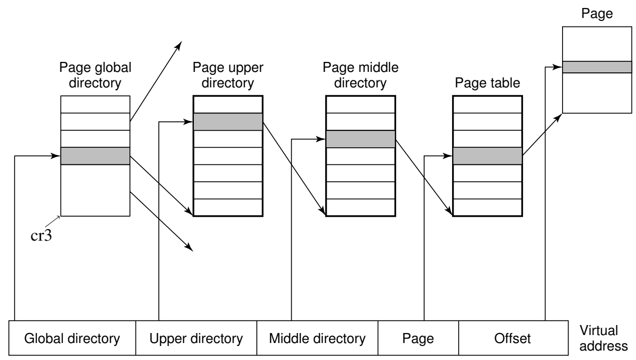
then $\frac{64-12}{10} = 5$ levels are required

5 memory access 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	$9+9+9+\ \ 9+12$

9 Process

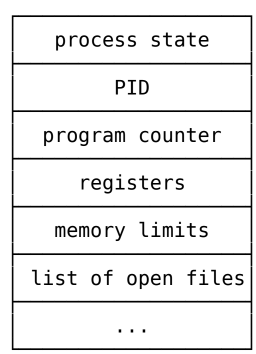
From kernel's point of view

A process consists of

User-space memory program code, variable...

Kernel data structures keep the state of the process

Process Control Block (PCB)

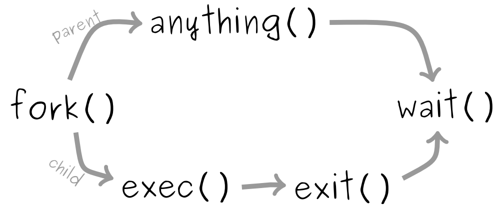


Implementation

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

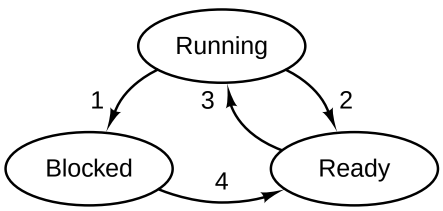
- Each process is represented by a *PCB*
- `task_struct` in 🐧

Process Creation



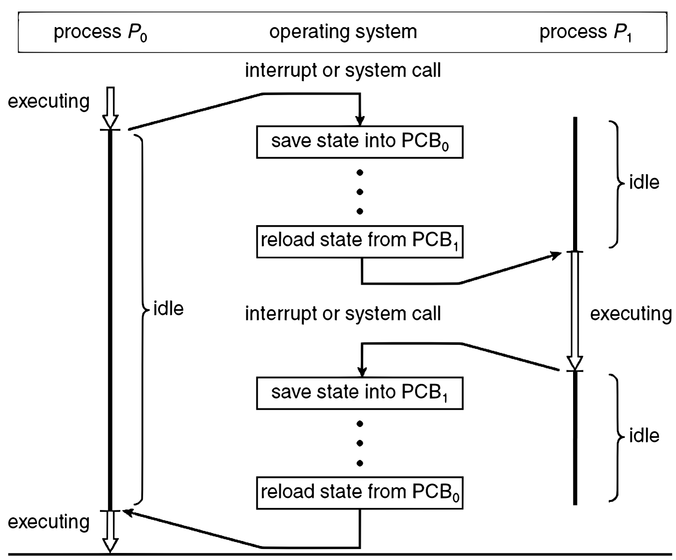
- When a process is created, it is almost identical to its parent
  - It receives a (logical) copy of the parent's address space, and
  - executes the same code as the parent
- The parent and child have separate copies of the data (stack and heap)

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

```
/* Basically, the fork() call, inside a process, creates an exact copy of that process somewhere
   else in the memory (meaning it'll copy variable values, etc...), and runs the copy from the
↪  point
   the call was made (for the assembly kids : it means that the relative value of the next
   instruction pointer is also copied)  */

/* When we launch this program, it first goes through the first puts(). Then, the fork() makes a
   copy of this program. Finally, each one of this program and its copy goes through the second
   puts().  */

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

```
int main ()
{
  puts("Hello World!");
  fork();
  puts("Goodbye Cruel World!");
  return 0;
}
/* Local Variables: */
/* compile-command: "gcc -Wall fork.c -o /tmp/fork" */
/* End: */
```

`exec()`

```
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

10 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);
}

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

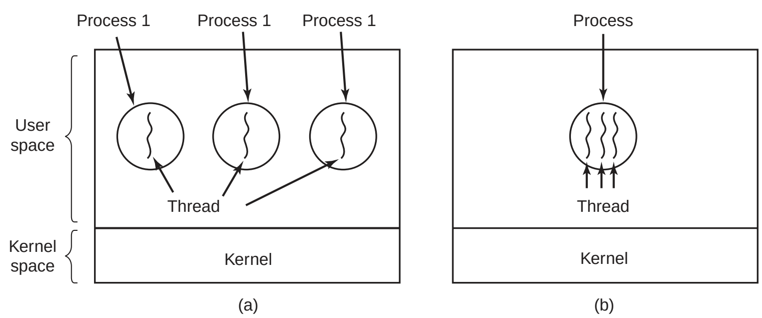
Fig. 1: `caller.c`

```c
#include <stdio.h>

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

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

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

```c
#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 /tmp/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

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

#define NUMBER_OF_THREADS 5

void *hello(void *tid)
{
  printf ("Hello from thread %d\n", *(int*)tid);
  pthread_exit(NULL);
}

int main(void)
{
  pthread_t t[NUMBER_OF_THREADS];
  int status, i;


  for (i=0; i<NUMBER_OF_THREADS; i++){
        printf("Main: creating thread %d ...", i);

    if( (status = pthread_create(&t[i], NULL, hello, (void *)&i)) ){
          perror("pthread_create");
      exit(-1);
    }
    puts("done.");
  }

  for (i=0; i<NUMBER_OF_THREADS; i++){
    printf("Joining thread %d ...",i);

    if( pthread_join(t[i], NULL) ){
      perror("pthread_join");
      abort() ;
    }
    puts("done.");
  }
  exit(0);
}

/* Local Variables: */
/* compile-command: "gcc -Wall -Wextra thread2.c -o /tmp/thread2 -pthread" */
/* End: */
```

Linux Threads

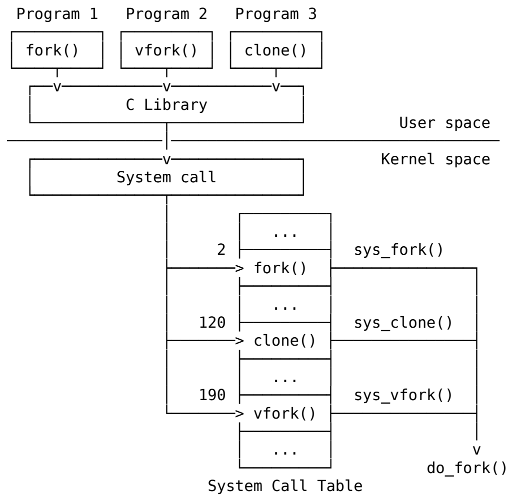
To the Linux kernel, there is no concept of a thread

- 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()`

```
#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

```
/* http://stackoverflow.com/questions/5255320/reason-for-segmentation-fault */
#define _GNU_SOURCE
#include <unistd.h>
#include <sched.h>
#include <sys/types.h>
#include <stdlib.h>
#include <string.h>
#include <stdio.h>
#include <fcntl.h>

int variable;
```

```c

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

int main(void) {
    void *child_stack;

    variable = 9;
    child_stack = (void *) malloc(8192); // WRONG!
    // child_stack = (void **) malloc(8192) + 8192 / sizeof(*child_stack); // Right!
    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;
}

/* Local Variables: */
/* compile-command: "gcc -Wall clone.c" */
/* End: */
```

11 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

```bash
#!/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() */
#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");
    exit(EXIT_FAILURE);
  }
  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(EXIT_SUCCESS);
}

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

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

Example
SIGUSR1

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

void sig_usr(int);

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

  if( signal(SIGUSR1, sig_usr) == SIG_ERR ){
    perror("signal<SIGUSR1>");
        exit(EXIT_FAILURE);
  }

  for(;;) pause();
}

void sig_usr(int signo)
{
  if (signo == SIGUSR1)
        puts("received SIGUSR1.");
  else{
    perror("sig_usr");
        exit(EXIT_FAILURE);
  }
}

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

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

Example
SIGALRM

```
#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 /tmp/alarm" */
/* End: */
```

Part VI
Interprocess Communication

- 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/

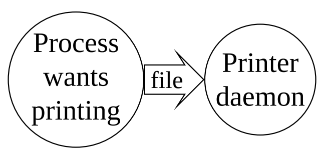
Interprocess Communication

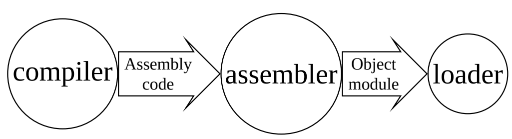
Example:
`$ unicode skull | head -1 | cut -f1 -d' ' | sm -`

IPC issues:
1. How one process can pass information to another
2. Be sure processes do not get into each other's way
   e.g. in an airline reservation system, two processes compete for the last seat
3. Proper sequencing when dependencies are present
   e.g. if A produces data and B prints them, B has to wait until A has produced some data

Two models of IPC:
- Shared memory
- Message passing (e.g. sockets)

Producer-Consumer Problem





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.

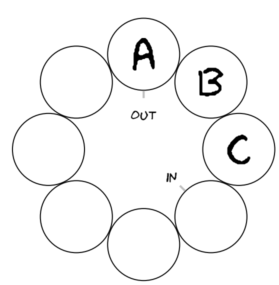
```
while(TRUE){
    while(FULL);
    item = produceItem();
    insertItem(item);
}
```

```
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 “(in + 1)%BUFFER_SIZE == out”
Actually, this is “full − 1”
Empty: when “in == out”
Can only use “BUFFER_SIZE − 1” elements

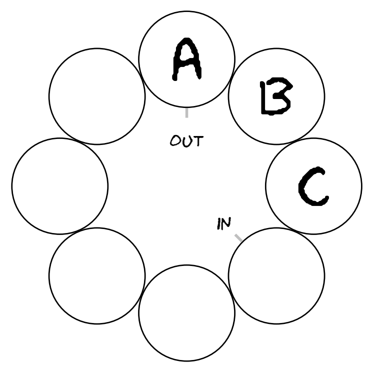
Shared data:

```c
#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:

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

  produce(buffer[in]);

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



Consumer:

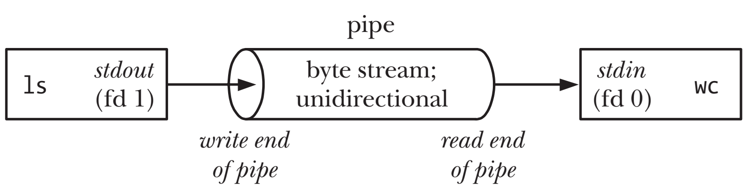
```c
while (true) {
  while (in == out); /* do nothing */

  consume(buffer[out]);

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

12 Pipes and FIFOs

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

Pipe

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

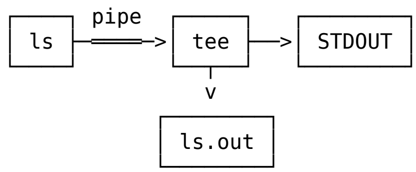


- A pipe is a byte stream
- Unidirectional

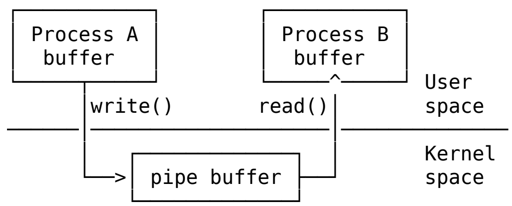
- `read()` would be blocked if nothing written at the other end

`tee`

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



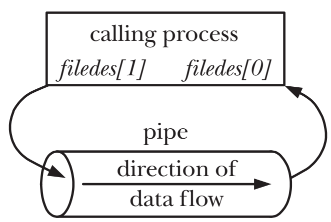
- When we say that a pipe is a byte stream, we mean that there is no concept of messages or message boundaries when using a pipe. The process reading from a pipe can read blocks of data of any size, regardless of the size of blocks written by the writing process. Furthermore, the data passes through 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]



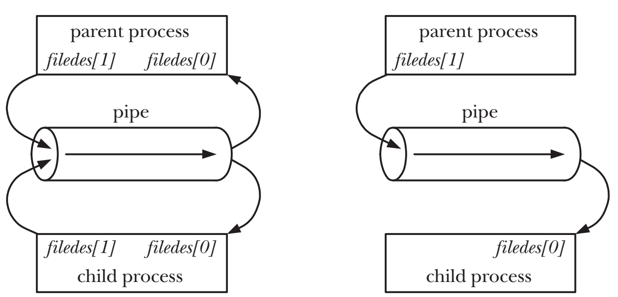
- No direct link between A and B (need system calls)
- A pipe is simply a buffer maintained in kernel memory
  ```
  $ cat /proc/sys/fs/pipe-max-size
  ```

`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.

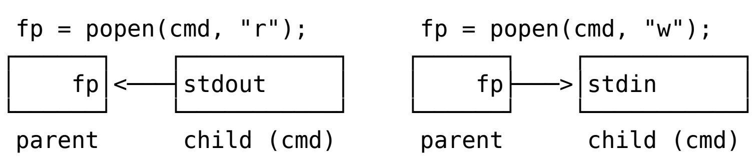
  One final reason for closing unused file descriptors is that it is only after all file descriptors in all processes that refer to a pipe are closed that the pipe is destroyed and its resources released for reuse by other processes. At this point, any unread data in the pipe is lost.

```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 ){
```

```c
        perror("child - partial/failed write");
                exit(EXIT_FAILURE);
          }
      }
      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");
            exit(EXIT_FAILURE);
          }

      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 /tmp/simple_pipe" */
/* End: */
```

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

`popen()`



`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 ) {
```

```c
    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 /tmp/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];

  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 /tmp/popen2" */
/* End: */
```

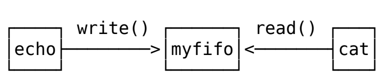
```
$ echo -n hello | od -c
```

Named Pipe (FIFO)

PIPEs pass data between related processes.
FIFOs pass data between any processes.

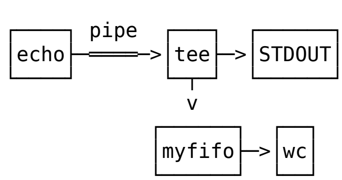
```
$ mkfifo myfifo
```

```
$ 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 /tmp/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

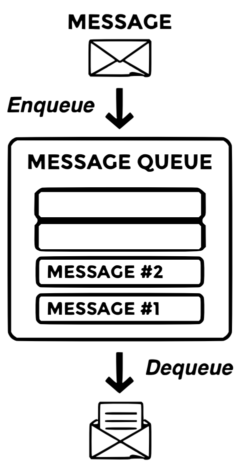
  - Okay if someone's reading the FIFO
- If opened with `O_RDWR`, the result is undefined

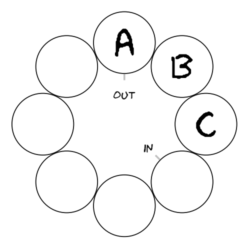
- If opened with `O_RDWR`, the result is undefined. If you do want to pass data in both directions, it's much better to use a pair of FIFOs or pipes, one for each direction.
- There are four legal combinations of `O_RDONLY`, `O_WRONLY`, and the `O_NONBLOCK` flag.

```
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. */
```

13 Message Queues

Message Queues





- [*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

```
#include <fcntl.h>
#include <limits.h>
#include <mqueue.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
```

```c
#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 /tmp/mq-send -lrt" */
/* End: */
```

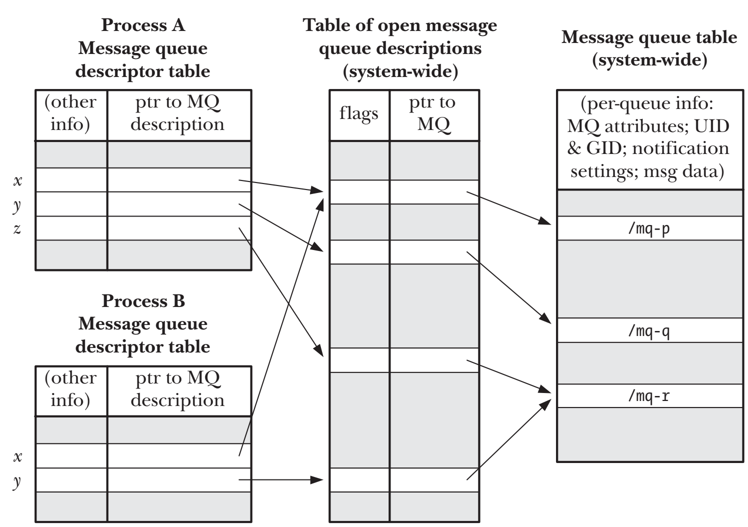
Message Queues

Receive

```c
#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;
```

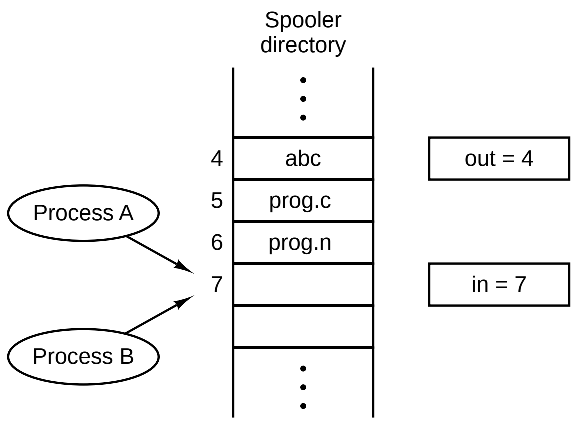
```c

  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 /tmp/mq-recv -lrt" */
/* End: */
```

Relationship Between Kernel Data Structures



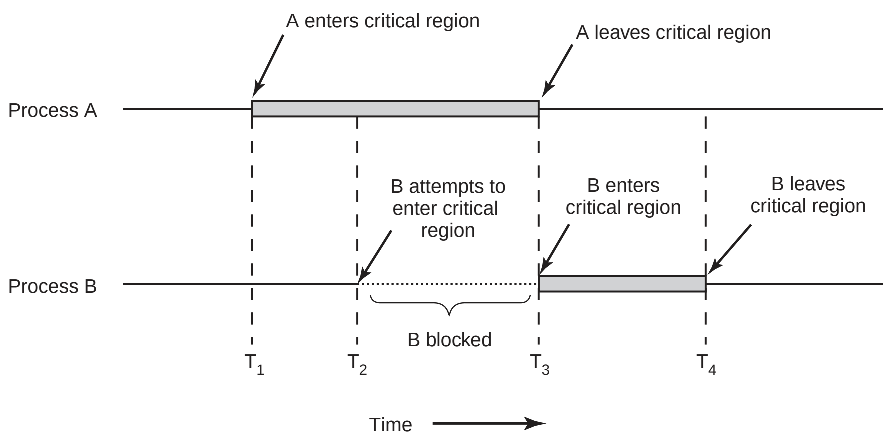
14 Semaphores

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>

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 /tmp/lock2" */
/* End: */
```

☹ Lock file could be left in system after Ctrl+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";

```

```c
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 /tmp/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

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

```c
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

```c
#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 /tmp/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!

```c
#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 /tmp/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()
```

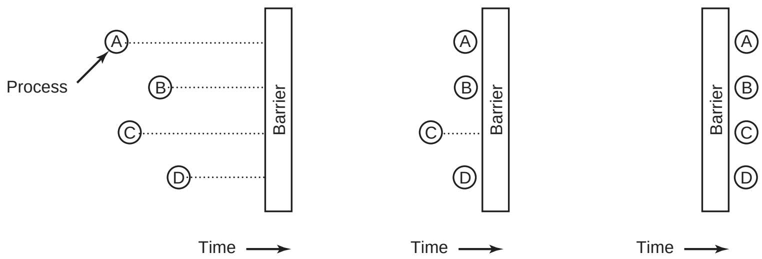
```
mutex.wait()
    i++
mutex.signal()
```

```c
#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 ){
        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 /tmp/atomic-mutex -pthread" */
/* End: */
```

```
#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");
    }
  }

  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 /tmp/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 (≤ 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

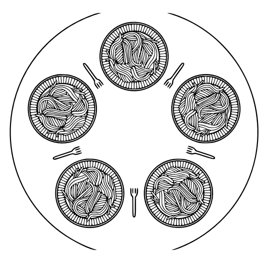
- it allows one thread to pass at a time, and
- it can be locked to bar all threads

15 Classical IPC Problems

15.1 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

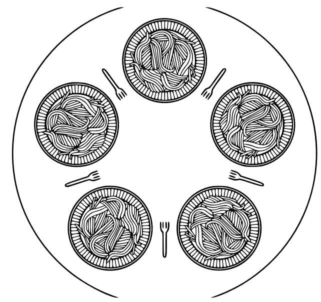
Deadlock

```
#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)

```c
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!

15.1.1 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

15.2 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.

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

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

```c
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();
  }
}
```

15.3 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

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

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

```
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);
  }
}
```

16 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);
}
```

17 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

<table>
<tr><td colspan="5">0</td><td colspan="8">1</td><td>2</td><td>3</td></tr>
<tr><td colspan="13">Source Port</td><td colspan="2">Destination Port</td></tr>
<tr><td colspan="15">Sequence Number</td></tr>
<tr><td colspan="15">Acknowledgment Number</td></tr>
<tr><td>Data
Offset</td><td>0</td><td>0</td><td>0</td><td>N
S</td><td>C
W
R</td><td>E
C
E</td><td>U
R
G</td><td>A
C
K</td><td>P
S
H</td><td>R
S
T</td><td>S
Y
N</td><td>F
I
N</td><td colspan="2">Window</td></tr>
<tr><td colspan="13">Checksum</td><td colspan="2">Urgent Pointer</td></tr>
<tr><td colspan="14">Options</td><td>Padding</td></tr>
</table>

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) */
};
```

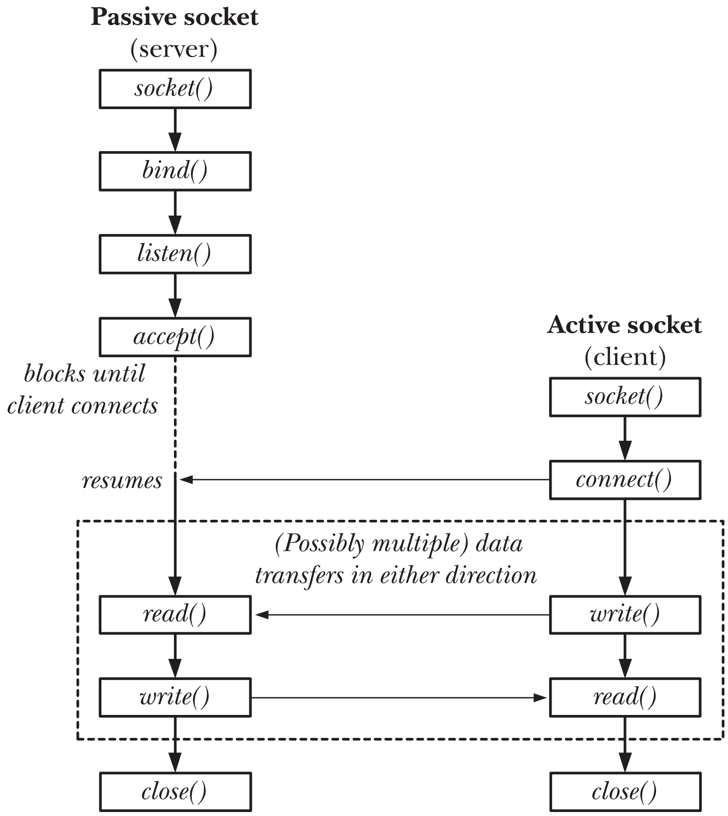
Example

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

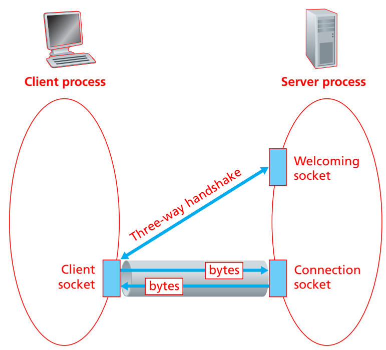
- Why does a cast from `sockaddr_in` to `sockaddr` work? `sockaddr` is defined the way it is to maintain size-compatibility with `sockaddr_in`, which is 16 bytes, and is what `sockaddr` used to be in the days when `AF_INET` was the only address family. But newer families are NOT limited to 14 bytes of 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)

17.1 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]

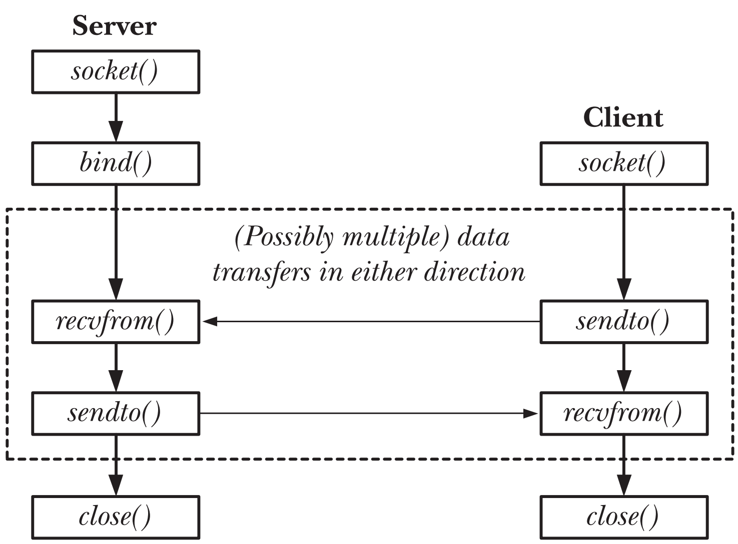
`int listen(int sockfd, int backlog);` To understand the purpose of the `backlog` argument, we first observe that the client may call `connect()` before the server calls `accept()`. This could happen, for example, because the server is busy handling some other client(s). This results in a pending connection. 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.

17.2 Datagram Sockets

Datagram Sockets



17.3 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

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 /tmp/us-xfr-sv" */
/* End: */
```

Stream client

```
#include <sys/un.h>
#include <sys/socket.h>
```

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

#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 /tmp/us-xfr-cl" */
/* End: */
```

Datagram server
Datagram client

17.4 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) */
};
```