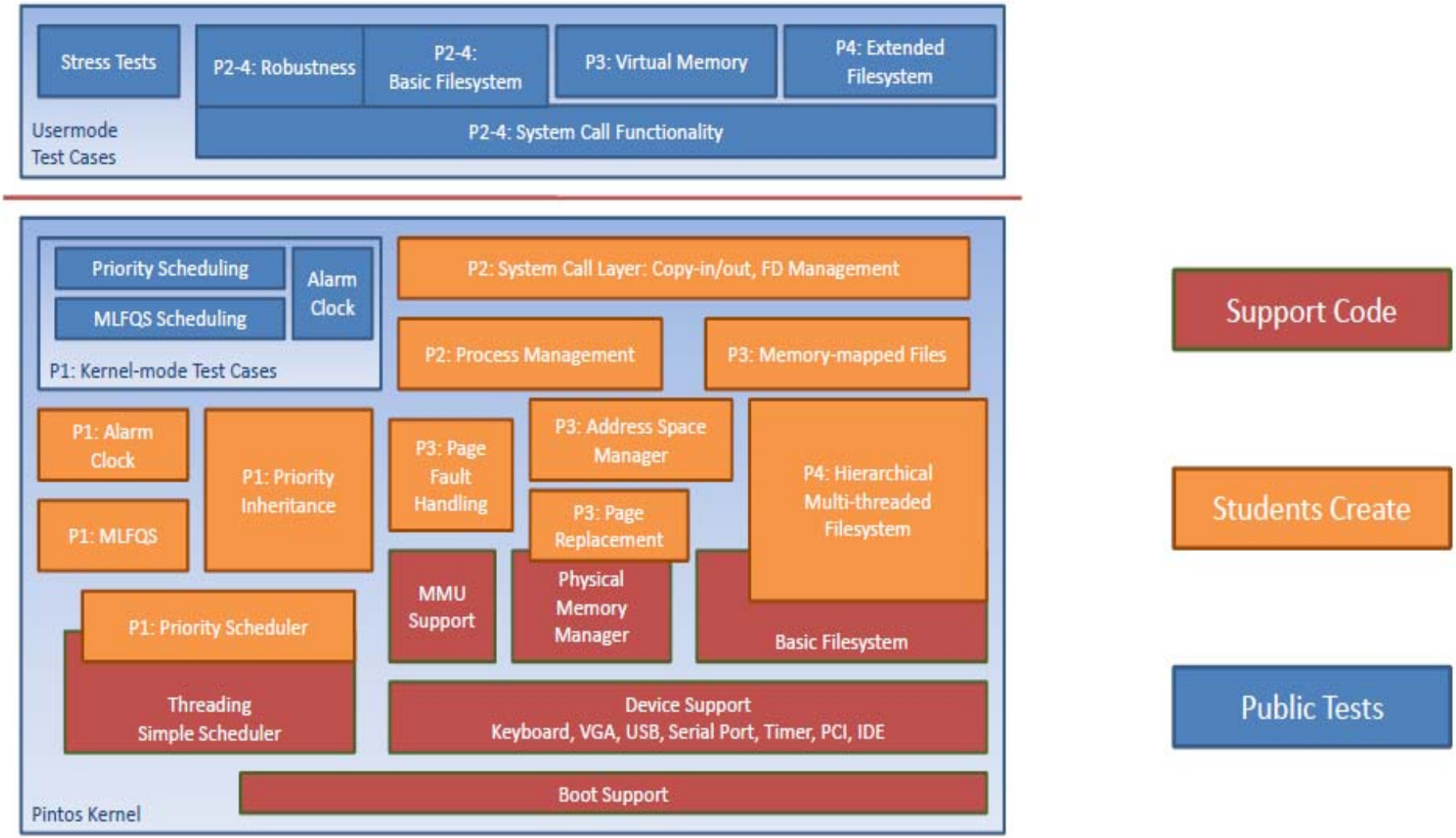
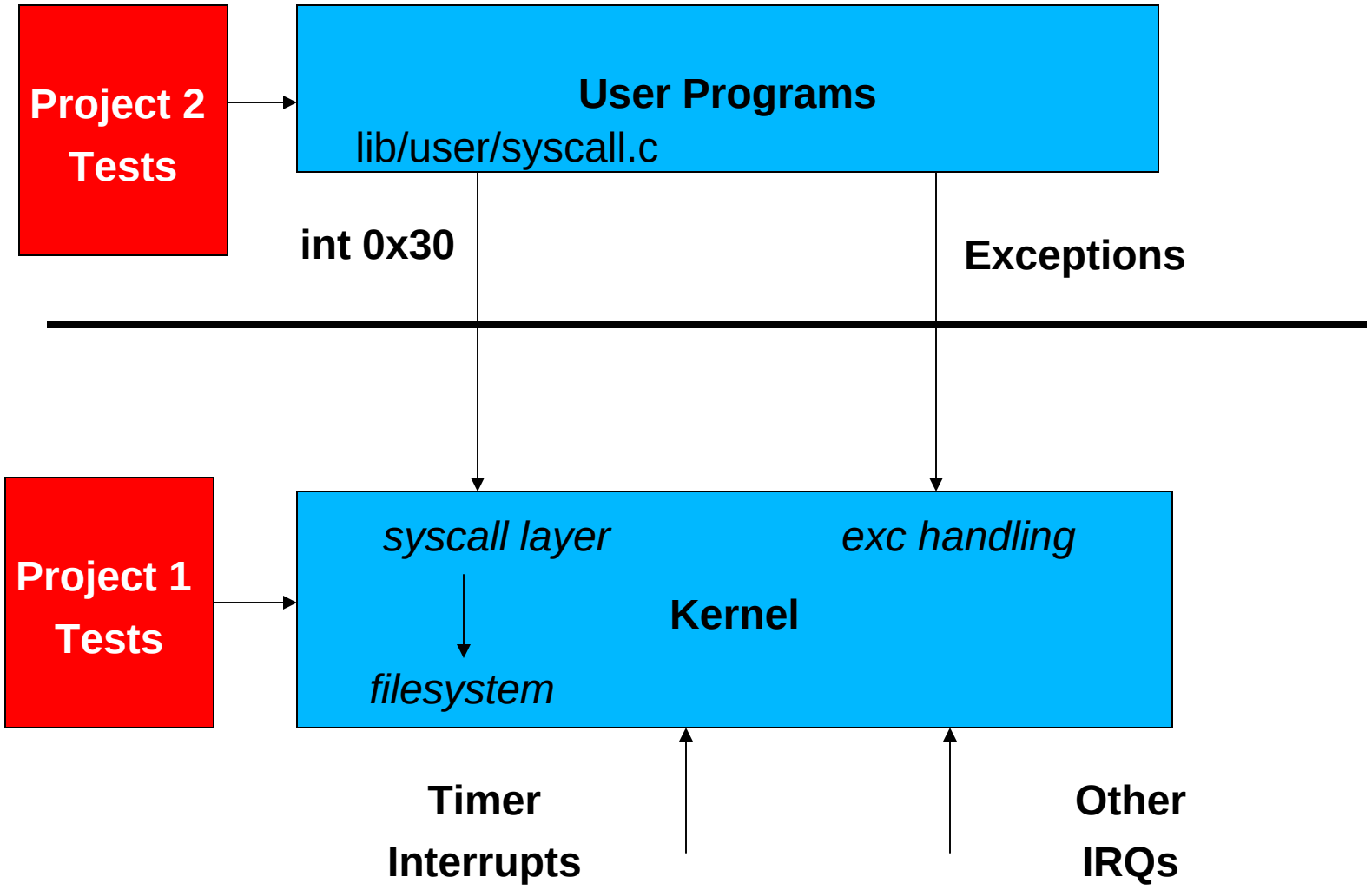
Project 2: User Programs and System Calls

P2: Project 2 – System Calls



Project 1 and Project 2



Using the File system

- Interfacing with the file system
- No need to modify the file system
- Certain limitations
  - No internal synchronization
  - File size fixed
  - File data allocated as a single extent
  - No subdirectories
  - File names limited to 14 chars
  - System crash might corrupt the file system
- Files to take a look at: ‘filesys.h’ & ‘file.h’

Some commands

- In **userprog/build**, create a new simulated disk
  - pintos-mkdisk fs.dsk --filesys-size=2
- Format the disk
  - pintos -f -q
  - This will only work after your disk is created and kernel is built!
- Copy the program "echo" onto the disk
  - pintos -p ../../examples/echo -a echo -- -q
- Run the program
  - pintos -q run ’echo x’
- All in a single command:

```
pintos --filesys-size=2 -p ../../examples/echo -a echo -- -f
   -q run 'echo x'
```

`pintos ... -v -- ..  -` to from terminal without X11 server

- $ **make check** or **make grade** – builds the disk automatically
  - You can just copy & paste the commands that make check does!

Various directories

- Few user programs:
  - src/examples
- Relevant files:
  - userprog/
- Other files:
  - threads/

Project 2 Requirements

- Process Termination Messages
- Argument Passing
- System Calls
- Deny writes to executables

1. Process Termination

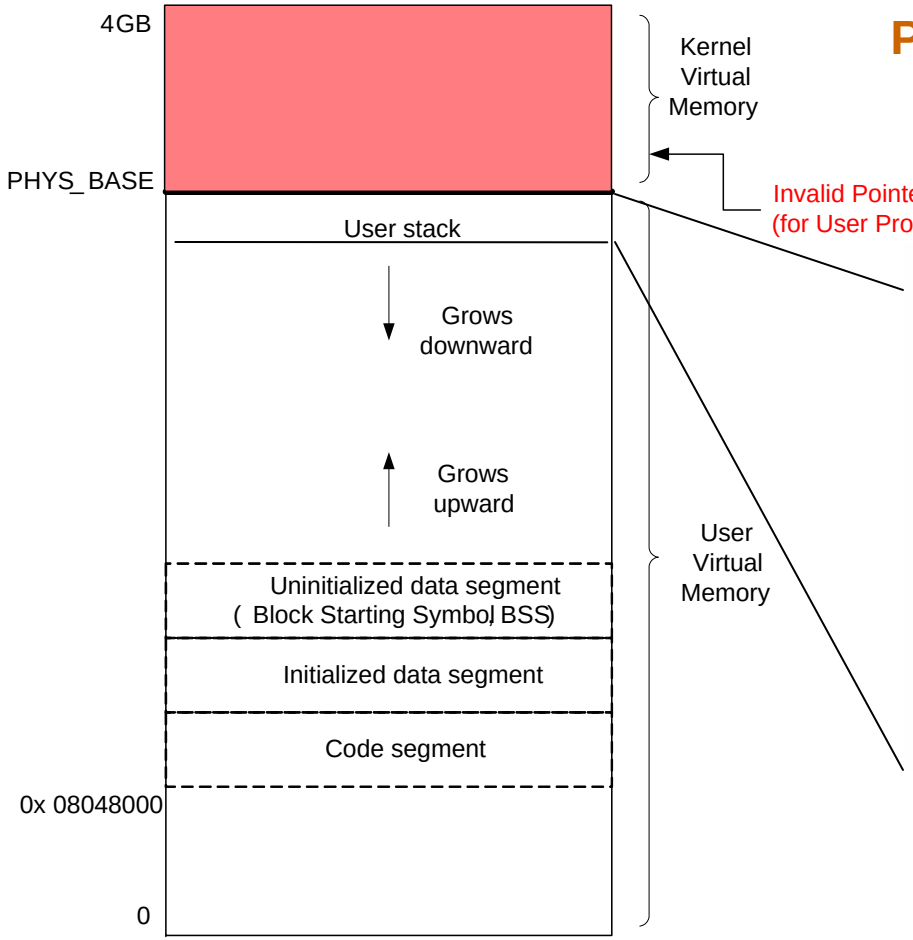
- When a Process Terminates
  - printf ("%s: exit(%d)\n", ...);
- Name: Full name passed to process_execute() in process.c
- Exit Code
- Do not print any other message!

2. Argument Passing

- No support currently for argument passing
- Change *esp = PHYS_BASE to *esp = PHYS_BASE – 12 in setup_stack() to get started
- Change process_execute() to process multiple arguments
- Can limit the arguments to fit in a page(4 kb)
- String Parsing: strtok_r() in lib/string.h

```
pgm.c
main(int argc,
        char *argv[]) {
        ...
   }
$ pintos run ‘pgm alpha beta’
argc = 3
argv[0] = “pgm”
argv[1] = “alpha”
argv[2] = “beta”
```

Memory Layout



PHYS_BASE = 3GB

Invalid Pointer Area
(for User Programs)

Address	Name	Data	Type
0xbffffffc	argv[3][...]	'bar\0'	char[4]
0xbffffff8	argv[2][...]	'foo\0'	char[4]
0xbffffff5	argv[1][...]	'-l\0'	char[3]
0xbfffffed	argv[0][...]	'/bin/ls\0'	char[8]
0xbfffffec	word-align	0	uint8_t
0xbfffffe8	argv[4]	0	char *
0xbfffffe4	argv[3]	0xbffffffc	char *
0xbfffffe0	argv[2]	0xbffffff8	char *
0xbfffffdc	argv[1]	0xbffffff5	char *
0xbfffffd8	argv[0]	0xbfffffed	char *
0xbfffffd4	argv	0xbfffffd8	char **
0xbfffffd0	argc	4	int
0xbfffffcc	return address	0	void (*) ()

Setting up the Stack

How to setup the stack for the program - /bin/ls –l foo bar

Address	Name	Data	Type
0xbffffffc	argv[3][...]	'bar\0'	char[4]
0xbffffff8	argv[2][...]	'foo\0'	char[4]
0xbffffff5	argv[1][...]	'-l\0'	char[3]
0xbfffffed	argv[0][...]	'/bin/ls\0'	char[8]
0xbfffffec	word-align	0	uint8_t
0xbfffffe8	argv[4]	0	char *
0xbfffffe4	argv[3]	0xbffffffc	char *
0xbfffffe0	argv[2]	0xbffffff8	char *
0xbfffffdc	argv[1]	0xbffffff5	char *
0xbfffffd8	argv[0]	0xbfffffed	char *
0xbfffffd4	argv	0xbfffffd8	char **
0xbfffffd0	argc	4	int
0xbfffffcc	return address	0	void (*) ()

3. System Calls – already discussed some; e.g. open( ) system call

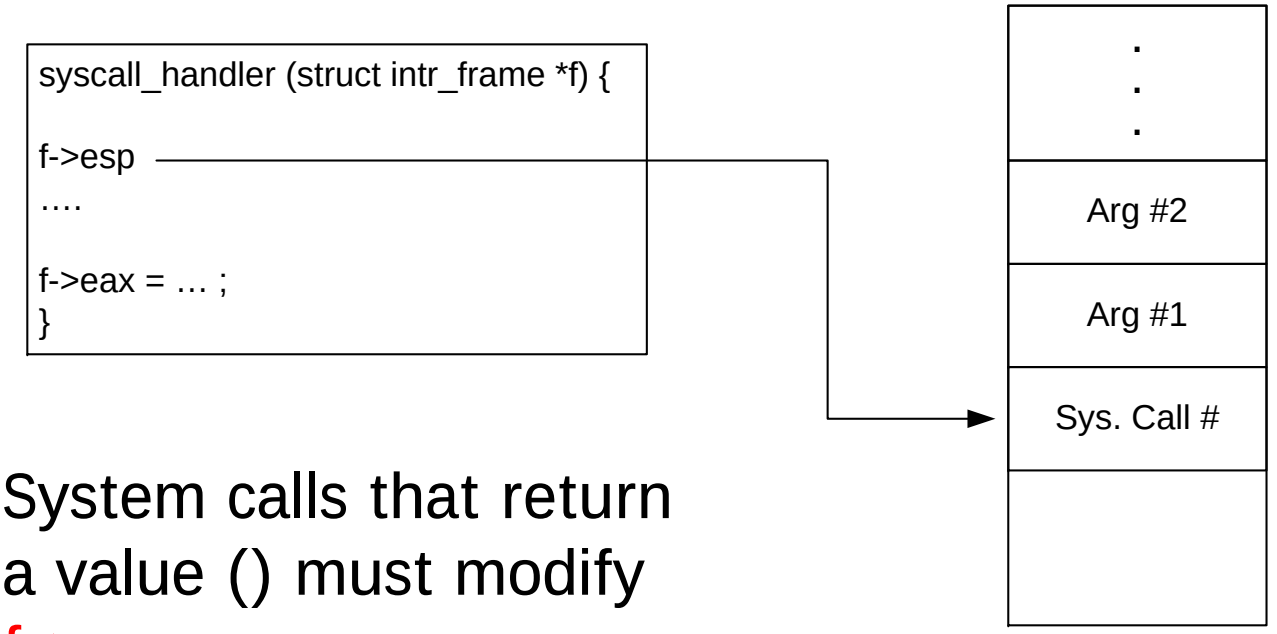
- No Support for system calls currently
- Implement the system call handler in userprog/syscall.c
- System call numbers defined in lib/syscall-nr.h
- Process Control: exit, exec, wait
- File system: create, remove, open, filesize, read, write, seek, tell, close
- Others: halt

System Call Details

- Types of Interrupts – External and Internal
- System calls – Internal Interrupts or Software Exceptions
- 80x86 – ‘int’ instruction to invoke system calls
- Pintos – ‘int $0x30’ to invoke system call

Continued…

- A system call has:
  - System call number
  - (possibly) arguments
- When syscall_handler() gets control:



  - System calls that return a value () must modify f->eax

System calls – File system

- Decide on how to implement the file descriptors – keep it simple -- O(n) data structures will entail no deduction
- Access granularity is the entire file system – add one global lock
- write() – fd 1 writes to console – use putbuf() to write entire buffer to console
- read() – fd 0 reads from console – use input_getc() to get input from keyboard
- Implement the rest of the system calls

System calls – Process Control

- wait(pid) – Waits for process pid to die and returns the status pid returned from exit
- Returns -1 if
  - pid was terminated by the kernel
  - pid does not refer to child of the calling thread
  - wait() has already been called for the given pid
- exec(cmd) – runs the executable whose name is given in command line
  - returns -1 if the program cannot be loaded
- exit(status) – terminates the current user program, returns status
  - status of 0 indicates success, non zero otherwise

Process Control – continued…

- Parent may or may not wait for its child
- Parent may call wait() after child terminates!
- Implement process_wait() in process.c
- Then, implement wait() in terms of process_wait()
- Cond variables and/or semaphores will help
  - Think about what semaphores may be used for and how they must be initialized

```
main() {
int i; pid_t p;
p = exec("pgm a b");
i = wait (p);
... /* i must be 5 */
}
```

```
main() {
int status;
... status = 5;
exit(status);
}
```

pgm.c

Memory Access

- Invalid pointers must be rejected. Why?
  - Kernel has access to all of physical memory including that of other processes
  - Kernel like user process would fault when it tries to access unmapped addresses
- User process cannot access kernel virtual memory
- User Process after it has entered the kernel can access kernel virtual memory and user virtual memory
- How to handle invalid memory access?

Memory Access – contd…

- Two methods to handle invalid memory access
  - Verify the validity of user provided pointer and then dereference it
    - Look at functions in userprog/pagedir.c, threads/vaddr.h
    - Strongly recommended!
  - Check if user pointer is below PHYS_BASE and dereference it
    - Could cause page fault
    - Handle the page fault by modifying the page_fault() code in userprog/exception.c
  - Make sure that resources are not leaked

Some Issues to look at…

- Check the validity of the system call parameters
- Every single location should be checked for validity before accessing it; e.g. not only for f->esp, but also the locations f->esp +1, f->esp+2 and f->esp+3 should be checked
- Read system call parameters into kernel memory (except for long buffers) – write a copy_in function for this purpose.

Denying writes to Executables

- Use file_deny_write() to prevent writes to an open file
- Use file_allow_write() to re-enable write
- Closing a file will re-enable writes

Suggested Order of Implementation

- Change *esp = PHYS_BASE to *esp = PHYS_BASE – 12 to get started
- Implement the system call infrastructure
- Change process_wait() to a infinite loop to prevent pintos getting powered off before the process gets executed
- Implement exit system call
- Implement write system call
- Start making other changes

Pintos Project 2 Sample Test

- Example Open System Call
- Test: tests/userprog/open-normal.c

```
/* Open a file. */
#include <syscall.h>
#include "tests/lib.h"
#include "tests/main.h"

void
test_main (void)
{
  int handle = open ("sample.txt");
  if (handle < 2)
    fail ("open() returned %d", handle);
}
```

userprog/ - make check

```
gcc -c ../../tests/userprog/open-normal.c -o tests/userprog/open-normal.o
 -g -msoft-float -O -fno-stack-protector -nostdinc -I../.. -I../../lib
 -I../../lib/user -I. -Wall -W -Wstrict-prototypes -Wmissing-prototypes
 -Wsystem-headers  -MMD -MF tests/userprog/open-normal.d
gcc  -Wl,--build-id=none -nostdlib -static -Wl,-T,../../lib/user/user.lds
 tests/userprog/open-normal.o tests/main.o tests/lib.o lib/user/entry.o
 libc.a -o tests/userprog/open-normal
pintos -v -k -T 60 --qemu  --filesys-size=2 -p tests/userprog/open-normal
 -a open-normal -p ../../tests/userprog/sample.txt -a sample.txt -- -q
 -f run open-normal < /dev/null 2> tests/userprog/open-normal.errors
 > tests/userprog/open-normal.output
perl -I../.. ../../tests/userprog/open-normal.ck
 tests/userprog/open-normal tests/userprog/open-normal.result
pass tests/userprog/open-normal
----------------------------------------------------------------------
ar r libc.a lib/debug.o lib/random.o lib/stdio.o lib/stdlib.o lib/string.o
 lib/arithmetic.o lib/ustar.o lib/user/debug.o lib/user/syscall.o
 lib/user/console.o
ranlib libc.a
```

$ objdump -D open-normal

```
080480a0 <test_main>:
 80480a0:       55                      push   %ebp
 80480a1:       89 e5                   mov    %esp,%ebp
 80480a3:       83 ec 18                sub    $0x18,%esp
 80480a6:       c7 04 24 6a a7 04 08    movl   $0x804a76a,(%esp)
 80480ad:       e8 1f 21 00 00          call   804a1d1 <open>
 80480b2:       83 f8 01                cmp    $0x1,%eax
..
0804a1d1 <open>:
 804a1d1:       55                      push   %ebp
 804a1d2:       89 e5                   mov    %esp,%ebp
 804a1d4:       ff 75 08                pushl  0x8(%ebp)
 804a1d7:       6a 06                   push   $0x6
 804a1d9:       cd 30                   int    $0x30
 804a1db:       83 c4 08                add    $0x8,%esp
 804a1de:       5d                      pop    %ebp
 804a1df:       c3                      ret
..
0804a76a <.rodata.str1.1>:
 804a76a:       73 61 6d 70 6c 65 2e 74 78 74 00
                 s  a  m  p  l  e  .  t  x  t
```

src/userprog/syscall.c

```
void
syscall_init (void)
{
  intr_register_int (0x30, 3, INTR_ON, syscall_handler,
   "syscall");
  lock_init (&fs_lock);
}
```

src/userprog/syscall.c

```
/* System call handler. */
static void
syscall_handler (struct intr_frame *f)
{
  typedef int syscall_function (int, int, int);
  /* A system call. */
  struct syscall
    {
      size_t arg_cnt;           /* Number of arguments. */
      syscall_function *func;   /* Implementation. */
    };
  /* Table of system calls. */
  static const struct syscall syscall_table[] =
    {
      {0, (syscall_function *) sys_halt},
      {1, (syscall_function *) sys_exit},
      {1, (syscall_function *) sys_exec},
      {1, (syscall_function *) sys_wait},
      {2, (syscall_function *) sys_create},
      {1, (syscall_function *) sys_remove},
      {1, (syscall_function *) sys_open},  <-- call number 6
```

src/userprog/syscall.c

```
 ...
  const struct syscall *sc;
  unsigned call_nr;
  int args[3];

  /* Get the system call. */
  copy_in (&call_nr, f->esp, sizeof call_nr);
  if (call_nr >= sizeof syscall_table / sizeof *syscall_table)
    thread_exit ();
  sc = syscall_table + call_nr;

  /* Get the system call arguments. */
  ASSERT (sc->arg_cnt <= sizeof args / sizeof *args);
  memset (args, 0, sizeof args);
  copy_in (args, (uint32_t *) f->esp + 1, sizeof *args * sc->arg_cnt);

  /* Execute the system call,
     and set the return value. */
  f->eax = sc->func (args[0], args[1], args[2]);
}
```

src/userprog/syscall.c

```
/* Open system call. */
static int
sys_open (const char *ufile)
{
  char *kfile = copy_in_string (ufile);
  struct file_descriptor *fd;
  int handle = -1;

  fd = malloc (sizeof *fd);
  if (fd != NULL)
    {
      lock_acquire (&fs_lock);
      fd->file = filesys_open (kfile);
      if (fd->file != NULL)
...
```

Copy a byte from user space to kernel space

```
/* Copies a byte from user address USRC to kernel address DST. */
static inline bool
get_user (uint8_t *dst, const uint8_t *usrc)
{
  int eax;
  asm ("movl $1f, %%eax; movb %2, %%al; movb %%al, %0; 1:"
       : "=m" (*dst), "=&a" (eax) : "m" (*usrc));
  return eax != 0;
}
/* Writes BYTE to user address UDST. */
static inline bool
put_user (uint8_t *udst, uint8_t byte)
{
  int eax;
  asm ("movl $1f, %%eax; movb %b2, %0; 1:"
       : "=m" (*udst), "=&a" (eax) : "q" (byte));
  return eax != 0;
}
```

Copy a string from user space to kernel space

```
static char *
copy_in_string (const char *us)
{
  char *ks;
  size_t length;
  ks = palloc_get_page (0);
  if (ks == NULL)
    thread_exit ();
    for (length = 0; length < PGSIZE; length++)
    {
      if (us >= (char *) PHYS_BASE || !get_user (ks + length, us++))
      {
          palloc_free_page (ks);
          thread_exit ();
      }
      if (ks[length] == '\0')
        return ks;
    }
  ks[PGSIZE - 1] = '\0';
  return ks;
}
```

Run a single test

- From userprog/build:
  - **`rm tests/userprog/open-normal.output`**
  - **`make test/userprog/open-normal.output`**

pintos -v -k -T 60 --qemu --filesys-size=2 -p tests/userprog/open-normal -a open-normal -p ../../tests/userprog/sample.txt -a sample.txt -- -q -f run open-normal < /dev/null 2> tests/userprog/open-normal.errors > tests/userprog/open-normal.output

examples/shell.c

```
int main (void)
{
  printf ("Shell starting..\n");
  for (;;)
    {
      char command[80];
      /* Read command. */
      printf ("--");
      read_line (command, sizeof command);

      /* Execute command. */
      if (!strcmp (command, "exit"))
        break;
      else if (!memcmp (command, "cd ", 3))
        {
          if (!chdir (command + 3))
            printf ("\"%s\": chdir failed\n", command + 3);
        }
      else if (command[0] == '\0')
```

examples/shell.c

```
 else if (command[0] == '\0')
        {
          /* Empty command. */
        }
      else
        {
          pid_t pid = exec (command);
          if (pid != PID_ERROR)
            printf ("\"%s\": exit code %d\n", command, wait (pid));
          else
            printf ("exec failed\n");
        }
    }

  printf ("Shell exiting.");
  return EXIT_SUCCESS;
}
```

$ objdump -D examples/shell

```
080480cc <main>:
 80480cc:       55                      push   %ebp
 80480cd:       89 e5                   mov    %esp,%ebp
 80480cf:       83 e4 f0                and    $0xfffffff0,%esp
 80480d2:       57                      push   %edi
 80480d3:       56                      push   %esi
 80480d4:       53                      push   %ebx
 80480d5:       83 ec 74                sub    $0x74,%esp
 80480d8:       c7 04 24 3e a1 04 08    movl   $0x804a13e,(%esp)
 80480df:       e8 23 1d 00 00          call   8049e07 <puts>
 80480e4:       c7 04 24 5a a1 04 08    movl   $0x804a15a,(%esp)
 80480eb:       e8 2f 0c 00 00          call   8048d1f <printf>
 80480f0:       8d 44 24 18             lea    0x18(%esp),%eax
 80480f4:       89 44 24 68             mov    %eax,0x68(%esp)
 80480f8:       89 c3                   mov    %eax,%ebx
 80480fa:       c7 44 24 08 01 00 00    movl   $0x1,0x8(%esp)
 8048101:       00
 8048102:       8d 44 24 6f             lea    0x6f(%esp),%eax
 8048106:       89 44 24 04             mov    %eax,0x4(%esp)
 804810a:       c7 04 24 00 00 00 00    movl   $0x0,(%esp)
 8048111:       e8 a9 1a 00 00          call   8049bbf <read>
```

$ objdump -D examples/shell

```
..
 80481f1:       80 7c 24 18 00          cmpb   $0x0,0x18(%esp)
 80481f6:       0f 84 e8 fe ff ff       je     80480e4 <main+0x18>
 80481fc:       8d 44 24 18             lea    0x18(%esp),%eax
 8048200:       89 04 24                mov    %eax,(%esp)
 8048203:       e8 50 19 00 00          call   8049b58 <exec>
..
08049bbf <read>:
 8049bbf:       55                      push   %ebp
 8049bc0:       89 e5                   mov    %esp,%ebp
 8049bc2:       ff 75 10                pushl  0x10(%ebp)
 8049bc5:       ff 75 0c                pushl  0xc(%ebp)
 8049bc8:       ff 75 08                pushl  0x8(%ebp)
 8049bcb:       6a 08                   push   $0x8
 8049bcd:       cd 30                   int    $0x30
 8049bcf:       83 c4 10                add    $0x10,%esp
 8049bd2:       5d                      pop    %ebp
 8049bd3:       c3                      ret
```

syscall exec() calls process_execute

```
/* Starts a new thread running a user program loaded from
   FILENAME.  The new thread may be scheduled (and may even exit)
   before process_execute() returns.  Returns the new process's
   thread id, or TID_ERROR if the thread cannot be created. */
tid_t process_execute (const char *file_name)
{
  struct exec_info exec;
  char thread_name[15];
  char *save_ptr;
  tid_t tid;
  /* Initialize exec_info. */
  exec.file_name = file_name;
  sema_init (&exec.load_done, 0);
  /* Create a new thread to execute FILE_NAME. */
  strlcpy (thread_name, file_name, sizeof thread_name);
  strtok_r (thread_name, " ", &save_ptr);
  tid = thread_create (thread_name, PRI_DEFAULT, start_process, &exec);
```

process_execute

```
/* Starts a new thread running a user program loaded from
   FILENAME.  The new thread may be scheduled (and may even exit)
   before process_execute() returns.  Returns the new process's
   thread id, or TID_ERROR if the thread cannot be created. */
tid_t process_execute (const char *file_name)
{
..

  if (tid != TID_ERROR)
  {
      sema_down (&exec.load_done);
      if (exec.success)
        list_push_back (&thread_current ()->children,
                        &exec.wait_status->elem);
      else
        tid = TID_ERROR;
  }
  return tid;
}
```

start_process

```
static void start_process (void *exec_)
{
  struct exec_info *exec = exec_;
  struct intr_frame if_;
  bool success;

  /* Initialize interrupt frame and load executable. */
  memset (&if_, 0, sizeof if_);
  if_.gs = if_.fs = if_.es = if_.ds = if_.ss = SEL_UDSEG;
  if_.cs = SEL_UCSEG;
  if_.eflags = FLAG_IF | FLAG_MBS;
  success = load (exec->file_name, &if_.eip, &if_.esp);

  /* Allocate wait_status. */
  if (success)
  {
      exec->wait_status = thread_current ()->wait_status
        = malloc (sizeof *exec->wait_status);
      success = exec->wait_status != NULL;
  }
```

start_process

```
 /* Initialize wait_status. */
  if (success)
  {
      ..
  }
  /* Notify parent thread and clean up. */
  exec->success = success;
  sema_up (&exec->load_done);
  if (!success)
    thread_exit ();
  /* Start the user process by simulating a return from an
     interrupt, implemented by intr_exit (in
     threads/intr-stubs.S).  Because intr_exit takes all of its
     arguments on the stack in the form of a `struct intr_frame',
     we just point the stack pointer (%esp) to our stack frame
     and jump to it. */
  asm volatile ("movl %0, %%esp; jmp intr_exit" : : "g" (&if_) : "memory");
}
```

Cycle Counters

- Most modern systems have built in registers that are incremented every clock cycle
  - Very fine grained
  - Maintained as part of process state
    - In Linux, counts elapsed global time
- Special assembly code instruction to access
- On (recent model) Intel machines:
  - 64 bit counter.
  - RDTSC instruction sets `%edx` to high order 32-bits, `%eax` to low order 32-bits
- Aside: Is this a security issue?

Cycle Counter Period

- Wrap Around Times for 550 MHz machine
  - Low order 32 bits wrap around every 2^{32} / (550 * 10^6) = 7.8 seconds
  - High order 64 bits wrap around every 2^{64} / (550 * 10^6) = 33539534679 seconds
    - 1065 years
- For 2 GHz machine
  - Low order 32 bits every 2.1 seconds
  - High order 64 bits every 293 years

Measuring with Cycle Counter

- Idea
  - Get current value of cycle counter
    - store as pair of unsigned's `cyc_hi` and `cyc_lo`
  - Compute something
  - Get new value of cycle counter
  - Perform double precision subtraction to get elapsed cycles

```
/* Keep track of most recent reading of cycle counter */
static unsigned cyc_hi = 0;
static unsigned cyc_lo = 0;

void start_counter()
{
  /* Get current value of cycle counter */
  access_counter(&cyc_hi, &cyc_lo);
}
```

Accessing the Cycle Counter

- GCC allows inline assembly code with mechanism for matching registers with program variables
- Code only works on x86 machine compiling with GCC

```
void access_counter(unsigned *hi, unsigned *lo)
{
  /* Get cycle counter */
  asm("rdtsc; movl %%edx,%0; movl %%eax,%1"
      : "=r" (*hi), "=r" (*lo)
      : /* No input */
      : "%edx", "%eax");
}
```

- Emit assembly with `rdtsc` and two `movl` instructions

Closer Look at Extended ASM

```
asm("Instruction String"
      : Output List
      : Input List
      : Clobbers List);
}
```

```
void access_counter
  (unsigned *hi, unsigned *lo)
{
  /* Get cycle counter */
  asm("rdtsc; movl %%edx,%0; movl %%eax,%1"
      : "=r" (*hi), "=r" (*lo)
      : /* No input */
      : "%edx", "%eax");
}
```

- Instruction String
  - Series of assembly commands
    - Separated by “;” or “\n”
    - Use “%%” where normally would use “%”

Closer Look at Extended ASM

```
asm("Instruction String"
      : Output List
      : Input List
      : Clobbers List
}
```

```
void access_counter
  (unsigned *hi, unsigned *lo)
{
  /* Get cycle counter */
  asm("rdtsc; movl %%edx,%0; movl %%eax,%1"
      : "=r" (*hi), "=r" (*lo)
      : /* No input */
      : "%edx", "%eax");
}
```

- Output List
  - Expressions indicating destinations for values %0, %1, …, %*j*
    - Enclosed in parentheses
    - Must be *lvalue*
      - Value that can appear on LHS of assignment
  - Tag "=r" indicates that symbolic value (%0, etc.), should be replaced by a register

Closer Look at Extended ASM

```
asm("Instruction String"
      : Output List
      : Input List
      : Clobbers List)
}
```

```
void access_counter
  (unsigned *hi, unsigned *lo)
{
  /* Get cycle counter */
  asm("rdtsc; movl %%edx,%0; movl %%eax,%1"
      : "=r" (*hi), "=r" (*lo)
      : /* No input */
      : "%edx", "%eax");
}
```

- Input List
  - Series of expressions indicating sources for values %*j*+1, %*j*+2, …
    - Enclosed in parentheses
    - Any expression returning value
  - Tag `"r"` indicates that symbolic value (`%0`, etc.) will come from register

Closer Look at Extended ASM

```
asm("Instruction String"
      : Output List
      : Input List
      : Clobbers List);
}
```

```
void access_counter
  (unsigned *hi, unsigned *lo)
{
  /* Get cycle counter */
  asm("rdtsc; movl %%edx,%0; movl %%eax,%1
      : "=r" (*hi), "=r" (*lo)
      : /* No input */
      : "%edx", "%eax");
}
```

- Clobbers List
  - List of register names that get altered by assembly instruction
  - Compiler will make sure doesn't store something in one of these registers that must be preserved across `asm`
    - Value set before & used after

Completing Measurement

- Get new value of cycle counter
- Perform double precision subtraction to get elapsed cycles
- Express as `double` to avoid overflow problems

```
double get_counter()
{
  unsigned ncyc_hi, ncyc_lo
  unsigned hi, lo, borrow;
  /* Get cycle counter */
  access_counter(&ncyc_hi, &ncyc_lo);
  /* Do double precision subtraction */
  lo = ncyc_lo - cyc_lo;
  borrow = lo > ncyc_lo;
  hi = ncyc_hi - cyc_hi - borrow;
  return (double) hi * (1 << 30) * 4 + lo;
}
```

Timing With Cycle Counter

- Determine Clock Rate of Processor
  - Count number of cycles required for some fixed number of seconds

```
double MHZ;
int sleep_time = 10;
start_counter();
sleep(sleep_time);
MHZ = get_counter()/(sleep_time * 1e6);
```

- Time Function P( )
  - First attempt: Simply count cycles for one execution of P

```
double tsecs;
start_counter();
P();
tsecs = get_counter() / (MHZ * 1e6);
```

Example – testClock.c

```
#include <stdio.h>
#include "clock.h"


int main()
{

  double cycles, Mhz;

  Mhz = mhz(1);
  start_counter();
  sleep(2);
  cycles = get_counter();

  printf("cycles = %f, MHz = %f, cycles/Mhz = %f\n", cycles, Mhz,
 cycles/Mhz);
  printf("elapsed time = %f seconds \n", cycles/(1.0e6*Mhz));

  return 0;
}
```

```
Processor Clock Rate ~= 2673.5 MHz
cycles = 5343976388.000000, MHz = 2673.526339, cycles/Mhz = 1998849.351153
elapsed time = 1.998849 seconds
```

Measurement Pitfalls

- Overhead
  - Calling `get_counter()` incurs small amount of overhead
  - Want to measure long enough code sequence to compensate