Processes and System Calls

key concepts

process,system call,processor exception,fork/execv,multiprocessing

reading

Three Easy Pieces: Chapter 4 (Processes), Chapter 5 (Process API), Chapter 6 (Direct Execution)

What is a Process?

A process is an environment in which an application program runs.

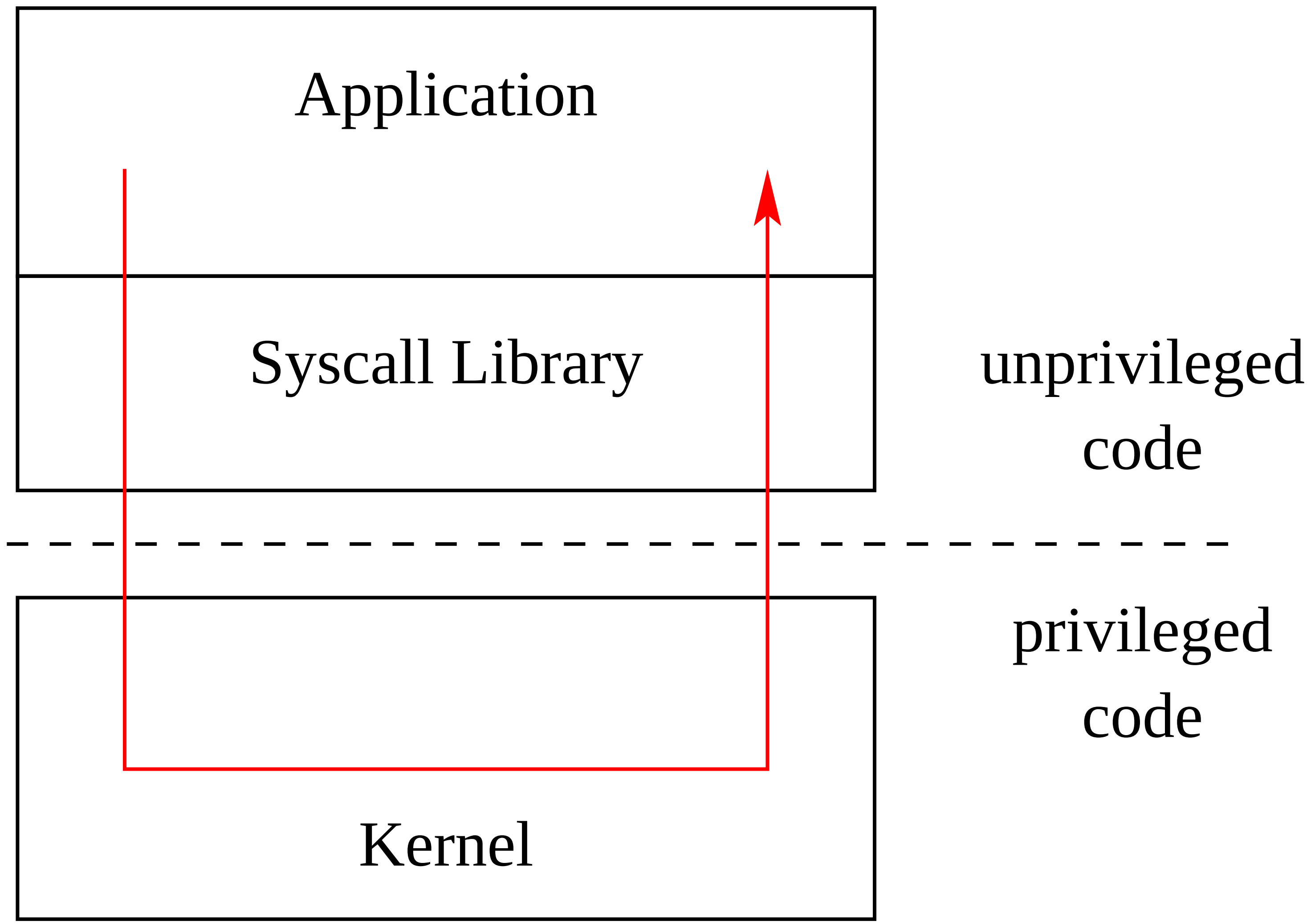
- a process includes virtualized *resources* that its program can use:
  - one (or more) threads
  - virtual memory, used for the program's code and data
  - other resources, e.g., file and socket descriptors
- processes are created and managed by the kernel
- each program's process *isolates* it from other programs in other processes

System Calls

- System calls are the interface between processes and the kernel.
- A process uses system calls to request operating system services.
- Some examples:

Service	OS/161 Examples
create,destroy,manage processes	`fork,execv,waitpid,getpid`
create,destroy,read,write files	`open,close,remove,read,write`
manage file system and directories	`mkdir,rmdir,link,sync`
interprocess communication	`pipe,read,write`
manage virtual memory	`sbrk`
query,manage system	`reboot,__time`

System Call Software Stack



Kernel Privilege

- Kernel code runs at a higher level of *execution privilege* than application code
  - privilege levels are implemented by the CPU
- The kernel's higher privilege level allows it to do things that the CPU prevents less-privileged (application) programs from doing. For example:
  - application programs cannot modify the page tables that the kernel uses to implement process virtual memories
  - application programs cannot halt the CPU
- These restrictions allow the kernel to keep processes isolated from one another - and from the kernel.

Application programs cannot directly call kernel functions or access kernel data structures.

How System Calls Work (Part 1)

Since application programs can't directly call the kernel, how does a program make a system call?

- There are only two things that make kernel code run:
  - **Interrupts**
    - interrupts are generated by devices
    - an interrupt means a device (hardware) needs attention
  - **Exceptions**
    - exceptions are caused by instruction execution
    - an exception means that a running program needs attention

Interrupts, Revisited

- We have described interrupts already. Remember:
  - An interrupt causes the hardware to transfer control to a fixed location in memory, where an *interrupt handler* is located
- Interrupt handlers are part of the kernel
  - If an interrupt occurs while an application program is running, control will jump from the application to the kernel's interrupt handler
- When an interrupt occurs, the processor switches to privileged execution mode when it transfers control to the interrupt handler
  - This is how the kernel gets its execution privilege

Exceptions

- Exceptions are conditions that occur during the execution of a program instruction.
  - Examples: arithmetic overflows, illegal instructions, or page faults (to be discussed later).
- Exceptions are detected by the CPU during instruction execution
- The CPU handles exceptions like it handles interrupts:
  - control is transferred to a fixed location, where an *exception handler* is located
  - the processor is switched to privileged execution mode
- The exception handler is part of the kernel

MIPS Exception Types

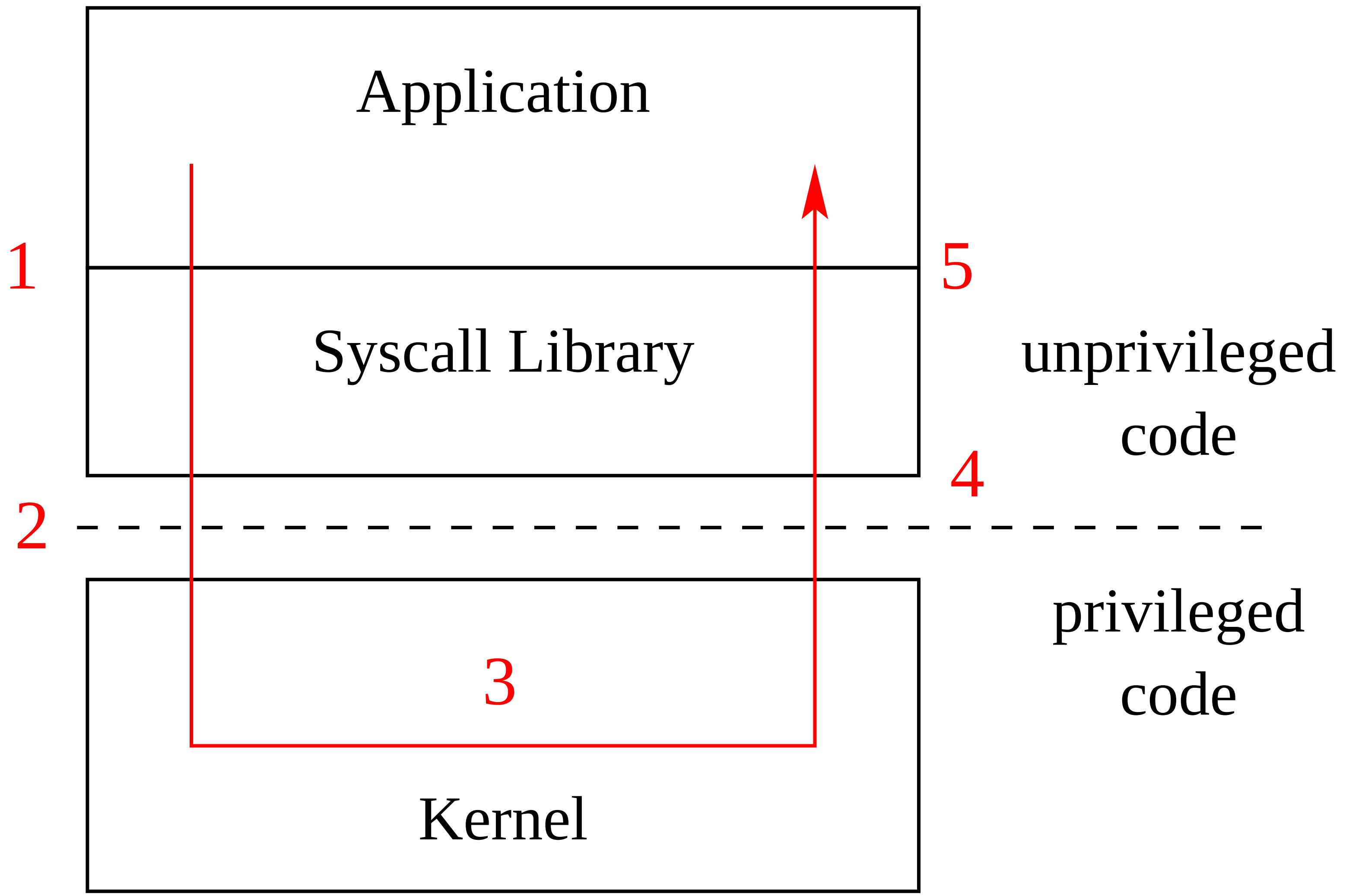
```
EX_IRQ     0    /* Interrupt */
EX_MOD     1    /* TLB Modify (write to read-only page) */
EX_TLBL    2    /* TLB miss on load */
EX_TLBS    3    /* TLB miss on store */
EX_ADEL    4    /* Address error on load */
EX_ADES    5    /* Address error on store */
EX_IBE     6    /* Bus error on instruction fetch */
EX_DBE     7    /* Bus error on data load *or* store */
EX_SYS     8    /* Syscall */
EX_BP      9    /* Breakpoint */
EX_RI      10   /* Reserved (illegal) instruction */
EX_CPU     11   /* Coprocessor unusable */
EX_OVF     12   /* Arithmetic overflow */
```

On the MIPS, the same mechanism handles exceptions and interrupts, and there is a single handler for both in the kernel. The handler uses these codes to determine what triggered it to run.

How System Calls Work (Part 2)

- To perform a system call, the application program needs to cause an exception to make the kernel execute:
  - on the MIPS, `EX_SYS` is the system call exception
- To cause this exception on the MIPS, the application executes a special purpose instruction: `syscall`
  - other processor instruction sets include similar instructions, e.g., `syscall` on x86
- The kernel's exception handler checks the exception code (set by the CPU when the exception is generated) to distinguish system call exceptions from other types of exceptions.

System Call Software Stack (again)



System Call Timeline

1. application calls library wrapper function for desired system call
2. library function performs `syscall` instruction
3. kernel exception handler runs
   - creates trap frame to save application program state
   - determines that this is a system call exception
   - determines which system call is being requested
   - does the work for the requested system call
   - restores the application program state from the trap frame
   - returns from the exception
4. library wrapper function finishes and returns from its call
5. application continues execution

Which System Call?

- Q. There are many different system calls, but only one `syscall` exception. How does the kernel know *which* system call the application is requesting?
- A. system call codes
  - the kernel defines a code for each system call it understands
  - the kernel expects the application to place a code in a specified location before executing the `syscall` instruction
    - for OS/161 on the MIPS, the code goes in register `v0`
  - the kernel's exception handler checks this code to determine which system call has been requested
  - the codes and code location are part of the *kernel ABI* (Application Binary Interface)

Some OS/161 System Call Codes

```
...
#define SYS_fork         0
#define SYS_vfork        1
#define SYS_execv        2
#define SYS__exit        3
#define SYS_waitpid      4
#define SYS_getpid       5
...
```

This comes from `kern/include/kern/syscall.h`. The files in `kern/include/kern` define things (like system call codes) that must be known by both the kernel and applications.

System Call Parameters

- Q. System calls take parameters and return values, like function calls. How does this work, since system calls are really just exceptions?
- A. The application places parameter values in kernel-specified locations before the `syscall`, and looks for return values in kernel-specified locations after the exception handler returns
  - The locations are part of the kernel ABI
  - Parameter and return value placement is handled by the application system call library functions
  - On the MIPS
    * parameters go in registers `a0`,`a1`,`a2`,`a3`
    * result success/fail code is in `a3` on return
    * return value or error code is in `v0` on return

User and Kernel Stacks

- Every OS/161 process thread has two stacks, although it only uses one at a time
  - **User (Application) Stack:** used while application code is executing
    - this stack is located in the application's virtual memory
    - it holds activation records for application functions
    - the kernel creates this stack when it sets up the virtual address memory for the process
  - **Kernel Stack:** used while the thread is executing kernel code, after an exception or interrupt
    - this stack is a kernel structure
    - in OS/161, the `t_stack` field of the `thread` structure points to this stack
    - this stack holds activation records for kernel functions
    - this stack also holds *trap frames* and *switch frames* (because the kernel creates trap frames and switch frames)

Exception Handling in OS/161

- first to run is careful assembly code that
  - saves the application stack pointer
  - switches the stack pointer to point to the thread's kernel stack
  - carefully saves application state and the address of the instruction that was interrupted in a trap frame on the thread's kernel stack
  - calls `mips_trap`, passing a pointer to the trap frame as a parameter
- after `mips_trap` is finished, the handler will
  - restore application state (including the application stack pointer) from the trap frame on the thread's kernel stack
  - jump back to the application instruction that was interrupted, and switch back to unprivileged execution mode
- see `kern/arch/mips/locore/exception-mips1.S`

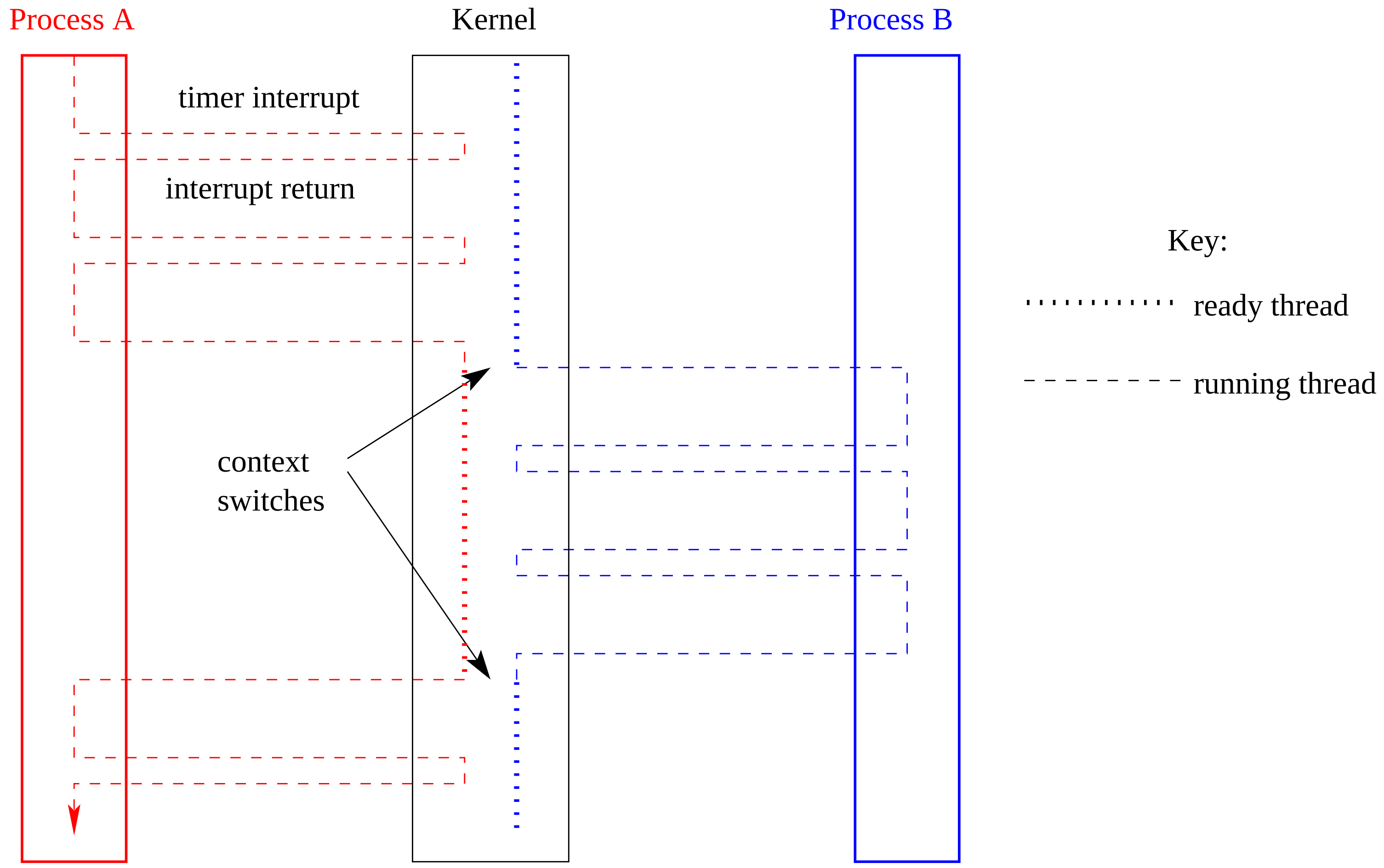
mips_trap

- mips_trap determines what type of exception this is by looking at the exception code: interrupt? system call? something else?
- there is a separate handler in the kernel for each type of exception:
  - interrupt? call mainbus_interrupt
  - address translation exception? call vm_fault (important for later assignments!)
  - system call? call syscall (kernel function), passing it the trap frame pointer
  - syscall is in kern/arch/mips/syscall/syscall.c
- see kern/arch/mips/locore/trap.c

Multiprocessing

- Multiprocessing (or multitasking) means having multiple processes existing at the same time
- All processes share the available hardware resources, with the sharing coordinated by the operating system:
  - Each process' virtual memory is implemented using some of the available physical memory. The OS decides how much memory each process gets.
  - Each process' threads are scheduled onto the available CPUs (or CPU cores) by the OS.
  - Processes share access to other resources (e.g., disks, network devices, I/O devices) by making system calls. The OS controls this sharing.
- The OS ensures that processes are isolated from one another. Interprocess communication should be possible, but only at the explicit request of the processes involved.

Multiprocessing Example



Two process' threads timesharing a single CPU.

System Calls for Process Management

	Linux	OS/161
Creation	fork,execv	fork,execv
Destruction	_exit,kill	_exit
Synchronization	wait,waitpid,pause,. . .	waitpid
Attribute Mgmt	getpid,getuid,nice,getrusage,. . .	getpid

fork, _exit, and waitpid

- `fork` creates a new process (the *child*) that is a clone of the original (the *parent*)
  - after `fork`, both parent and child are executing copies of the same program
  - virtual memories of parent and child are identical at the time of the fork, but may diverge afterwards
  - `fork` is called by the parent, but returns in *both* the parent and the child
    - parent and child see different return values from fork
- `_exit` terminates the process that calls it
  - process can supply an exit status code when it exits
  - kernel records the exit status code in case another process asks for it (via `waitpid`)
- `waitpid` lets a process wait for another to terminate, and retrieve its exit status code

The fork, _exit, getpid and waitpid system calls

```
main() {
   rc = fork();  /* returns 0 to child, pid to parent */
   if (rc == 0) {  /* child executes this code */
      my_pid = getpid();
      x = child_code();
      _exit(x);
   } else {   /* parent executes this code */
     child_pid = rc;
     parent_pid = getpid();
     parent_code();
     p = waitpid(child_pid,&child_exit,0);
     if (WIFEXITED(child_exit))
       printf("child exit status was %d\n",
              WEXITSTATUS(child_exit))
   }
}
```

The execv system call

- `execv` changes the program that a process is running
- The calling process's current virtual memory is destroyed
- The process gets a new virtual memory, initialized with the code and data of the new program to run
- After `execv`, the new program starts executing

execv example

```
int main()
{
  int rc = 0;
  char *args[4];

  args[0] = (char *) "/testbin/argtest";
  args[1] = (char *) "first";
  args[2] = (char *) "second";
  args[3] = 0;

  rc = execv("/testbin/argtest", args);
  printf("If you see this execv failed\n");
  printf("rc = %d errno = %d\n", rc, errno);
  exit(0);
}
```

Combining fork and execv

```
main()
{
   char *args[4];
   /* set args here */
   rc = fork();  /* returns 0 to child, pid to parent */
   if (rc == 0) {
     status = execv("/testbin/argtest",args);
     printf("If you see this execv failed\n");
     printf("status = %d errno = %d\n", status, errno);
     exit(0);
   } else {
     child_pid = rc;
     parent_code();
     p = waitpid(child_pid,&child_exit,0);
   }
}
```