GNU/Linux Application Programming

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Textbooks

- MATTHEW N, STONES R. Beginning linux programming. John Wiley & Sons, 2008.
- COOPER M. Advanced Bash Scripting Guide 5.3 Volume 1. Lulu.com, 2010.
- RAYMOND E S. The art of Unix programming. Addison-Wesley, 2003.
- STEVENS W R, RAGO S A. Advanced programming in the UNIX environment. Addison-Wesley, 2013.
- LOVE R. Linux System Programming: Talking Directly to the Kernel and C Library. O'Reilly Media, Inc., 2007.
- KERRISK M. The Linux Programming Interface: A Linux and UNIX System Programming Handbook. No Starch Press, 2010.
- BRYANT R E, O'HALLARON D R. Computer Systems: A Programmer's Perspective. 2nd ed. Addison-Wesley, 2010.

Course Web Links

- https://cs6.swfu.edu.cn/moodle
- https://cs2.swfu.edu.cn/~wx672/lecture_notes/linux-app/slides/
- https://cs2.swfu.edu.cn/~wx672/lecture_notes/linux-app/src/
- https://cs3.swfu.edu.cn/tech

/etc/hosts

```
202.203.132.241   cs6.swfu.edu.cn
202.203.132.242   cs2.swfu.edu.cn
202.203.132.245   cs3.swfu.edu.cn
```

Homework

Weekly tech question

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

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𝔼 Preferably in English

in stackoverflow style

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

Getting Started

Linux Commands

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

```
$ echo $PATH
```

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

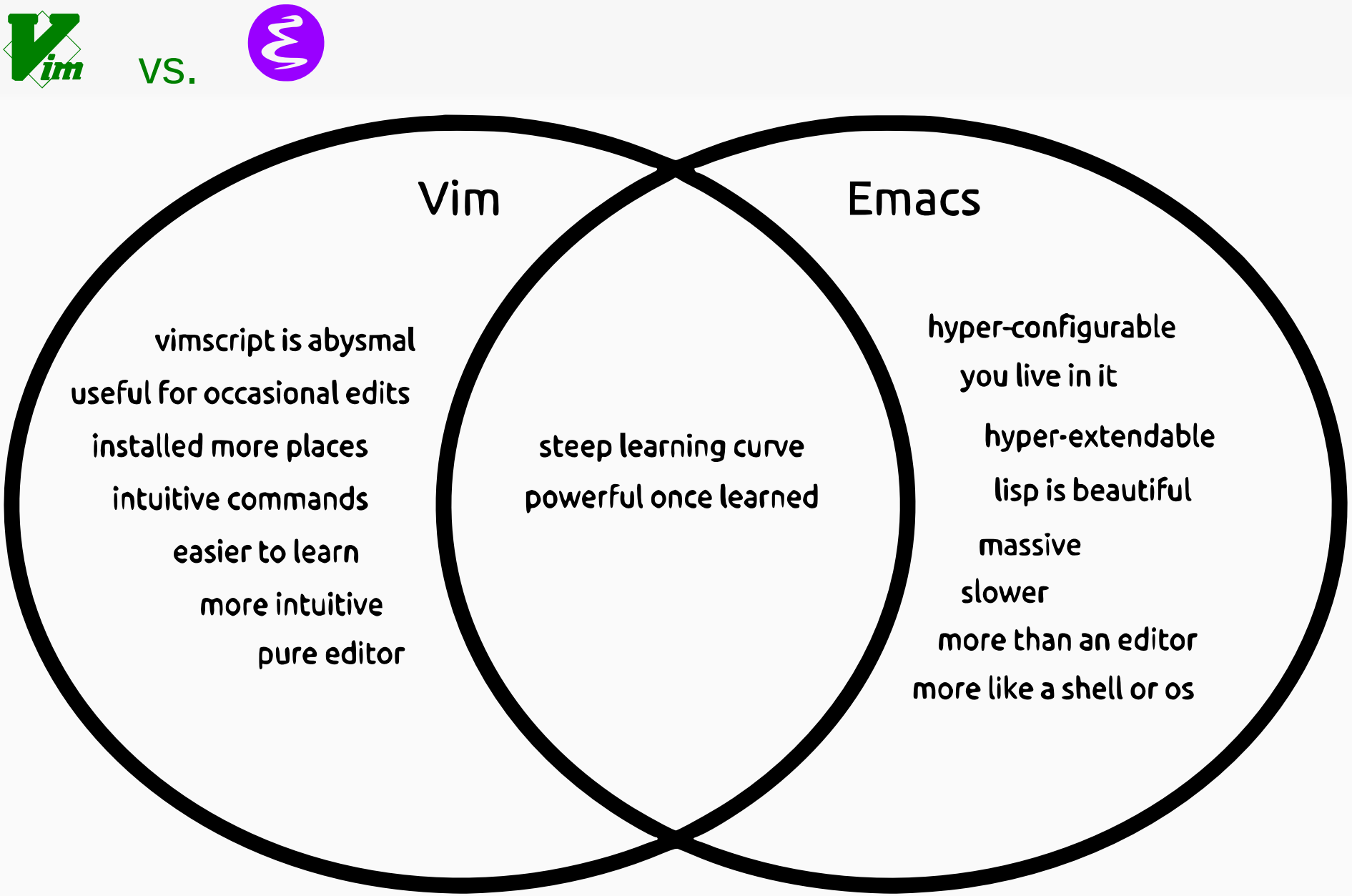
Command not found?

First double check your spelling

Then try:

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

Text Editors

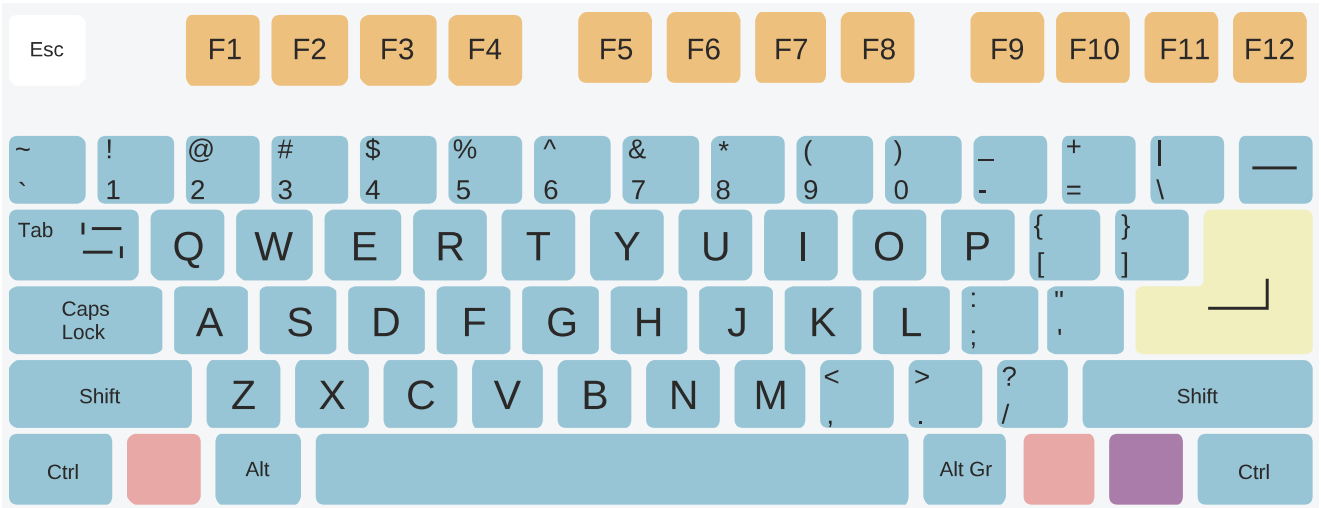


Help Your Editor

Suffix matters

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

Keyboard



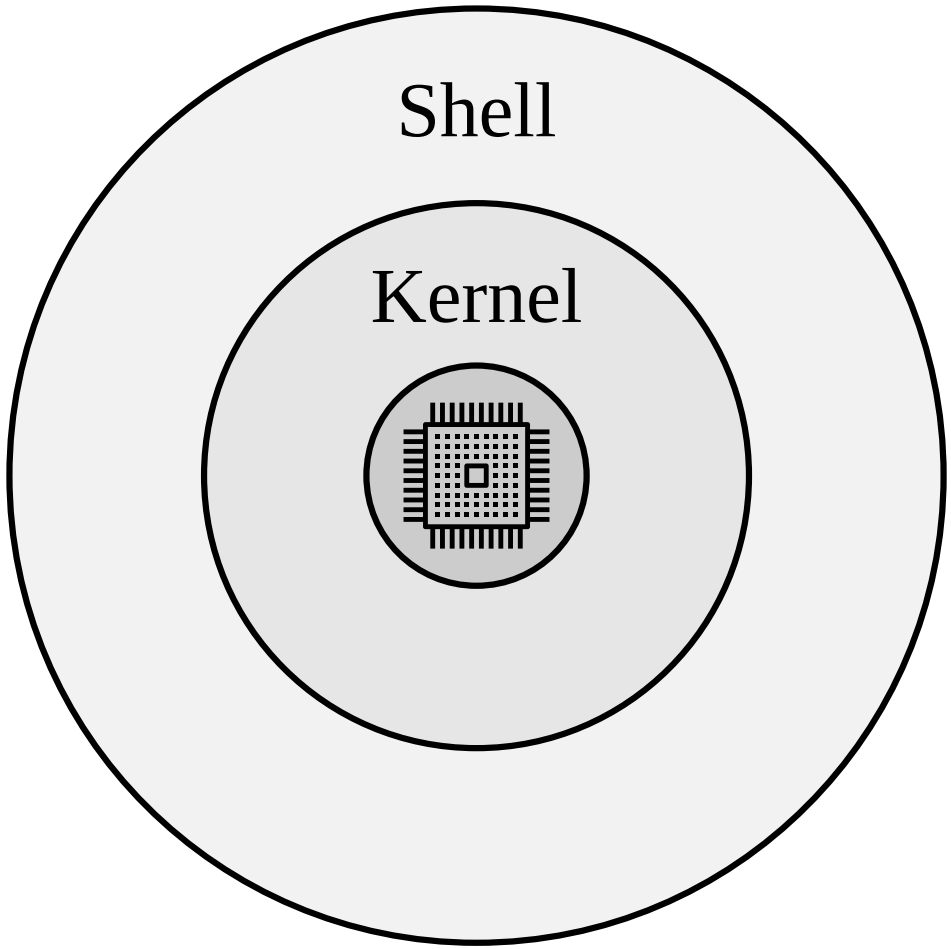
vimtutor

Ctrl + h t

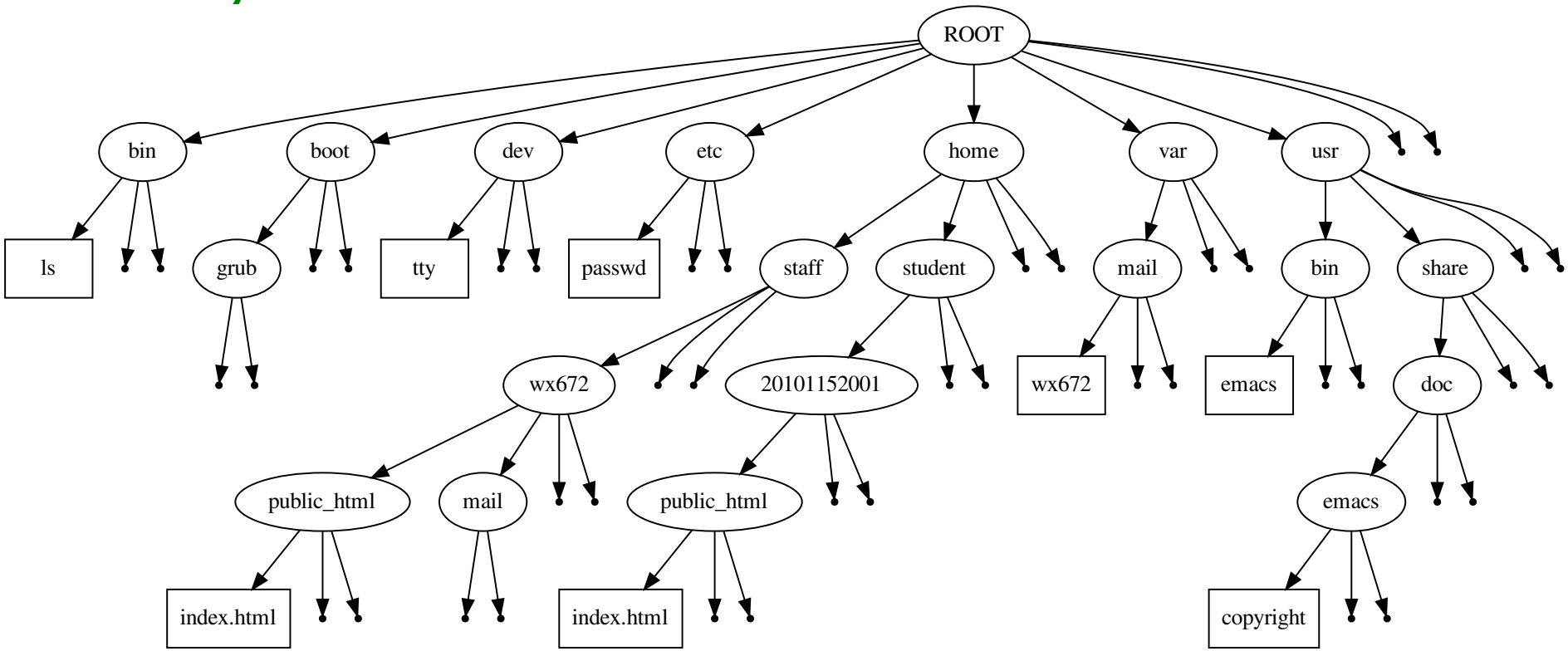
Shell Basics

Shell

- A command line interpreter
- A programming language



Directory Structure



Todo	How
Where am I?	`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`

Process Operations

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

System Info

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

APT — package management

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

CLI Shortcuts

Ctrl + a :	beginning of line	Ctrl + e :	end of line
Ctrl + f :	forward	Ctrl + b :	backward
Ctrl + n :	next	Ctrl + p :	previous
Ctrl + r :	reverse search	Ctrl + u :	cut to beginning
Ctrl + k :	kill (cut to end)	Ctrl + y :	yank (paste)
Ctrl + d :	delete a character	⇆ :	completion

Tmux

Ctrl + a c :	create window	Ctrl + a Ctrl + a :	switch window
Ctrl + a n :	next window	Ctrl + a p :	previous window
Ctrl + a - :	split window	Ctrl + a | :	split widnow
Ctrl + a j :	go down	Ctrl + a k :	go up
Ctrl + a l :	go right	Ctrl + a h :	go left

Understanding "`ls -l`"

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

- File Name
- Modification Time
- Size (in bytes)
- Group
- Owner
- Number of hard links
- File Permissions
- File types

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

9-bit permission

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

- Other
- Group
- User

```
$ chmod 755 foo
$ chmod 000 foo
$ chmod a-r foo
$ chmod g+w foo
```

```
$ chmod 644 foo
$ chmod 777 foo
$ chmod u+x foo
$ chmod go=rx foo
```

Wildcard Expansion

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

Example

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

output:

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

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

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

Everything Is A File

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

Redirection

Redirecting output

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

Redirecting input

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

Pipe

Chain processes together

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

Shell Programming

Variables

```
$ a=8; b=2
$ a=a+5; a=$a+5
$ let a=a+5; let a+=5
$ let b=b+a; let b+=a
$ echo a; echo $a
$ (( a=5, b=6, a+=b ))
$ (( b=a<5?8:9 ))
$ r=$(( RANDOM%100 ))
$ echo "$a" # partial quoting
$ echo '$a' # full quoting
$ a=$(ls -l); echo $a; echo "$a"
$ a=hello; b=world; let a+=b
```

Positional Parameters

`$0, $1, $2, …, $@, $#`

```bash
#!/bin/bash

echo "You said:"

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

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

```c
#include <stdio.h>

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

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

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

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

  return 0;
}
```

Parameter Substitution

Default value

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

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

Example

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

Parameter Substitution

Substring removal

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

Substring replacement

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

Environmental Variables

Each process has an environment

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

```
export HISTSIZE=2000

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

export EDITOR='vim'

export ALTERNATE_EDITOR="vim"

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

```
$ env
$ declare
```

Tests I

```
$ (( 5 < 6 )) && echo should be
$ [[ 1 < 2 ]] && echo of course
$ [[ $a -lt $b ]] && echo yes || echo no
$ if [[ $a -lt $b ]]; then echo yes; else echo no; fi
$ if test $a -lt $b; then echo of course; fi
$ if a = 5; then echo a=$a; fi # whitespace matters ✘
$ if a=5; then echo a=$a; fi ☹
$ if test a=5; then echo a=$a; fi ☹
$ if test a = 5; then echo a=$a; fi ☹
$ if test $a = 5; then echo a=$a; fi ✔
$ test $a = 5 && echo a=$a ✔
$ [[ $a = 5 ]] && echo a=$a ✔
```

Tests II

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

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

$ if cmp a b; then echo same file; fi ✔

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

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

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

$ help test
```

Tests III

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

Loops

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

```
$ for i in 1 2 3; do echo -n i="$i "; done
$ for i in {1..10}; do echo $i; done
$ for i in $(seq 10); do echo $i; done
$ for ((i=1; i<=10; i++)); do echo $i; done
$ for ((i=1, j=1; i<=10; i++, j++)); do
    echo $i-$j ☹
    echo $(($i-$j)) ☺
  done
$ for ((i=1; i<=10; i++)) { echo $i; } # C style
$ for i in hello world; do echo -n "$i "; done
```

Loops

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

```
$ a=0; while [[ a < 10 ]]; do echo $a; ((a++)); done ☹
$ while [[ $a < 10 ]]; do echo $a; ((a++)); done ☹
$ while [[ $a -lt 10 ]]; do echo $a; ((a++)); done ✔
$ while [ $a -lt 10 ]; do echo $a; ((a++)); done ✔
$ while (( a < 10 )); do echo $a; ((a++)); done ✔
$ until (( a = 10 )); do echo $a; ((a++)); done ☹
$ until (( a == 10 )); do echo $a; ((a++)); done ✔
$ while read n; do n2 $n; done
$ while read n; do n2 $n; done < datafile
$ until (( n == 0 )); do read n; n2 $n; done
```

case

```
#!/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

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

Functions

```
#!/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
}
```

C Programming Basics

Programming Environment

Program Languages

Machine code

The binary numbers that the CPUs can understand.

```
10011100001110111001111 ... and so on ...
```

Assembly language — friendly to humans

People don't think in numbers.

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

The ASM programs are translated to machine code by assemblers.

High level languages

Even easier to understand for humans. Examples:

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

High level languages

Even easier to understand for humans. Examples:

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

Compilers do the translation work.

Compilation

Editor (emacs)

$ emacs hello.c

C source code (hello.c)

Include files, macros (stdio.h)

C Preprocessor (cpp)

$ cpp hello.c
$ gcc -E hello.c

Extended C source code (hello.c)

Compiler (gcc)

$ cc1 hello.i -o hello.s
$ gcc -S hello.c

ASM source code (hello.s)

Assembler (gas)

$ as hello.s -o hello.o
$ gcc -c hello.c

Object code (hello.o)

Libraries (printf)

Linker (ld)

$ ld hello.o LIBs
$ gcc -o hello hello.c

Executable program (hello)

Debugger (gdb)

$ gcc -g hello.c -o hello
$ gdb hello

Compiler vs. Interpreter

hello.c

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

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

hello.sh

```
#!/bin/bash
echo 'Hello, world!'
```

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

hello.py

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

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

Header Files

Why?

```c
#include "add.h"

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

Why not?

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

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

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

In the header files…

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

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

Library Files

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

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

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

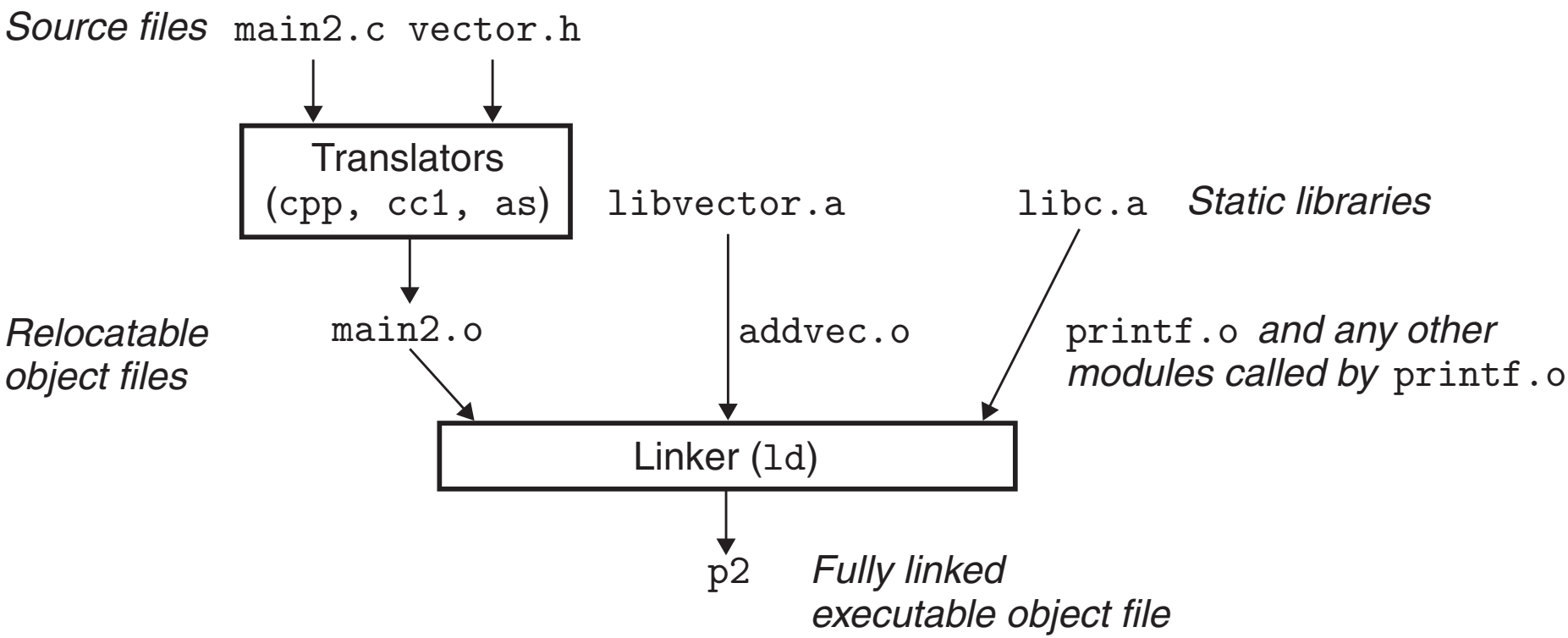
```
$ find /usr/lib -name "*.so.*"
```

Examples:

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

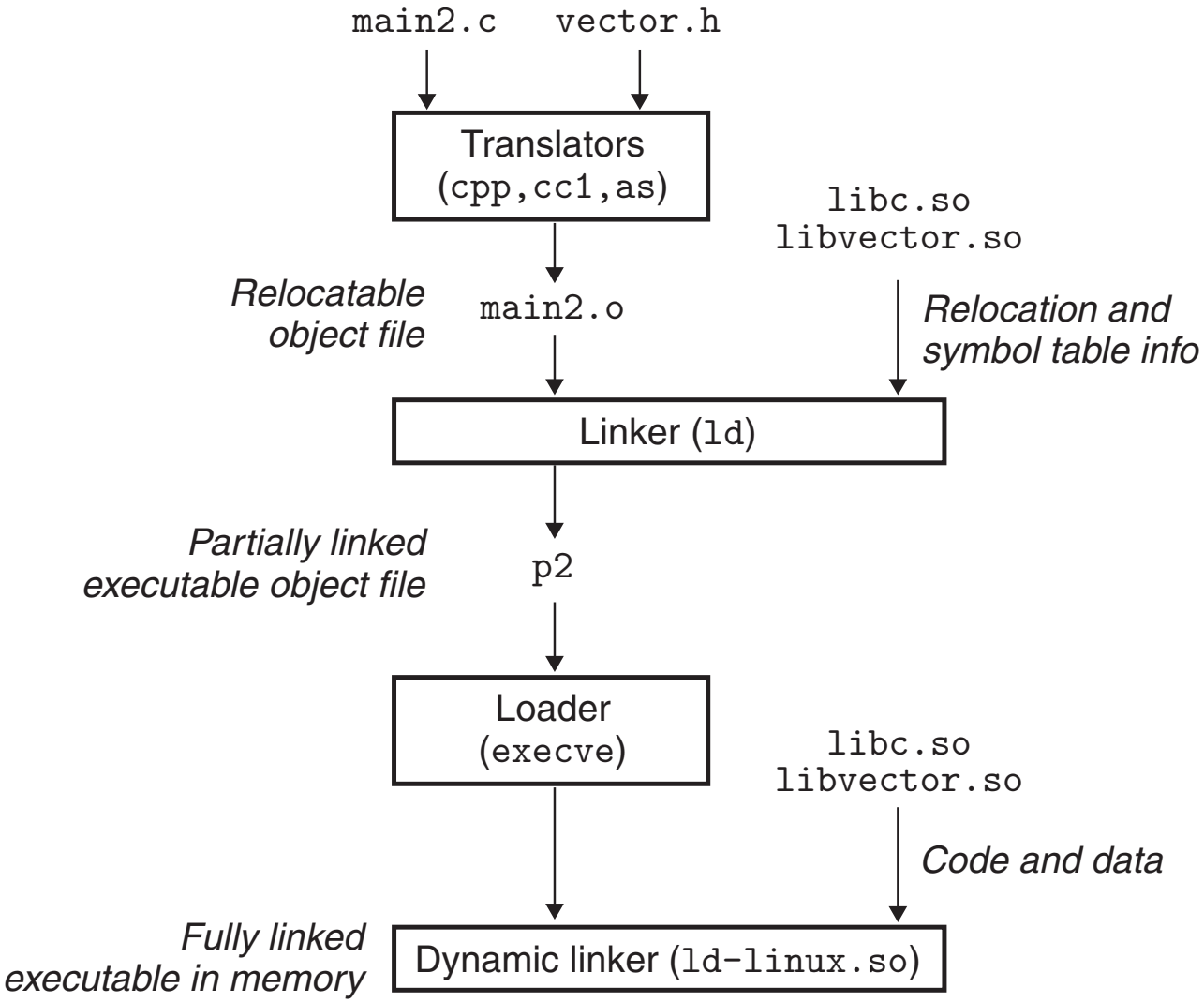
Static Linking

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



Dynamic Linking

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



Build A Static Library

Source codes

main.c

```c
#include "lib.h"

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

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

lib.h

```c
#include <stdio.h>

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

hello.c

```c
#include <stdio.h>

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

hi.c

```c
#include <stdio.h>

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

Build A Static Library

Step by step

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

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

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

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

3. Use `libhi.a`

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

Build A Static Library

Makefile

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

Build A Shared Library

Source codes

hello.c

```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

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

int hi(char*);
```

hi.c

```c
#include "hello.h"

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

Build A Shared Library

Step by step

1. Get `hi.o`

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

2. Get `libhi.so`

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

3. Use `libhi.so`

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

4. Check it

   ```
   $ ldd a.out
   ```

Build A Shared Library

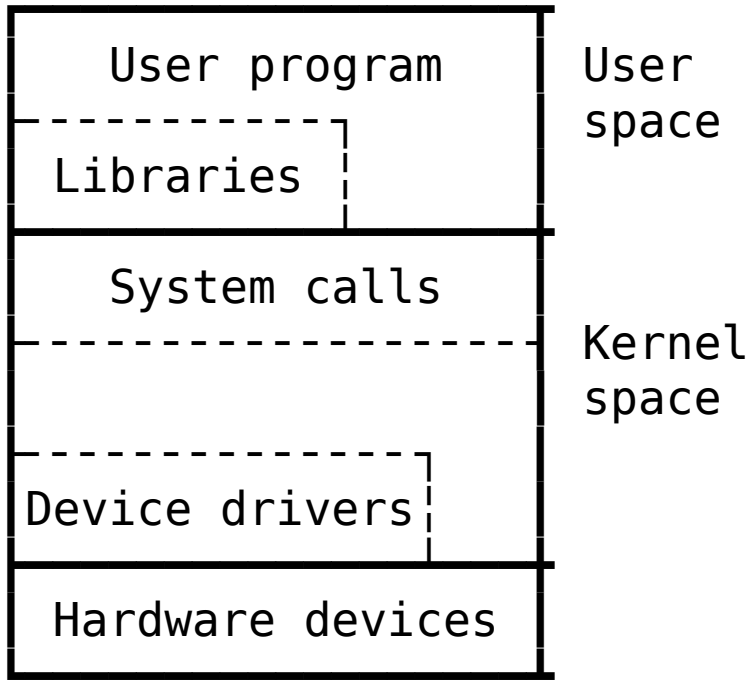
Makefile

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

GNU C Library

Linux API > POSIX API

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



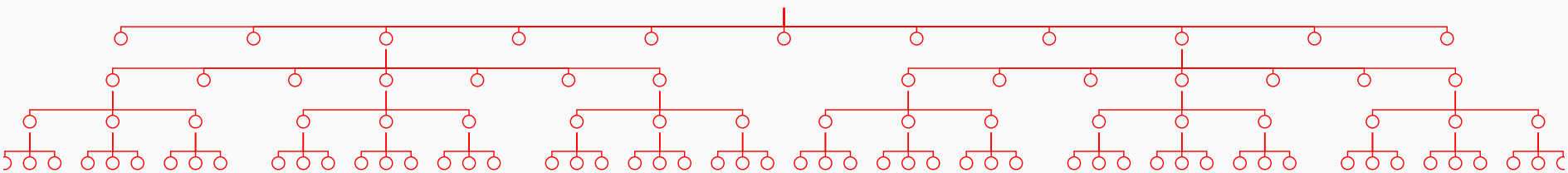
The Make Utility

To compile a single C program:

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

✔ OK. But...

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



Linux 4.9 source tree: 3799 directories, 55877 files

make: help you maintain your programs.

Makefile

```
1 target: dependencies
2 |——TAB——→ command
```

Example

```
1 hello: hello.c
2 |——TAB——→ 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
```

git

To create a new local git repo

In your source code directory, do:

```
$ git init
$ git add .
$ git commit -m "something to say…"
```

To clone a remote repo

Example:

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

Most commonly used git Commands

```
$ git add filename[s]
$ git rm filename[s]
$ git commit
$ git status
$ git log
$ git diff
$ git push
$ git pull
$ git help {add,rm,commit,…}
```

$ man gittutorial

$ man gittutorial-2

sudo apt install git

https://github.com

Man page

Layout

```
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

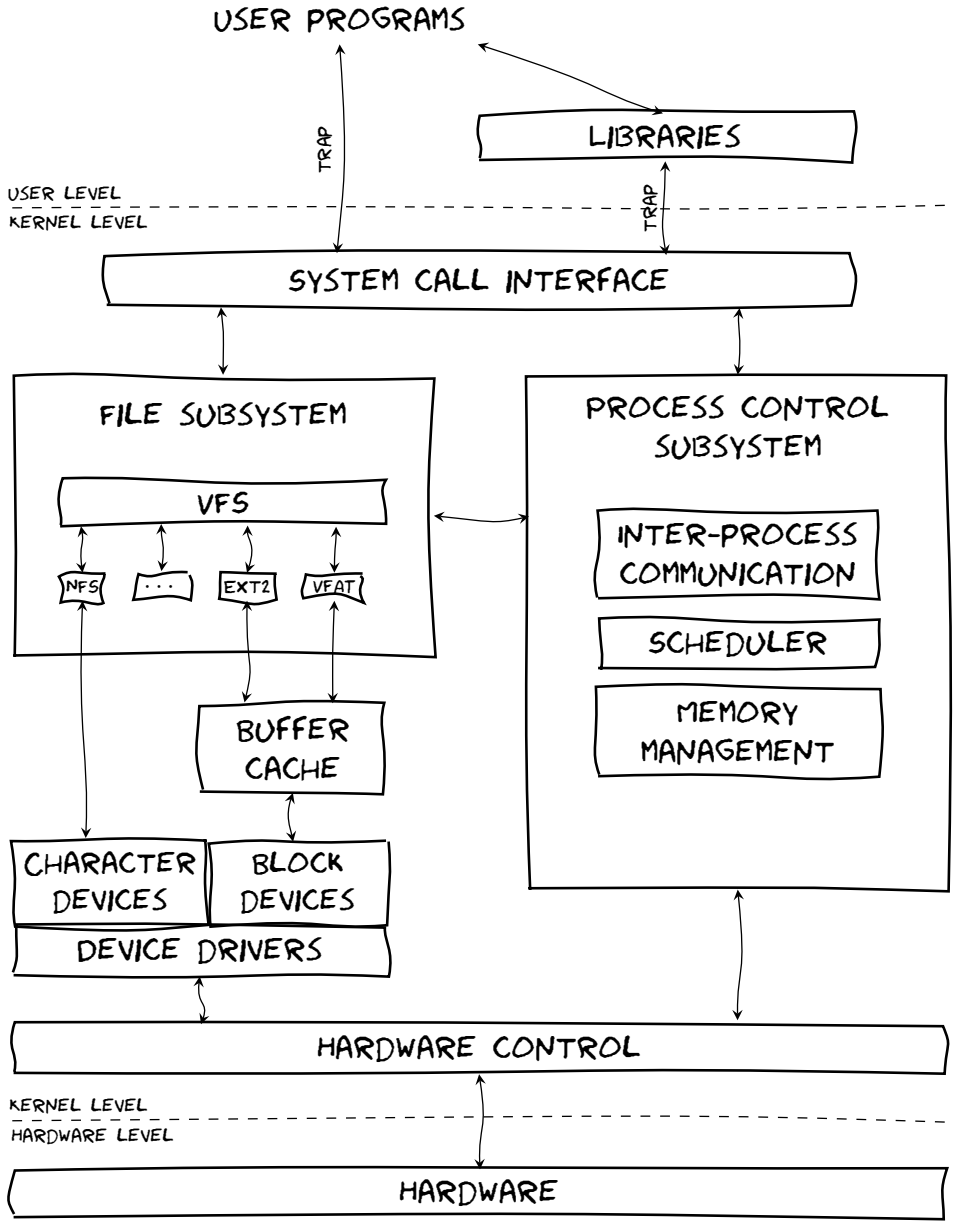
Groff source code

```
.\" 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
```

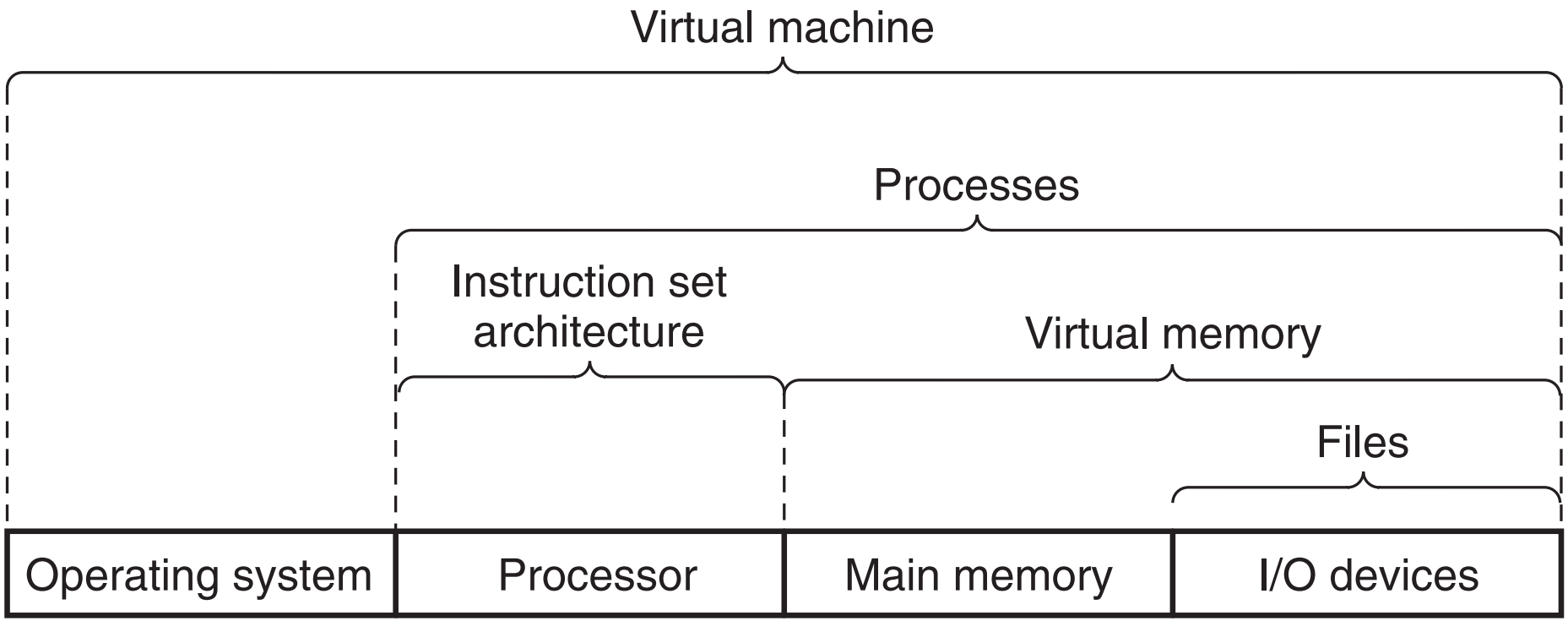
OS Basics

Operating System

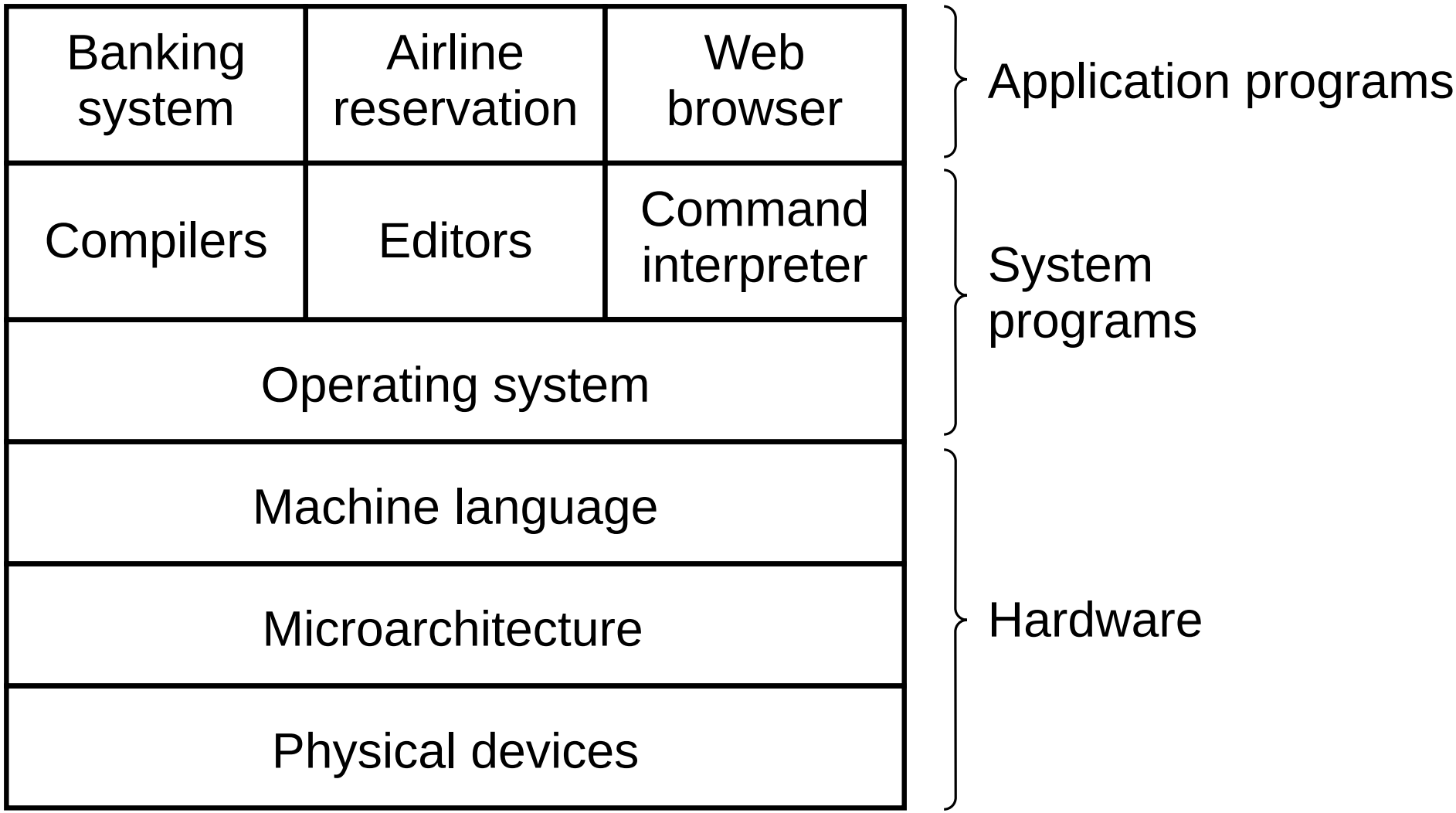


Abstractions

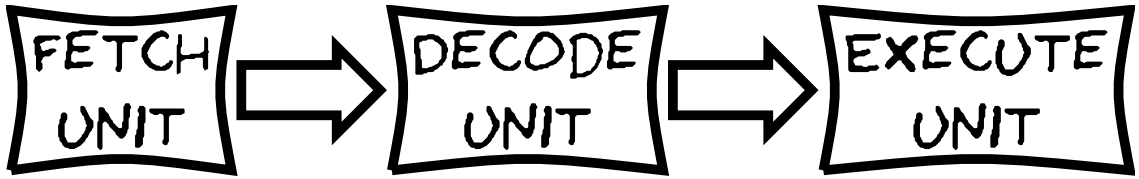
To hide the complexity of the actual implementations



A Computer System



CPU Working Cycle



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

Special CPU Registers

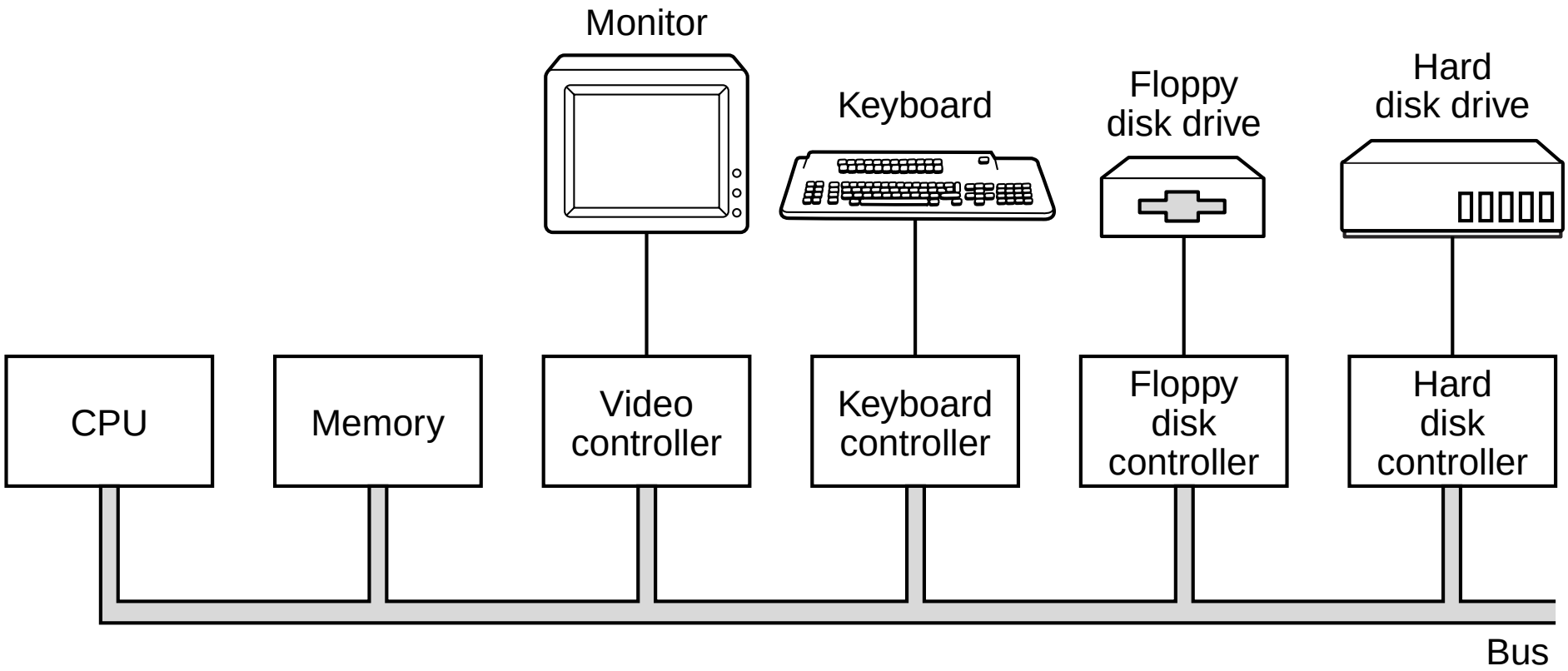
Program counter (PC): keeps the memory address of the next instruction to be fetched

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

Program status (PS): holds

- condition code bits
- processor state

System Bus



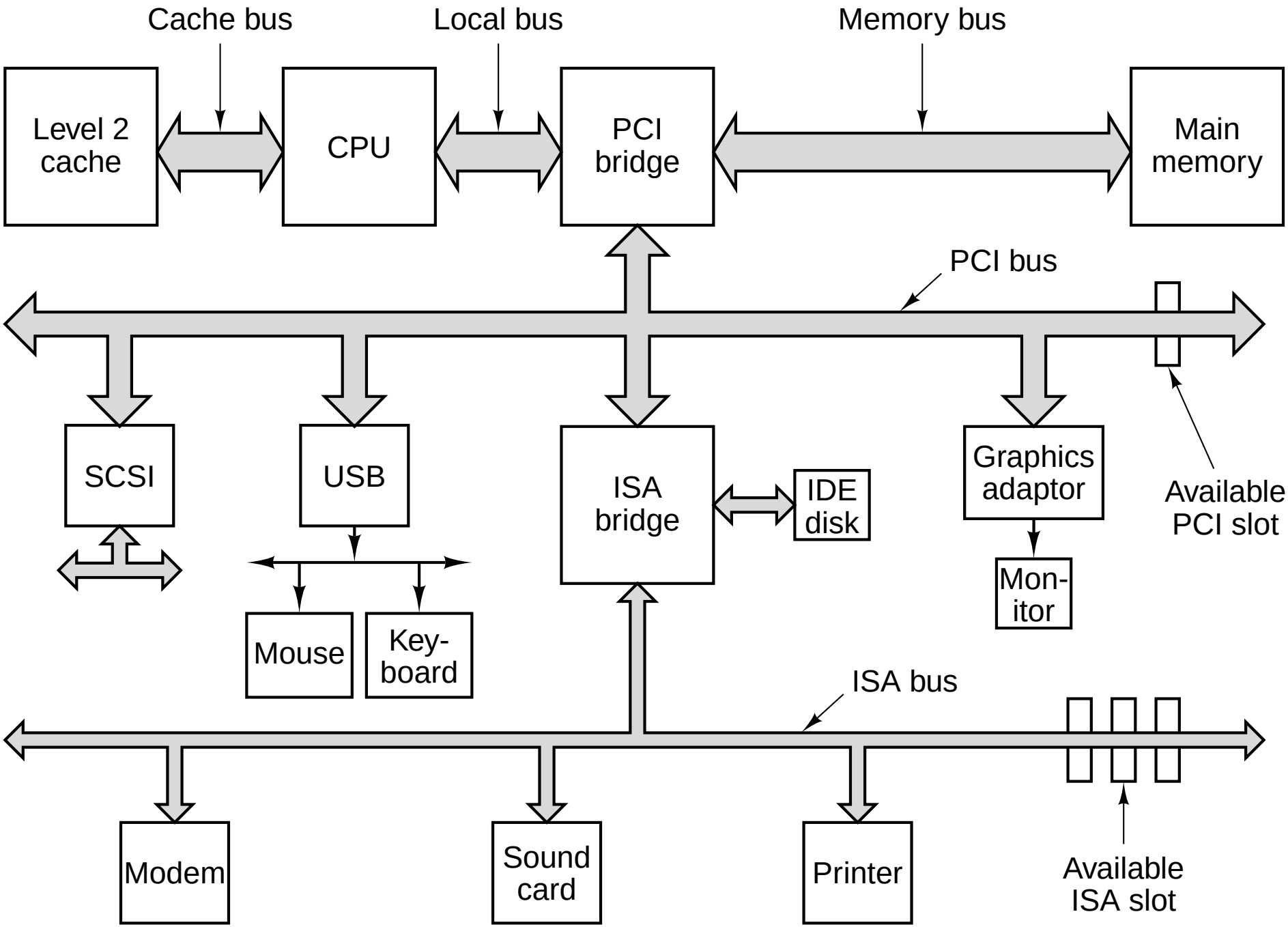
Address Bus: specifies the memory locations (addresses) for the data transfers

Data Bus: holds the data transfered. Bidirectional

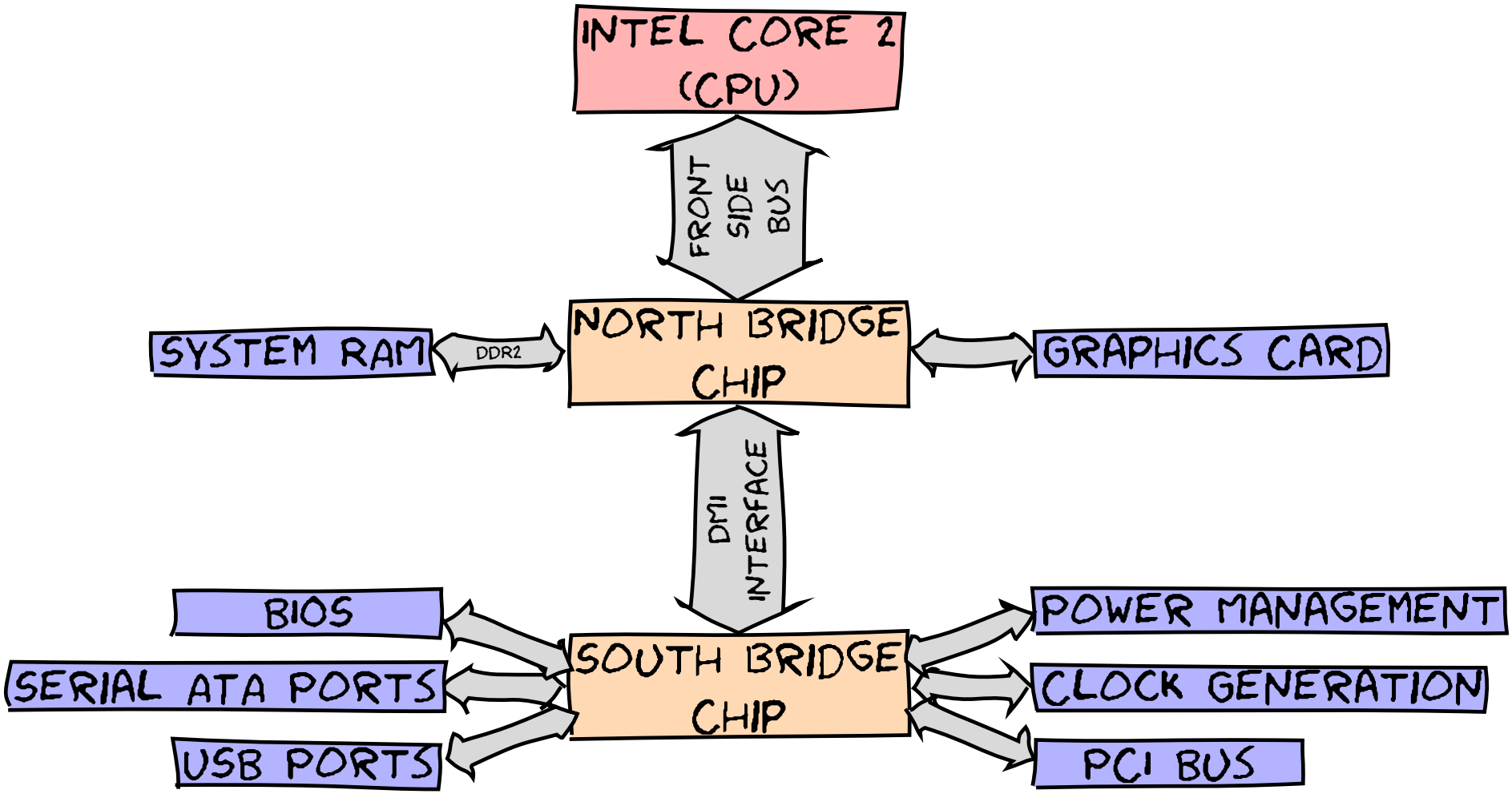
Control Bus: contains various lines used to route timing and control signals throughout the system

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


Cache bus
Local bus
Memory bus
Level 2 cache
CPU
PCI bridge
Main memory
PCI bus
SCSI
USB
ISA bridge
IDE disk
Graphics adaptor
Available PCI slot
Mon-itor
Mouse
Key-board
ISA bus
Modem
Sound card
Printer
Available ISA slot

Motherboard Chipsets



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

Intel Core 2 QX6600

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

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

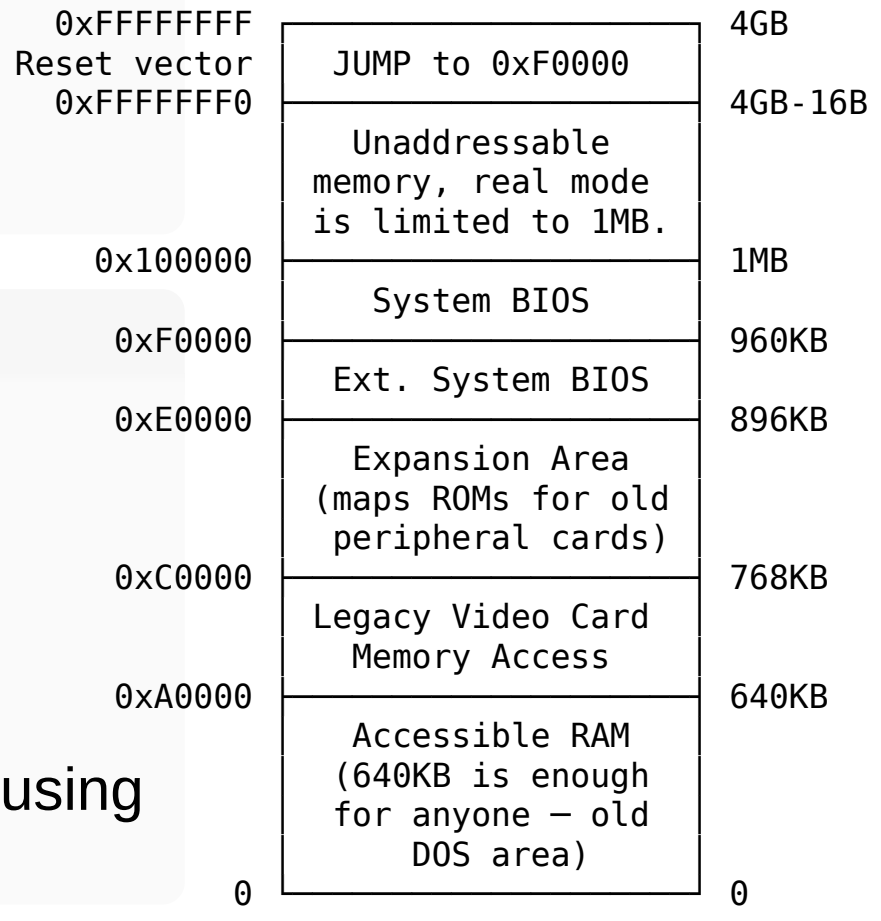
Some physical memory addresses are mapped away!

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

Memory-mapped I/O

- BIOS ROM
- video cards
- PCI cards
- …

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



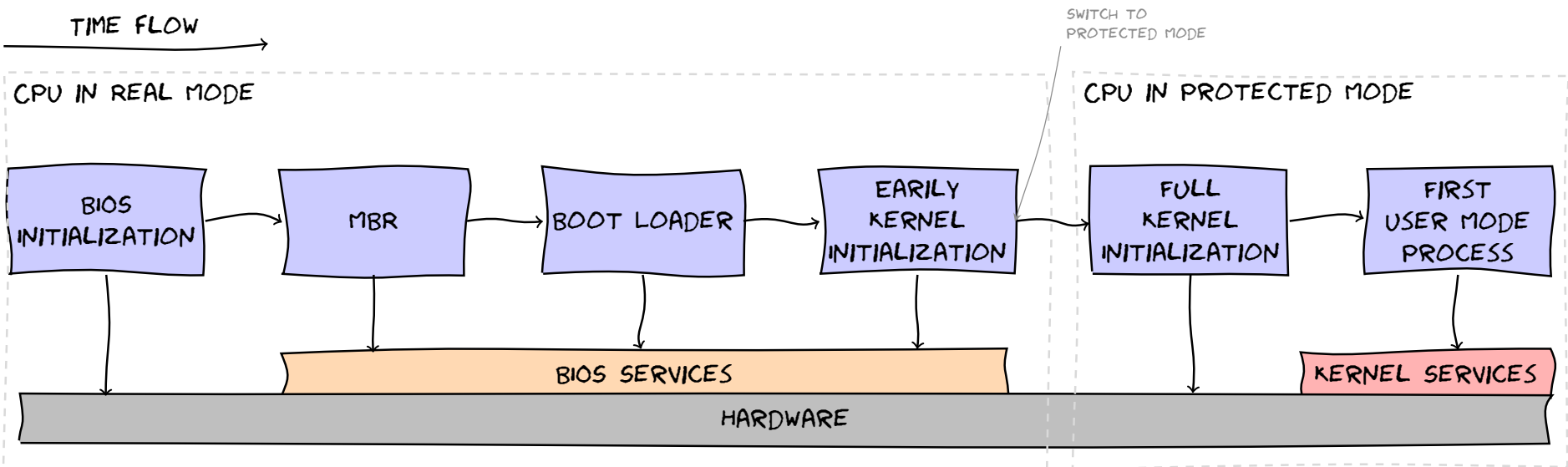
the northbridge

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

Bootstrapping

Can you pull yourself up by your own bootstraps?

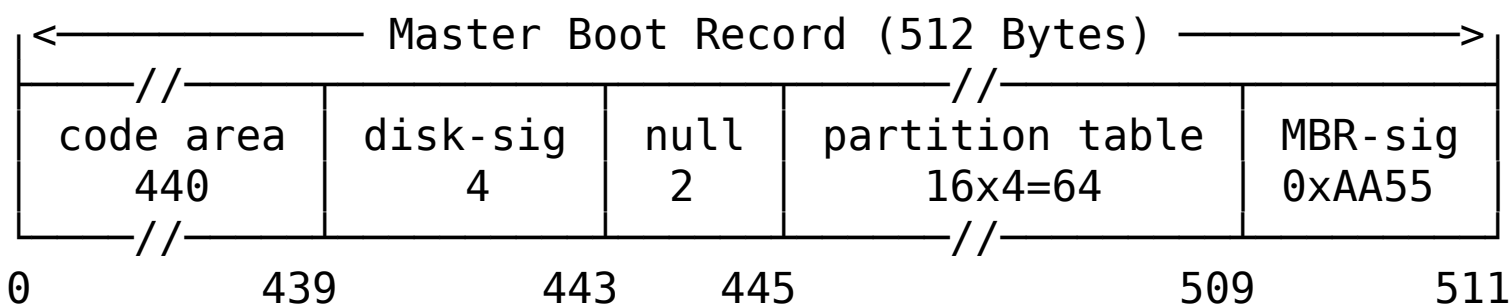
A computer cannot run without first loading software but must be running before any software can be loaded.



Intel x86 Bootstrapping

1. BIOS (`0xffffff0`)

   ➠ 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




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

Why Interrupt?

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

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

Modern OS are Interrupt Driven

HW INT by sending a signal to CPU

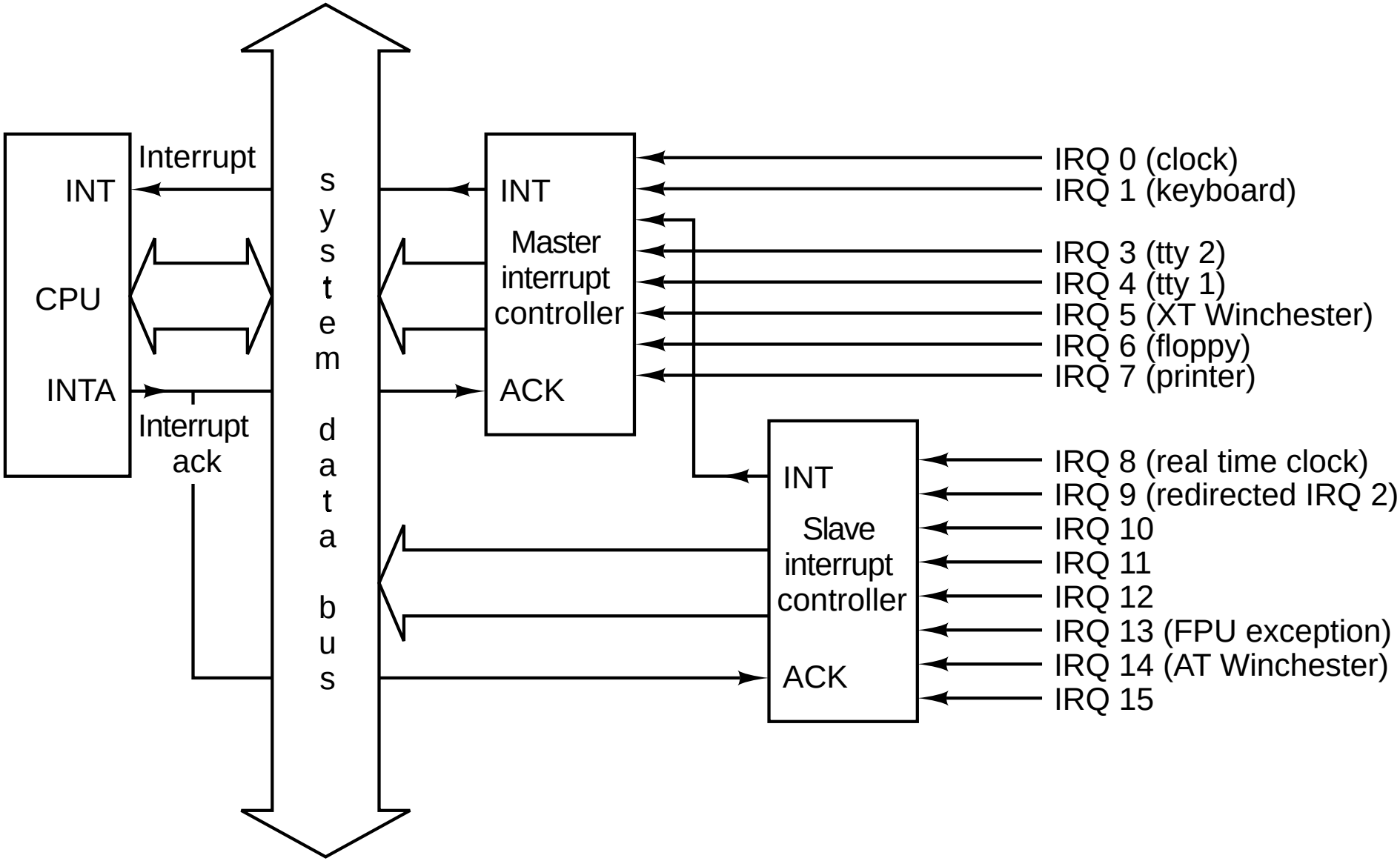
SW INT by executing a system call

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

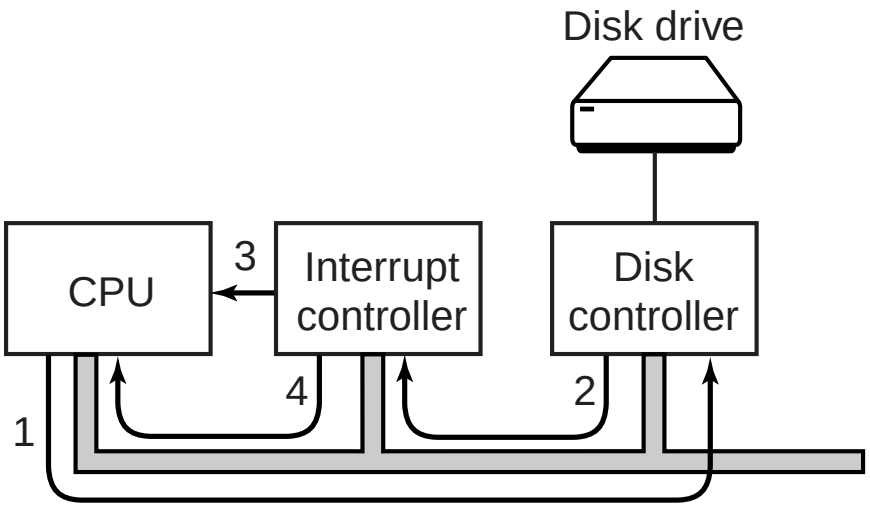
Interrupt vector is an array of pointers ☛ the memory addresses of interrupt handlers. This array is indexed by a unique device number

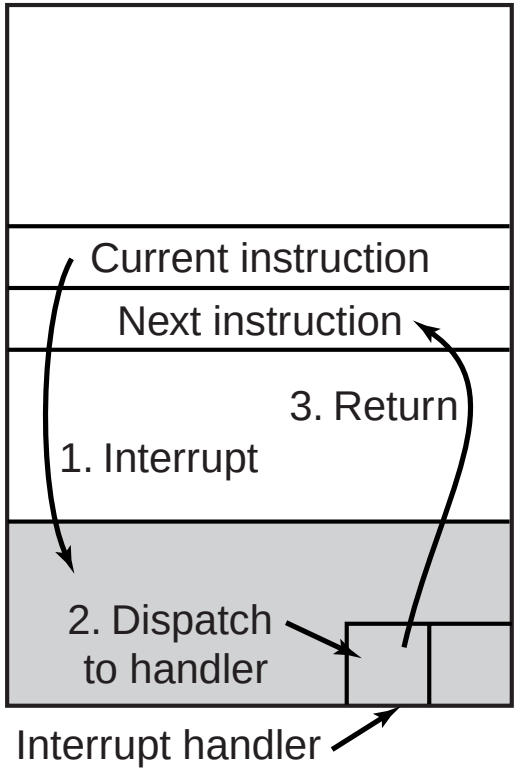
```
$ less /proc/devices
$ less /proc/interrupts
```

Programmable Interrupt Controllers

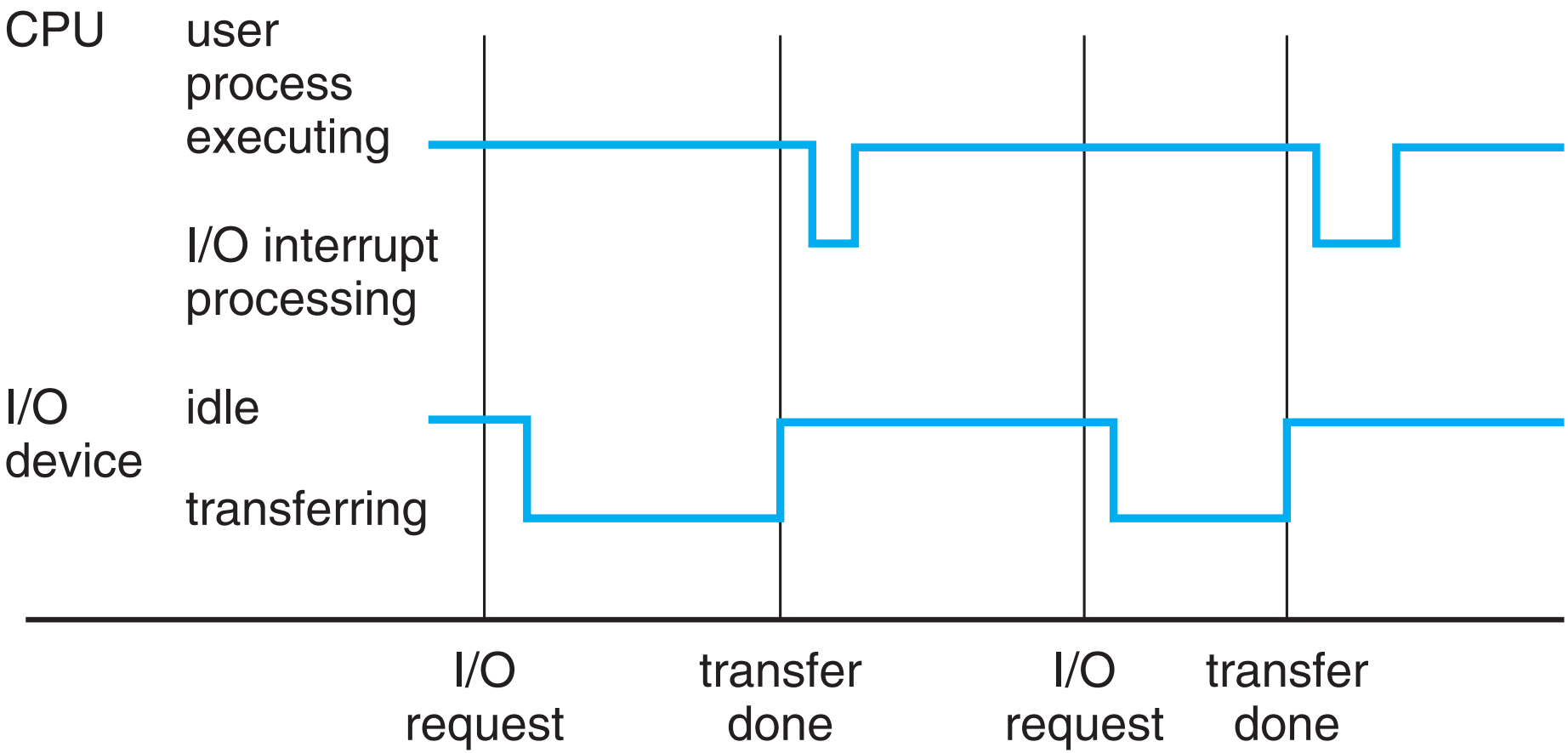


Interrupt Processing





Interrupt Timeline

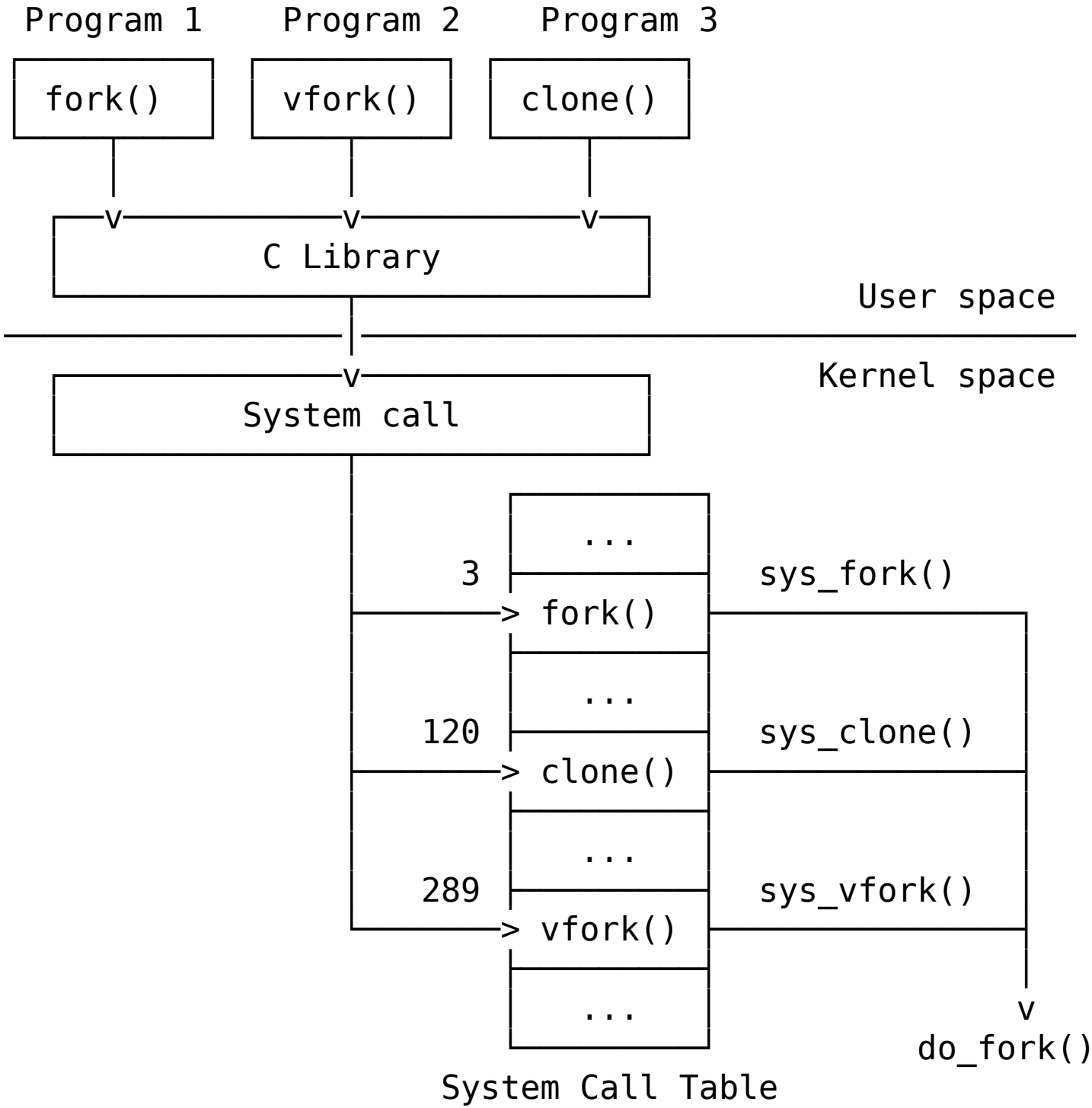


System Calls

A System Call

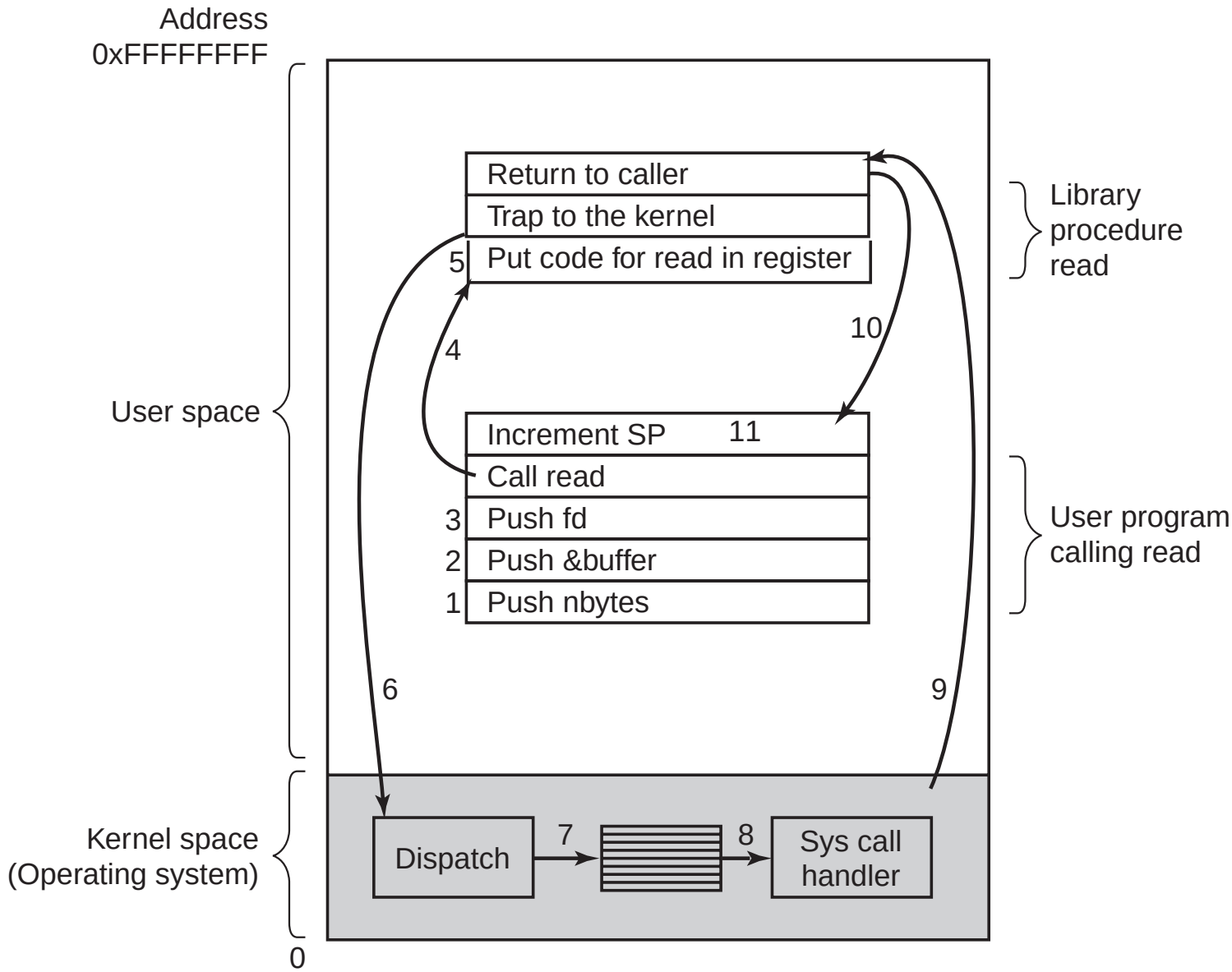
- is how a program requests a service from an OS kernel
- provides the interface between a process and the OS

```
$ man 2 intro
$ man 2 syscalls
```


Program 1
Program 2
Program 3
fork()
vfork()
clone()
C Library
User space
Kernel space
System call
...
3
sys_fork()
fork()
...
120
sys_clone()
clone()
...
289
sys_vfork()
vfork()
...
do_fork()
System Call Table

The 11 steps in making a system call

`read(fd,buffer,nbytes)`



Example

Linux `INT 80h`

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

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

Example

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

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

Process management

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

File management

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

Directory and file system management

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

Miscellaneous

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

System Call Examples

fork()

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

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

```
$ man 2 fork
```

exec()

```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 3 exec
```

The Linux Environment

Command Line Options

getopt.c

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

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

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

```
$ man 3 getopt
```

Command Line Options

getopt.sh

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

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

Environment Variable

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

extern char** environ;

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

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

  return 0;
}
```

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

Time and Date

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

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

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

  return 0;
}
```

- January 1 1970 — start of the Unix epoch

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

Temporary Files

mkstemp.c

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

mktemp.sh

```sh
#!/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;
}
```

logger.sh

```sh
#!/bin/bash

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

Working With Files

File

File

A logical view of information storage

User's view

A file is the smallest storage unit on disk.

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

UNIX view

Each file is a sequence of 8-bit bytes

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

File

What is stored in a file?

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

Different type of files have different structure

- UNIX looks at contents to determine type

  Shell scripts start with "`#!`"

  PDF start with "`%PDF...`"

  Executables start with magic number
- Windows uses file naming conventions

  executables end with "`.exe`" and "`.com`"

  MS-Word end with "`.doc`"

  MS-Excel end with "`.xls`"

File Types

Regular files: ASCII, binary

Directories: Maintaining the structure of the FS

In UNIX, everything is a file

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

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

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

File Operations

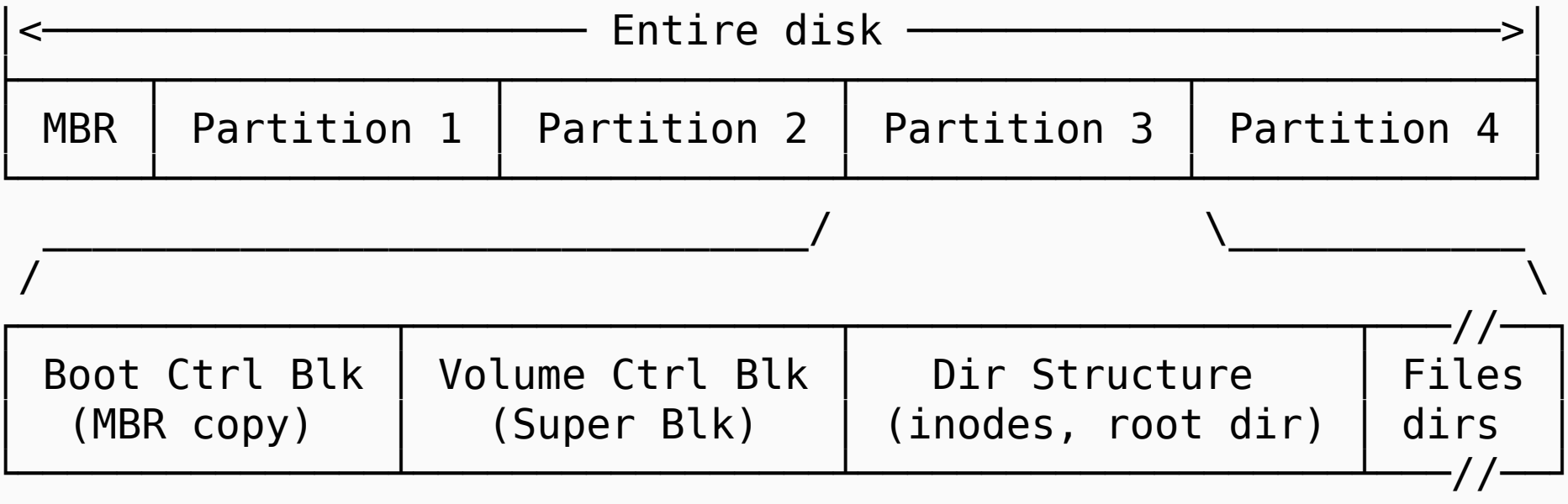
POSIX file system calls

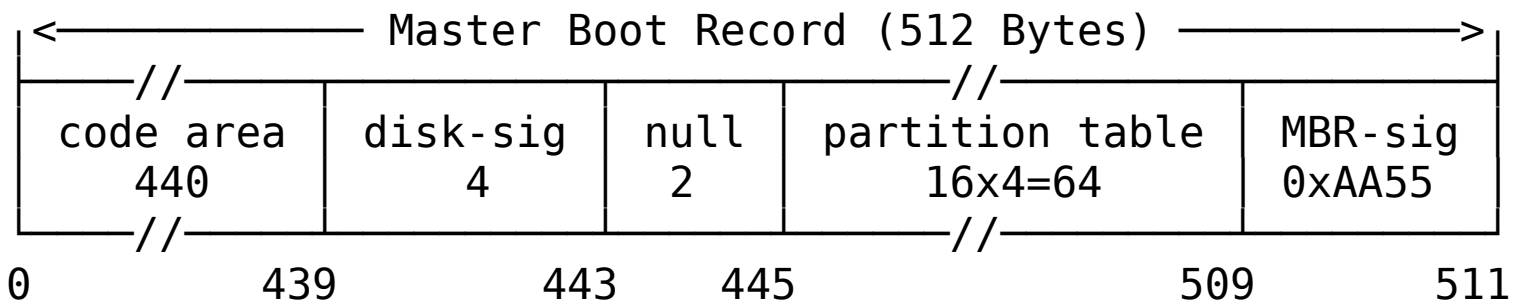
```
creat(name, mode)
open(name, flags)
close(fd)
link(oldname, newname)
unlink(name)
truncate(name, size)
ftruncate(fd, size)
stat(name, buffer)
fstat(fd, buffer)
```

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

File System Implementation

A typical file system layout





On-Disk Information Structure

Boot block a MBR copy

Superblock Contains volume details

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

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

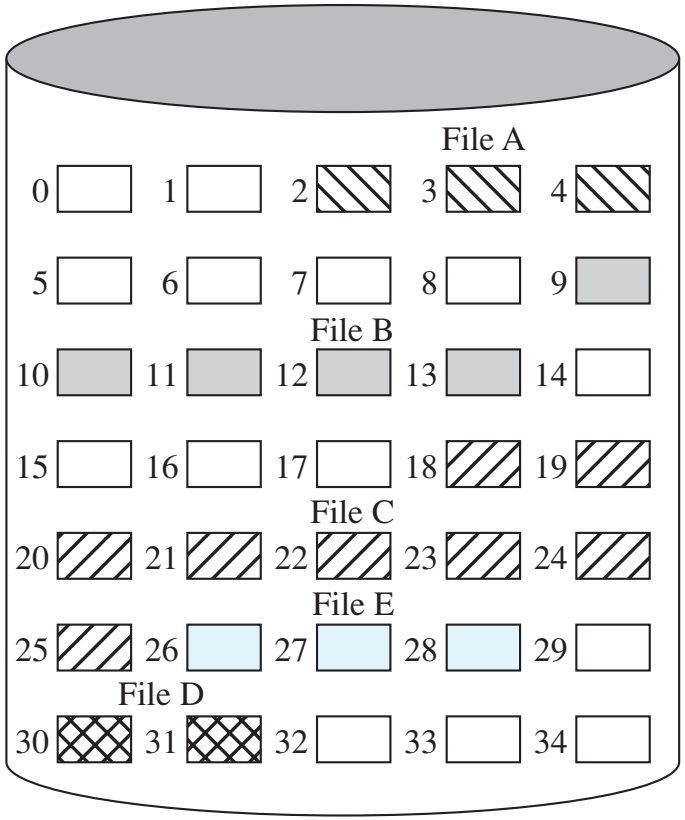
Superblock

Keeps information about the file system

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

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

Implementing Files

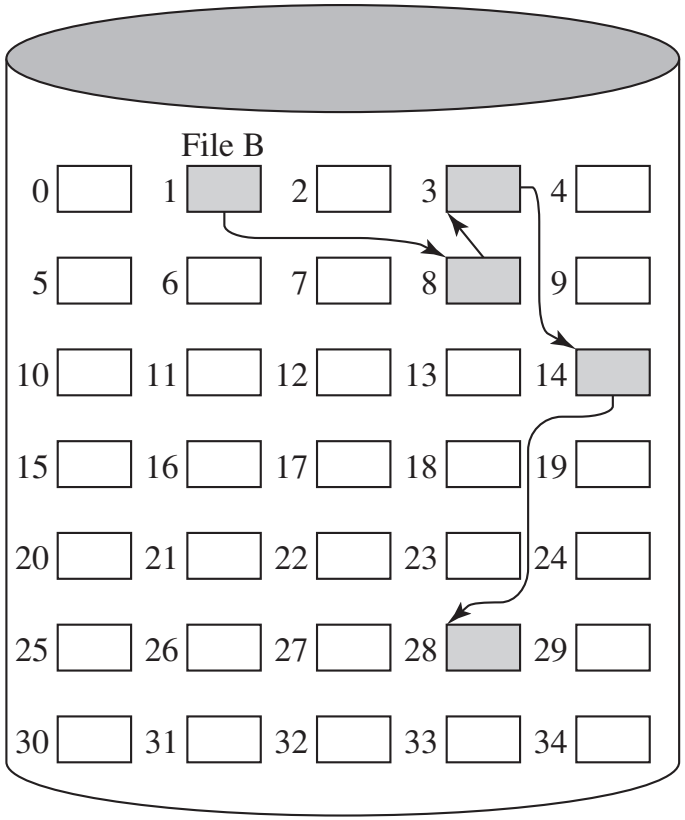


File Allocation Table

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

Contiguous Allocation

- ☺ simple
- ☺ good for read only
- ☹ fragmentation



File Allocation Table

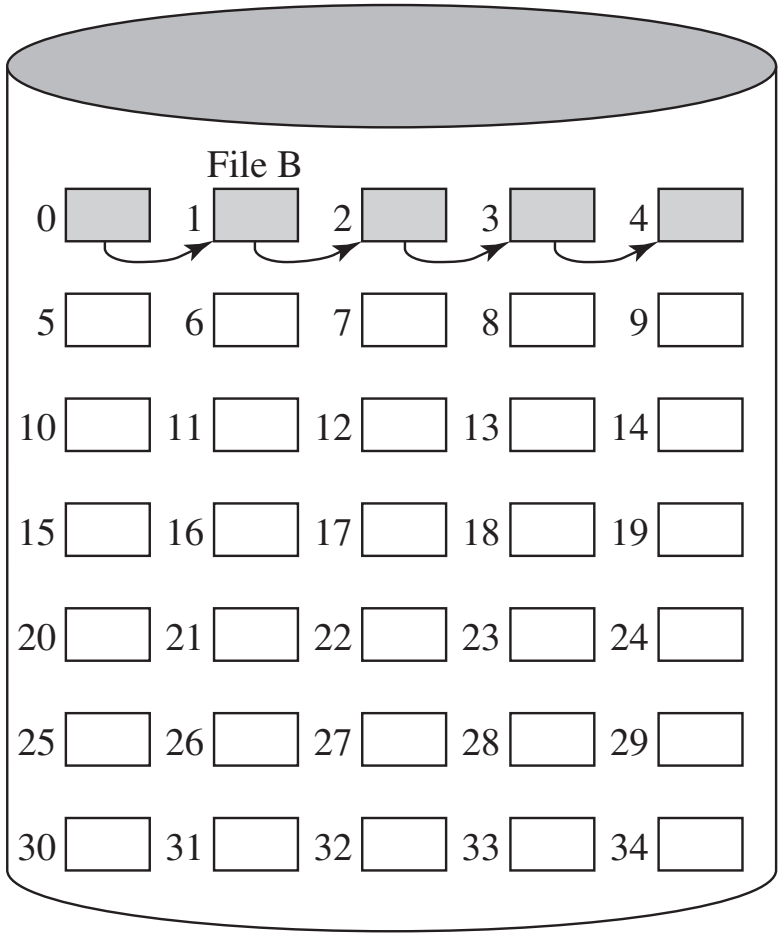
File Name	Start Block	Length
• • •	• • •	• • •
File B	1	5
• • •	• • •	• • •

Linked List (Chained) Allocation

A pointer in each disk block

- ☺ no waste block
- ☹ slow random access
- ☹ not 2^n

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



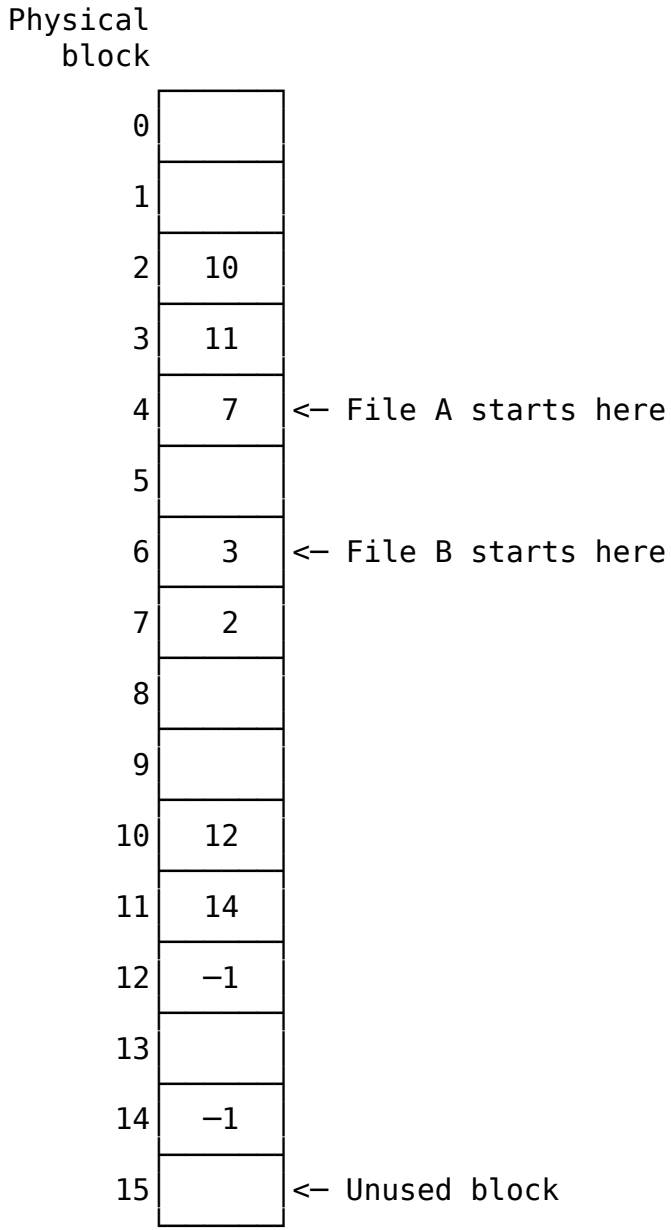
File Allocation Table

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

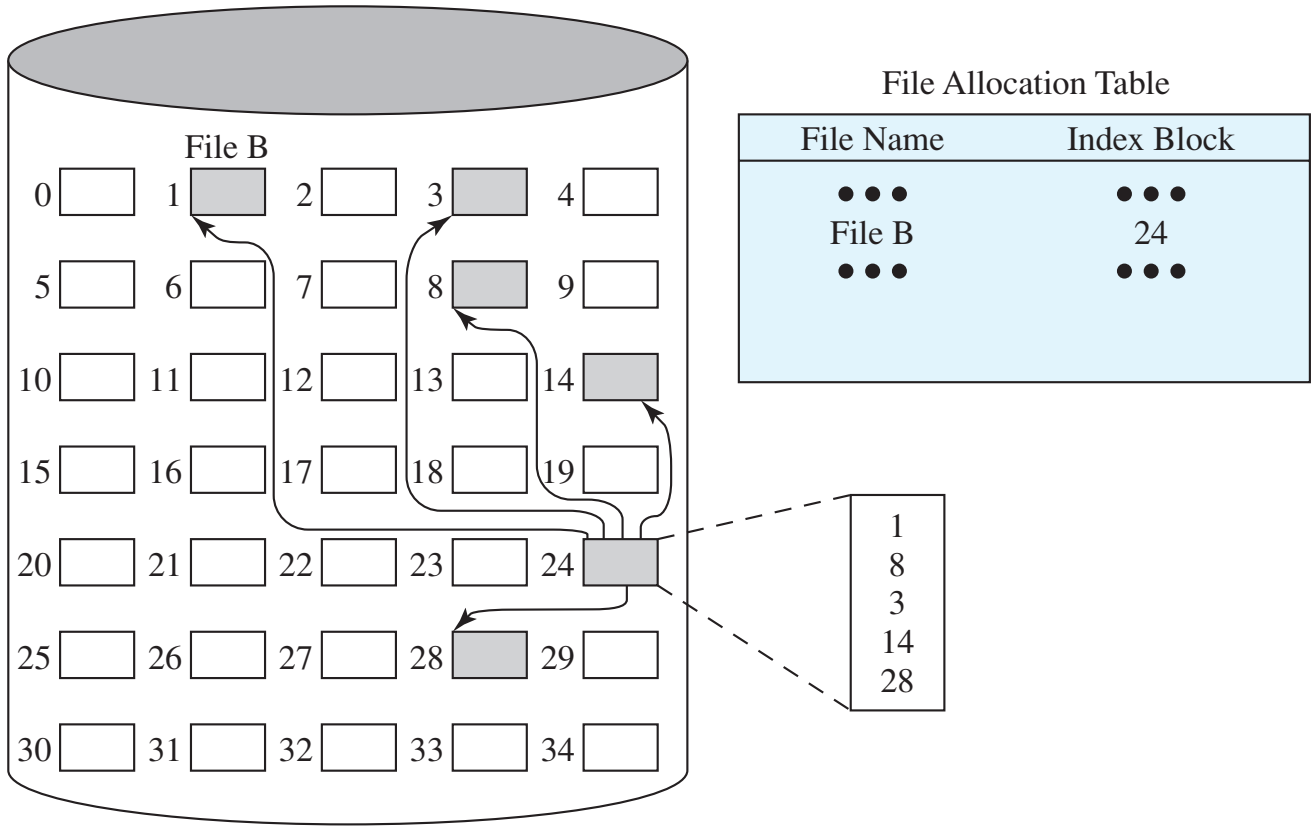
FAT: Linked list allocation with a table in RAM

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

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



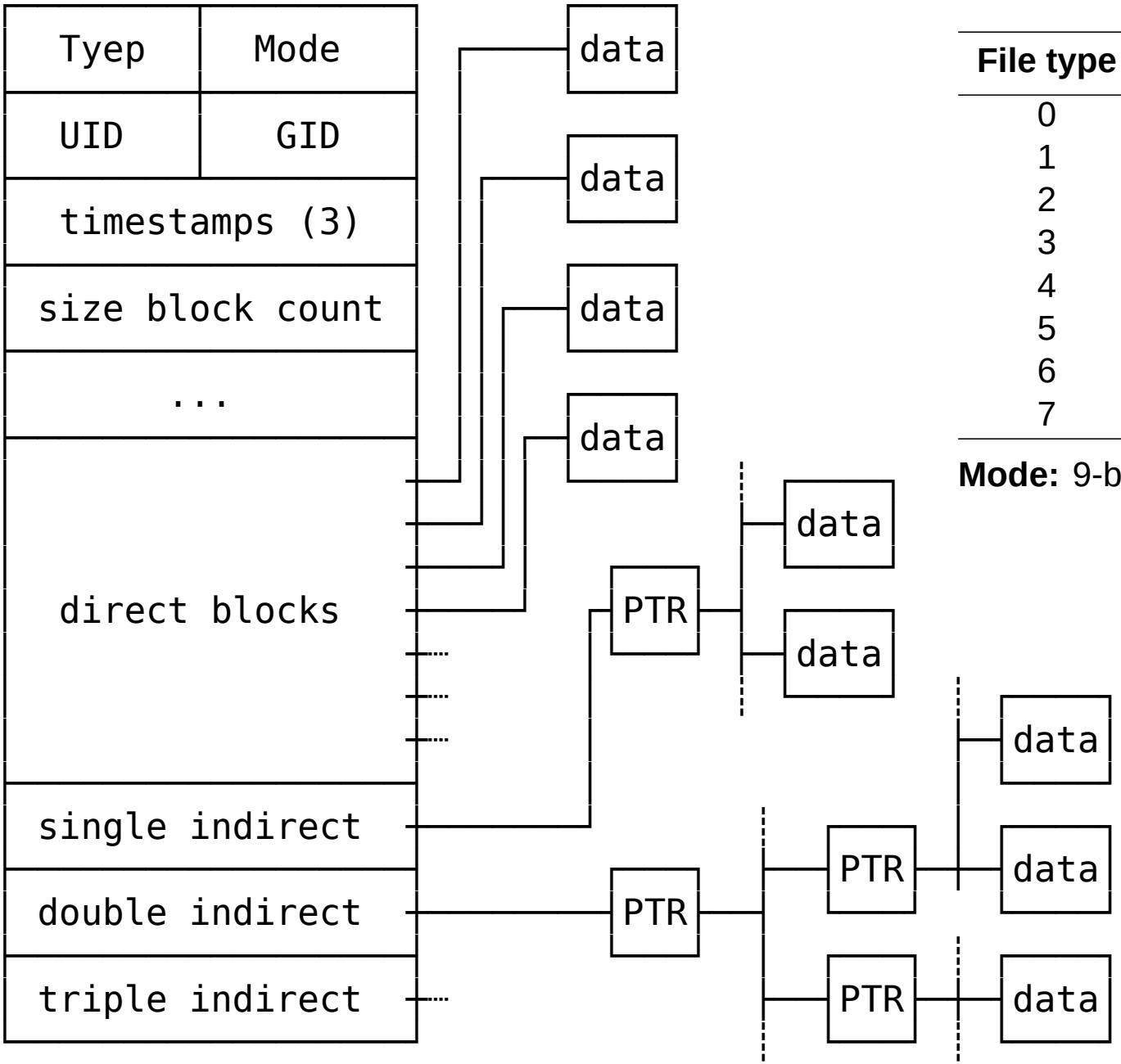
Indexed Allocation



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

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

I-node

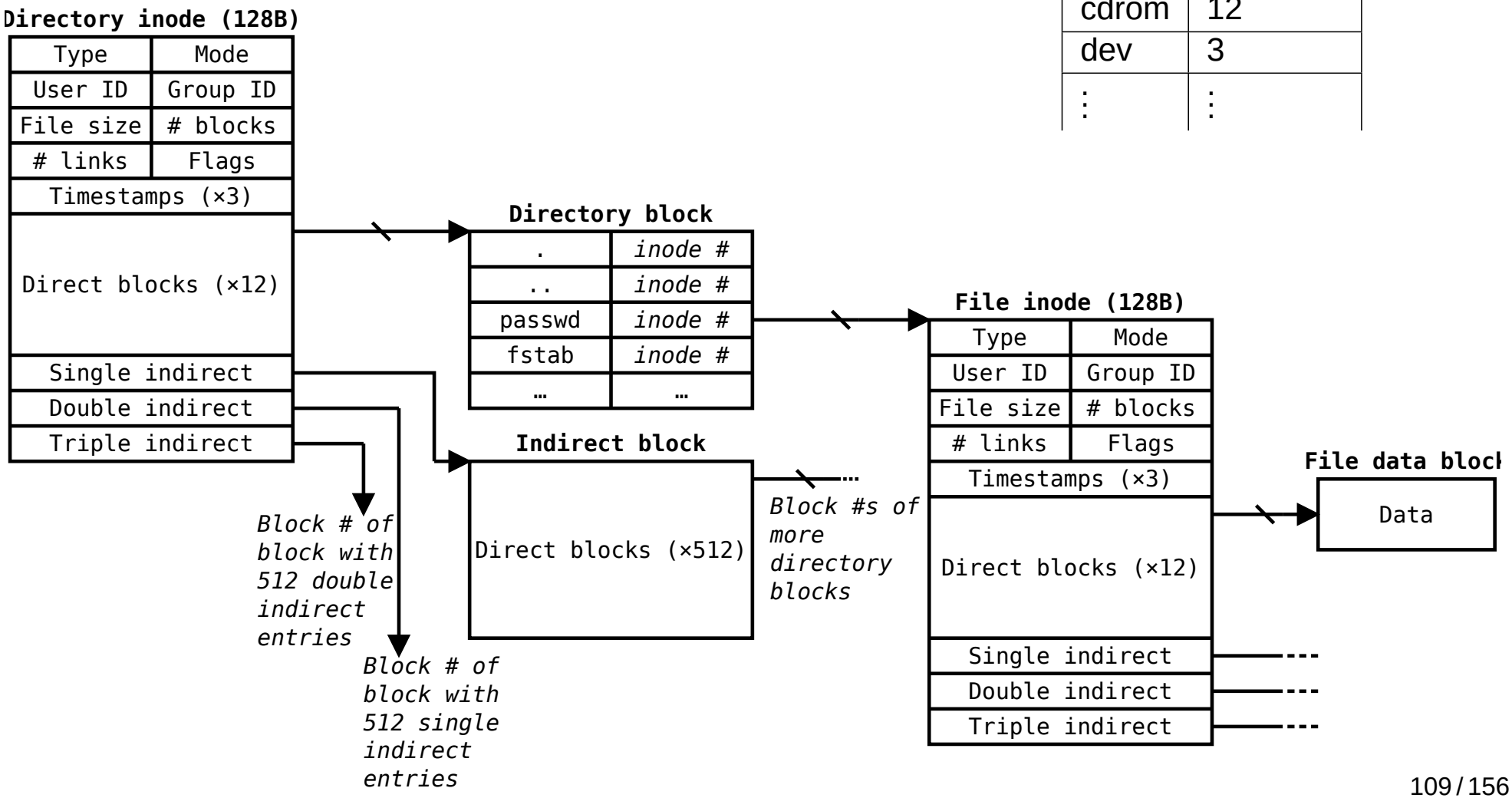


File type	Description
0	Unknown
1	Regular file
2	Directory
3	Character device
4	Block device
5	Named pipe
6	Socket
7	Symbolic link

Mode: 9-bit pattern

UNIX Treats a Directory as a File

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

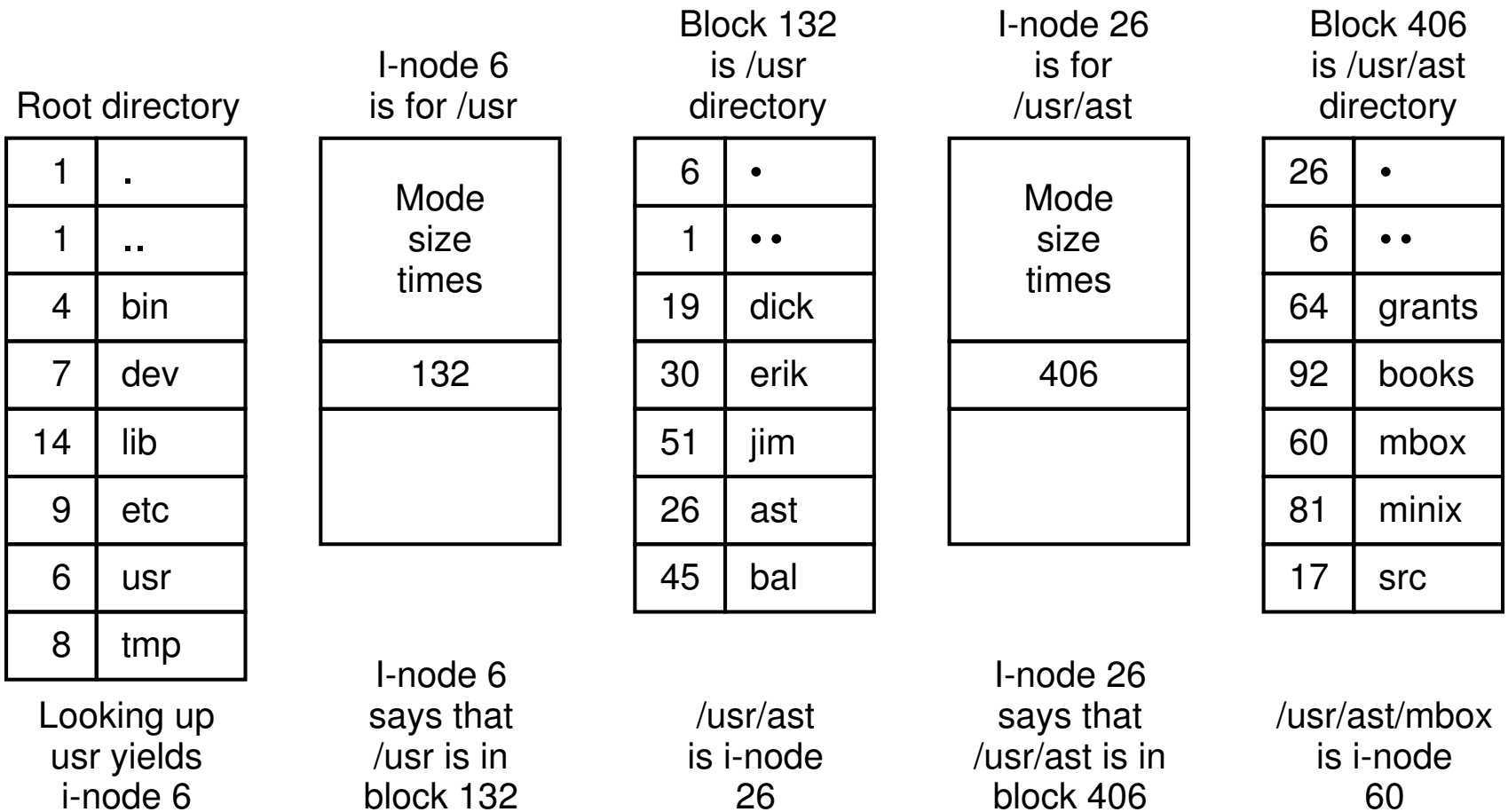


`open()`

Why? To avoid constant searching

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

The steps in looking up `/usr/ast/mbox`



`fd open(pathname, flags)`

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

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

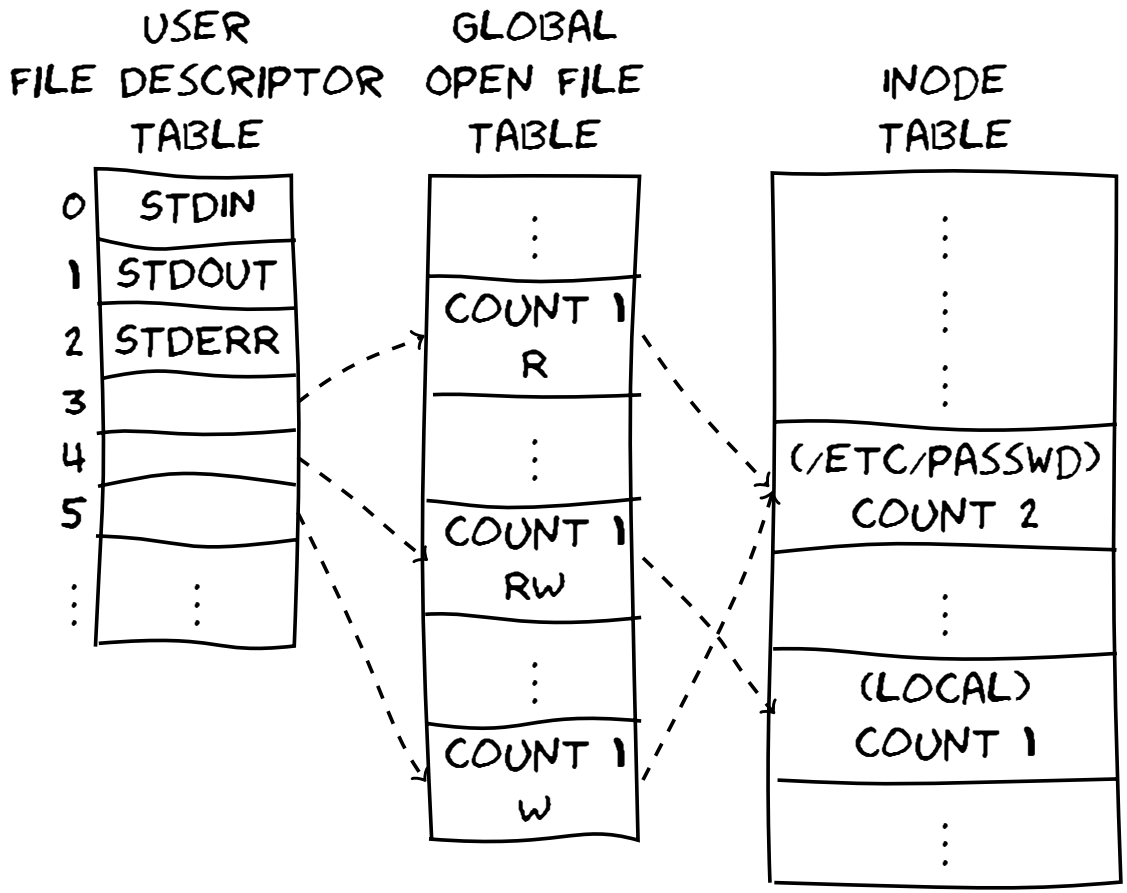
To see files opened by a process, e.g. `init`

```
$ lsof -p 1
```

```
$ man 2 open
```

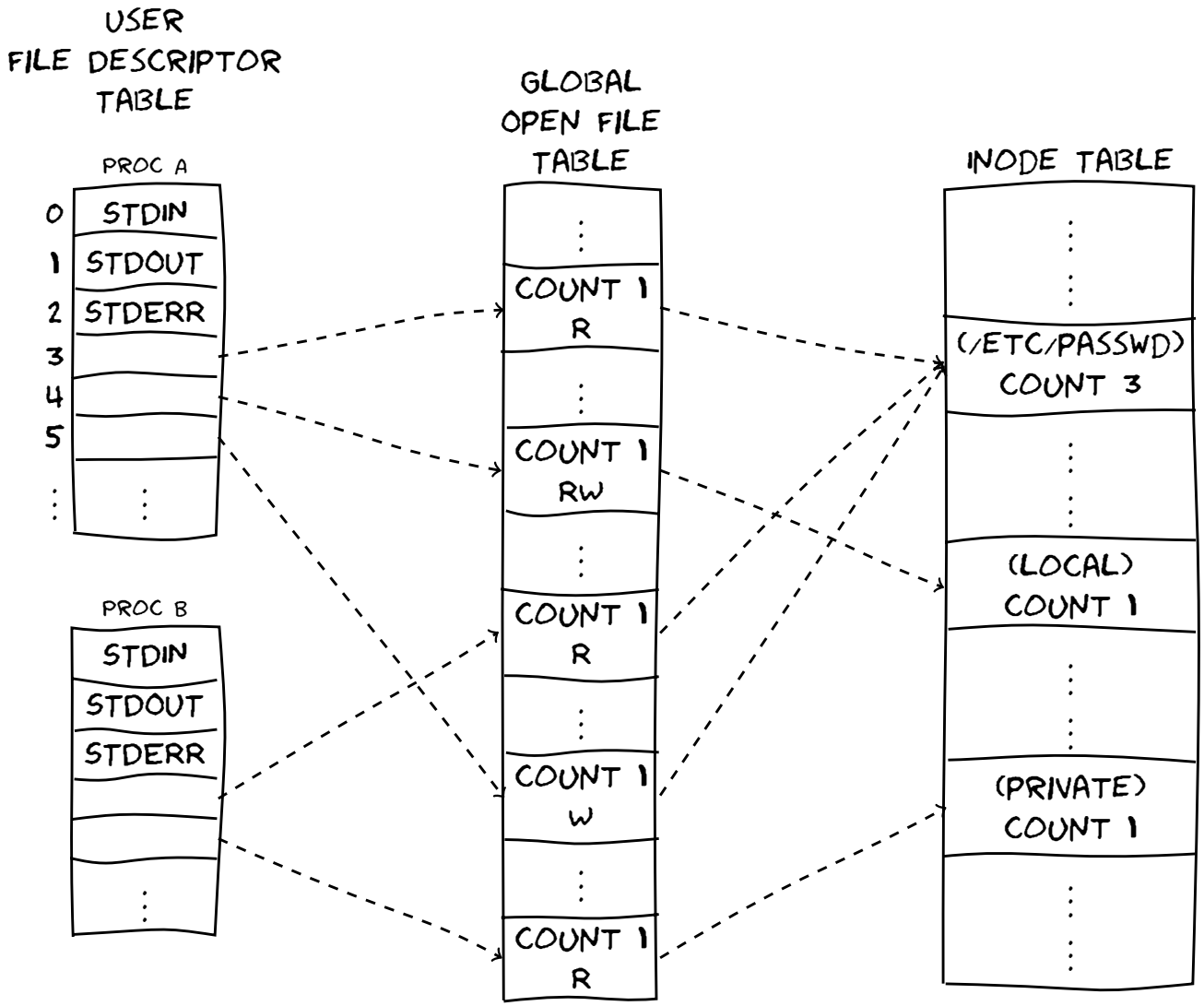
A process executes the following code:

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



One more process B:

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



write()

```c
#include <unistd.h>

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

  return 0;
}
```

```
$ 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;
}
```

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

cp

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

#define BUF_SIZE 4096    /* use a buffer size of 4096 bytes */
#define OUTPUT_MODE 0700 /* protection bits for output file */

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); /* open source file */

  if ( (out = creat(argv[2], OUTPUT_MODE)) < 0 ) exit(3); /* create destination file */

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

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

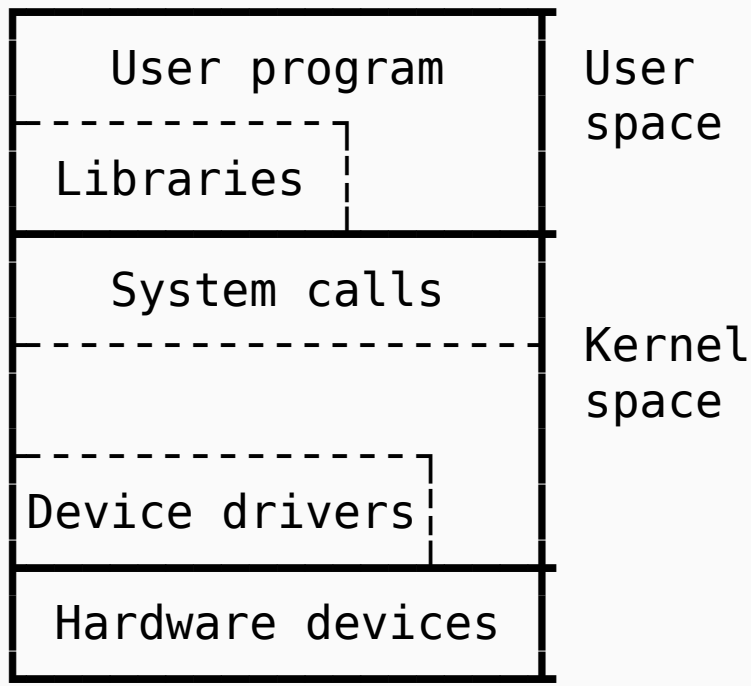
`stdio` — The Standard I/O Library

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

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

Avoid calling syscalls directly as much as you can

- Portability
- Buffered I/O



open() vs. fopen()

open()

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

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

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

  return 0;
}
```

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

fopen() — Buffered I/O

```c
#include <stdio.h>

int main(void)
{
  FILE *stream;

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

  while ( fgetc(stream) != EOF );

  fclose(stream);

  return 0;
}
```

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

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

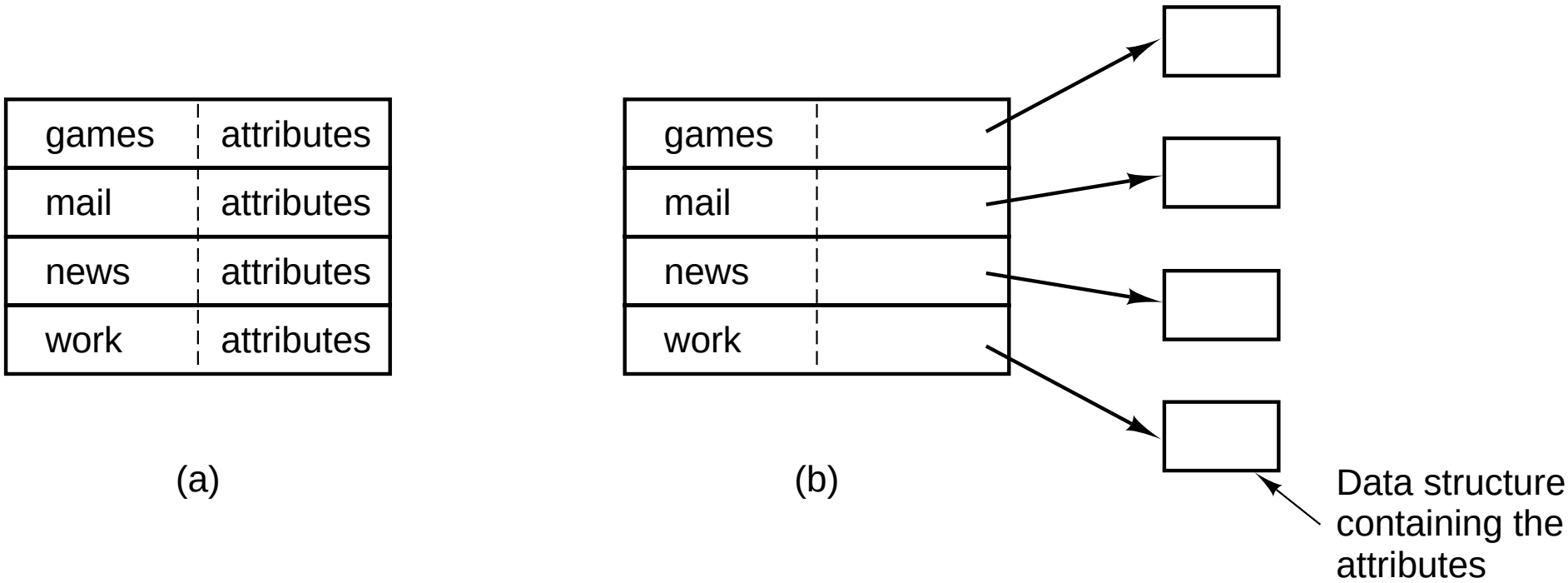
cp — With stdio

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

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

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

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

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

        return 0;
}
```

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

Directory

Implementing Directories



(a) A simple directory (Windows)

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

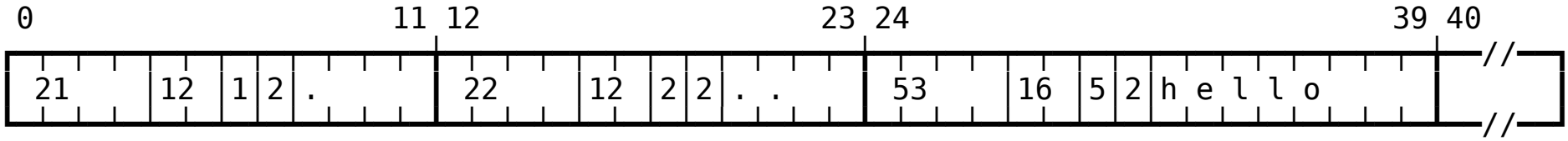
(b) Directory in which each entry just refers to an i-node (UNIX)

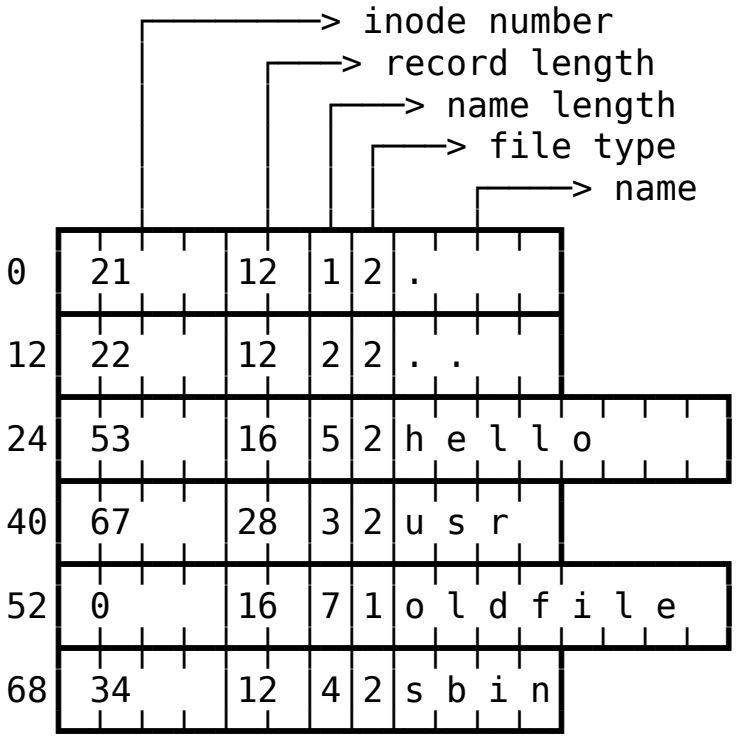
Directory entry in `glibc`

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

```
$ man readdir
$ view /usr/include/x86_64-linux-gnu/bits/dirent.h
```

Ext2 Directories





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

ls

```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;
}
```

The real `ls.c`?

116 A4 pages
5308 lines

Do one thing, and do it really well.

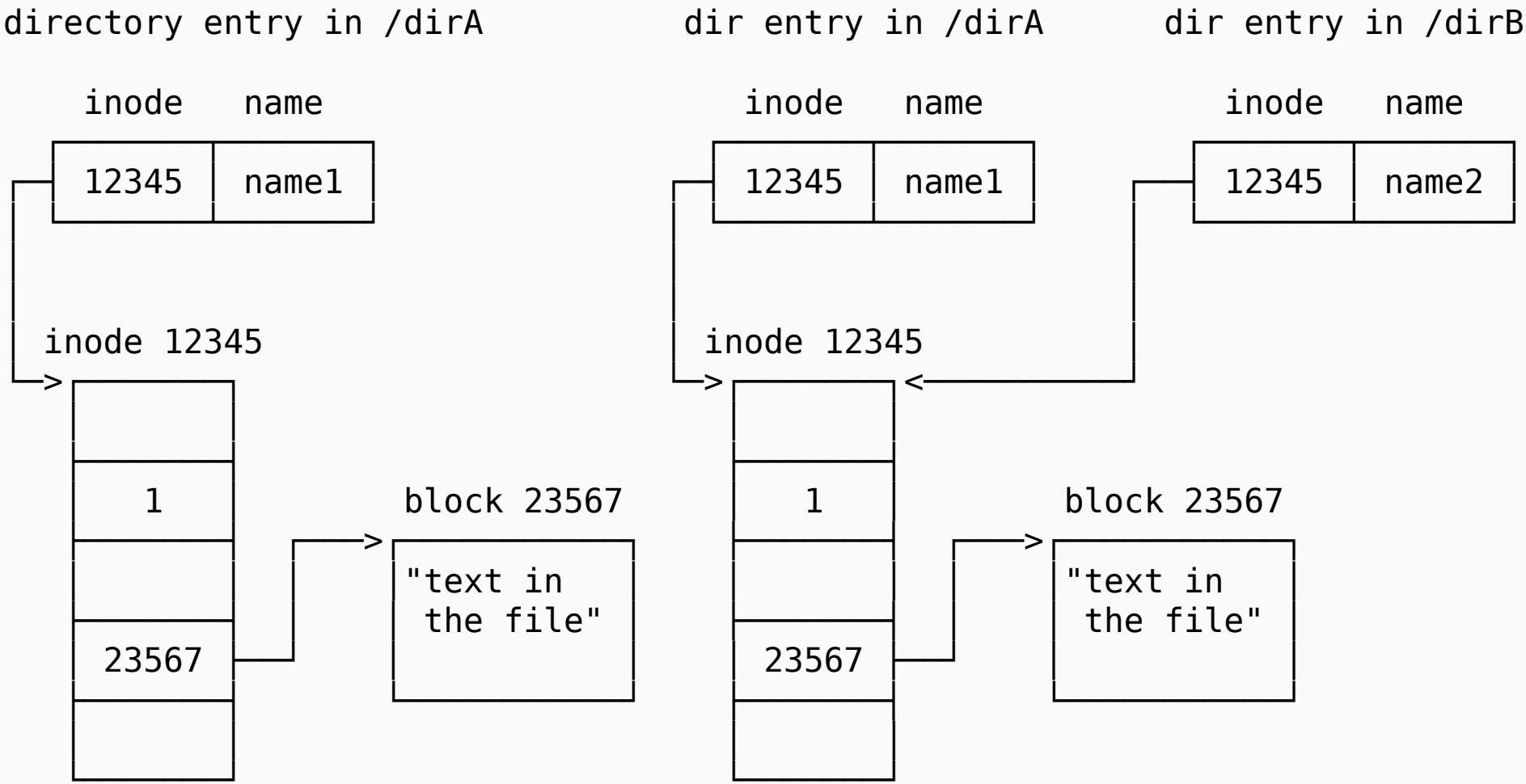
```
$ apt source coreutils
```

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

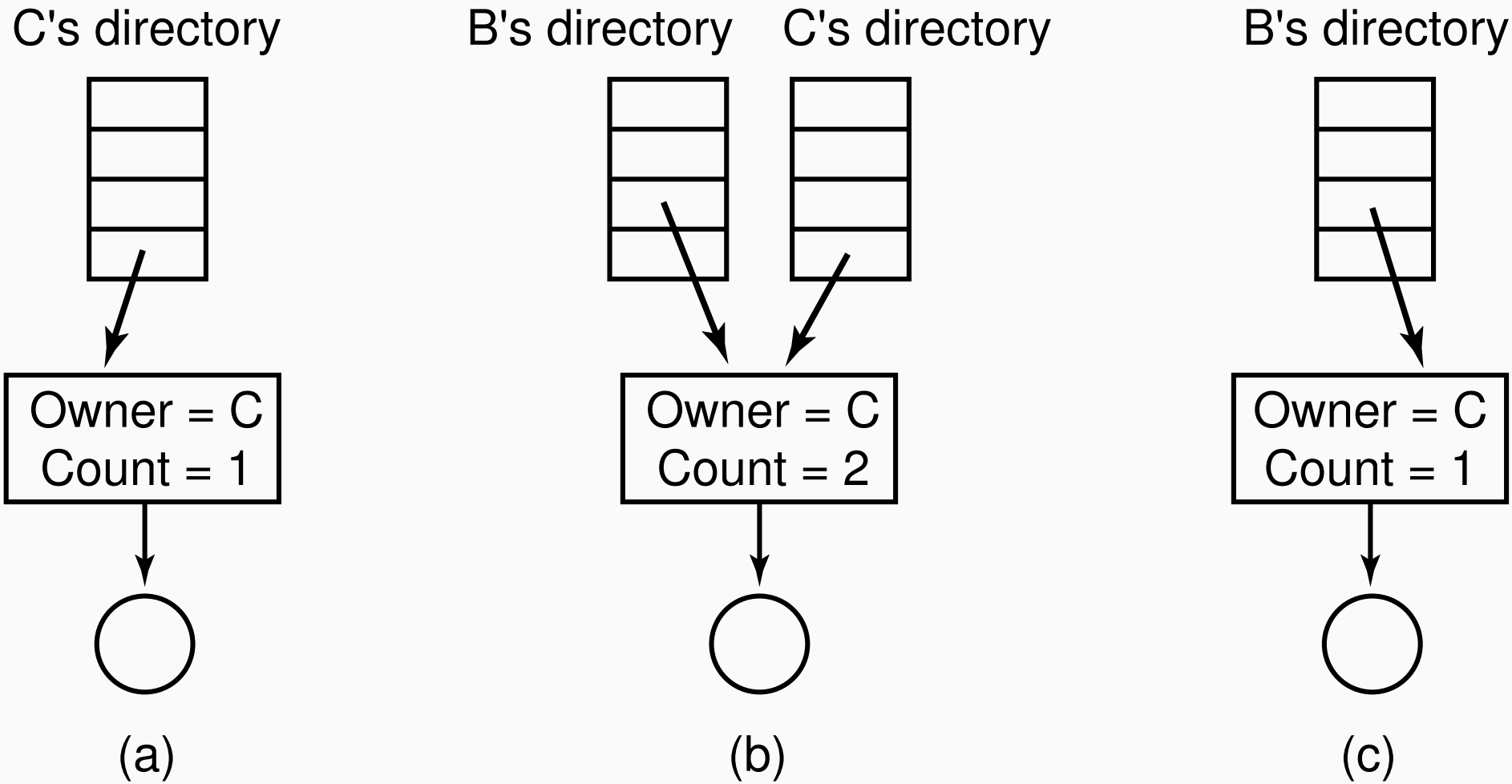
```c
#include <sys/stat.h>
#include <sys/types.h>
#include <unistd.h>
#include <stdio.h>

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;
}
```

Hard Links

Hard links ☛ the same inode

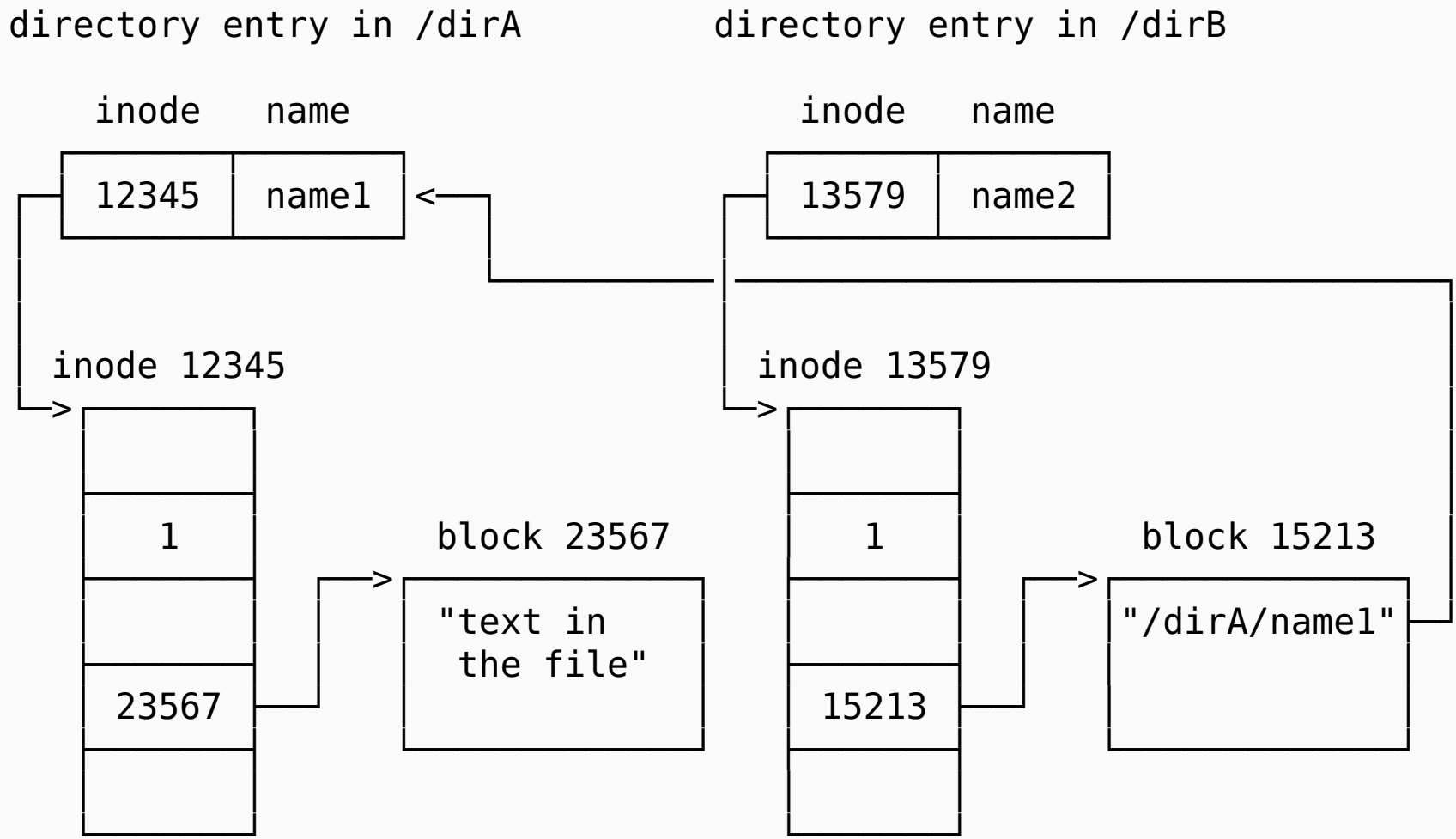


Drawback


C's directory
Owner = C
Count = 1
(a)
B's directory
C's directory
Owner = C
Count = 2
(b)
B's directory
Owner = C
Count = 1
(c)

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[])
{
  link(argv[1], argv[2]);
  perror(argv[0]);
  return 0;
}

/* symlink(argv[1], argv[2]); */
/* unlink(argv[1]); */
```

Processes and signals

Process

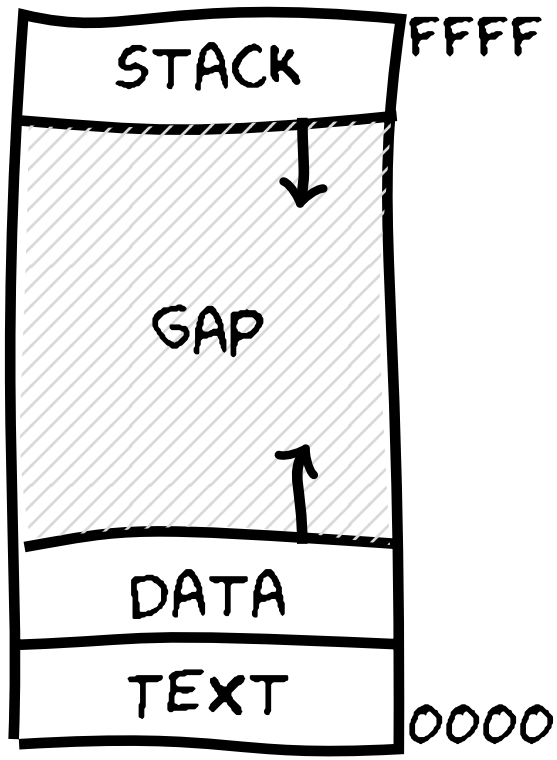
A process is an instance of a program in execution

Processes are like human beings:

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

A small difference:

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

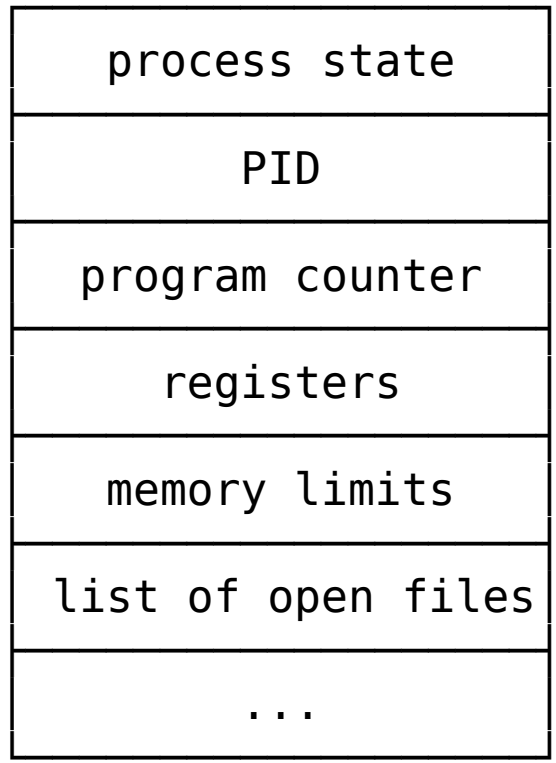


Process Control Block (PCB)

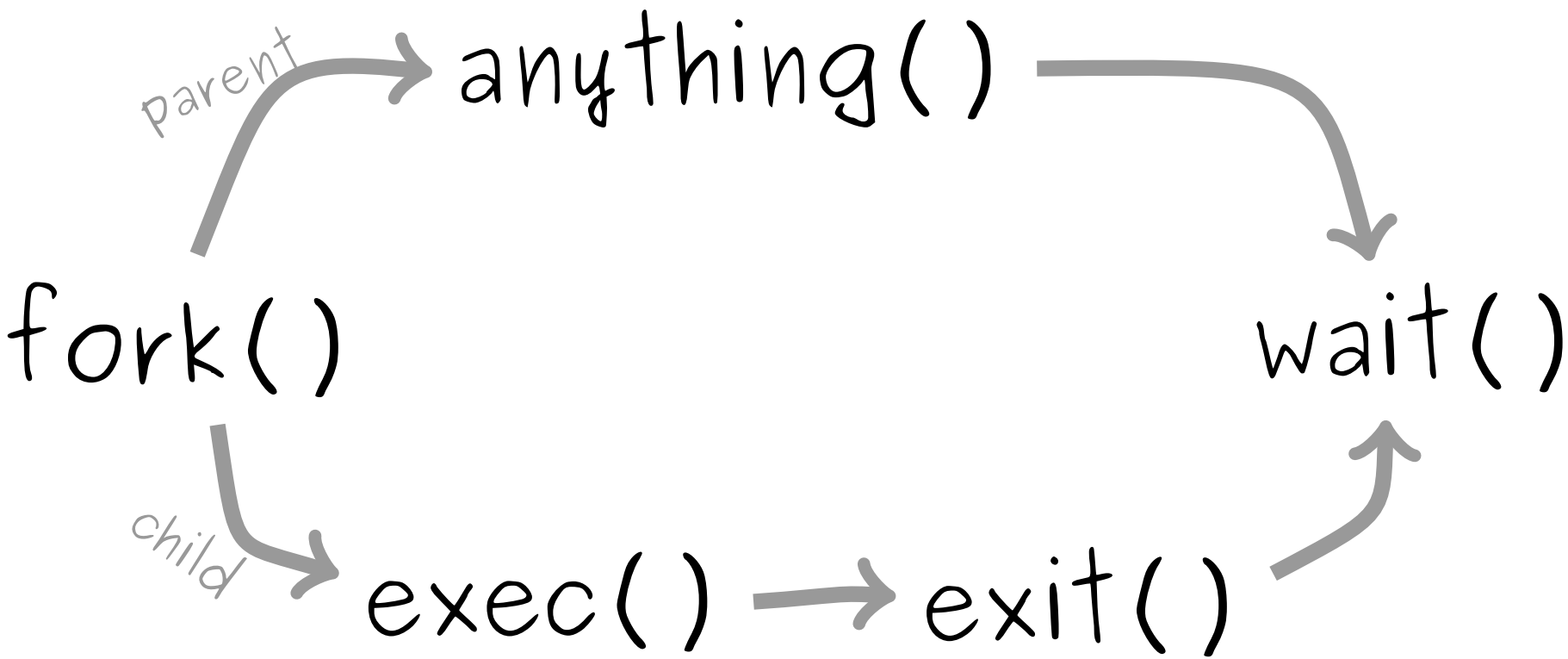
Implementation

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

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



Process 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)

Forking in C

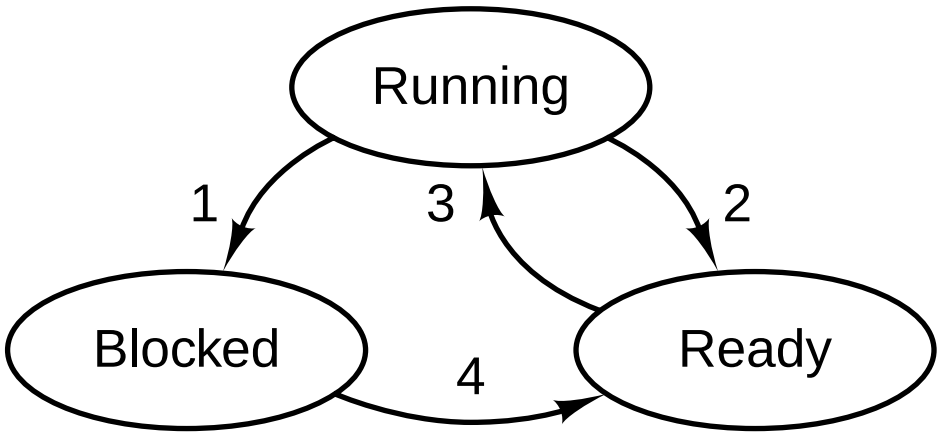
```c
#include <stdio.h>
#include <unistd.h>

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

```
$ man fork
```

exec()

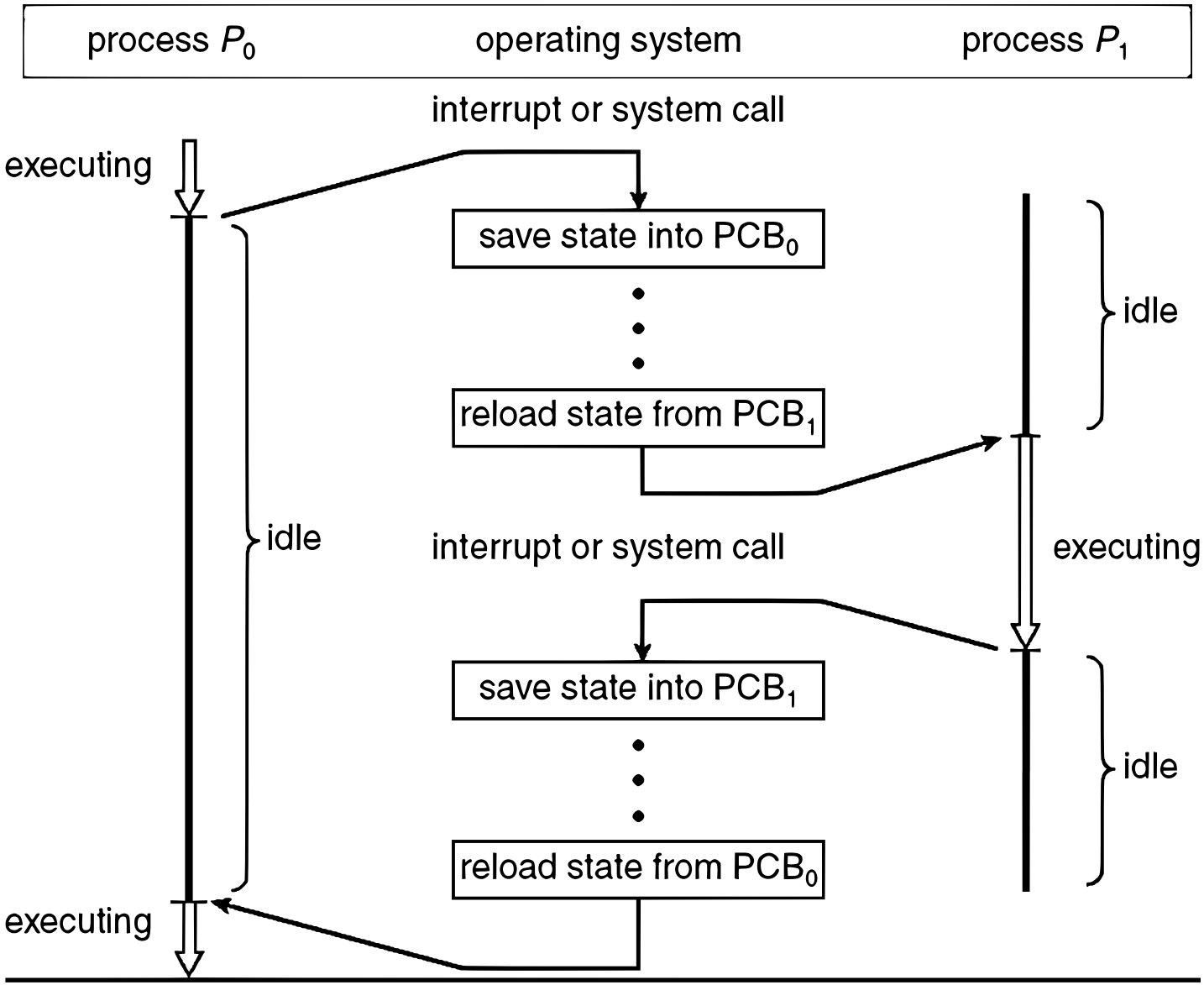
```c
int main()
{
  pid_t pid;
  /* fork another process */
  pid = fork();
  if (pid < 0) { /* error occurred */
    fprintf(stderr, "Fork Failed");
    exit(-1);
  }
  else if (pid == 0) { /* child process */
    execlp("/bin/ls", "ls", NULL);
  }
  else { /* parent process */
    /* wait for the child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

Process State Transition



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

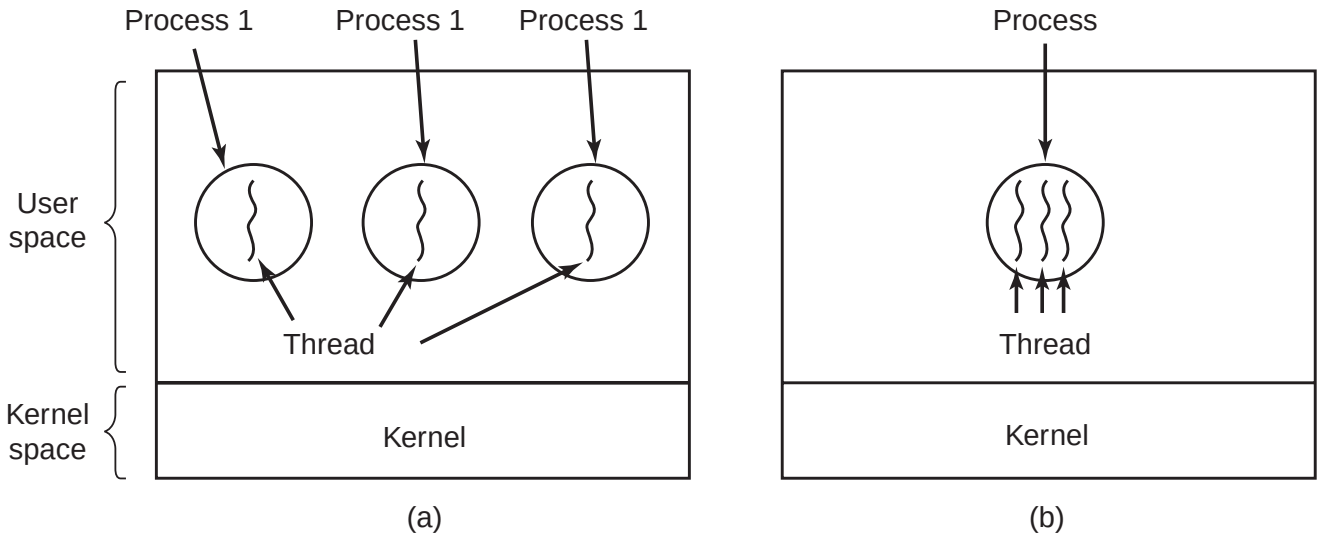
CPU Switch From Process To Process



Process vs. Thread

a single-threaded process = resource + execution

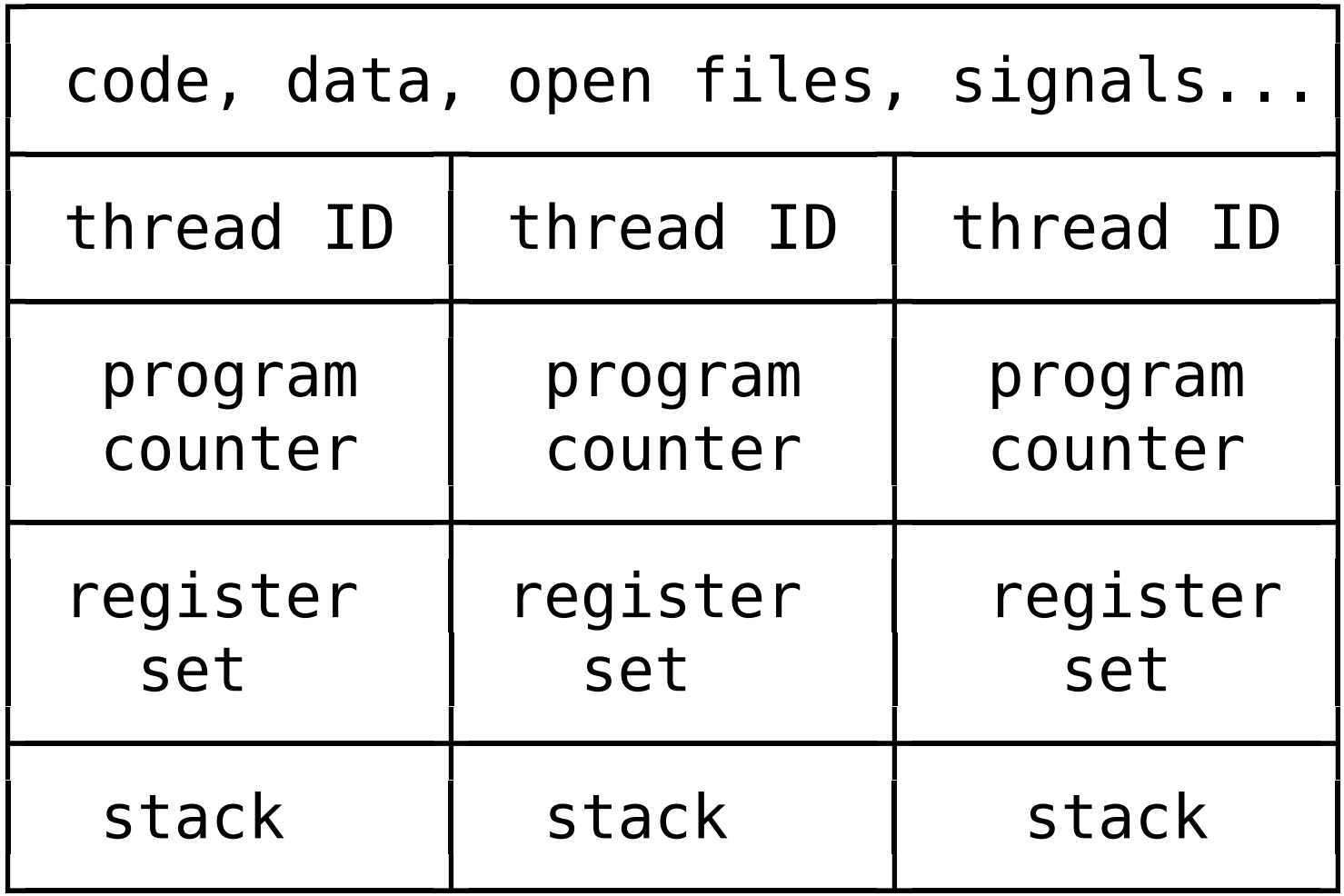
a multi-threaded process = resource + executions



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

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

Threads


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

POSIX Threads

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

Some of the Pthreads function calls

Thread call	Description
`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<20; i++ ){
    printf("Thread says hi!\n");
    sleep(1);
  }
  return NULL;
}

int main(void){
  pthread_t mythread;
  if(pthread_create(&mythread, NULL, thread_function, NULL)){
    printf("error creating thread.");
    abort();
  }

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

Pthreads

`pthread_t` defined in `pthread.h`, is often called a ”thread id” (`tid`);

`pthread_create()` returns zero on success and a non-zero value on failure;

`pthread_join()` returns zero on success and a non-zero value on failure;

How to use pthread?

- `#include<pthread.h>`

```
$ gcc thread1.c -o thread1 -pthread
$ ./thread1
```

Pthreads

Example 2

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

#define NUMBER_OF_THREADS 10

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

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

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

Linux Threads

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

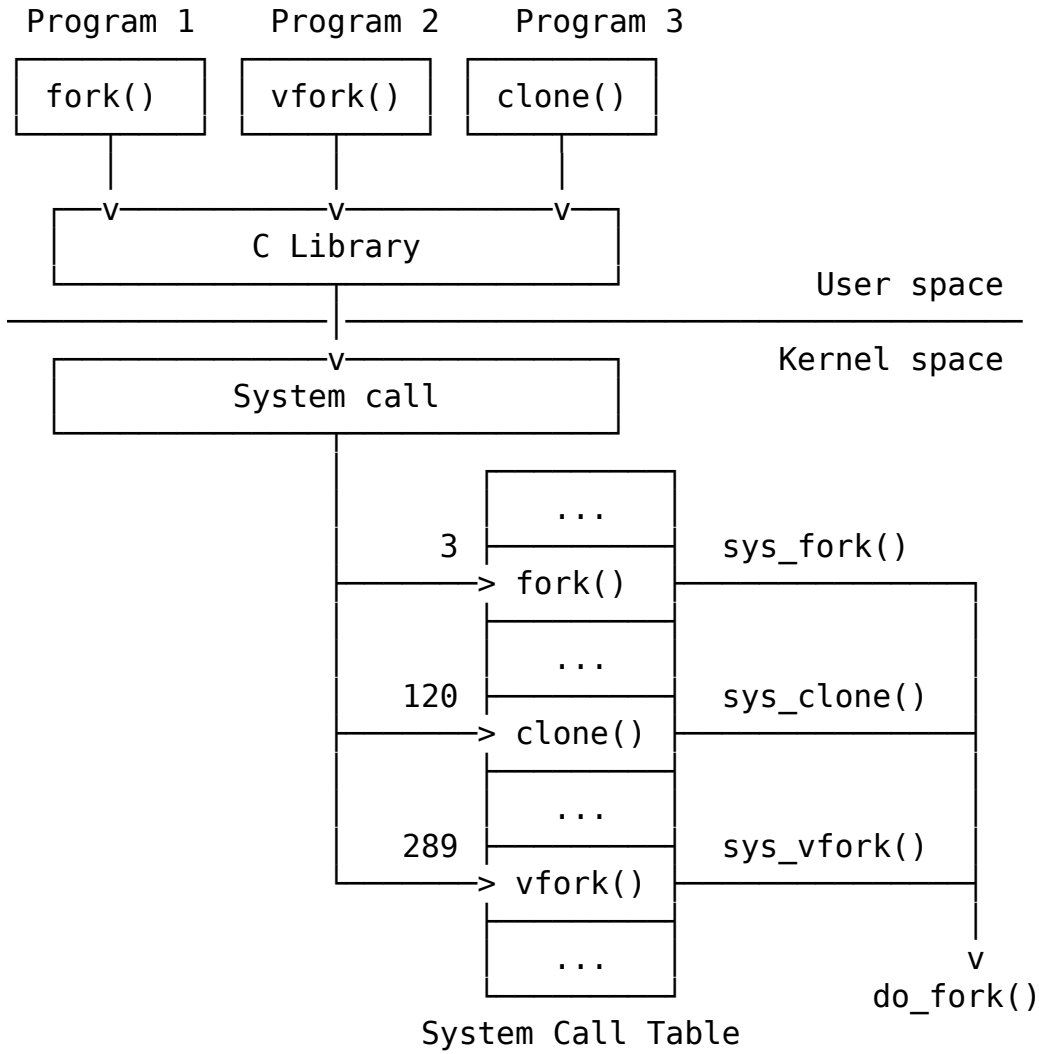
- Linux implements all threads as standard processes
- To Linux, a thread is merely a process that shares certain resources with other processes
- Some OS (MS Windows, Sun Solaris) have cheap threads and expensive processes.
- Linux processes are already quite lightweight

On a 75MHz Pentium

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

Linux Threads

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



clone()

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

- arg 1 the function to be executed, i.e. `fn(arg)`, which returns an `int`;
- arg 2 a pointer ☛ a (usually malloced) memory space to be used as the stack for the new thread;
- arg 3 a set of flags used to indicate how much the calling process is to be shared. In fact,

  `clone(0) == fork()`

- arg 4 the arguments passed to the function.

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

```
$ man clone
```

The `clone()` System Call

Some flags:

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

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

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

clone() Example

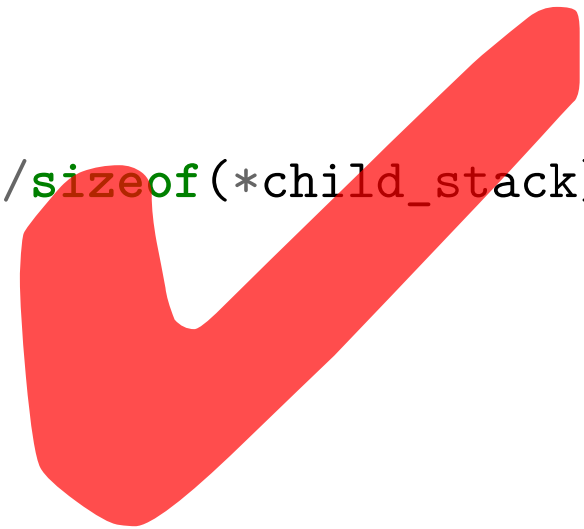
```c
#include <unistd.h>
#include <sched.h>
#include <sys/types.h>
#include <stdlib.h>
#include <string.h>
#include <stdio.h>
#include <fcntl.h>

int variable;

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

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

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

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

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

clone() Example

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

int variable;

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

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

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

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

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

Stack Grows Downwards

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



IPC

User Interface

Dialog, Zenity

Ncurses

GTK+

Qt

Terminal

IDE