What is a Process?

Answer 1: a process is an abstraction of a program in execution

Answer 2: a process consists of

- an *address space*, which represents the memory that holds the program's code and data
- a *thread* of execution (possibly several threads)
- other resources associated with the running program. For example:
  - open files
  - sockets
  - attributes, such as a name (process identifier)
  - . . .

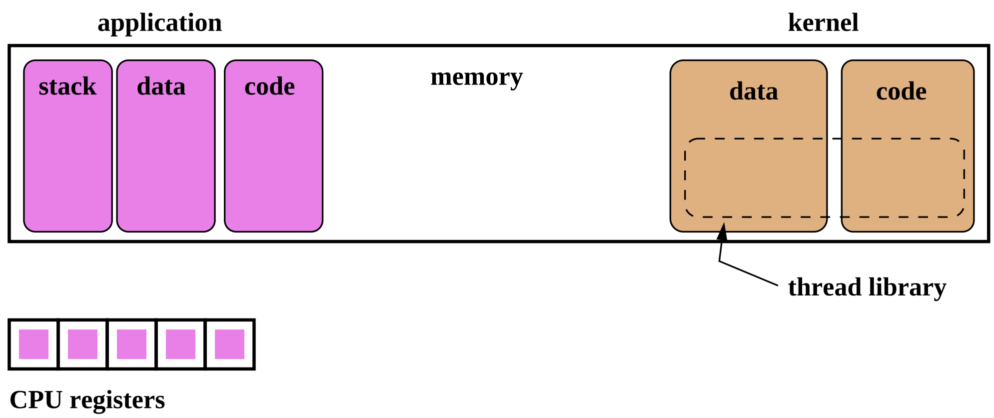
A process with one thread is a *sequential* process. A process with more than one thread is a *concurrent* process.

Multiprogramming

- multiprogramming means having multiple processes existing at the same time
- most modern, general purpose operating systems support multiprogramming
- all processes share the available hardware resources, with the sharing coordinated by the operating system:
  - Each process uses some of the available memory to hold its address space. The OS decides which memory and how much memory each process gets
  - OS can coordinate shared access to devices (keyboards, disks), since processes use these devices indirectly, by making system calls.
  - Processes *timeshare* the processor(s). Again, timesharing is controlled by the operating system.
- OS ensures that processes are isolated from one another. Interprocess communication should be possible, but only at the explicit request of the processes involved.

The OS Kernel

- The kernel is a program. It has code and data like any other program.
- Usually kernel code runs in a privileged execution mode, while other programs do not



Kernel Privilege, Kernel Protection

- What does it mean to run in privileged mode?
- Kernel uses privilege to
  - control hardware
  - protect and isolate itself from processes
- privileges vary from platform to platform, but may include:
  - ability to execute special instructions (like `halt`)
  - ability to manipulate processor state (like execution mode)
  - ability to access memory addresses that can't be accessed otherwise
- kernel ensures that it is *isolated* from processes. No process can execute or change kernel code, or read or write kernel data, except through controlled mechanisms like system calls.

System Calls

- System calls are an 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`

How System Calls Work

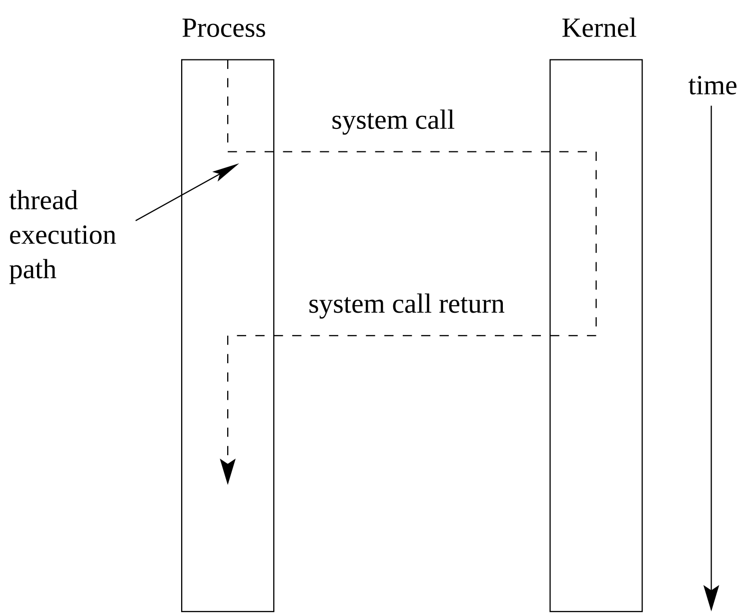
- The hardware provides a mechanism that a running program can use to cause a system call. Often, it is a special instruction, e.g., the MIPS `syscall` instruction.
- What happens on a system call:
  - the processor is switched to system (privileged) execution mode
  - key parts of the current thread context, such as the program counter, are saved
  - the program counter is set to a fixed (specified by the hardware) memory address, which is within the kernel's address space

System Call Execution and Return

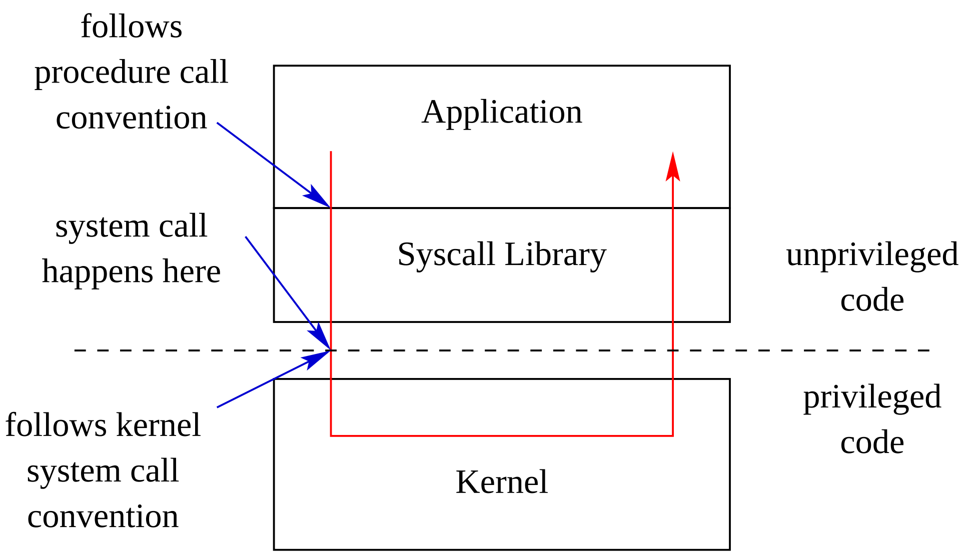
- Once a system call occurs, the calling thread will be executing a system call handler, which is part of the kernel, in privileged mode.
- The kernel's handler determines which service the calling process wanted, and performs that service.
- When the kernel is finished, it returns from the system call. This means:
  - restore the key parts of the thread context that were saved when the system call was made
  - switch the processor back to unprivileged (user) execution mode
- Now the thread is executing the calling process' program again, picking up where it left off when it made the system call.

A system call causes a thread to stop executing application code and to start executing kernel code in privileged mode. The system call return switches the thread back to executing application code in unprivileged mode.

System Call Diagram



System Call Software Stack



OS/161 `close` System Call Description

Library: standard C library (libc)

Synopsis:

```
#include <unistd.h>
int
close(int fd);
```

Description: The file handle `fd` is closed. . . .

Return Values: On success, `close` returns 0. On error, -1 is returned and `errno` is set according to the error encountered.

Errors:

EBADF: `fd` is not a valid file handle

EIO: A hard I/O error occurred

An Example System Call: A Tiny OS/161 Application that Uses `close`

```
/* Program: user/uw-testbin/syscall.c */
#include <unistd.h>
#include <errno.h>

int
main()
{
  int x;
  x = close(999);
  if (x < 0) {
    return errno;
  }
  return x;
}
```


Disassembly listing of user/uw-testbin/syscall

```
00400050 <main>:
  400050: 27bdffe8  addiu sp,sp,-24
  400054: afbf0010  sw  ra,16(sp)
  400058: 0c100077  jal 4001dc <close>
  40005c: 240403e7  li  a0,999
  400060: 04410003  bgez  v0,400070 <main+0x20>
  400064: 00000000  nop
  400068: 3c021000  lui v0,0x1000
  40006c: 8c420000  lw  v0,0(v0)
  400070: 8fbf0010  lw  ra,16(sp)
  400074: 00000000  nop
  400078: 03e00008  jr  ra
  40007c: 27bd0018  addiu sp,sp,24
```

MIPS procedure call convention: arguments in a0,a1,. . ., return value in v0.

The above can be obtained using `cs350-objdump -d`.

OS/161 MIPS System Call Conventions

- When the `syscall` instruction occurs:
  - An integer system call code should be located in register R2 (v0)
  - Any system call arguments should be located in registers R4 (a0), R5 (a1), R6 (a2), and R7 (a3), much like procedure call arguments.
- When the system call returns
  - register R7 (a3) will contain a 0 if the system call succeeded, or a 1 if the system call failed
  - register R2 (v0) will contain the system call return value if the system call succeeded, or an error number (errno) if the system call failed.

OS/161 System Call Code Definitions

```
/* Contains a number for every more-or-less standard  */
/* Unix system call (you will implement some subset). */
...
#define SYS_close        49
#define SYS_read         50
#define SYS_pread        51
//#define SYS_readv      52  /* won't be implementing */
//#define SYS_preadv     53  /* won't be implementing */
#define SYS_getdirentry  54
#define SYS_write        55
...
```

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 Wrapper Functions from the Standard Library

```
...
004001dc <close>:
  4001dc: 08100030  j 4000c0 <__syscall>
  4001e0: 24020031  li  v0,49

004001e4 <read>:
  4001e4: 08100030  j 4000c0 <__syscall>
  4001e8: 24020032  li  v0,50
...
```

The above is disassembled code from the standard C library (libc), which is linked with `user/uw-testbin/syscall.o`.

The OS/161 System Call and Return Processing

```
004000c0 <__syscall>:
  4000c0: 0000000c  syscall
  4000c4: 10e00005  beqz  a3,4000dc <__syscall+0x1c>
  4000c8: 00000000  nop
  4000cc: 3c011000  lui at,0x1000
  4000d0: ac220000  sw  v0,0(at)
  4000d4: 2403ffff  li  v1,-1
  4000d8: 2402ffff  li  v0,-1
  4000dc: 03e00008  jr  ra
  4000e0: 00000000  nop
```

The system call and return processing, from the standard C library. Like the rest of the library, this is unprivileged, user-level code.

OS/161 MIPS Exception Handler

```
common_exception:
  mfc0 k0, c0_status /* Get status register */
  andi k0, k0, CST_KUp /* Check the we-were-in-user-mode bit */
  beq  k0, $0, 1f /* If clear, from kernel, already have stack */
                  /* 1f is branch forward to label 1: */
  nop             /* delay slot */

  /* Coming from user mode - find kernel stack */
  mfc0 k1, c0_context    /* we keep the CPU number here */
  srl k1, k1, CTX_PTBASESHIFT /* shift to get the CPU number */
  sll k1, k1, 2          /* shift back to make array index */
  lui k0, %hi(cpustacks) /* get base address of cpustacks[] */
  addu k0, k0, k1        /* index it */
  move k1, sp            /* Save previous stack pointer */
  b 2f                   /* Skip to common code */
  lw sp, %lo(cpustacks)(k0) /* Load kernel sp (in delay slot) */
```

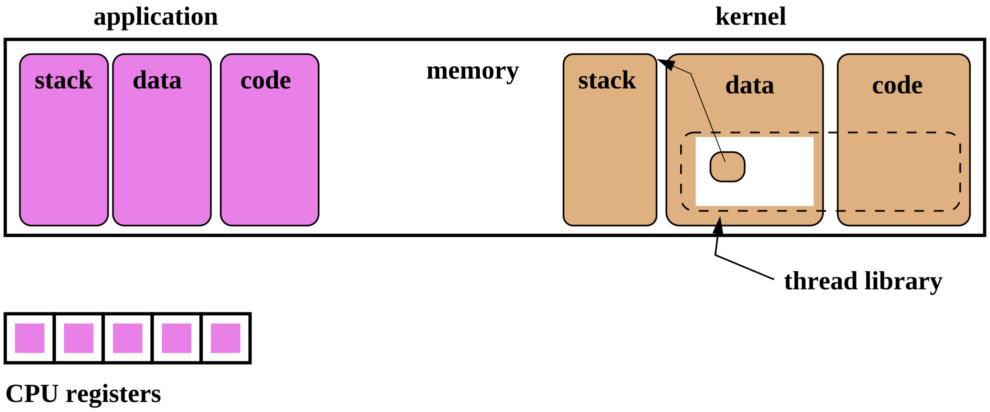

OS/161 MIPS Exception Handler

```
1:
  /* Coming from kernel mode - just save previous stuff */
  move k1, sp      /* Save previous stack in k1 (delay slot) */
2:

  /* At this point:
   * Interrupts are off. (The processor did this for us.)
   * k0 contains the value for curthread, to go into s7.
   * k1 contains the old stack pointer.
   * sp points into the kernel stack.
   * All other registers are untouched.
   */
```

When the `syscall` instruction occurs, the MIPS transfers control to address `0x80000080`. This kernel exception handler lives there. See `kern/arch/mips/locore/exception-mips1.S`

OS/161 User and Kernel Thread Stacks



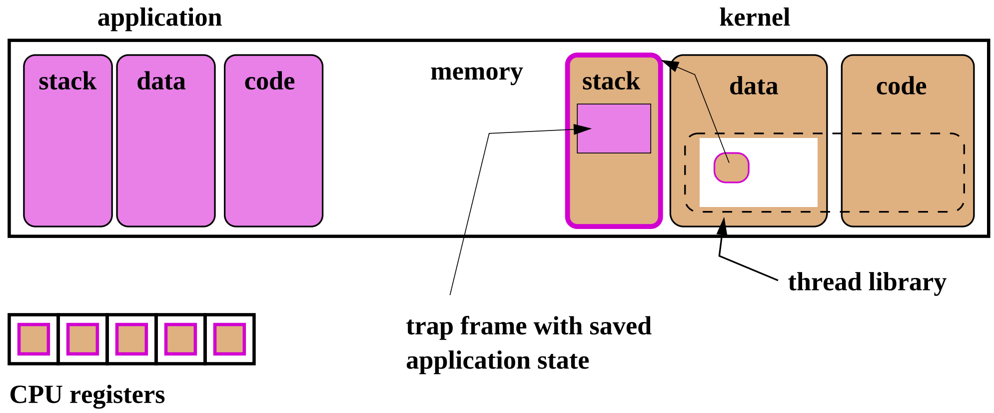
Each OS/161 thread has two stacks, one that is used while the thread is executing unprivileged application code, and another that is used while the thread is executing privileged kernel code.

OS/161 MIPS Exception Handler (cont'd)

The `common_exception` code then does the following:

1. allocates a *trap frame* on the thread's kernel stack and saves the user-level application's complete processor state (all registers except k0 and k1) into the trap frame.
2. calls the `mips_trap` function to continue processing the exception.
3. when `mips_trap` returns, restores the application processor state from the trap frame to the registers
4. issues MIPS `jr` and `rfe` (restore from exception) instructions to return control to the application code. The `jr` instruction takes control back to the location specified by the application program counter when the `syscall` occurred (i.e., exception PC) and the `rfe` (which happens in the delay slot of the `jr`) restores the processor to unprivileged mode

OS/161 Trap Frame



While the kernel handles the system call, the application's CPU state is saved in a trap frame on the thread's kernel stack, and the CPU registers are available to hold kernel execution state.

`mips_trap`: Handling System Calls, Exceptions, and Interrupts

- On the MIPS, the same exception handler is invoked to handle system calls, exceptions and interrupts
- The hardware sets a code to indicate the reason (system call, exception, or interrupt) that the exception handler has been invoked
- OS/161 has a handler function corresponding to each of these reasons. The `mips_trap` function tests the reason code and calls the appropriate function: the system call handler (`syscall`) in the case of a system call.
- `mips_trap` can be found in `kern/arch/mips/locore/trap.c`.

Interrupts and exceptions will be presented shortly

OS/161 System Call Handler

```
syscall(struct trapframe *tf)
{  callno = tf->tf_v0; retval = 0;
   switch (callno) {
     case SYS_reboot:
       err = sys_reboot(tf->tf_a0);
       break;
     case SYS___time:
       err = sys___time((userptr_t)tf->tf_a0,
         (userptr_t)tf->tf_a1);
       break;

     /* Add stuff here */

     default:
       kprintf("Unknown syscall %d\n", callno);
       err = ENOSYS;
       break;
   }
```

`syscall` checks system call code and invokes a handler for the indicated system call. See `kern/arch/mips/syscall/syscall.c`

OS/161 MIPS System Call Return Handling

```
  if (err) {
    tf->tf_v0 = err;
    tf->tf_a3 = 1;      /* signal an error */
  } else {
    /* Success. */
    tf->tf_v0 = retval;
    tf->tf_a3 = 0;      /* signal no error */
  }

  /* Advance the PC, to avoid the syscall again. */
  tf->tf_epc += 4;

  /* Make sure the syscall code didn't forget to lower spl */
  KASSERT(curthread->t_curspl == 0);
  /* ...or leak any spinlocks */
  KASSERT(curthread->t_iplhigh_count == 0);
}
```

`syscall` must ensure that the kernel adheres to the system call return convention.

Exceptions

- Exceptions are another way that control is transferred from a process to the kernel.
- Exceptions are conditions that occur during the execution of an instruction by a process. For example, arithmetic overflows, illegal instructions, or page faults (to be discussed later).
- Exceptions are detected by the hardware.
- When an exception is detected, the hardware transfers control to a specific address.
- Normally, a kernel exception handler is located at that address.

Exception handling is similar to, but not identical to, system call handling. (What is different?)

MIPS Exceptions

```
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 */
```

In OS/161, `mips_trap` uses these codes to decide whether it has been invoked because of an interrupt, a system call, or an exception.

Interrupts (Revisited)

- Interrupts are a third mechanism by which control may be transferred to the kernel
- Interrupts are similar to exceptions. However, they are caused by hardware devices, not by the execution of a program. For example:
  - a network interface may generate an interrupt when a network packet arrives
  - a disk controller may generate an interrupt to indicate that it has finished writing data to the disk
  - a timer may generate an interrupt to indicate that time has passed
- Interrupt handling is similar to exception handling - current execution context is saved, and control is transferred to a kernel interrupt handler at a fixed address.

Interrupts, Exceptions, and System Calls: Summary

- Interrupts, exceptions and system calls are three mechanisms by which control is transferred from an application program to the kernel
- When these events occur, the hardware switches the CPU into privileged mode and transfers control to a predefined location, at which a kernel *handler* should be located.
- The kernel handler creates a *trap frame* and uses it to saves the application thread context so that the handler code can be executed on the CPU.
- Just before the kernel handler finishes executing, it restores the application thread context from the trap frame, before returning control to the application.

In OS/161, trap frames are placed on the *kernel stack* of the thread performed the system call, or of the thread that was running when the interrupt or exception occurred

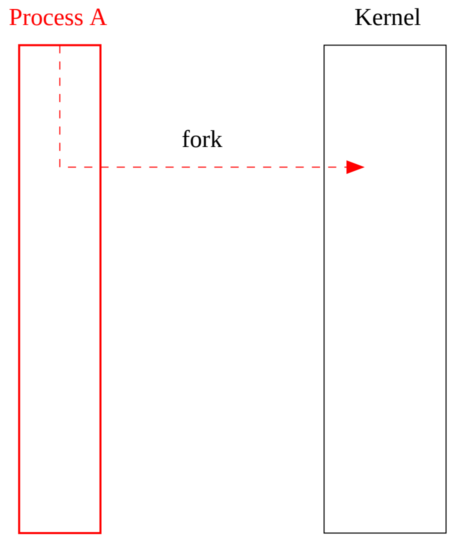
System Calls for Process Management

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

The fork, _exit, getpid and waitpid system calls

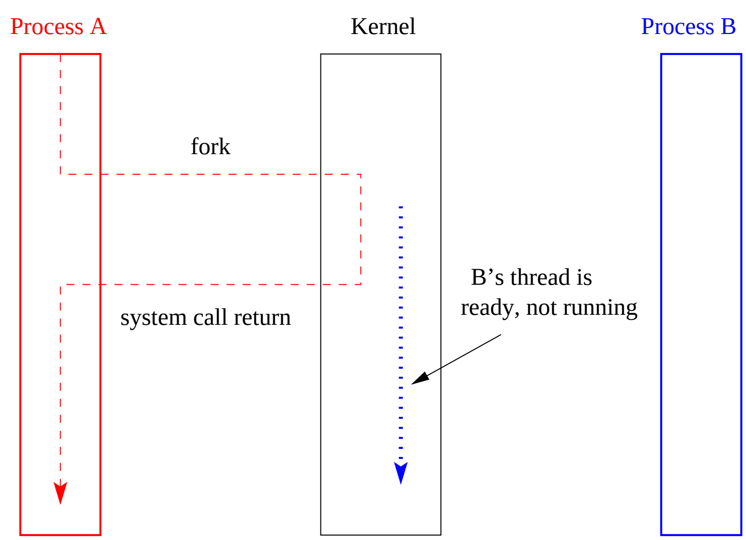
```
main() {
   rc = fork();  /* returns 0 to child, pid to parent */
   if (rc == 0) {  /* child executes this code */
      my_pid = getpid();
      x = child_code();
      _exit(x);
   } else {   /* parent executes this code */
     child_pid = rc;
     parent_pid = getpid();
     parent_code();
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

Process Creation Example (Part 1)



Parent process (Process A) requests creation of a new process.

Process Creation Example (Part 2)



Kernel creates new process (Process B)

The execv system call

```
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);
   }
}
```

Implementation of Processes

- The kernel maintains information about all of the processes in the system in a data structure often called the process table.
- Per-process information may include:
  - process identifier and owner
  - the address space for the process
  - threads belonging to the process
  - lists of resources allocated to the process, such as open files
  - accounting information

OS/161 Process

```
/* From kern/include/proc.h */
struct proc {
  char *p_name;  /* Name of this process */
  struct spinlock p_lock; /* Lock for this structure */
  struct threadarray p_threads; /* Threads in process */

  struct addrspace *p_addrspace; /* virtual address space */
  struct vnode *p_cwd; /* current working directory */

  /* add more material here as needed */
};
```

OS/161 Process

```
/* From kern/include/proc.h */
/* Create a fresh process for use by runprogram() */
struct proc *proc_create_runprogram(const char *name);

/* Destroy a process */
void proc_destroy(struct proc *proc);

/* Attach a thread to a process */
/* Must not already have a process */
int proc_addthread(struct proc *proc, struct thread *t);

/* Detach a thread from its process */
void proc_remthread(struct thread *t);
...
```

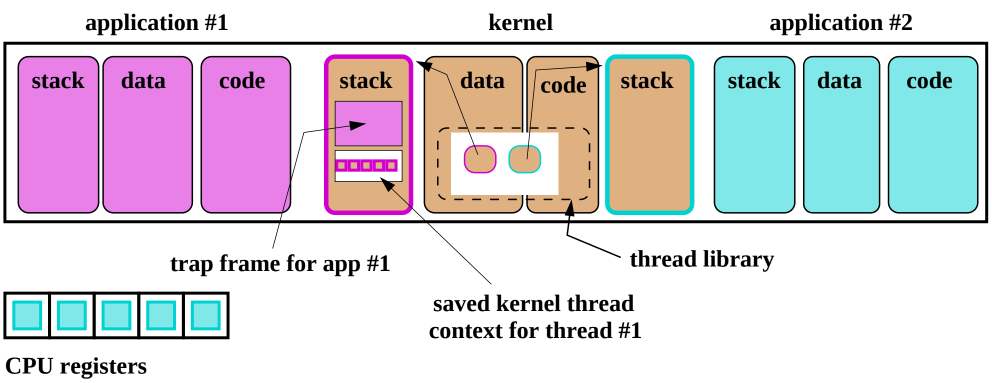

Implementing Timesharing

- whenever a system call, exception, or interrupt occurs, control is transferred from the running program to the kernel
- at these points, the kernel has the ability to cause a context switch from the running process' thread to another process' thread
- notice that these context switches always occur while a process' thread is executing kernel code

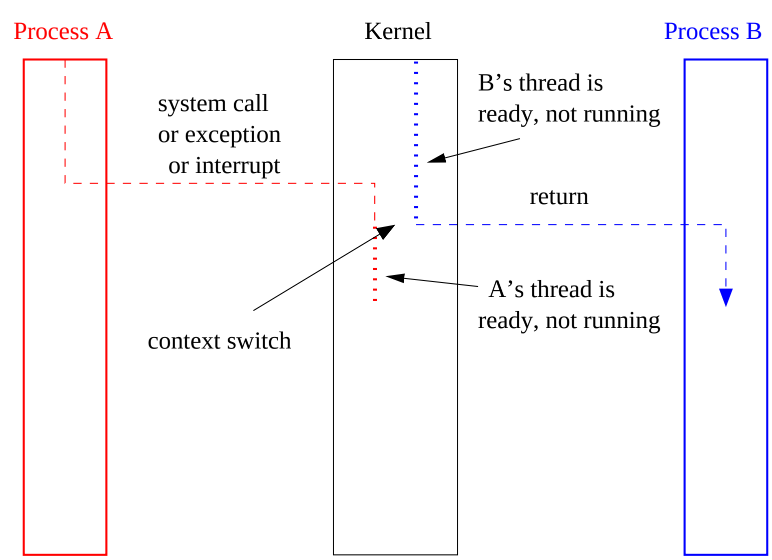
---

By switching from one process's thread to another process's thread, the kernel timeshares the processor among multiple processes.

Two Processes in OS/161

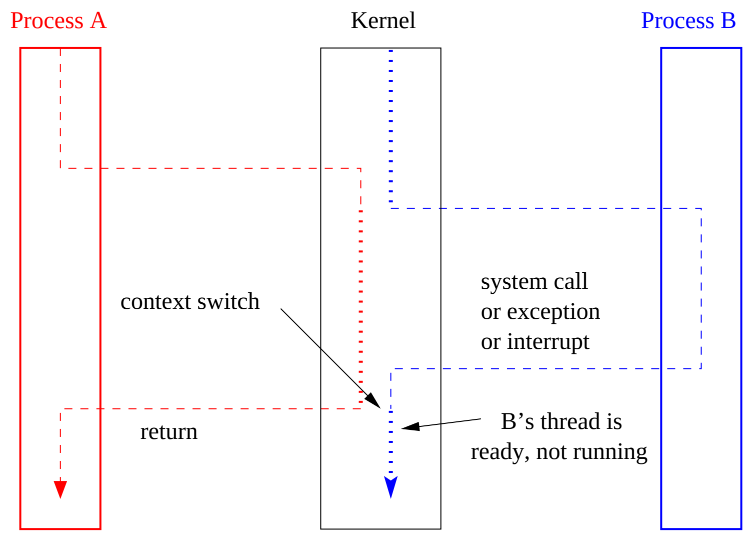


Timesharing Example (Part 1)



Kernel switches execution context to Process B.

Timesharing Example (Part 2)



Kernel switches execution context back to process A.

Implementing Preemption

- the kernel uses interrupts from the system timer to measure the passage of time and to determine whether the running process's quantum has expired.
- a timer interrupt (like any other interrupt) transfers control from the running program to the kernel.
- this gives the kernel the opportunity to preempt the running thread and dispatch a new one.

Preemptive Multiprogramming Example