last time

overall course themes

logistics

static versus dynamic linking

- dynamic (.so, .dll, .dylib): libraries loaded at runtime
- static (.a, .lib): library code copied to executable file

steps for building applications + libraries

on lab due times

when submission is allowed, moved to 8:59am next day

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*

make rules

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

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

after colon: prerequisite(s)

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

`make` will run the commands if any prerequisite is newer than the target

make rules

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make rules

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

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

after colon: prerequisite(s)

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

`make` will run the commands if any prerequisite is newer than the target

...after making sure prerequisites up to date

make rule chains

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

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

▶           clang -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 dependencies, if needed) so it is

"`make` *`target1 target2`*"

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

"`make`"

if "*`firstTarget`*" is the first rule in Makefile,
same as '`make` *`firstTarget`*"

exercise: what will run?

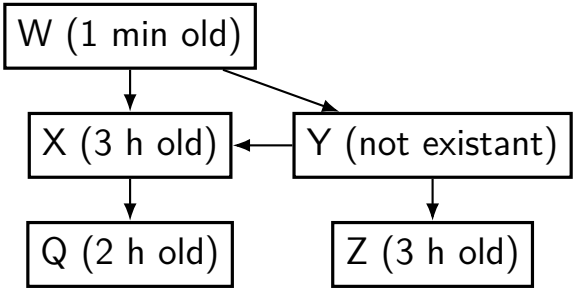
```
W: X Y
▶    buildW
X: Q
▶    buildX
Y: X Z
▶    buildY
```

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

explanation



first: to make W, need X, Y up to date

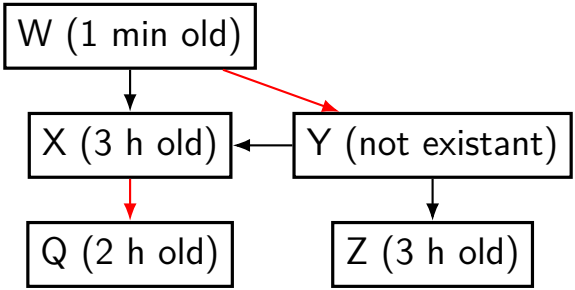
to make X up to date:
need Q up to date ✓
then build X if less recent than Q (yes) ✓

---

to make Y up to date: need X up to date ✓
need Z up to date ✓
then build Y if less recent than X (yes) or Z (yes) ✓

then build W if less recent than X (no) or Y (yes) ✓

explanation



first: to make W, need X, Y up to date

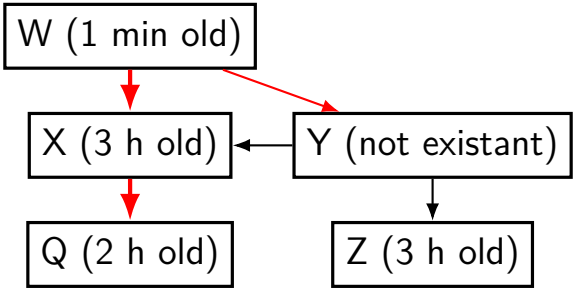
to make X up to date:
need Q up to date ✓
then build X if less recent than Q (yes) ✓

---

to make Y up to date: need X up to date ✓
need Z up to date ✓
then build Y if less recent than X (yes) or Z (yes) ✓

then build W if less recent than X (no) or Y (yes) ✓

explanation



first: to make W, need X, Y up to date

to make X up to date:
need Q up to date ✓
then build X if less recent than Q (yes) ✓

---

to make Y up to date: need X up to date ✓
need Z up to date ✓
then build Y if less recent than X (yes) or Z (yes) ✓

then build W if less recent than X (no) or Y (yes) ✓

‘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 -o program main.o extra.o

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

what if I want to change 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
```

variables/macros (2)

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

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.

suffix rules

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

program: main.o extra.o
▶       $(CC) $(LDFLAGS) -o $@ $^

.c.o:
▶       $(CC) $(CFLAGS) -o $@ -c $<

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

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

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!)

writing Makefiles?

error-prone to automatically all .h dependencies

`-M` option to `gcc` or `clang`

- outputs Make rule
- ways of having make run this

Makefile generators

- other programs that write Makefiles

other build systems

alternatives to writing Makefiles:

other make-ish build systems

- ninja, scons, bazel, maven, xcodebuild, msbuild, ...

tools that generate inputs for make-ish build systems

- cmake, autotools, qmake, ...

things programs on portal shouldn't do

read other user's files

modify OS's memory

read other user's data in memory

hang the entire system

things programs on portal shouldn't do

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privileged instructions

can't let any program run some instructions

example: talk to I/O device

allows machines to be shared between users (e.g. lab servers)

processor has two modes:

- kernel mode — privileged instructions work
- user mode — privileged instructions cause exception instead

only *trusted* OS code runs in kernel mode

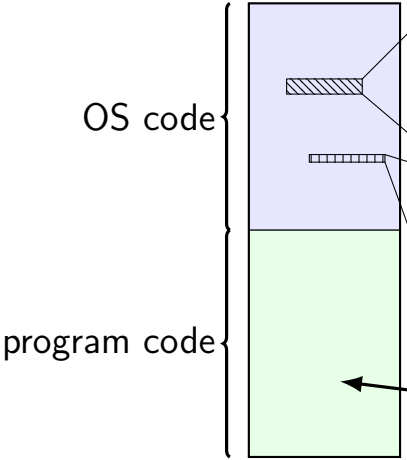
kernel mode

extra one-bit register: “are we in kernel mode”

processor switches to kernel mode to run OS

OS switches processor back to use mode when running normal code

calling the OS?




```
void readFromDiskInto(int diskLocation, char *dest) {
    ...
    runPrivilegedInstruction(...);
    ...
}
```

```
void readFileSafely(const char *name, char *dest) {
    if (canCurrentProgramCanAccessFile(name)) {
        readFromDiskInto(lookupFile(name), dest)
    }
}
```

how do we let this code run `readFromSafely` in kernel mode but not `readFromDisk`?

controlled entry to kernel mode (1)

special instruction: “system call”

runs OS code in kernel mode at location specified earlier

OS sets up at boot

location can’t be changed without privilieged instrution

controlled entry to kernel mode (2)

OS needs to make specified location:

figure out what operation the program wants

- calling convention, similar to function arguments + return value

be "safe" — not allow the program to do 'bad' things

- example: checks whether current program is allowed to read file before reading it
- requires exceptional care — program can try weird things

Linux x86-64 system calls

special instruction: `syscall`

runs OS specified code in kernel mode

Linux syscall calling convention

before `syscall`:

`%rax` — system call number

`%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9` — args

after `syscall`:

`%rax` — return value

on error: `%rax` contains -1 times "error number"

almost the same as normal function calls

Linux x86-64 hello world

```
.globl _start
.data
hello_str: .asciz "Hello, World!\n"
.text
_start:
  movq $1, %rax # 1 = "write"
  movq $1, %rdi # file descriptor 1 = stdout
  movq $hello_str, %rsi
  movq $15, %rdx # 15 = strlen("Hello, World!\n")
  syscall

  movq $60, %rax # 60 = exit
  movq $0, %rdi
  syscall
```

approx. system call handler

```
sys_call_table:
    .quad handle_read_syscall
    .quad handle_write_syscall
    // ...

handle_syscall:
    ... // save old PC, etc.
    pushq %rcx // save registers
    pushq %rdi
    ...
    call *sys_call_table(,%rax,8)
    ...
    popq %rdi
    popq %rcx
    return_from_exception
```

Linux system call examples

`mmap`, `brk` — allocate memory

`fork` — create new process

`execve` — run a program in the current process

`_exit` — terminate a process

`open`, `read`, `write` — access files

`socket`, `accept`, `getpeername` — socket-related

system call wrappers

library functions to not write assembly:

```
open:
    movq $2, %rax // 2 = sys_open
    // 2 arguments happen to use same registers
    syscall
    // return value in %eax
    cmp $0, %rax
    jl has_error
    ret
has_error:
    neg %rax
    movq %rax, errno
    movq $-1, %rax
    ret
```

system call wrappers

library functions to not write assembly:

```
open:
    movq $2, %rax // 2 = sys_open
    // 2 arguments happen to use same registers
    syscall
    // return value in %eax
    cmp $0, %rax
    jl has_error
    ret
has_error:
    neg %rax
    movq %rax, errno
    movq $-1, %rax
    ret
```

system call wrapper: usage

```
/* unistd.h contains definitions of:
    O_RDONLY (integer constant), open() */
#include <unistd.h>
int main(void) {
  int file_descriptor;
  file_descriptor = open("input.txt", O_RDONLY);
  if (file_descriptor < 0) {
      printf("error: %s\n", strerror(errno));
      exit(1);
  }
  ...
  result = read(file_descriptor, ...);
  ...
}
```

system call wrapper: usage

```
/* unistd.h contains definitions of:
    O_RDONLY (integer constant), open() */
#include <unistd.h>
int main(void) {
  int file_descriptor;
  file_descriptor = open("input.txt", O_RDONLY);
  if (file_descriptor < 0) {
      printf("error: %s\n", strerror(errno));
      exit(1);
  }
  ...
  result = read(file_descriptor, ...);
  ...
}
```

strace hello_world (1)

`strace` — Linux tool to trace system calls

run on assembly program we saw earlier:

```
$ strace -o trace.txt ./hello_world
$ cat trace.txt
execve("./hello_world", ["./hello_world"],
        0x7ffeedafd0a0 /* 28 vars */) = 0
write(1, "Hello, World!\n\0", 15)       = 15
exit(0)                                 = ?
+++ exited with 0 +++
```

strace hello_world (2)

```
#include <stdio.h>
int main() { puts("Hello, World!"); }
```

when statically linked:

```
execve("./hello_world", ["./hello_world"], 0x7ffeb4127f70 /* 28 vars */)
                                        = 0
brk(NULL)                               = 0x22f8000
brk(0x22f91c0)                          = 0x22f91c0
arch_prctl(ARCH_SET_FS, 0x22f8880)      = 0
uname({sysname="Linux", nodename="reiss-t3620", ...}) = 0
readlink("/proc/self/exe", "/u/cr4bd/spring2023/cs3130/slide"..., 4096)
                                        = 57
brk(0x231a1c0)                          = 0x231a1c0
brk(0x231b000)                          = 0x231b000
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or
                                                     directory)
fstat(1, {st_mode=S_IFCHR|0620, st_rdev=makedev(136, 4), ...}) = 0
write(1, "Hello, World!\n", 14)         = 14
exit_group(0)                           = ?
+++ exited with 0 +++
```

aside: what are those syscalls?

execve: run program

brk: allocate heap space

arch_prctl(ARCH_SET_FS, ...): thread local storage pointer

may make more sense when we cover concurrency/parallelism later

uname: get system information

readlink of /proc/self/exe: get name of this program

access: can we access this file?

(file indicates whether to use 'advanced' processo features)

fstat: get information about open file

exit_group: variant of exit

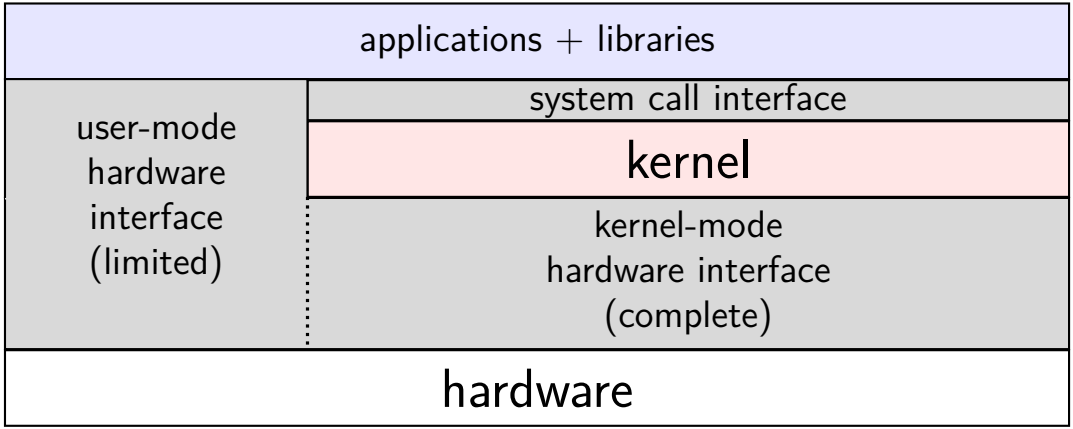
strace hello_world (2)

```
#include <stdio.h>
int main() { puts("Hello, World!"); }
```

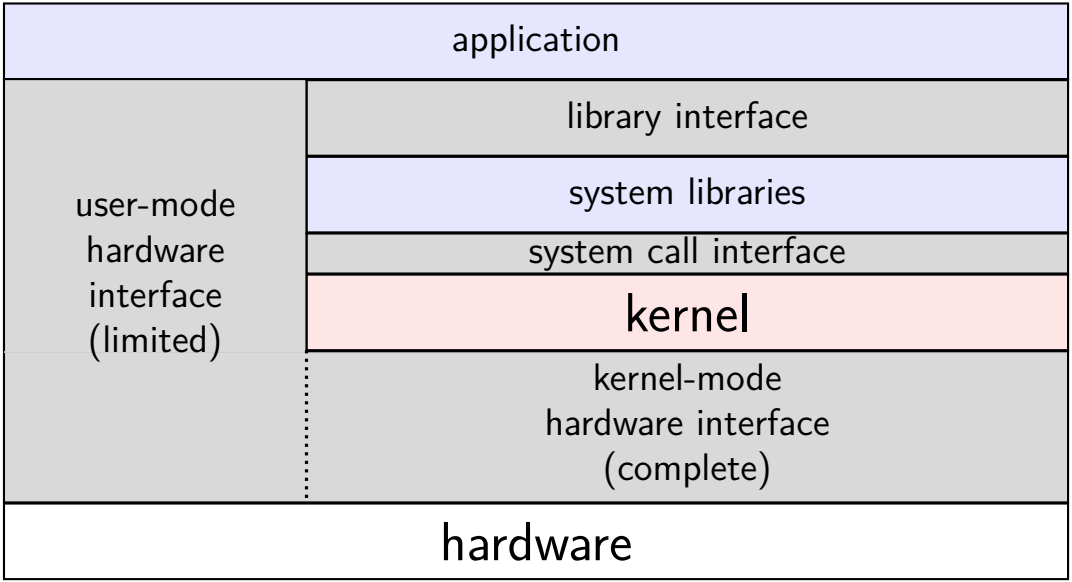
when dynamically linked:

```
execve("./hello_world", ["./hello_world"], 0x7ffcfe91d540 /* 28 vars */)
                                        = 0
brk(NULL)                               = 0x55d6c351b000
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or direc
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or direc
openat(AT_FDCWD, "/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=196684, ...}) = 0
mmap(NULL, 196684, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7f7a62dd3000
close(3)                                = 0
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or direc
openat(AT_FDCWD, "/lib/x86_64-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) =
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0\20\35\2\0\0\0\0\0"
                                        = 832
...
close(3)                                = 0
write(1, "Hello, World!\n", 14)         = 14
exit_group(0)                           = ?
```

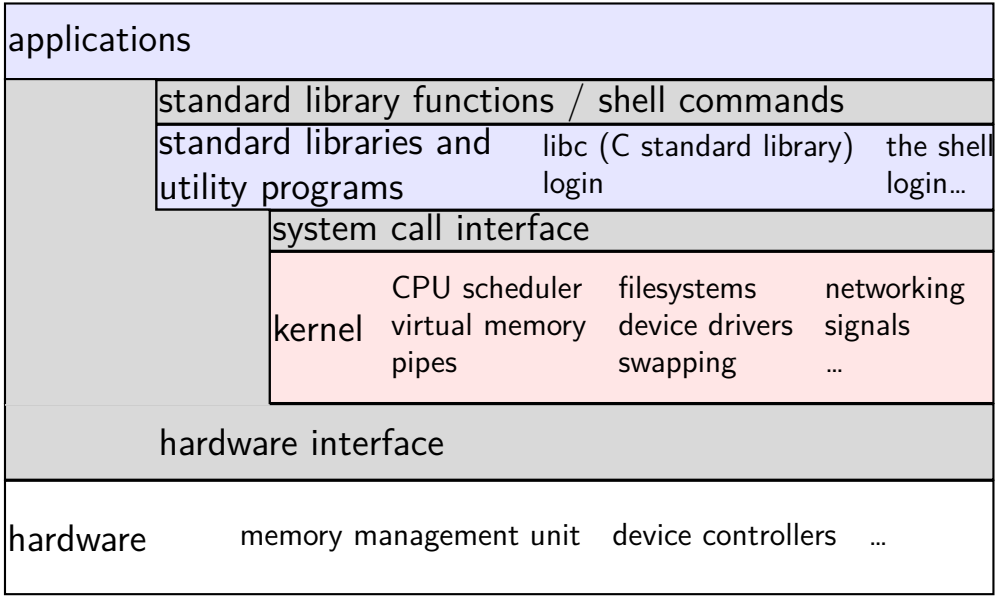
hardware + system call interface



hardware + system call + library interface



the classic Unix design



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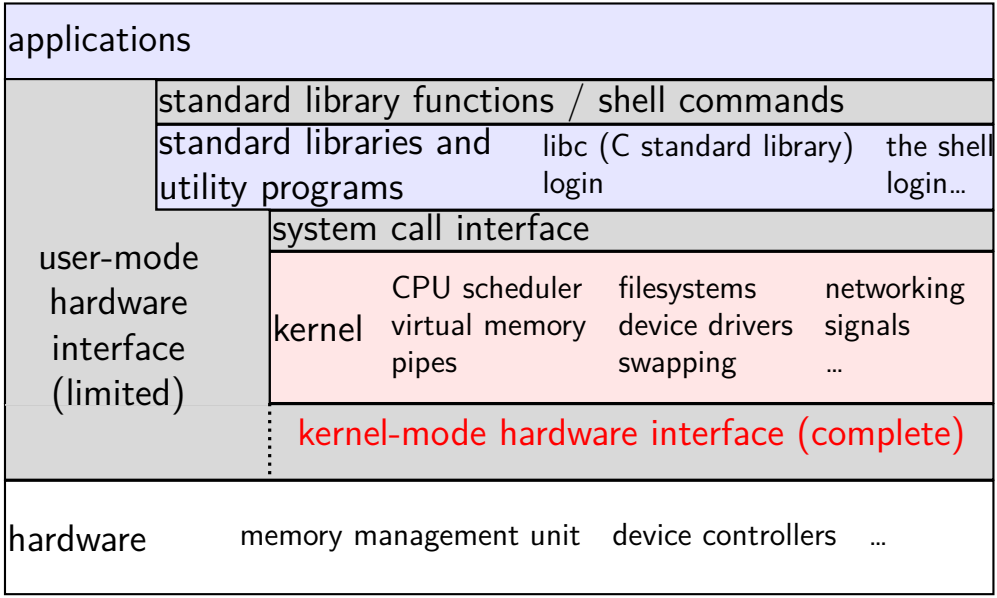
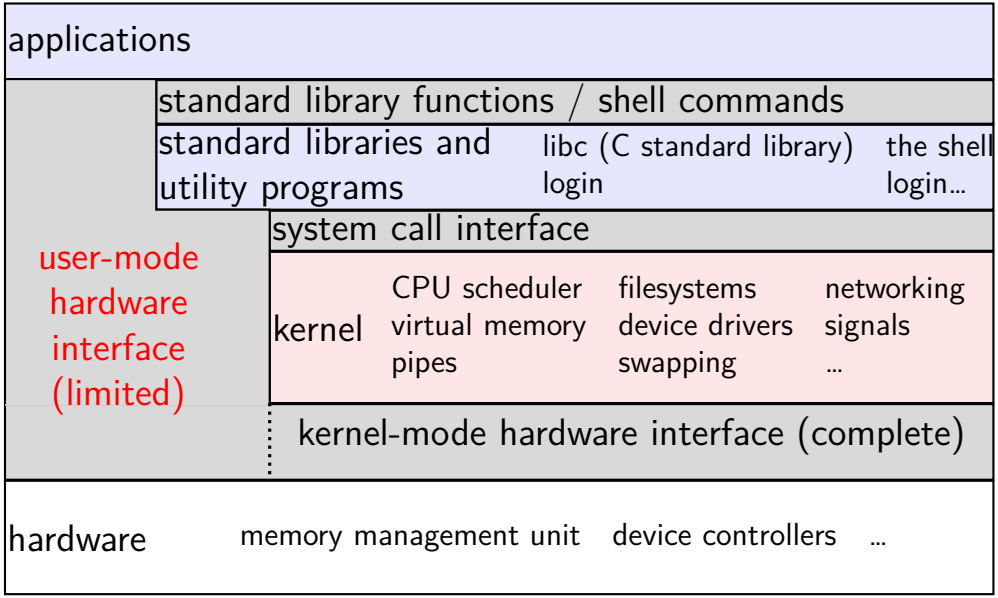


the classic Unix design



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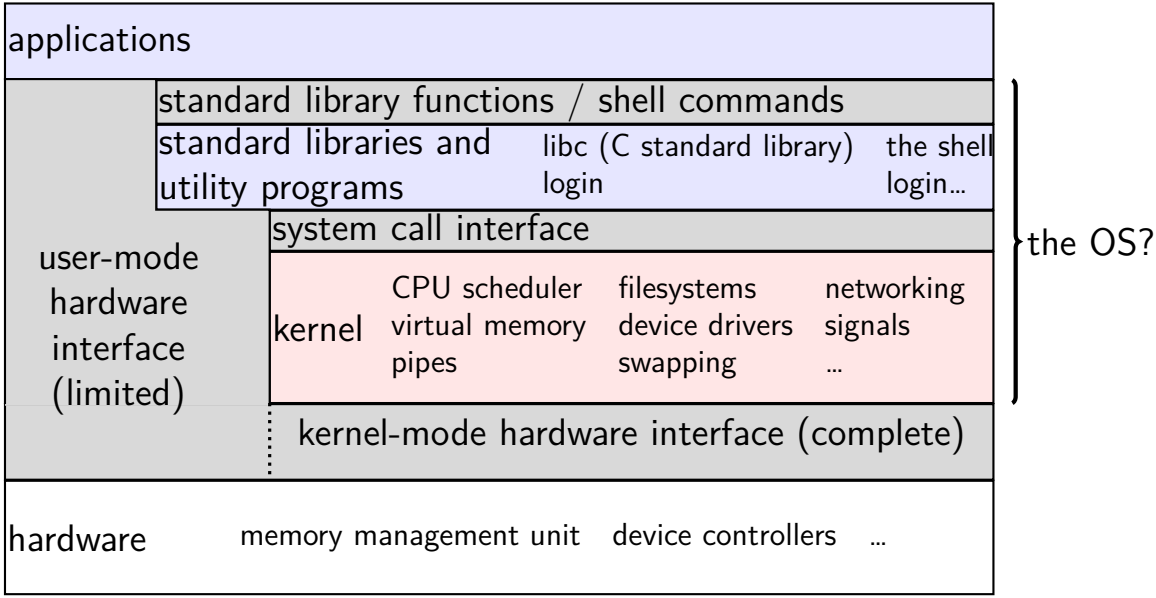

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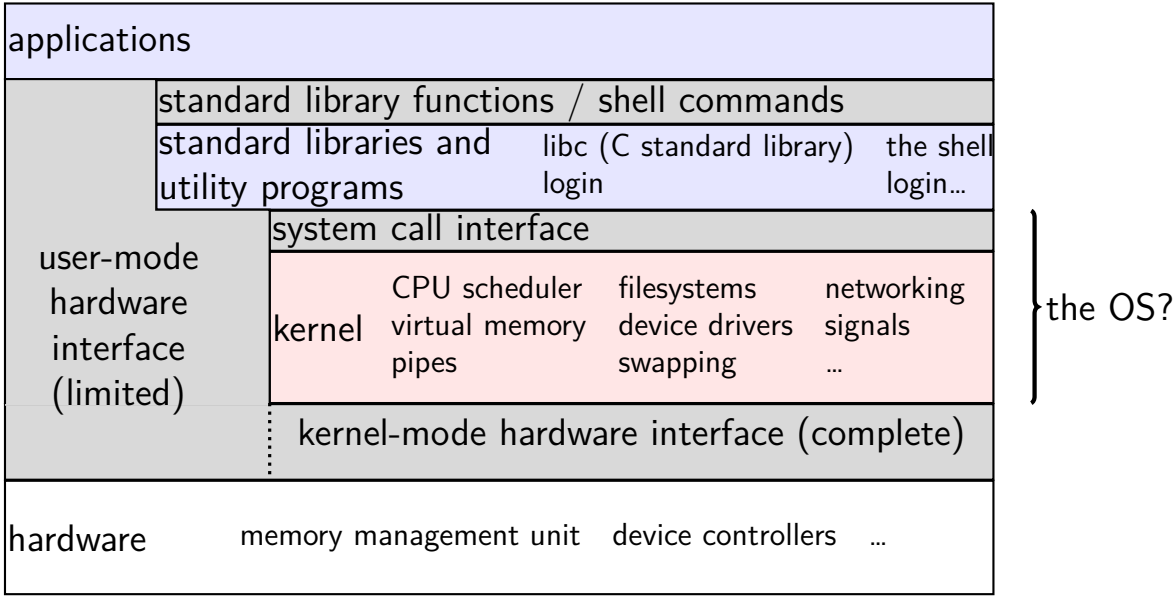


aside: is the OS the kernel?

OS = stuff that runs in kernel mode?

OS = stuff that runs in kernel mode + libraries to use it?

OS = stuff that runs in kernel mode + libraries + utility programs (e.g. shell, finder)?

OS = everything that comes with machine?

no consensus on where the line is

each piece can be replaced separately...

things programs on portal shouldn't do

read other user's files

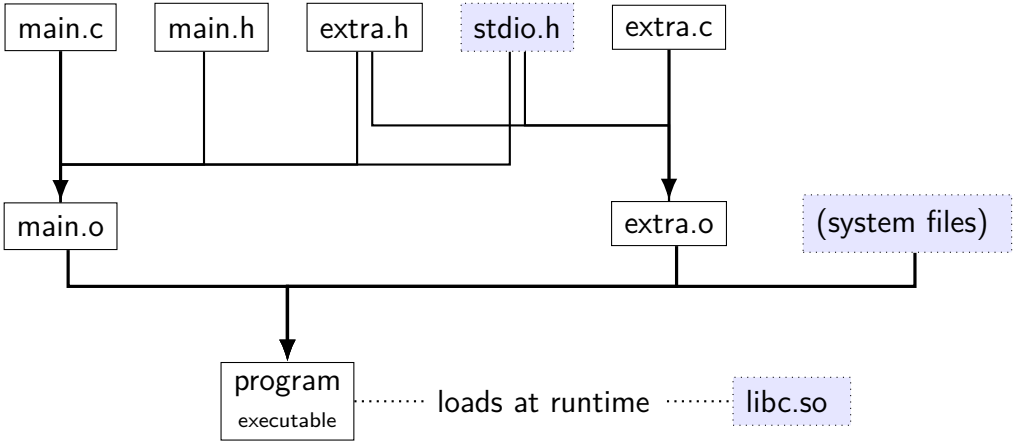
modify OS's memory

read other user's data in memory

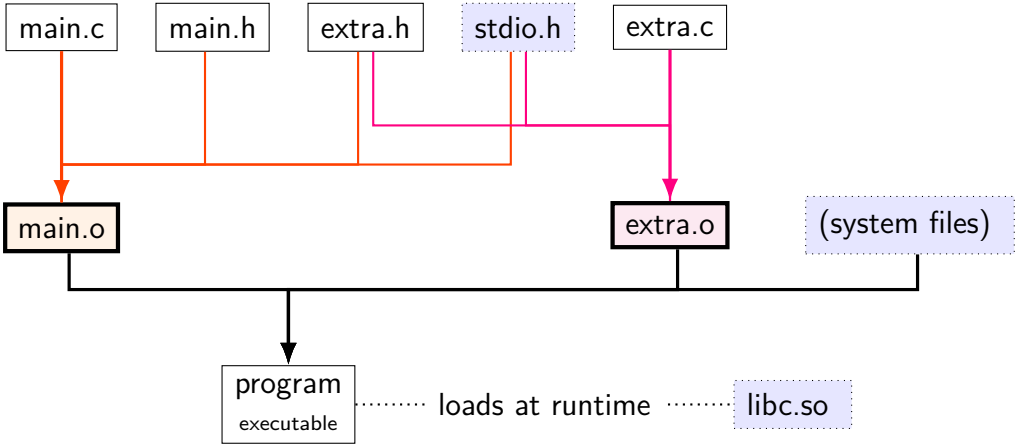
hang the entire system

backup slides

files in building C programs [dynamic linking]

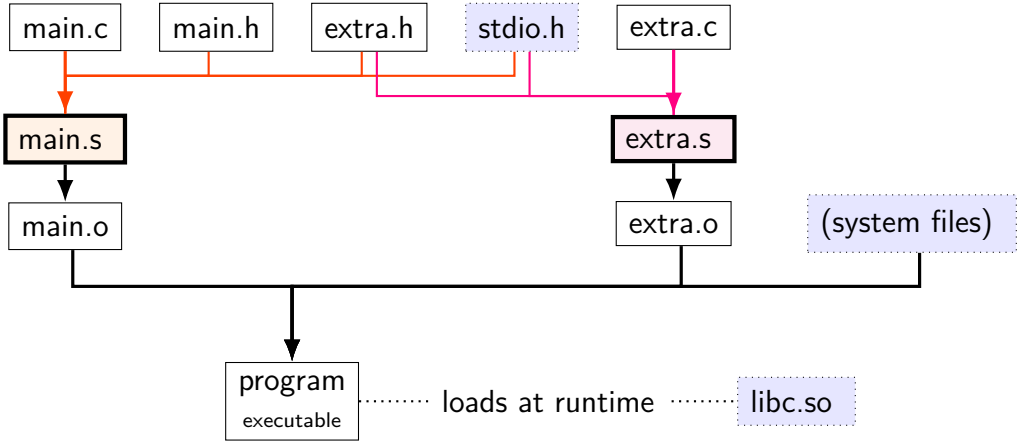


files in building C programs [dynamic linking]



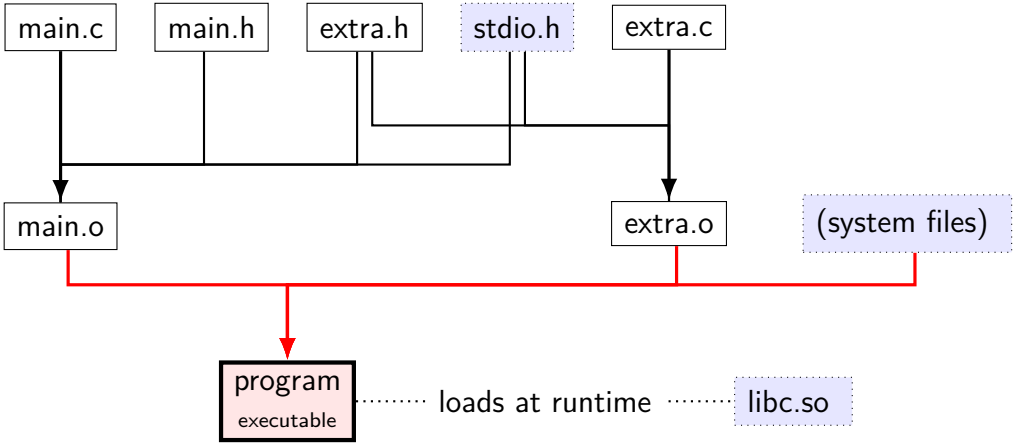

```
clang -c main.c
clang -c extra.c
```

files in building C programs [dynamic linking]



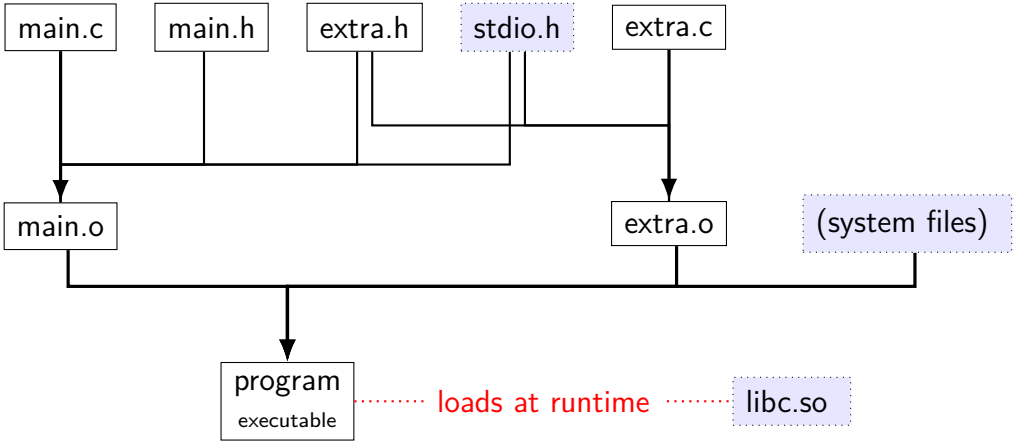

```
clang -S -c main.c
clang -S -c extra.c
```

files in building C programs [dynamic linking]



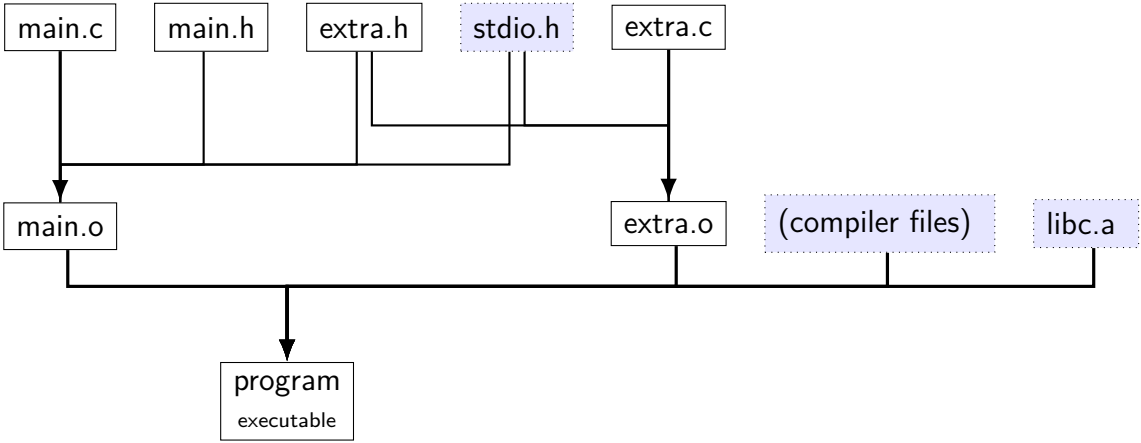

```
clang -o program main.o extra.o
```

files in building C programs [dynamic linking]




```
./program ...
```

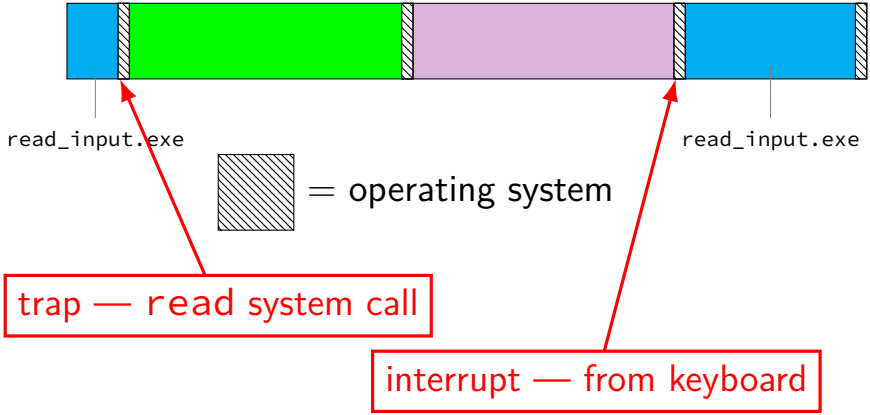
files in building C programs [static linking]



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 [collection of .o files]
.so	(or `.dll`)	dynamically linked library [‘shared object’]

keyboard input timeline



exceptions in exceptions

```
handle_timer_interrupt:
  save_old_pc save_pc
  movq %r15, save_r15
  /* key press here */

  movq %r14, save_r14
  ...
```

exceptions in exceptions

```
handle_timer_interrupt:
  save_old_pc save_pc
  movq %r15, save_r15
  /* key press here */
  movq %r14, save_r14
  ...
```

```
handle_keyboard_interrupt:
  save_old_pc save_pc
  movq %r15, save_r15
  movq %r14, save_r14
  movq %r13, save_r13
  ...
```

exceptions in exceptions

```
handle_timer_interrupt:
  save_old_pc save_pc
  movq %r15, save_r15
  /* key press here */
  movq %r14, save_r14
  ...
```

```
handle_keyboard_interrupt:
  save_old_pc save_pc
  movq %r15, save_r15
  movq %r14, save_r14
  movq %r13, save_r13
  ...
```

oops, overwrote saved values?

interrupt disabling

CPU supports disabling (most) interrupts

interrupts will wait until it is reenabled

CPU has extra state:

- are interrupts enabled?
- is keyboard interrupt pending?
- is timer interrupt pending?

exceptions in exceptions

```
handle_timer_interrupt:
  /* interrupts automatically disabled here */
  movq %rsp, save_rsp
  save_old_pc save_pc
  /* key press here */
  jmpIfFromKernelMode skip_exception_stack
  movq current_exception_stack, %rsp
skip_set_kernel_stack:
  pushq save_rsp
  pushq save_pc
  enable_intterupts2
  pushq %r15
  ...
  /* interrupt happens here! */
  ...
```

exceptions in exceptions

```
handle_timer_interrupt:
  /* interrupts automatically disabled here */
  movq %rsp, save_rsp
  save_old_pc save_pc
  /* key press here */
  jmpIfFromKernelMode skip_exception_stack
  movq current_exception_stack, %rsp
skip_set_kernel_stack:
  pushq save_rsp
  pushq save_pc
  enable_intterupts2
  pushq %r15
  ...
  /* interrupt happens here! */
  ...
```

exceptions in exceptions

```
handle_timer_interrupt:
  /* interrupts automatically disabled here */
  movq %rsp, save_rsp
  save_old_pc save_pc
  /* key press here */
  jmpIfFromKernelMode skip_exception_stack
  movq current_exception_stack, %rsp
skip_set_kernel_stack:
  pushq save_rsp
  pushq save_pc
  enable_intterupts2
  pushq %r15
  ...
  /* interrupt happens here! */
  ...
```

```
handle_keyboard_interrupt:
  movq %rsp, save_rsp
```

disabling interrupts

automatically disabled when exception handler starts

also can be done with privileged instruction:

```
change_keyboard_parameters:
  disable_interrupts
  ...
  /* change things used by
     handle_keyboard_interrupt here */
  ...
  enable_interrupts
```