

CS02

# themes

automating building software

- libraries, taking advantage of incremental compilation

sharing machines

- multiple users/programs on one system

parallelism and concurrency

- doing two+ things at once

under the hood of sockets

- layered design of networks

- implementing secure communication

under the hood of fast processors

- caching, (hidden) parallelism, avoiding idle time

# themes

## automating building software

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## sharing machines

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## under the hood of fast processors

- caching, (hidden) parallelism, avoiding idle time

# make

```
$ ./foo.exe
```

```
...
```

```
...
```

```
$ edit readline.c
```

```
$ make
```

```
clang -g -O -Wall -c readline.c -o readline.o
```

```
ar rcs terminal.o readline.o libreadline.a
```

```
clang -o foo.exe foo.o foo-utility.o -L. -lreadline
```

```
$
```

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# address translation



# address translation



# address translation



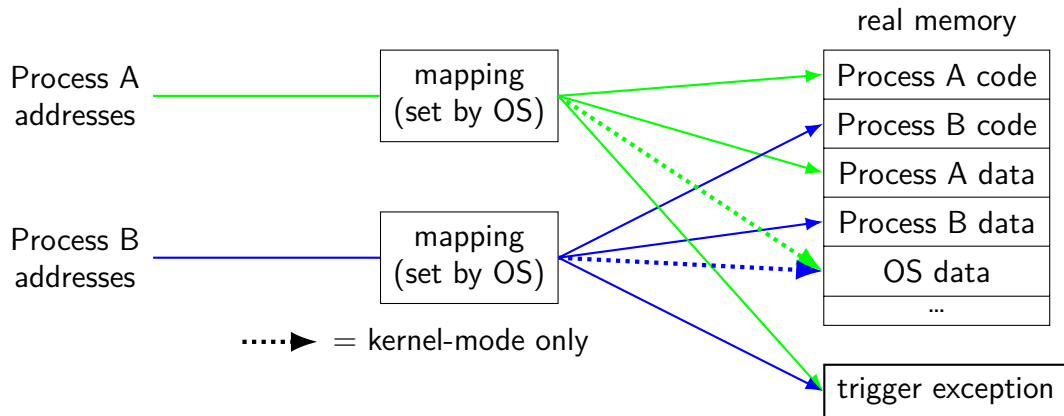


# address translation



# address spaces

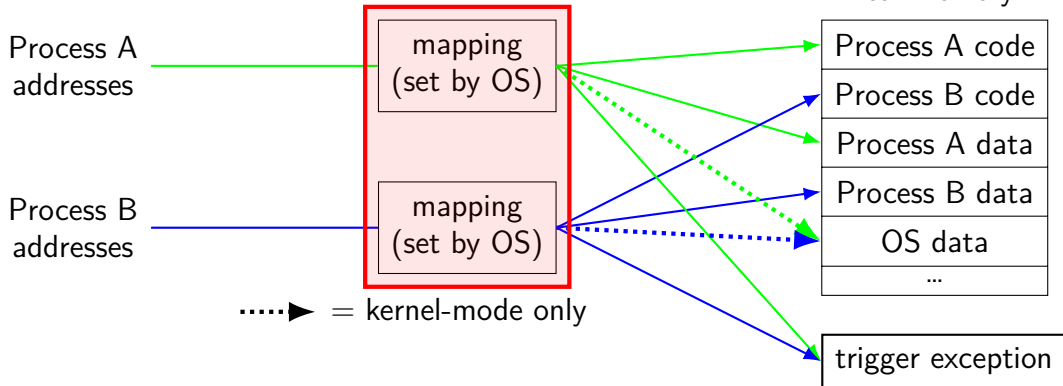
illusion of **dedicated memory**



# address spaces

illusion of **dedicated memory**

chose one during context switch



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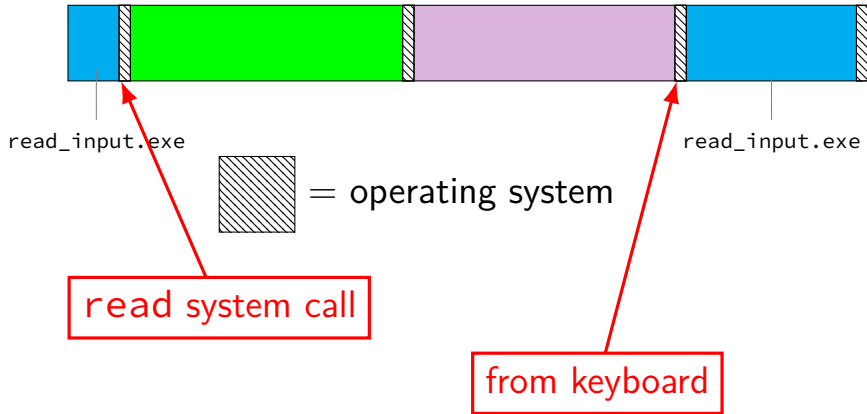
layered design of networks

implementing secure communication

under the hood of fast processors

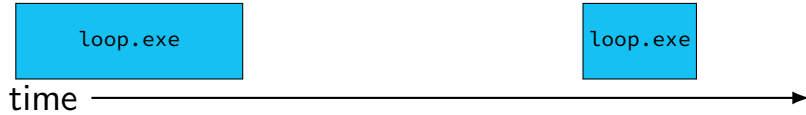
caching, (hidden) parallelism, avoiding idle time

# keyboard input timeline



# time multiplexing

processor:



# time multiplexing

processor:



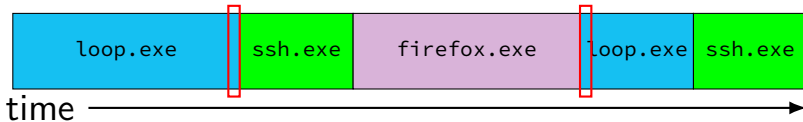
```
...  
loop: ...  
    ...  
    jmp loop  
loop: ...  
    ...
```

million cycle delay

```
    ...  
    jmp loop  
loop: ...  
    ...
```

# time multiplexing

processor:



```
...  
loop: ...  
    ...  
    jmp loop  
loop: ...  
    ...
```

million cycle delay

```
...  
    jmp loop  
loop: ...  
    ...
```



# multiple cores+threads

core 1:



core 2:



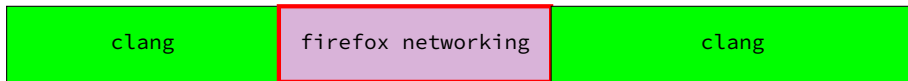
multiple cores? each core still divided up

# multiple cores+threads

core 1:



core 2:



one program with multiple *threads*

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# permissions

```
$ ls /u/other/secret
```

```
ls: cannot open directory '/u/other/secret': Permission denied
```

```
$ shutdown
```

```
shutdown: Permission denied
```

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# layers

|             |                      |   |
|-------------|----------------------|---|
| application | HTTP, SSH, SMTP, ... | application-defined meanings                            |
| transport   | TCP, UDP, ...        | reach      correct      program,<br>reliability/streams |
| network     | IPv4, IPv6, ...      | reach      correct      machine<br>(across networks)    |
| link        | Ethernet, Wi-Fi, ... | coordinate shared wire/radio                            |
| physical    | ...                  | encode bits for wire/radio                              |

# layers terminology

|             |   |                    |
|-------------|---|--------------------|
| application | application-defined meanings                            |                    |
| transport   | reach      correct      program,<br>reliability/streams | segments/datagrams |
| network     | reach      correct      machine<br>(across networks)    | packets            |
| link        | coordinate shared wire/radio                            | frames             |
| physical    | encode bits for wire/radio                              |                    |

# names and addresses

| name                                 | address                               |
|--------------------------------------|---------------------------------------|
| logical identifier                   | location/how to locate                |
| variable counter                     | memory address 0x7FFF9430             |
| DNS name www.virginia.edu            | IPv4 address 128.143.22.36            |
| DNS name mail.google.com             | IPv4 address 216.58.217.69            |
| DNS name mail.google.com             | IPv6 address 2607:f8b0:4004:80b::2005 |
| DNS name reiss-t3620.cs.virginia.edu | IPv4 address 128.143.67.91            |
| DNS name reiss-t3620.cs.virginia.edu | MAC address 18:66:da:2e:7f:da         |
| service name https                   | port number 443                       |
| service name ssh                     | port number 22                        |



# secure communication?

how do you know who your socket is to?

who can read what's on the socket?

what can you do to restrict this?

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# 2004 CPU

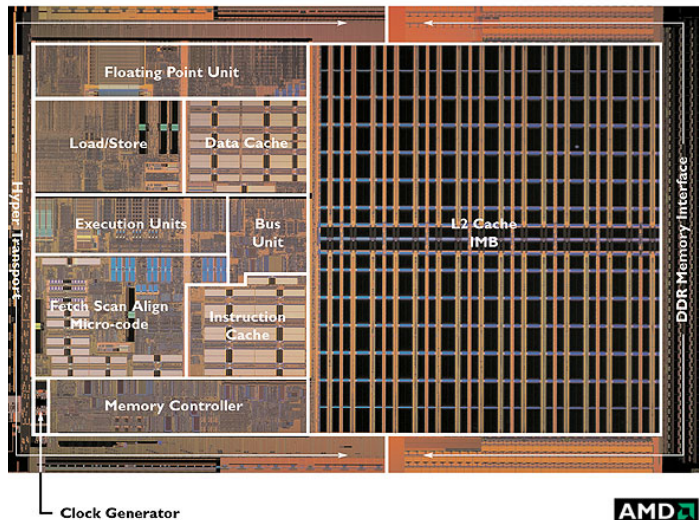


Image: approx 2004 AMD press image of Opteron die;  
approx register location via [chip-architect.org](http://chip-architect.org) (Hans de Vries)

# 2004 CPU

▲ Registers

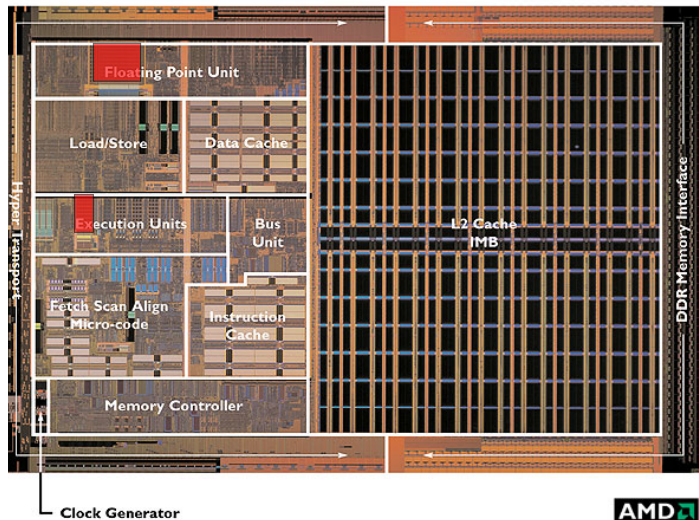


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approx register location via [chip-architect.org](http://chip-architect.org) (Hans de Vries)

# 2004 CPU

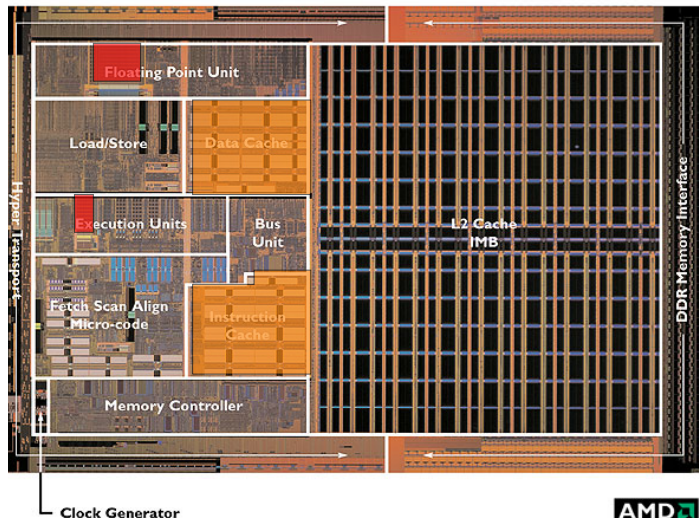


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# 2004 CPU



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# 2004 CPU

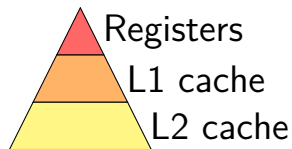


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# 2004 CPU

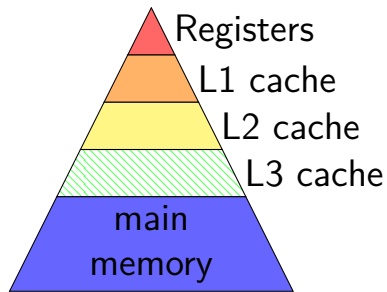
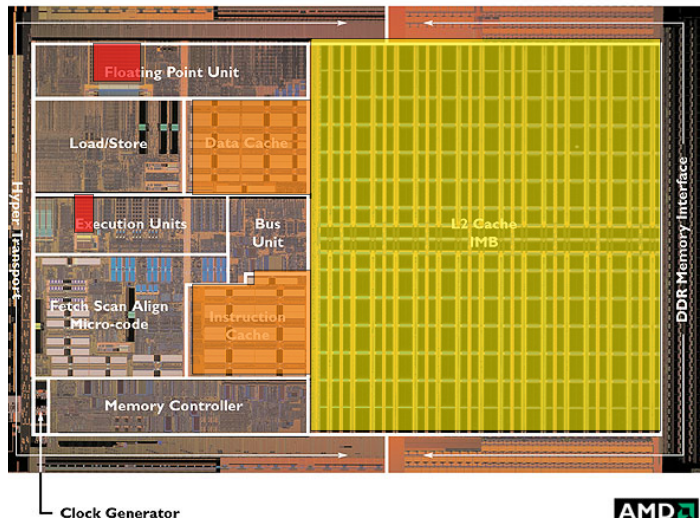
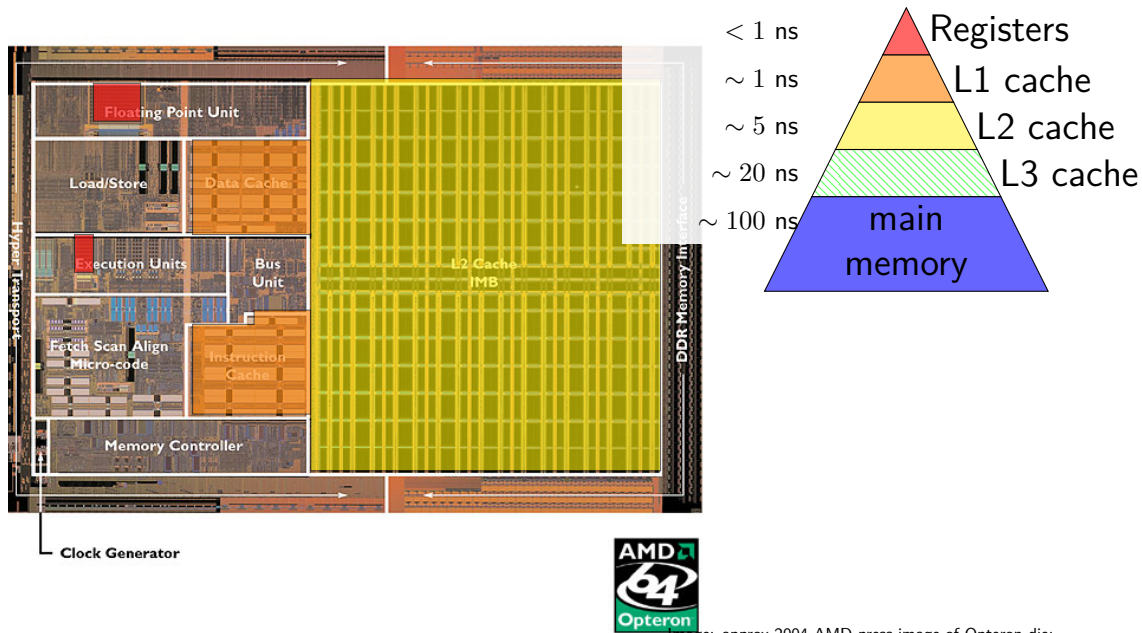


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# 2004 CPU



## some performance examples

```
example1:  
    movq $1000000000000, %rax  
loop1:  
    addq %rbx, %rcx  
    decq %rax  
    jge loop1  
    ret
```

about 30B instructions  
my desktop: approx 2.65 sec

```
example2:  
    movq $1000000000000, %rax  
loop2:  
    addq %rbx, %rcx  
    addq %r8, %r9  
    decq %rax  
    jge loop2  
    ret
```

about 40B instructions  
my desktop: approx 2.65 sec

## some performance examples

```
example1:  
    movq $1000000000000, %rax  
loop1:  
    addq %rbx, %rcx  
    decq %rax  
    jge loop1  
    ret
```

about 30B instructions

my desktop: approx 2.65 sec

```
example2:  
    movq $1000000000000, %rax  
loop2:  
    addq %rbx, %rcx  
    addq %r8, %r9  
    decq %rax  
    jge loop2  
    ret
```

about 40B instructions

my desktop: approx 2.65 sec

## C exercise

```
int array[4] = {10,20,30,40};  
int *p;  
p = &array[0];  
p += 2;  
p[1] += 1;
```

array =

- |                             |                  |
|-----------------------------|------------------|
| A. compile or runtime error | B. {10,20,30,41} |
| C. {10,20,32,41}            | D. {10,21,30,40} |
| E. {12,21,30,40}            | F. none of these |

## C exercise (2)

```
int *array2[4]; int array1[4] = {10,20,30,40};
void mystery(int **p) {
    *p = &array1[2];
}
int main() {
    int **q;
    q = array2;
    mystery(q);
    array1[1] = *q;
    ...
}
```

array1 =

- |                             |                  |
|-----------------------------|------------------|
| A. compile or runtime error | B. {10,10,30,40} |
| C. {10,30,30,40}            | D. {10,10,20,30} |
| E. {10,20,10,20}            | F. none of these |

# some avenues for review

review CSO1 stuff

labs 9–12 (of last Fall)

<https://researcher111.github.io/uva-cso1-F23-DG/>

exercises we've used in the past:

implement strsep library function

implement conversion from dynamic array to linked list

## some pointer stuff

0x040

0x038

0x030

0x028

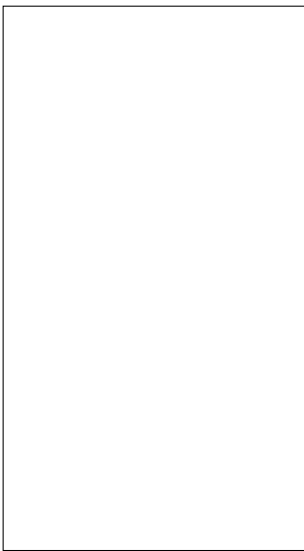
0x020

0x018

0x010

0x008

0x000



```
int array[3]={0x12,0x45,0x67};  
int single = 0x78;  
int *ptr;
```

## some pointer stuff

0x040

0x038

0x030

0x028

0x020

0x018

0x010

0x008

0x000

|                |
|----------------|
|                |
| array[2]: 0x67 |
| array[1]: 0x45 |
| array[0]: 0x12 |
| single: 0x78   |
| ptr = ???      |
|                |
|                |
|                |
|                |
|                |
|                |
|                |

```
int array[3]={0x12,0x45,0x67};  
int single = 0x78;  
int *ptr;
```



## some pointer stuff

0x040

0x038

0x030

0x028

0x020

0x018

0x010

0x008

0x000

|                |
|----------------|
|                |
| array[2]: 0x67 |
| array[1]: 0x45 |
| array[0]: 0x12 |
| single: 0x78   |
| ptr = ???      |
|                |
|                |
|                |
|                |
|                |
|                |
|                |
|                |

```
int array[3]={0x12,0x45,0x67};  
int single = 0x78;  
int *ptr;
```

~~\*ptr = 0xAB;~~ runtime error

## some pointer stuff

|       |                |
|-------|----------------|
| 0x040 |                |
| 0x038 |                |
| 0x030 | array[2]: 0x67 |
|       | array[1]: 0x45 |
|       | array[0]: 0x12 |
| 0x028 | single: 0x78   |
|       | ptr: 0x28      |
| 0x020 |                |
| 0x018 |                |
| 0x010 |                |
| 0x008 |                |
| 0x000 |                |

```
int array[3]={0x12,0x45,0x67};  
int single = 0x78;  
int *ptr;
```

```
ptr = &single;
```

```
ptr = (int*) 0x28;  addr. of single
```

## some pointer stuff

|       |                |
|-------|----------------|
| 0x040 |                |
| 0x038 |                |
| 0x030 | array[2]: 0x67 |
|       | array[1]: 0x45 |
|       | array[0]: 0x12 |
| 0x028 | single: 0x78   |
|       | ptr: 0x28      |
| 0x020 |                |
| 0x018 |                |
| 0x010 |                |
| 0x008 |                |
| 0x000 |                |

```
int array[3]={0x12,0x45,0x67};  
int single = 0x78;  
int *ptr;
```

```
ptr = &single;  
ptr = (int*) 0x28;    addr. of single
```

~~ptr = 0x28; compile error~~

~~ptr = (int\*) single;~~  
pointer to unknown place

## some pointer stuff

|       |                |
|-------|----------------|
| 0x040 |                |
| 0x038 | array[2]: 0x67 |
|       | array[1]: 0x45 |
| 0x030 | array[0]: 0x12 |
| 0x028 | single: 0xFF   |
|       | ptr: 0x28      |
| 0x020 |                |
| 0x018 |                |
| 0x010 |                |
| 0x008 |                |
| 0x000 |                |

```
int array[3]={0x12,0x45,0x67};  
int single = 0x78;  
int *ptr;  
ptr = &single;
```

```
*ptr = 0xFF;
```

## some pointer stuff

|       |                |
|-------|----------------|
| 0x040 |                |
| 0x038 |                |
| 0x030 | array[2]: 0x67 |
|       | array[1]: 0x45 |
|       | array[0]: 0x12 |
| 0x028 | single: 0x78   |
|       | ptr: 0x2C      |
| 0x020 |                |
| 0x018 |                |
| 0x010 |                |
| 0x008 |                |
| 0x000 |                |

```
int array[3]={0x12,0x45,0x67};  
int single = 0x78;  
int *ptr;
```

```
ptr = array;  
ptr = &array[0];  
ptr = (int*) 0x2C;
```

## some pointer stuff

|       |                |
|-------|----------------|
| 0x040 |                |
| 0x038 |                |
| 0x030 | array[2]: 0x67 |
|       | array[1]: 0x45 |
|       | array[0]: 0x12 |
| 0x028 | single: 0x78   |
|       | ptr: 0x2C      |
| 0x020 |                |
| 0x018 |                |
| 0x010 |                |
| 0x008 |                |
| 0x000 |                |

```
int array[3]={0x12,0x45,0x67};  
int single = 0x78;  
int *ptr;
```

```
ptr = array;  
ptr = &array[0];  
ptr = (int*) 0x2C;
```

~~ptr = array[0]; compile error~~

~~ptr = (int\*) array[0];~~

pointer to unknown place

## some pointer stuff

0x040

0x038

0x030

0x028

0x020

0x018

0x010

0x008

0x000

|                |
|----------------|
|                |
| array[2]: 0xFF |
| array[1]: 0x45 |
| array[0]: 0x12 |
| single: 0x78   |
| ptr: 0x2C      |
|                |
|                |
|                |
|                |
|                |
|                |
|                |
|                |

```
int array[3]={0x12,0x45,0x67};  
int single = 0x78;  
int *ptr;  
ptr = &array[0];
```

```
ptr[2] = 0xFF;  
*(ptr + 2) = 0xFF;
```

```
int *temp1; temp1 = ptr + 2;  
*temp1 = 0xFF;
```

```
int *temp2; temp2 = &ptr[2];  
*temp2 = 0xFF;
```

## some pointer stuff

|       |                |
|-------|----------------|
| 0x040 |                |
| 0x038 |                |
| 0x030 | array[2]: 0x67 |
|       | array[1]: 0x45 |
|       | array[0]: 0x12 |
| 0x028 | single: ...    |
|       | ptr: 0x2C      |
| 0x020 |                |
| 0x018 |                |
| 0x010 |                |
| 0x008 |                |
| 0x000 |                |

```
int array[3]={0x12,0x45,0x67};  
int single = 0x78;  
int *ptr;
```

```
void change_arg(int *x) {  
    *x = compute_some_value();  
}  
...  
change_arg(&single);
```



## two sections

Skadron's section [12:30p] and Reiss's [2p]

same labs, homeworks, [probably] quizzes

tentatively mostly separate lectures

(some exceptions when we have travel/other conflicts)

# labs

attend lab in person and get checked off by TA, *or*

(most labs) submit something to submission site and we'll grade it

submit to submission site? don't care if you attend the lab

more strict about submissions without checkoffs

in-person lab checkoff of incomplete lab at least 50% credit

some labs will basically require attendance

or contact me for other arrangements if you can't (sick, etc.)

logistically won't work otherwise — e.g. code review

if can't make lab in-person (example: sick)

let me know, can arrange late/alternate checkoff

# lab collaboration and submissions

please collaborate on labs!

when working with others on lab and submitting code files

please indicate who you worked with in those files  
via comment or similar

## lab space

if labs are full, might kick out students from 'wrong' lab section

# homeworks

several homework assignments

done individually

generally due on Fridays

(tentative dates on schedule)

# homework/lab automatic testing

some homeworks/labs have automatic testing

with some delay after you submit

- usually 10s of minutes

- depending on assignment, number of submissions in queue

- if you submit very early, testing program might not be setup yet

when testing program doesn't understand/can't test something,  
left for manual grading (“not yet graded”)

intention is that testing results are not surprises

if you did some manual testing (no hidden requirements, etc.)

if you think testing program made a mistake,  
please submit regrade request

# warmup assignment

first homework

write C function to split a string into array of strings  
with dynamic memory allocation

write C program to call function using input/command-line  
arguments

write Makefile for it (next topic, next week's lab)

# quizzes

released evening after Thursday lecture  
starting *next* week

due 15 minutes before lecture on Tuesdays

about lecture and/or lab from the prior week

5–6ish questions

*individual*, open book, open notes, open Internet



# quizzes and work/comments

quizzes will have place for comments/work

will be used to do grading

delay: about 1 week after quiz is due

please use so we can give partial credit

if you find possible error in quiz question

please make your best guess about what was meant

and explain what you did in the comments

# on help on quiz questions

I and the TAs won't answer quiz questions...

but we will answer questions about the lecture material, etc.

(and TAs (not you) are responsible for knowing  
what they can't answer

but we'd prefer you don't try to test those limits)

## going over past quizzes

have in past gone over quiz Qs in lecture  
either when a lot missed it or  
on request in lecture

also fine office hour/Piazza question

# readings

in lieu of textbook, have readings

mostly written by Prof Tychnovich (now at UIUC) with edits by me

on website; should be indicated with corresponding lecture

readings often link to alternative/supplemental readings on topic

# lecture + assignment sync

generally:

quiz after lecture and/or lab coverage

labs after lecture coverage

homework after lab coverage

means homework (and sometimes quiz)

may be relatively delayed from lecture coverage

# exams

1 final exam

likely in-person

see official exam schedule

no midterms — instead:

quizzes count a lot

# development enviroment

we will test via something like SSH into portal  
officially supported environment

no restrictions re: IDEs

but make sure you test/know how to run from command line

many students had success with VSCode + its SSH support

## some notes on VSCode

I don't use VSCode (I use vim via SSH+tmux...)

but many of our TAs do; their advice:...

use SSH support to run on portal (dept machine)

tutorial in last semester's CS 2130 lab (linked off main course website)

install Microsoft's C/C++ extension

set C standard in settings as 'gnu17' or similar

install Microsoft's Makefile Tools extension



# getting help

office hours — calendar will be posted on website

mix of in-person and remote, indicated on calendar

remote OH will use Discord + online queue

in-person OH may or may not — indicated on whiteboard, probably

## Piazza

use private questions if homework code, etc.

emailing me (preferably with '3130' in subject)

# collaboration (1)

labs — you can/should work with other students  
everyone should understand the work submitted  
we may ask questions/etc. to check on occasion

homeworks — individual

write your own code / do not share your code  
can ask/look up *conceptual* questions of others  
others includes other students, Q&A sites, code generation tools, etc.  
**cite** any sources you use (comments in code)

## collaboration (2)

quizzes — individual

but open book+notes+etc.

can/should have help reviewing lecture/readings/etc.

legitimate questions for office hours

don't ask other students, stack overflow, gen AI tools, etc. the quiz questions

don't try to find exactly the quiz question on stack overflow

# feedback

anonymous feedback on Canvas

would appreciate feedback (esp. when I can do something)

(but not a good way to ask for regrades, etc.)

# late policy

no late quizzes

one quiz dropped (unconditionally)

90% credit for 0–72 hours late homeworks

for labs that allow submission only

lab submission due time is 11:59am the next day

90% credit for 0–24 hours late

no late lab checkoffs except by special arrangement

# excused lateness

special circumstances?

illness, emergency, etc.

contact me, we'll figure something out

please don't attend lab/etc. sick!

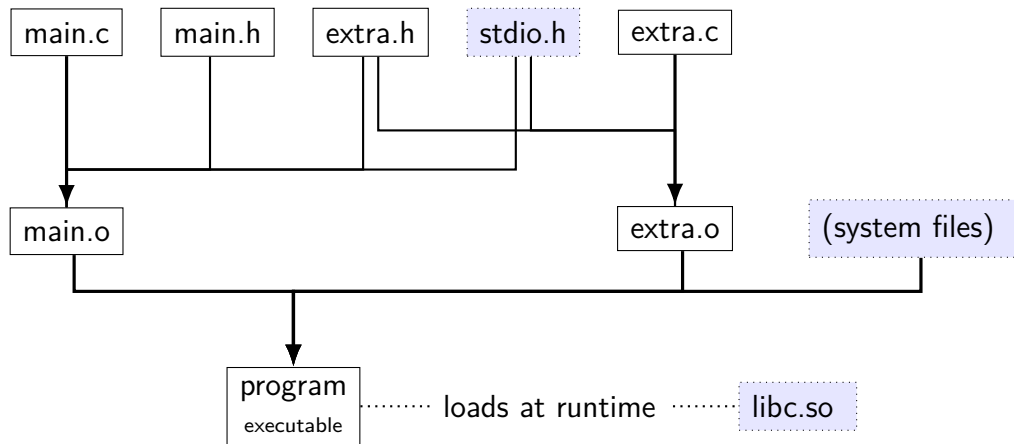
# attendance

I won't take attendance in lecture

I will attempt to have lecture recordings

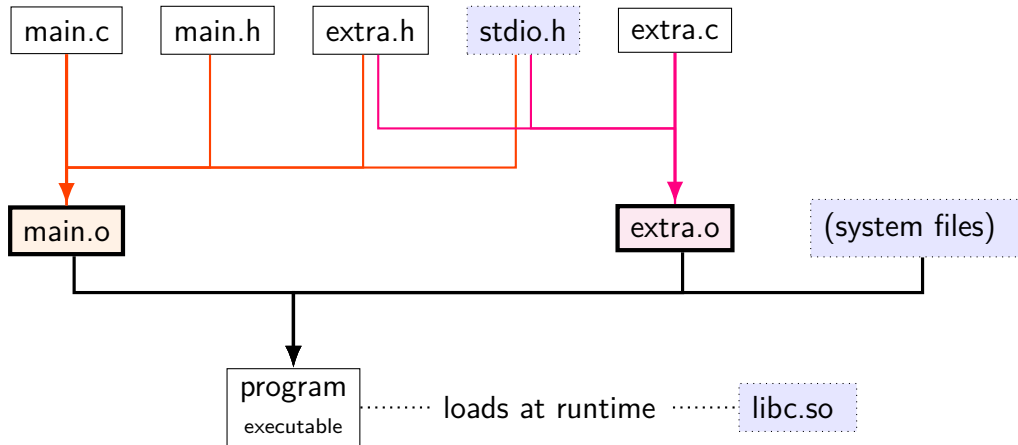
sometimes there may be issues with the recording

# files in building C programs [dynamic linking]



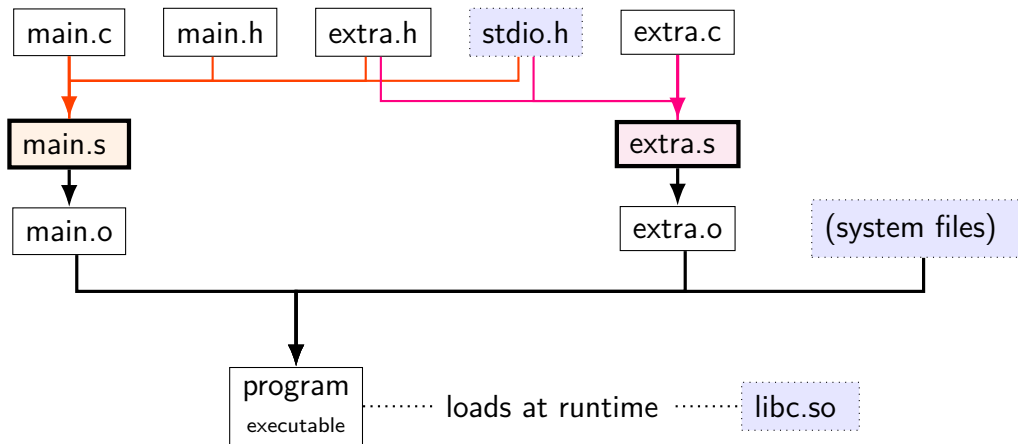


# files in building C programs [dynamic linking]



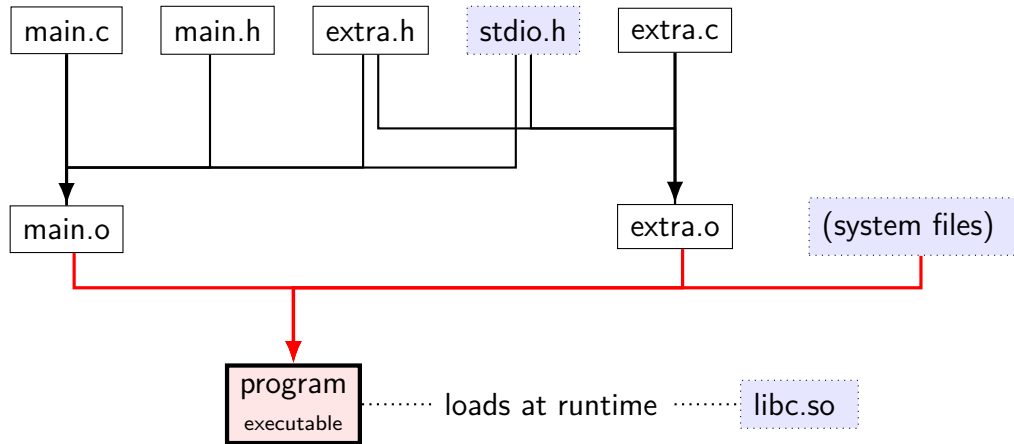
```
clang -c main.c  
clang -c extra.c
```

# files in building C programs [dynamic linking]



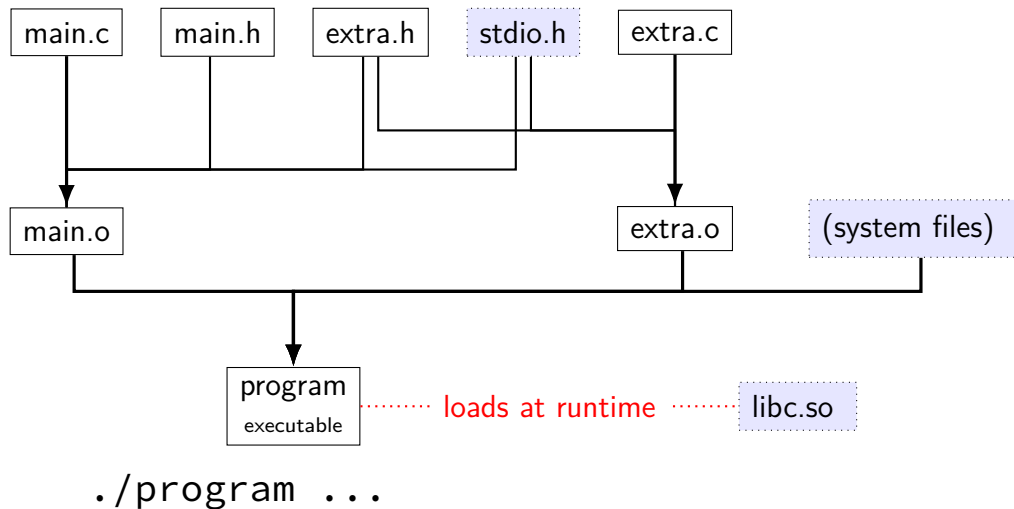
```
clang -S -c main.c  
clang -S -c extra.c
```

# files in building C programs [dynamic linking]

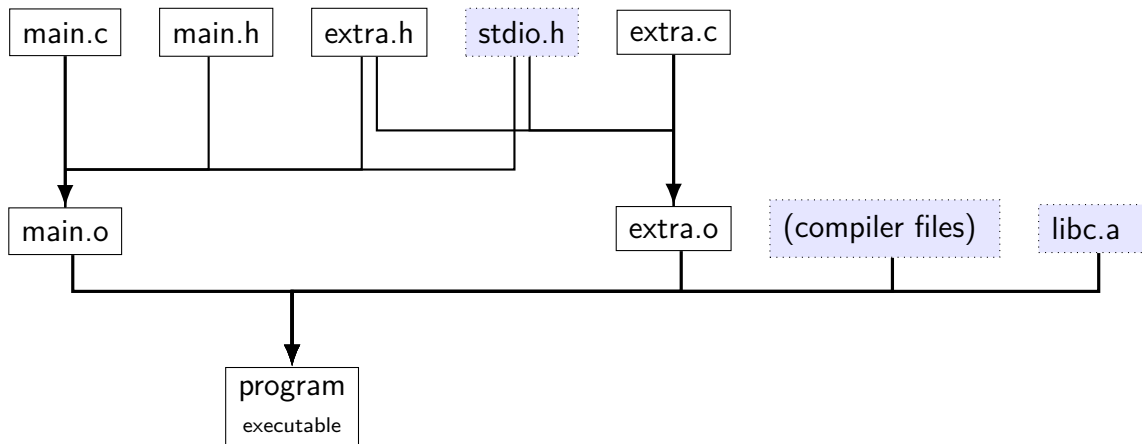


```
clang -o program main.o extra.o
```

# files in building C programs [dynamic linking]



# files in building C programs [static linking]



# file extensions

| name   |                     |   |
|--------|---------------------|---|
| .c     |                     | C source code   |
| .h     |                     | C header file   |
| .s     | (or .asm)           | assembly file   |
| .o     | (or .obj)           | object file (binary of assembly)                      |
| (none) | (or .exe)           | executable file                                       |
| .a     | (or .lib)           | statically linked library<br>[collection of .o files] |
| .so    | (or .dll or .dylib) | dynamically linked library<br>['shared object']       |

# static libraries

Unix-like *static* libraries: libfoo.a

internally: archive of .o files with index

create: `ar rcs libfoo.a file1.o file2.o ...`

use: `cc ... -o program -L/path/to/lib ... -lfoo`

no space between `-l` and library name

`cc` could be `clang`, `gcc`, `clang++`, `g++`, etc.

`-L/path/to/lib` not needed if in standard location

# shared libraries

Linux *shared* libraries: libfoo.so

create:

compile .o files with -fPIC (position independent code)

then: `cc -shared ... -o libfoo.so`

use: `cc ...-o program -L/path/to/lib ...-lfoo`



# shared libraries

Linux *shared* libraries: libfoo.so

create:

compile .o files with -fPIC (position independent code)

then: `cc -shared ... -o libfoo.so`

use: `cc ...-o program -L/path/to/lib ...-lfoo`

`-L...` sets path *only when making executable*

runtime path set separately

# finding shared libraries (1)

```
$ ls
libexample.so  main.c
$ clang -o main main.c -lexample
/usr/bin/ld: cannot find -lexample
clang: error: linker command failed with exit code 1 (use -v to see)
$ clang -o main main.c -L. -lexample
$ ./main
./main: error while loading shared libraries:
  libexample.so: cannot open shared object file: No such
  file or directory
```

# finding shared libraries (1)

```
$ ls
libexample.so  main.c
$ clang -o main main.c -lexample
/usr/bin/ld: cannot find -lexample
clang: error: linker command failed with exit code 1 (use -v to see)
$ clang -o main main.c -L. -lexample
$ ./main
./main: error while loading shared libraries:
  libexample.so: cannot open shared object file: No such
  file or directory
```

---

```
$ LD_LIBRARY_PATH=. ./main
```

*or*

```
$ export LD_LIBRARY_PATH=.
$ ./main
```

*or*

```
$ clang -o main main.c -L. -lexample -Wl,-rpath .
$ ./main
```

# finding shared libraries (1)

```
cc ...-o program -L/path/to/lib ...-lfoo
```

on Linux: /path/to/lib only used to create program  
program contains `libfoo.so` *without full path*

Linux default: `libfoo.so` expected to be in `/usr/lib`, `/lib`, and other 'standard' locations

possible overrides:

`LD_LIBRARY_PATH` environment variable  
paths specified with `-Wl,-rpath=/path/to/lib` when creating executable

# libraries and command line

when linking against libraries use:

```
clang -o executable foo.o bar.o -lName
```

rather than

```
clang -o executable -lName foo.o bar.o
```

by default, linker processes files in order

might only grab things that previous files needed from library  
(especially for static libraries)

## exercise (incremental compilation)

program built from main.c + extra.c

main.c, extra.c both include extra.h, stdio.h

```
clang -c main.c                # command 1
clang -c extra.c                # command 2
clang -o program main.o extra.o # command 3
```

What commands need to be rerun if...

Question A: ...main.c changes?

Question B: ...extra.h changes?

# make

make — Unix program for “making” things...

...by running commands based on what's changed

what commands? based on *rules* in *makefile*

(text file called `makefile` or `Makefile` (no extension))

## make rules

```
main.o: main.c main.h extra.h
▶      clang -Wall -c main.c
```

before colon: target(s) (file(s) generated/updated)

after colon: prerequisite(s) (also known as dependencies)

following lines prefixed by a tab character: command(s) to run

make runs commands if any prereq modified date after target



## make rules

```
main.o: main.c main.h extra.h  
▶      clang -Wall -c main.c
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before colon: **target(s)** (file(s) generated/updated)

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## make rules

```
main.o: main.c main.h extra.h
►      clang -Wall -c main.c
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before colon: target(s) (file(s) generated/updated)

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following lines prefixed by a tab character: command(s) to run

make runs commands **if any prereq modified date after target**

## make rules

```
main.o: main.c main.h extra.h
►      clang -Wall -c main.c
```

before colon: target(s) (file(s) generated/updated)

after colon: prerequisite(s) (also known as dependencies)

following lines prefixed by a tab character: command(s) to run

make runs commands if any prereq modified date after target

...after making sure prerequisites up to date

## make rule chains

```
program: main.o extra.o
```

```
▶          clang -Wall -o program main.o extra.o
```

```
extra.o: extra.c extra.h
```

```
▶          clang -Wall -c extra.c
```

```
main.o: main.c main.h extra.h
```

```
▶          clang -Wall -c main.c
```

to *make* program, first...

update main.o and extra.o if they aren't

# running make

“make *target*”

- look in Makefile in current directory for rules

- check if *target* is up-to-date

- if not, rebuild it (and prerequisites, if needed) so it is

“make *target1 target2*”

- check if both *target1* and *target2* are up-to-date

- if not, rebuild it as needed so they are

“make”

- if “*firstTarget*” is the first rule in Makefile,

- same as ‘make *firstTarget*’



## exercise: what will run?

W: X Y

► buildW

X: Q

► buildX

Y: X Z

► buildY

W modified 1 minute ago

X modified 3 hours ago

Y does not exist

Z modified 1 hour ago

Q modified 2 hours ago

exercise: “make W” will run what commands?

A. none

B. buildY only    C. buildW then buildY

D. buildY then buildW

E. buildX then buildY then buildW

F. buildX then buildW

G. something else

## ‘phony’ targets (1)

common to have Makefile targets that aren’t files

```
all: program1 program2 libfoo.a
```

“make all” effectively shorthand for “make program1  
program2 libfoo.a”

no actual file called “all”

## ‘phony’ targets (2)

sometimes want targets that don’t actually build file

example: “make clean” to remove generated files

clean:

► `rm --force main.o extra.o`

## but what if I create...

clean:

► `rm --force main.o extra.o`

`all: program1 program2 libfoo.a`

Q: if I make a file called “all” and then “make all” what happens?

Q: same with “clean” and “make clean”?

## marking phony targets

clean:

► `rm --force main.o extra.o`

`all: program1 program2 libfoo.a`

`.PHONY: all clean`

special .PHONY rule says “ ‘all’ and ‘clean’ not real files”

(not required by POSIX, but in every make version I know)

# conventional targets

common convention:

| target name    | purpose                      |
|----------------|------------------------------|
| (default), all | build everything             |
| install        | install to standard location |
| test           | run tests                    |
| clean          | remove generated files       |

## redundancy (1)

program: main.o extra.o

▶ clang -Wall -o program main.o extra.o

extra.o: extra.c extra.h

▶ clang -Wall -o extra.o -c extra.c

main.o: main.c main.h extra.h

▶ clang -o main.o -c main.c

what if I want to run clang with `-fsanitize=address` instead of `-Wall`?

what if I want to change clang to gcc?

# variables/macros (1)

CC = gcc

CFLAGS = -Wall -pedantic -std=c11 -fsanitize=address

LDFLAGS = -Wall -pedantic -fsanitize=address

LDLIBS = -lm

program: main.o extra.o

▶ \$(CC) \$(LDFLAGS) -o program main.o extra.o \$(LDLIBS)

extra.o: extra.c extra.h

▶ \$(CC) \$(CFLAGS) -o extra.o -c extra.c

main.o: main.c main.h extra.h

▶ \$(CC) \$(CFLAGS) -o main.o -c main.c



## aside: conventional names

chose names CC, CFLAGS, LDFLAGS, etc.

not required, but conventional names (incomplete list follows)

|                |                    |
|----------------|--------------------|
| CC             | C compiler         |
| CFLAGS         | C compiler options |
| LDFLAGS        | linking options    |
| LIBS or LDLIBS | libraries          |

## variables/macros (2)

```
CC = gcc
CFLAGS = -Wall
LDFLAGS = -Wall
LDLIBS = -lm
```

`$@`: target  
`$<`: first dependency  
`$^`: all dependencies

```
program: main.o extra.o
```

```
▶ $(CC) $(LDFLAGS) -o $@ $^ $(LDLIBS)
```

```
extra.o: extra.c extra.h
```

```
▶ $(CC) $(CFLAGS) -o $@ -c $<
```

```
main.o: main.c main.h extra.h
```

```
▶ $(CC) $(CFLAGS) -o $@ -c $<
```

aside: `$^` works on GNU make (usual on Linux), but not portable.

## aside: make versions

multiple implementations of make

for stuff we've talked about so far, no differences

most common on Linux: GNU make

will talk about 'pattern rules', which aren't supported by some other make versions

older, portable, (in my opinion less intuitive) alternative: suffix rules

## pattern rules

CC = gcc

CFLAGS = -Wall

LDFLAGS = -Wall

LDLIBS = -lm

program: main.o extra.o

▶ \$(CC) \$(LDFLAGS) -o \$@ \$^ \$(LDLIBS)

**%.o: %.c**

▶ \$(CC) \$(CFLAGS) -o \$@ -c \$<

extra.o: extra.c extra.h

main.o: main.c main.h extra.h

aside: these rules work on GNU make (usual on Linux), but less portable than suffix rules.

## built-in rules

'make' has the 'make .o from .c' rule built-in already, so:

```
CC = gcc
CFLAGS = -Wall
LDFLAGS = -Wall
LDLIBS = -lm
```

```
program: main.o extra.o
```

```
▶      $(CC) $(LDFLAGS) -o $@ $^ $(LDLIBS)
```

```
extra.o: extra.c extra.h
```

```
main.o: main.c main.h extra.h
```

(don't actually need to write supplied rule!)

# built-in rules

'make' has the 'make .o from .c' rule built-in already, so:

```
CC = gcc
CFLAGS = -Wall
LDFLAGS = -Wall
LDLIBS = -lm
```

```
program: main
```

```
▶ gcc $(CFLAGS) -o $@ $^ $(LDLIBS)
```

```
extra.o: extra.c extra.h
```

```
main.o: main.c main.h extra.h
```

(don't actually need to write supplied rule!)

**note: built-in rules not allowed on the make lab**

# writing Makefiles?

error-prone to write all .h dependencies

- MM (and related) options to gcc or clang
  - outputs make rule
  - ways of having make run this + use output

Makefile generators

other programs that write Makefiles

# other build systems

alternatives to writing Makefiles:

other make-ish build systems

ninja, scon, bazel, maven, xcodebuild, msbuild, ...

tools that generate inputs for make-ish build systems

cmake, autotools, qmake, ...



# backup slides