CS 350
Operating Systems
Course Notes (Part 1)

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What is an Operating System?

- Three views of an operating system

  Application View: what services does it provide?

  System View: what problems does it solve?

  Implementation View: how is it built?

An operating system is part cop, part facilitator.

Application View of an Operating System

- The OS provides an execution environment for running programs.
  - The execution environment provides a program with the processor time and memory space that it needs to run.
  - The execution environment provides interfaces through which a program can use networks, storage, I/O devices, and other system hardware components.
    - Interfaces provide a simplified, abstract view of hardware to application programs.
  - The execution environment isolates running programs from one another and prevents undesirable interactions among them.

Other Views of an Operating System

System View: The OS manages the hardware resources of a computer system.

- Resources include processors, memory, disks and other storage devices, network interfaces, I/O devices such as keyboards, mice and monitors, and so on.
- The operating system allocates resources among running programs. It controls the sharing of resources among programs.
- The OS itself also uses resources, which it must share with application programs.

Implementation View: The OS is a concurrent, real-time program.

- Concurrency arises naturally in an OS when it supports concurrent applications, and because it must interact directly with the hardware.
- Hardware interactions also impose timing constraints.

The Operating System and the Kernel

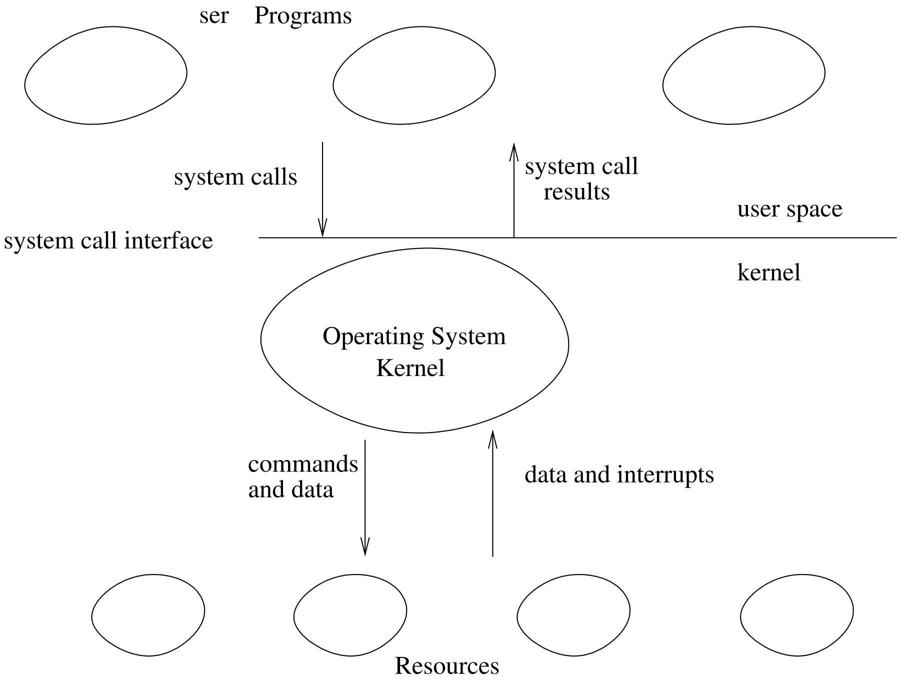
- Some terminology:

  kernel: The operating system kernel is the part of the operating system that responds to system calls, interrupts and exceptions.

  operating system: The operating system as a whole includes the kernel, and may include other related programs that provide services for applications. This may include things like:

  - utility programs
  - command interpreters
  - programming libraries

Schematic View of an Operating System



Operating System Abstractions

- The execution environment provided by the OS includes a variety of abstract entities that can be manipulated by a running program. Examples:

  files and file systems: abstract view of secondary storage

  address spaces: abstract view of primary memory

  processes, threads: abstract view of program execution

  sockets, pipes: abstract view of network or other message channels

- This course will cover
  - why these abstractions are designed the way they are
  - how these abstractions are manipulated by application programs
  - how these abstractions are implemented by the OS

Course Outline

- Introduction
- Threads and Concurrency
- Synchronization
- Processes and the Kernel
- Virtual Memory
- Scheduling
- Devices and Device Management
- File Systems
- Interprocess Communication and Networking (time permitting)

Review: Program Execution

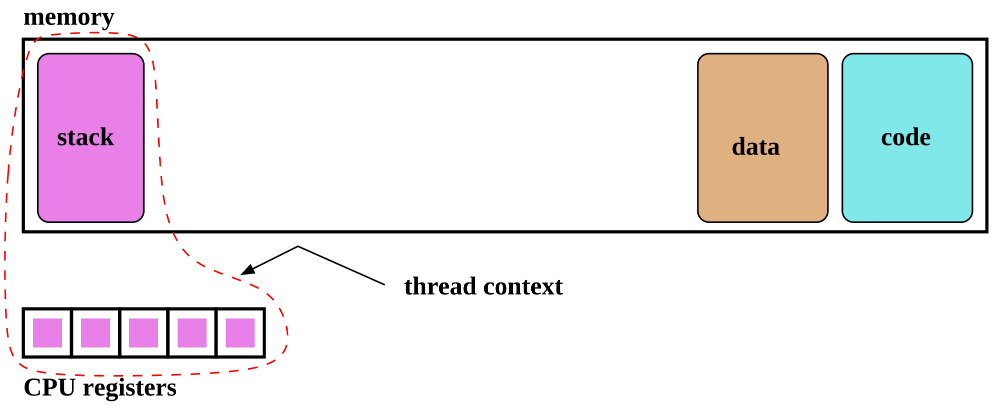
- Registers
  - program counter, stack pointer, . . .
- Memory
  - program code
  - program data
  - program stack containing procedure activation records
- CPU
  - fetches and executes instructions

What is a Thread?

- A thread represents the control state of an executing program.
- A thread has an associated *context* (or state), which consists of
  - the processor's CPU state, including the values of the program counter (PC), the stack pointer, other registers, and the execution mode (privileged/non-privileged)
  - a stack, which is located in the address space of the thread's process

> Imagine that you would like to suspend the program execution, and resume it again later. Think of the thread context as the information you would need in order to restart program execution from where it left off when it was suspended.

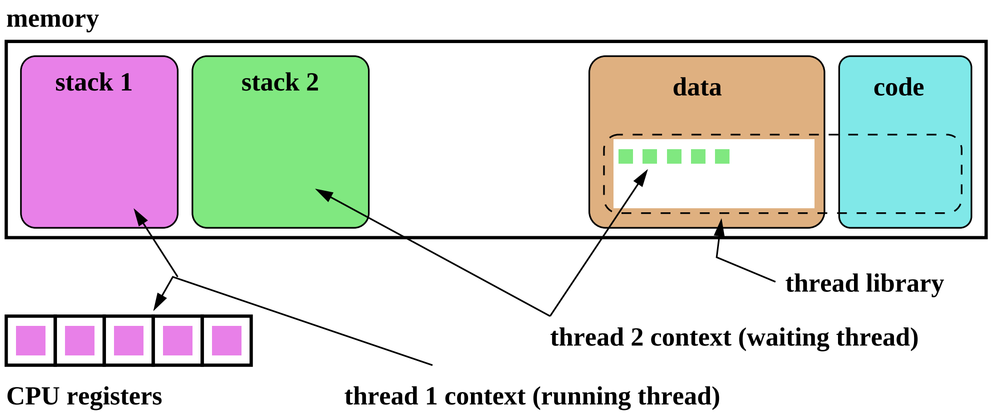
Thread Context



Concurrent Threads

- more than one thread may exist simultaneously (why might this be a good idea?)
- each thread has its own context, though they share access to program code and data
- on a uniprocessor (one CPU), at most one thread is actually executing at any time. The others are paused, waiting to resume execution.
- on a multiprocessor, multiple threads may execute at the same time, but if there are more threads than processors then some threads will be paused and waiting

Two Threads, One Running



memory

stack 1

stack 2

data

code

thread library

thread 2 context (waiting thread)

CPU registers

thread 1 context (running thread)

Thread Interface (Partial), With OS/161 Examples

- a *thread library* implements threads
- thread library provides a thread interface, used by program code to manipulate threads
- common thread interface functions include
  - create new thread

    ```
    int thread_fork(const char *name, struct proc *proc,
                    void (*func)(void *, unsigned long),
                    void *data1, unsigned long data2);
    ```
  - end (and destroy) the current thread

    ```
    void thread_exit(void);
    ```
  - cause current thread to *yield* (to be discussed later)

    ```
    void thread_yield(void);
    ```
- see `kern/include/thread.h`

Example: Creating Threads Using `thread_fork()`

```
/* From kern/synchprobs/catmouse.c */
for (index = 0; index < NumMice; index++) {
  error = thread_fork("mouse_simulation thread",
    NULL, mouse_simulation, NULL, index);
  if (error) {
    panic("mouse_simulation: thread_fork failed: %s\n",
     strerror(error));
  }
}

/* wait for all of the cats and mice to finish */
for(i=0;i<(NumCats+NumMice);i++) {
  P(CatMouseWait);
}
```

Example: Concurrent Mouse Simulation Threads

```
static void mouse_simulation(void * unusedpointer,
                             unsigned long mousenumber)
{
  int i; unsigned int bowl;

  for(i=0;i<NumLoops;i++) {
    /* for now, this mouse chooses a random bowl from
     * which to eat, and it is not synchronized with
     * other cats and mice
     */
    /* legal bowl numbers range from 1 to NumBowls */
    bowl = ((unsigned int)random() % NumBowls) + 1;
    mouse_eat(bowl);
  }
  /* indicate that this mouse is finished */
  V(CatMouseWait);

  /* implicit thread_exit() on return from this function */
}
```

Context Switch, Scheduling, and Dispatching

- the act of pausing the execution of one thread and resuming the execution of another is called a *(thread) context switch*
- what happens during a context switch?
  1. decide which thread will run next
  2. save the context of the currently running thread
  3. restore the context of the thread that is to run next
- the act of saving the context of the current thread and installing the context of the next thread to run is called *dispatching* (the next thread)
- sounds simple, but . . .
  - architecture-specific implementation
  - thread must save/restore its context carefully, since thread execution continuously changes the context
  - can be tricky to understand (at what point does a thread actually stop? what is it executing when it resumes?)

Scheduling

- scheduling means deciding which thread should run next
- scheduling is implemented by a *scheduler*, which is part of the thread library
- simple *round robin* scheduling:
  - scheduler maintains a queue of threads, often called the *ready queue*
  - the first thread in the ready queue is the running thread
  - on a context switch the running thread is moved to the end of the ready queue, and new first thread is allowed to run
  - newly created threads are placed at the end of the ready queue
- more on scheduling later . . .

Causes of Context Switches

- a call to **thread_yield** by a running thread
  - running thread *voluntarily* allows other threads to run
  - yielding thread remains runnable, and on the ready queue
- a call to **thread_exit** by a running thread
  - running thread is terminated
- running thread *blocks*, via a call to `wchan_sleep`
  - thread is no longer runnable, moves off of the ready queue and into a wait channel
  - more on this later . . .
- running thread is *preempted*
  - running thread *involuntarily* stops running
  - remains runnable, and on the ready queue

Preemption

- without preemption, a running thread could potentially run forever, without yielding, blocking, or exiting
- to ensure *fair* access to the CPU for all threads, the thread library may preempt a running thread
- to implement preemption, the thread library must have a means of "getting control" (causing thread library code to be executed) even though the running thread has not called a thread library function
- this is normally accomplished using *interrupts*

Review: Interrupts

- an interrupt is an event that occurs during the execution of a program
- interrupts are caused by system devices (hardware), e.g., a timer, a disk controller, a network interface
- when an interrupt occurs, the hardware automatically transfers control to a fixed location in memory
- at that memory location, the thread library places a procedure called an *interrupt handler*
- the interrupt handler normally:
  1. saves the current thread context (in OS/161, this is saved in a *trap frame* on the current thread's stack)
  2. determines which device caused the interrupt and performs device-specific processing
  3. restores the saved thread context and resumes execution in that context where it left off at the time of the interrupt.

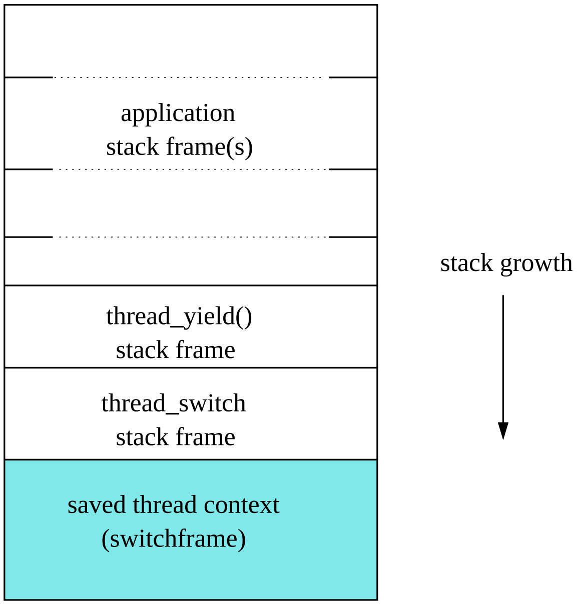
Preemptive Round-Robin Scheduling

- In preemptive round-robin scheduling, the thread library imposes a limit on the amound of time that a thread can run before being preempted
- the amount of time that a thread is allocated is called the scheduling *quantum*
- when the running thread's quantum expires, it is preempted and moved to the back of the ready queue. The thread at the front of the ready queue is dispatched and allowed to run.
- the quantum is an *upper bound* on the amount of time that a thread can run once it has been dispatched
- the dispatched thread may run for less than the scheduling quantum if it yields, exits, or blocks before its quantum expires

Implementing Preemptive Scheduling

- suppose that the system timer generates an interrupt every t time units, e.g., once every millisecond
- suppose that the thread library wants to use a scheduling quantum $q = 500t$, i.e., it will preempt a thread after half a second of execution
- to implement this, the thread library can maintain a variable called `running_time` to track how long the current thread has been running:
  - when a thread is intially dispatched, `running_time` is set to zero
  - when an interrupt occurs, the timer-specific part of the interrupt handler can increment `running_time` and then test its value
    * if `running_time` is less than q, the interrupt handler simply returns and the running thread resumes its execution
    * if `running_time` is equal to q, then the interrupt handler invokes `thread_yield` to cause a context switch

OS/161 Thread Stack after Voluntary Context Switch (`thread_yield()`)



application
stack frame(s)

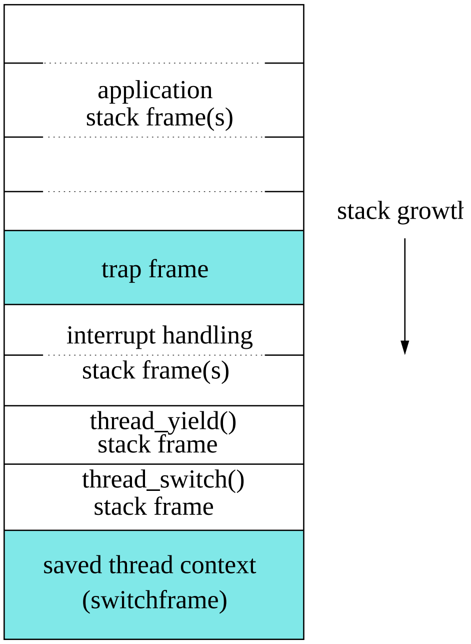
thread_yield()
stack frame

thread_switch
stack frame

saved thread context
(switchframe)

stack growth

OS/161 Thread Stack after Preemption



application
stack frame(s)

trap frame

interrupt handling
stack frame(s)

thread_yield()
stack frame

thread_switch()
stack frame

saved thread context
(switchframe)

stack growth

Implementing Threads

- the thread library is responsibile for implementing threads
- the thread library stores threads' contexts (or pointers to the threads' contexts) when they are not running
- the data structure used by the thread library to store a thread context is sometimes called a *thread control block*

In the OS/161 kernel's thread implementation, thread contexts are stored in `thread` structures.

The OS/161 `thread` Structure

```
/* see kern/include/thread.h */

struct thread {
 char *t_name;              /* Name of this thread */
 const char *t_wchan_name; /* Wait channel name, if sleeping */
 threadstate_t t_state;    /* State this thread is in */

 /* Thread subsystem internal fields. */
 struct thread_machdep t_machdep; /* Any machine-dependent goo */
 struct threadlistnode t_listnode; /* run/sleep/zombie lists */
 void *t_stack;                  /* Kernel-level stack */
 struct switchframe *t_context; /* Register context (on stack) */
 struct cpu *t_cpu;             /* CPU thread runs on */
 struct proc *t_proc;           /* Process thread belongs to */
 ...
```

Review: MIPS Register Usage

```
R0,  zero = ## zero (always returns 0)
R1,  at   = ## reserved for use by assembler
R2,  v0   = ## return value / system call number
R3,  v1   = ## return value
R4,  a0   = ## 1st argument (to subroutine)
R5,  a1   = ## 2nd argument
R6,  a2   = ## 3rd argument
R7,  a3   = ## 4th argument
```

Review: MIPS Register Usage

```
R08-R15,  t0-t7 = ## temps (not preserved by subroutines)
R24-R25,  t8-t9 = ## temps (not preserved by subroutines)
                  ##   can be used without saving
R16-R23,  s0-s7 = ## preserved by subroutines
                  ##   save before using,
                  ##   restore before return
R26-27,   k0-k1 = ## reserved for interrupt handler
R28,      gp    = ## global pointer
                  ## (for easy access to some variables)
R29,      sp    = ## stack pointer
R30,      s8/fp = ## 9th subroutine reg / frame pointer
R31,      ra    = ## return addr (used by jal)
```

Dispatching on the MIPS (1 of 2)

```
/* See kern/arch/mips/thread/switch.S */

switchframe_switch:
  /* a0: address of switchframe pointer of old thread. */
  /* a1: address of switchframe pointer of new thread. */

   /* Allocate stack space for saving 10 registers. 10*4 = 40 */
   addi sp, sp, -40

   sw   ra, 36(sp)  /* Save the registers */
   sw   gp, 32(sp)
   sw   s8, 28(sp)
   sw   s6, 24(sp)
   sw   s5, 20(sp)
   sw   s4, 16(sp)
   sw   s3, 12(sp)
   sw   s2, 8(sp)
   sw   s1, 4(sp)
   sw   s0, 0(sp)

   /* Store the old stack pointer in the old thread */
   sw   sp, 0(a0)
```

Dispatching on the MIPS (2 of 2)

```
/* Get the new stack pointer from the new thread */
lw   sp, 0(a1)
nop            /* delay slot for load */

/* Now, restore the registers */
lw   s0, 0(sp)
lw   s1, 4(sp)
lw   s2, 8(sp)
lw   s3, 12(sp)
lw   s4, 16(sp)
lw   s5, 20(sp)
lw   s6, 24(sp)
lw   s8, 28(sp)
lw   gp, 32(sp)
lw   ra, 36(sp)
nop                  /* delay slot for load */

/* and return. */
j ra
addi sp, sp, 40      /* in delay slot */
.end switchframe_switch
```

Dispatching on the MIPS (Notes)

- Not all of the registers are saved during a context switch
- This is because the context switch code is reached via a call to `thread_switch` and by convention on the MIPS not all of the registers are required to be preserved across subroutine calls
- thus, after a call to `switchframe_switch` returns, the caller (`thread_switch`) does not expect all registers to have the same values as they had before the call - to save time, those registers are not preserved by the switch
- if the caller wants to reuse those registers it must save and restore them

Concurrency

- On multiprocessors, several threads can execute simultaneously, one on each processor.
- On uniprocessors, only one thread executes at a time. However, because of preemption and timesharing, threads appear to run concurrently.

Concurrency and synchronization are important even on uniprocessors.

Thread Synchronization

- Concurrent threads can interact with each other in a variety of ways:
  - Threads share access, through the operating system, to system devices (more on this later . . .)
  - Threads may share access to program data, e.g., global variables.
- A common synchronization problem is to enforce *mutual exclusion*, which means making sure that only one thread at a time uses a shared object, e.g., a variable or a device.
- The part of a program in which the shared object is accessed is called a *critical section*.

Critical Section Example (Part 0)

```
/* Note the use of volatile */
int volatile total = 0;

void add() {                      void sub() {
   int i;                            int i;
   for (i=0; i<N; i++) {             for (i=0; i<N; i++) {
      total++;                          total--;
   }                                 }
}                                 }
```

If one thread executes `add` and another executes `sub` what is the value of `total` when they have finished?

Critical Section Example (Part 0)

```
/* Note the use of volatile */
int volatile total = 0;

void add() {                     void sub() {
   loadaddr R8 total                loadaddr R10 total
   for (i=0; i<N; i++) {            for (i=0; i<N; i++) {
      lw R9 0(R8)                      lw R11 0(R10)
      add R9 1                         sub R11 1
      sw R9 0(R8)                      sw R11 0(R10)
   }                                }
}                                }
```

Critical Section Example (Part 0)

```
Thread 1                    Thread 2
loadaddr R8 total
lw R9 0(R8)  R9=0
add R9 1     R9=1
               <INTERRUPT>
                            loadaddr R10 total
                            lw R11 0(R10)   R11=0
                            sub R11 1       R11=-1
                            sw R11 0(R10)   total=-1
               <INTERRUPT>
sw R9 0(R8) total=1
```

One possible order of execution.

Critical Section Example (Part 0)

```
Thread 1                    Thread 2
loadaddr R8 total
lw R9 0(R8)  R9=0
               <INTERRUPT>
                            loadaddr R10 total
                            lw R11 0(R10)   R11=0
               <INTERRUPT>
add R9 1     R9=1
sw R9 0(R8) total=1
               <INTERRUPT>
                            sub R11 1       R11=-1
                            sw R11 0(R10)   total=-1
```

Another possible order of execution. Many interleavings of instructions are possible. Synchronization is required to ensure a correct ordering.

The use of volatile

```
/* What if we DO NOT use volatile */
int ~~volatile~~ total = 0;

void add() {                      void sub() {
   loadaddr R8 total                 loadaddr R10 total
   lw R9 0(R8)                       lw R11 0(R10)
   for (i=0; i<N; i++) {             for (i=0; i<N; i++) {
      add R9 1                          sub R11 1
   }                                 }
   sw R9 0(R8)                       sw R11 0(R10)
}                                 }
```

Without volatile the compiler could optimize the code. If one thread executes `add` and another executes `sub`, what is the value of `total` when they have finished?

The use of volatile

```
/* What if we DO NOT use volatile */
int ~~volatile~~ total = 0;

void add() {                     void sub() {
   loadaddr R8 total                loadaddr R10 total
   lw R9 0(R8)                      lw R11 0(R10)
   add R9 N                         sub R11 N
   sw R9 0(R8)                      sw R11 0(R10)
}                                }
```

The compiler could aggressively optimize the code., Volatile tells the compiler that the object may change for reasons which cannot be determined from the local code (e.g., due to interaction with a device or because of another thread).

The use of volatile

```
/* Note the use of volatile */
int volatile total = 0;

void add() {                     void sub() {
   loadaddr R8 total                loadaddr R10 total
   for (i=0; i<N; i++) {            for (i=0; i<N; i++) {
      lw R9 0(R8)                      lw R11 0(R10)
      add R9 1                         sub R11 1
      sw R9 0(R8)                      sw R11 0(R10)
   }                                }
}                                }
```

The volatile declaration forces the compiler to load and store the value on every use. Using volatile is necessary but not sufficient for correct behaviour. Mutual exclusion is also required to ensure a correct ordering of instructions.

Ensuring Correctness with Multiple Threads

```
/* Note the use of volatile */
int volatile total = 0;

void add() {                      void sub() {
   int i;                            int i;
   for (i=0; i<N; i++) {             for (i=0; i<N; i++) {
     Allow one thread to execute and make others wait
        total++;                          total--;
     Permit one waiting thread to continue execution
   }                                 }
}                                 }
```

Threads must enforce mutual exclusion.

Another Critical Section Example (Part 1)

```
int list_remove_front(list *lp) {
   int num;
   list_element *element;
   assert(!is_empty(lp));
   element = lp->first;
   num = lp->first->item;
   if (lp->first == lp->last) {
     lp->first = lp->last = NULL;
   } else {
     lp->first = element->next;
   }
   lp->num_in_list--;
   free(element);
   return num;
}
```

The `list_remove_front` function is a critical section. It may not work properly if two threads call it at the same time on the same `list`. (Why?)

Another Critical Section Example (Part 2)

```
void list_append(list *lp, int new_item) {
   list_element *element = malloc(sizeof(list_element));
   element->item = new_item
   assert(!is_in_list(lp, new_item));
   if (is_empty(lp)) {
     lp->first = element; lp->last = element;
   } else {
     lp->last->next = element; lp->last = element;
   }
   lp->num_in_list++;
}
```

The `list_append` function is part of the same critical section as `list_remove_front`. It may not work properly if two threads call it at the same time, or if a thread calls it while another has called `list_remove_front`

Enforcing Mutual Exclusion

- mutual exclusion algorithms ensure that only one thread at a time executes the code in a critical section
- several techniques for enforcing mutual exclusion
  - exploit special hardware-specific machine instructions, e.g.,
    - *test-and-set*,
    - *compare-and-swap*, or
    - *load-link / store-conditional*,

    that are intended for this purpose
  - control interrupts to ensure that threads are not preempted while they are executing a critical section

Disabling Interrupts

- On a uniprocessor, only one thread at a time is actually running.
- If the running thread is executing a critical section, mutual exclusion may be violated if
  1. the running thread is preempted (or voluntarily yields) while it is in the critical section, and
  2. the scheduler chooses a different thread to run, and this new thread enters the same critical section that the preempted thread was in
- Since preemption is caused by timer interrupts, mutual exclusion can be enforced by disabling timer interrupts before a thread enters the critical section, and re-enabling them when the thread leaves the critical section.

Interrupts in OS/161

This is one way that the OS/161 kernel enforces mutual exclusion on a single processor. There is a simple interface

- `spl0()` sets IPL to 0, enabling all interrupts.
- `splhigh()` sets IPL to the highest value, disabling all interrupts.
- `splx(s)` sets IPL to S, enabling whatever state S represents.

These are used by splx() and by the spinlock code.

- `splraise(int oldipl, int newipl)`
- `spllower(int oldipl, int newipl)`
- For splraise, `NEWIPL > OLDIPL`, and for spllower, `NEWIPL < OLDIPL`.

See `kern/include/spl.h` and `kern/thread/spl.c`

Pros and Cons of Disabling Interrupts

- advantages:
  - does not require any hardware-specific synchronization instructions
  - works for any number of concurrent threads
- disadvantages:
  - indiscriminate: prevents all preemption, not just preemption that would threaten the critical section
  - ignoring timer interrupts has side effects, e.g., kernel unaware of passage of time. (Worse, OS/161's `splhigh()` disables *all* interrupts, not just timer interrupts.) Keep critical sections *short* to minimize these problems.
  - will not enforce mutual exclusion on multiprocessors (why??)

Hardware-Specific Synchronization Instructions

- a test-and-set instruction *atomically* sets the value of a specified memory location and either places that memory location's *old* value into a register
- abstractly, a test-and-set instruction works like the following function:

```
TestAndSet(addr,value)
  old = *addr;    // get old value at addr
  *addr = value; // write new value to addr
  return old;
```

these steps happen *atomically*

- example: x86 `xchg` instruction:

```
xchg src,dest
```

where `src` is typically a register, and `dest` is a memory address. Value in register `src` is written to memory at address `dest`, and the old value at `dest` is placed into `src`.

Alternatives to Test-And-Set

- Compare-And-Swap

```
CompareAndSwap(addr,expected,value)
  old = *addr;    // get old value at addr
  if (old == expected) *addr = value;
  return old;
```

- example: SPARC `cas` instruction

```
cas addr,R1,R2
```

if value at `addr` matches value in `R1` then swap contents of `addr` and `R2`

- load-linked and store-conditional
  - Load-linked returns the current value of a memory location, while a subsequent store-conditional to the same memory location will store a new value only if no updates have occurred to that location since the load-linked.
  - more on this later . . .

A Spin Lock Using Test-And-Set

- a test-and-set instruction can be used to enforce mutual exclusion
- for each critical section, define a `lock` variable, in memory

  ```
  boolean volatile lock;  /* shared, initially false */
  ```

  We will use the lock variable to keep track of whether there is a thread in the critical section, in which case the value of `lock` will be `true`
- before a thread can enter the critical section, it does the following:

  ```
    while (TestAndSet(&lock,true)) { }  /* busy-wait */
  ```
- when the thread leaves the critical section, it does

  ```
  lock = false;
  ```
- this enforces mutual exclusion (why?), but starvation is a possibility

This construct is sometimes known as a *spin lock*, since a thread "spins" in the while loop until the critical section is free.

Spinlocks in OS/161

```
struct spinlock {
  volatile spinlock_data_t lk_lock; /* word for spin */
  struct cpu *lk_holder; /* CPU holding this lock */
};

void spinlock_init(struct spinlock *lk);
void spinlock_cleanup(struct spinlock *lk);
void spinlock_acquire(struct spinlock *lk);
void spinlock_release(struct spinlock *lk);
bool spinlock_do_i_hold(struct spinlock *lk);
```

Spinning happens in `spinlock_acquire`

Spinlocks in OS/161

```
spinlock_init(struct spinlock *lk)
{
  spinlock_data_set(&lk->lk_lock, 0);
  lk->lk_holder = NULL;
}

void spinlock_cleanup(struct spinlock *lk)
{
  KASSERT(lk->lk_holder == NULL);
  KASSERT(spinlock_data_get(&lk->lk_lock) == 0);
}

void spinlock_data_set(volatile spinlock_data_t *sd,
  unsigned val)
{
  *sd = val;
}
```

Acquiring a Spinlock in OS/161

```
void spinlock_acquire(struct spinlock *lk)
{
  /* note: code that sets lk->holder has been removed! */
  splraise(IPL_NONE, IPL_HIGH);
  while (1) {
    /* Do test-and-test-and-set to reduce bus contention */
    if (spinlock_data_get(&lk->lk_lock) != 0) {
      continue;
    }
    if (spinlock_data_testandset(&lk->lk_lock) != 0) {
      continue;
    }
    break;
  }
}
```

Using Load-Linked / Store-Conditional

```
spinlock_data_testandset(volatile spinlock_data_t *sd)
{
  spinlock_data_t x,y;

  /* Test-and-set using LL/SC.
   * Load the existing value into X, and use Y to store 1.
   * After the SC, Y contains 1 if the store succeeded,
   * 0 if it failed. On failure, return 1 to pretend
   * that the spinlock was already held.
   */

  y = 1;
```

Using Load-Linked / Store-Conditional (Part 2)

```
  __asm volatile(
    ".set push;"      /* save assembler mode */
    ".set mips32;"    /* allow MIPS32 instructions */
    ".set volatile;"  /* avoid unwanted optimization */
    "ll %0, 0(%2);"   /*   x = *sd */
    "sc %1, 0(%2);"   /*   *sd = y; y = success? */
    ".set pop"        /* restore assembler mode */
    : "=r" (x), "+r" (y) : "r" (sd));
  if (y == 0) {
    return 1;
  }
  return x;
}
```

Releasing a Spinlock in OS/161

```
void spinlock_release(struct spinlock *lk)
{
  /* Note: code that sets lk->holder has been removed! */
  spinlock_data_set(&lk->lk_lock, 0);
  spllower(IPL_HIGH, IPL_NONE);
}
```

Pros and Cons of Spinlocks

- Pros:
  - can be efficient for short critical sections
  - works on multiprocessors
- Cons:
  - CPU is busy (nothing else runs) while waiting for lock
  - starvation is possible

Thread Blocking

- Sometimes a thread will need to wait for an event. For example, if a thread needs to access a critical section that is busy, it must wait for the critical section to become free before it can enter
- other examples that we will see later on:
  - wait for data from a (relatively) slow device
  - wait for input from a keyboard
  - wait for busy device to become idle
- With spinlocks, threads *busy wait* when they cannot enter a critical section. This means that a processor is busy doing useless work. If a thread may need to wait for a long time, it would be better to avoid busy waiting.
- To handle this, the thread scheduler can *block* threads.
- A blocked thread stops running until it is signaled to wake up, allowing the processor to run some other thread.

Thread Blocking in OS/161

- OS/161 thread library functions for blocking and unblocking threads:
  - `void wchan_lock(struct wchan *wc);`
  - `void wchan_unlock(struct wchan *wc);`
    - locks/unlocks the wait channel `wc`
  - `void wchan_sleep(struct wchan *wc);`
    - blocks calling thread on wait channel `wc`
    - channel must be locked, will be unlocked upon return
  - `void wchan_wakeall(struct wchan *wc);`
    - unblock all threads sleeping on wait channel `wc`
  - `void wchan_wakeone(struct wchan *wc);`
    - unblock one thread sleeping on wait channel `wc`

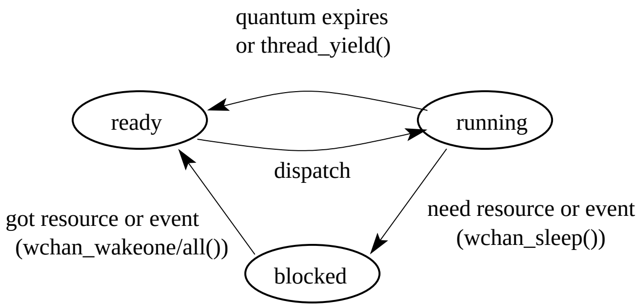
Note: current implementation is FIFO but not promised by the interface

Thread Blocking in OS/161

- wchan_sleep() is much like thread_yield(). The calling thread is voluntarily giving up the CPU, so the scheduler chooses a new thread to run, the state of the running thread is saved and the new thread is dispatched. However:
  - after a thread_yield(), the calling thread is *ready* to run again as soon as it is chosen by the scheduler
  - after a wchan_sleep(), the calling thread is *blocked*, and must not be scheduled to run again until after it has been explicitly unblocked by a call to wchan_wakeone() or wchan_wakeall().

Thread States

- a very simple thread state transition diagram



- the states:

  running: currently executing

  ready: ready to execute

  blocked: waiting for something, so not ready to execute.

Semaphores

- A semaphore is a synchronization primitive that can be used to enforce mutual exclusion requirements. It can also be used to solve other kinds of synchronization problems.
- A semaphore is an object that has an integer value, and that supports two operations:

  P: if the semaphore value is greater than 0, decrement the value. Otherwise, wait until the value is greater than 0 and then decrement it.

  V: increment the value of the semaphore
- Two kinds of semaphores:

  counting semaphores: can take on any non-negative value

  binary semaphores: take on only the values 0 and 1. (V on a binary semaphore with value 1 has no effect.)

By definition, the P and V operations of a semaphore are *atomic*.

A Simple Example using Semaphores

```
volatile int total = 0;

void add() {                    void sub() {
   int i;                          int i;
   for (i=0; i<N; i++) {           for (i=0; i<N; i++) {
     P(sem);                          P(sem);
       total++;                           total--;
     V(sem);                          V(sem);
   }                               }
}                               }
```

What type of semaphore can be used for sem?

OS/161 Semaphores

```
struct semaphore {
  char *sem_name;
  struct wchan *sem_wchan;
  struct spinlock sem_lock;
  volatile int sem_count;
};

struct semaphore *sem_create(const char *name,
  int initial_count);
void P(struct semaphore *s);
void V(struct semaphore *s);
void sem_destroy(struct semaphore *s);
```

see `kern/include/synch.h` and `kern/thread/synch.c`

Mutual Exclusion Using a Semaphore

```
struct semaphore *s;
s = sem_create("MySem1", 1); /* initial value is 1 */

P(s);  /* do this before entering critical section */

   critical section /* e.g., call to list_remove_front */

V(s);  /* do this after leaving critical section */
```

OS/161 Semaphores: P() from kern/thread/synch.c

```
P(struct semaphore *sem)
{
  KASSERT(sem != NULL);
  KASSERT(curthread->t_in_interrupt == false);

  spinlock_acquire(&sem->sem_lock);
    while (sem->sem_count == 0) {
      /* Note: we don't maintain strict FIFO ordering */
      wchan_lock(sem->sem_wchan);
      spinlock_release(&sem->sem_lock);
      wchan_sleep(sem->sem_wchan);
      spinlock_acquire(&sem->sem_lock);
    }
    KASSERT(sem->sem_count > 0);
    sem->sem_count--;
  spinlock_release(&sem->sem_lock);
}
```

OS/161 Semaphores: V() from kern/thread/synch.c

```
V(struct semaphore *sem)
{
  KASSERT(sem != NULL);

  spinlock_acquire(&sem->sem_lock);

    sem->sem_count++;
    KASSERT(sem->sem_count > 0);
    wchan_wakeone(sem->sem_wchan);

  spinlock_release(&sem->sem_lock);
}
```

Producer/Consumer Synchronization

- suppose we have threads that add items to a list (producers) and threads that remove items from the list (consumers)
- suppose we want to ensure that consumers do not consume if the list is empty - instead they must wait until the list has something in it
- this requires synchronization between consumers and producers
- semaphores can provide the necessary synchronization, as shown on the next slide

Producer/Consumer Synchronization using Semaphores

```
struct semaphore *s;
s = sem_create("Items", 0); /* initial value is 0 */

Producer's Pseudo-code:
  add item to the list (call list_append())
  V(s);

Consumer's Pseudo-code:
  P(s);
  remove item from the list (call list_remove_front())
```

The Items semaphore does not enforce mutual exclusion on the list. If we want mutual exclusion, we can also use semaphores to enforce it. (How?)

Bounded Buffer Producer/Consumer Synchronization

- suppose we add one more requirement: the number of items in the list should not exceed `N`
- producers that try to add items when the list is full should be made to wait until the list is no longer full
- We can use an additional semaphore to enforce this new constraint:
  - semaphore `Full` is used to count the number of full (occupied) entries in the list (to ensure nothing is produced if the list is full)
  - semaphore `Empty` is used to count the number of empty (unoccupied) entries in the list (to ensure nothing is consumed if the list is empty)

```
struct semaphore *full;
struct semaphore *empty;
full = sem_create("Full", 0);   /* initial value = 0 */
empty = sem_create("Empty", N); /* initial value = N */
```

Bounded Buffer Producer/Consumer Synchronization with Semaphores

```
Producer's Pseudo-code:
  P(empty);
  add item to the list (call list_append())
  V(full);

Consumer's Pseudo-code:
  P(full);
  remove item from the list (call list_remove_front())
  V(empty);
```

OS/161 Locks

- OS/161 also uses a synchronization primitive called a *lock*. Locks are intended to be used to enforce mutual exclusion.

```
struct lock *mylock = lock_create("LockName");

lock_aquire(mylock);
  critical section /* e.g., call to list_remove_front */
lock_release(mylock);
```

- A lock is similar to a binary semaphore with an initial value of 1. However, locks also enforce an additional constraint: the thread that releases a lock must be the same thread that most recently acquired it.
- The system enforces this additional constraint to help ensure that locks are used as intended.

Condition Variables

- OS/161 supports another common synchronization primitive: *condition variables*
- each condition variable is intended to work together with a lock: condition variables are only used *from within the critical section that is protected by the lock*
- three operations are possible on a condition variable:

  wait: This causes the calling thread to block, and it releases the lock associated with the condition variable. Once the thread is unblocked it reacquires the lock.

  signal: If threads are blocked on the signaled condition variable, then one of those threads is unblocked.

  broadcast: Like signal, but unblocks all threads that are blocked on the condition variable.

Using Condition Variables

- Condition variables get their name because they allow threads to wait for arbitrary conditions to become true inside of a critical section.
- Normally, each condition variable corresponds to a particular condition that is of interest to an application. For example, in the bounded buffer producer/consumer example on the following slides, the two conditions are:
  - $count > 0$ (condition variable `notempty`)
  - $count < N$ (condition variable `notfull`)
- when a condition is not true, a thread can `wait` on the corresponding condition variable until it becomes true
- when a thread detects that a condition is true, it uses `signal` or `broadcast` to notify any threads that may be waiting

Note that signalling (or broadcasting to) a condition variable that has no waiters has *no effect*. Signals do not accumulate.

Waiting on Condition Variables

- when a blocked thread is unblocked (by `signal` or `broadcast`), it reacquires the lock before returning from the `wait` call
- a thread is in the critical section when it calls `wait`, and it will be in the critical section when `wait` returns. However, in between the call and the return, while the caller is blocked, the caller is out of the critical section, and other threads may enter.
- In particular, the thread that calls `signal` (or `broadcast`) to wake up the waiting thread will itself be in the critical section when it signals. The waiting thread will have to wait (at least) until the signaller releases the lock before it can unblock and return from the `wait` call.

This describes Mesa-style condition variables, which are used in OS/161. There are alternative condition variable semantics (Hoare semantics), which differ from the semantics described here.

Bounded Buffer Producer Using Locks and Condition Variables

```
int volatile count = 0;  /* must initially be 0 */
struct lock *mutex;     /* for mutual exclusion */
struct cv *notfull, *notempty; /* condition variables */

/* Initialization Note: the lock and cv's must be created
 * using lock_create() and cv_create() before Produce()
 * and Consume() are called */

Produce(itemType item) {
  lock_acquire(mutex);
  while (count == N) {
     cv_wait(notfull, mutex);
  }
  add item to buffer (call list_append())
  count = count + 1;
  cv_signal(notempty, mutex);
  lock_release(mutex);
}
```

Bounded Buffer Consumer Using Locks and Condition Variables

```
itemType Consume() {
  lock_acquire(mutex);
  while (count == 0) {
     cv_wait(notempty, mutex);
  }
  remove item from buffer (call list_remove_front())
  count = count - 1;
  cv_signal(notfull, mutex);
  lock_release(mutex);
  return(item);
}
```

Both `Produce()` and `Consume()` call `cv_wait()` inside of a `while` loop. Why?

Deadlocks

- Suppose there are two threads and two locks, `lockA` and `lockB`, both initially unlocked.
- Suppose the following sequence of events occurs
  1. Thread 1 does `lock_acquire(lockA)`.
  2. Thread 2 does `lock_acquire(lockB)`.
  3. Thread 1 does `lock_acquire(lockB)` and blocks, because `lockB` is held by thread 2.
  4. Thread 2 does `lock_acquire(lockA)` and blocks, because `lockA` is held by thread 1.

These two threads are *deadlocked* - neither thread can make progress. Waiting will not resolve the deadlock. The threads are permanently stuck.

Deadlocks (Another Simple Example)

- Suppose a machine has 64 MB of memory. The following sequence of events occurs.
  1. Thread A starts, requests 30 MB of memory.
  2. Thread B starts, also requests 30 MB of memory.
  3. Thread A requests an additional 8 MB of memory. The kernel blocks thread A since there is only 4 MB of available memory.
  4. Thread B requests an additional 5 MB of memory. The kernel blocks thread B since there is not enough memory available.

These two threads are deadlocked.

Deadlock Prevention

No Hold and Wait: prevent a thread from requesting resources if it currently has resources allocated to it. A thread may hold several resources, but to do so it must make a single request for all of them.

Preemption: take resources away from a thread and give them to another (usually not possible). Thread is restarted when it can acquire all the resources it needs.

Resource Ordering: Order (e.g., number) the resource types, and require that each thread acquire resources in increasing resource type order. That is, a thread may make no requests for resources of type less than or equal to i if it is holding resources of type i.

Deadlock Detection and Recovery

- main idea: the system maintains the resource allocation graph and tests it to determine whether there is a deadlock. If there is, the system must recover from the deadlock situation.
- deadlock recovery is usually accomplished by terminating one or more of the threads involved in the deadlock
- when to test for deadlocks? Can test on every blocked resource request, or can simply test periodically. Deadlocks persist, so periodic detection will not “miss” them.

Deadlock detection and deadlock recovery are both costly. This approach makes sense only if deadlocks are expected to be infrequent.

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)
  - . . .

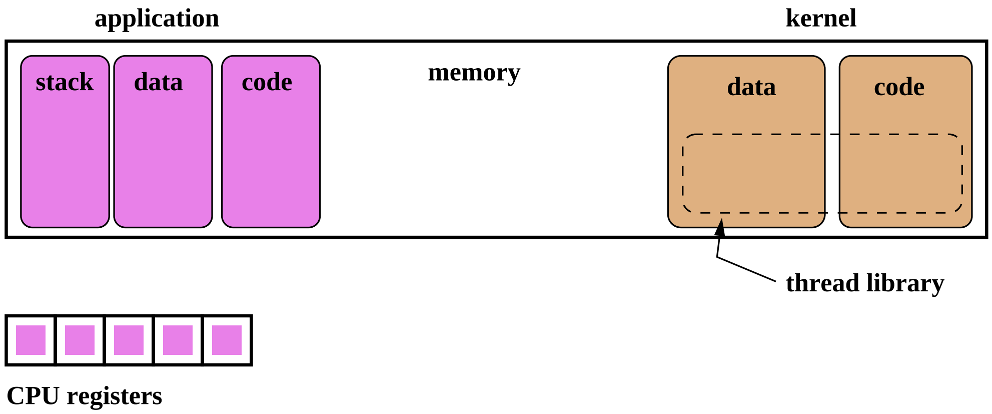
A process with one thread is a *sequential* process. A process with more than one thread is a *concurrent* process.

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

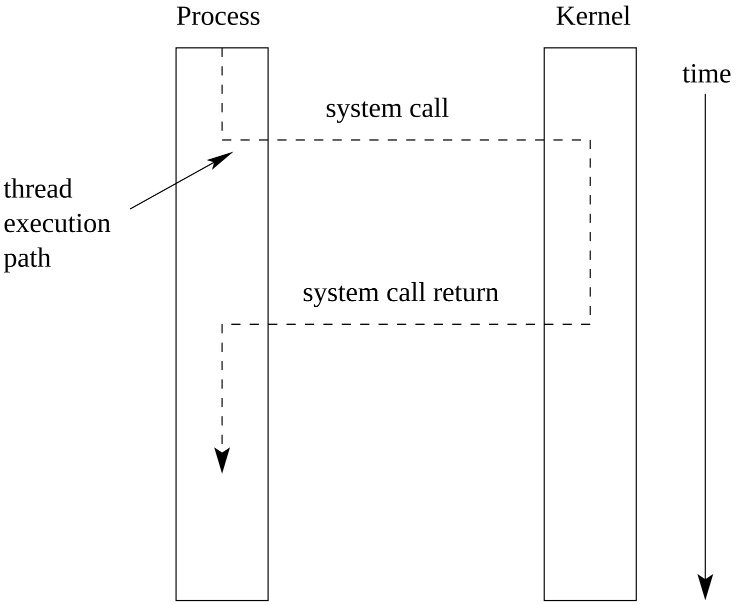
- The hardware provides a mechanism that a running program can use to cause a system call. Often, it is a special instruction, e.g., the MIPS `syscall` instruction.
- What happens on a system call:
  - the processor is switched to system (privileged) execution mode
  - key parts of the current thread 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

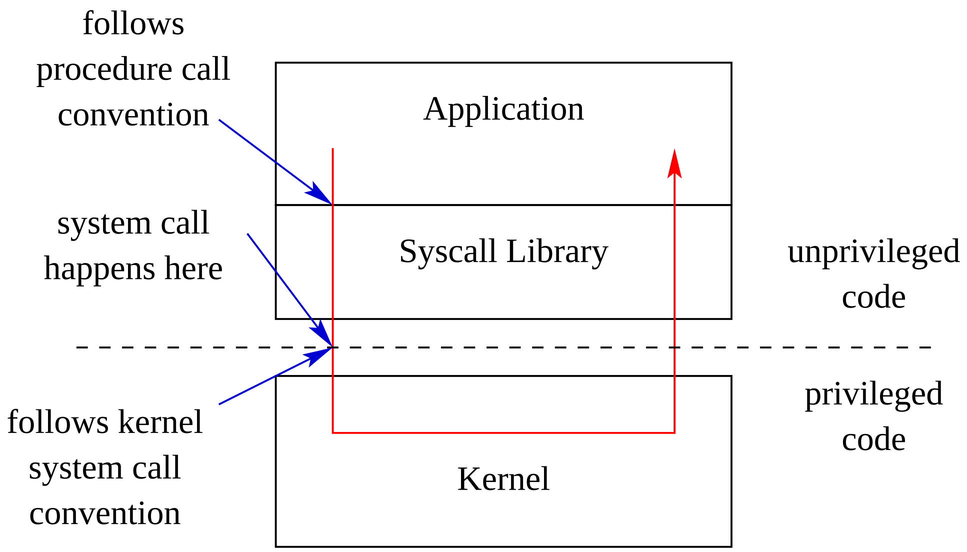
- Once a system call occurs, the calling thread will be executing a system call handler, which is part of the kernel, in privileged mode.
- The kernel's handler determines which service the calling process wanted, and performs that service.
- When the kernel is finished, it returns from the system call. 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

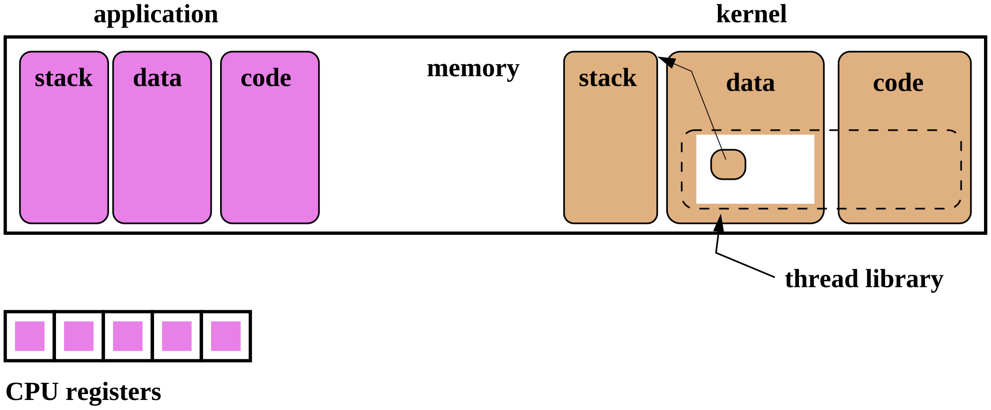
```
common_exception:
  mfc0 k0, c0_status /* Get status register */
  andi k0, k0, CST_KUp /* Check the we-were-in-user-mode bit */
  beq  k0, $0, 1f /* If clear, from kernel, already have stack */
                  /* 1f is branch forward to label 1: */
  nop             /* delay slot */

  /* 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



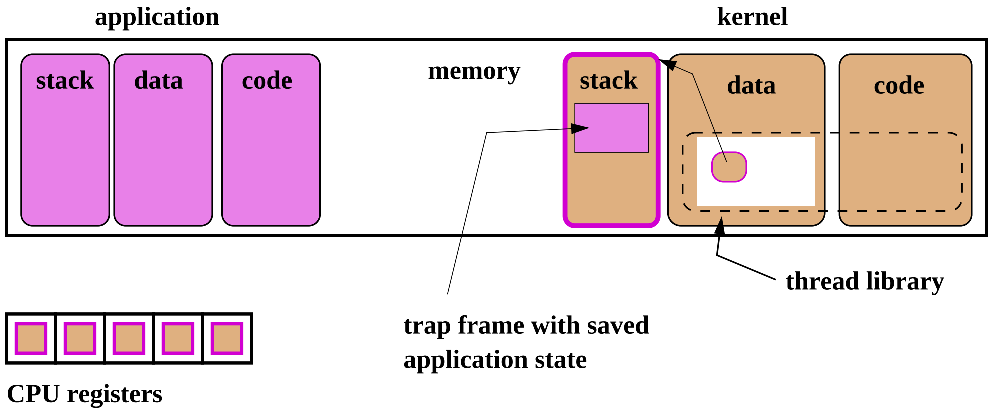
Each OS/161 thread has two stacks, one that is used while the thread is executing unprivileged application code, and another that is used while the thread is executing privileged kernel code.

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

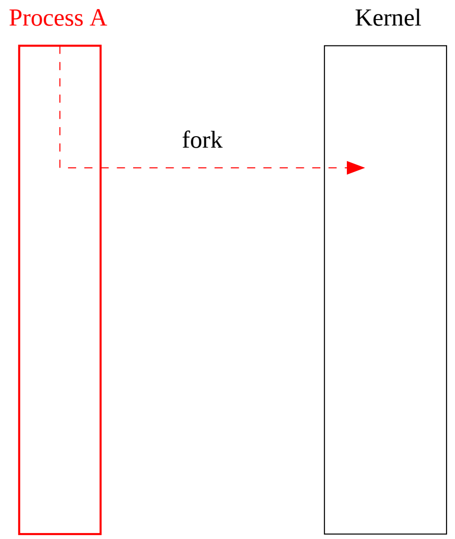
System Calls for Process Management

	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

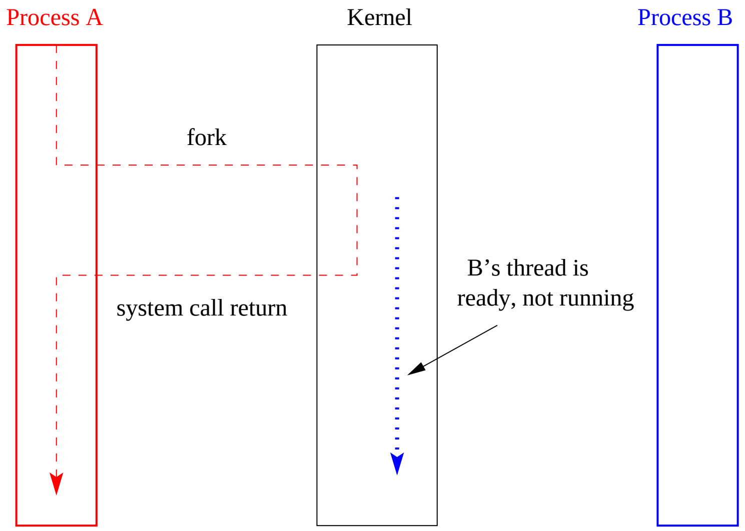
```
main()
{
   rc = fork();  /* returns 0 to child, pid to parent */
   if (rc == 0) {
      my_pid = getpid();
      x = child_code();
      _exit(x);
   } else {
     child_pid = rc;
     parent_code();
     child_exit = waitpid(child_pid);
     parent_pid = getpid();
   }
}
```

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[2] = 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();
     child_exit = waitpid(child_pid);
   }
}
```

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

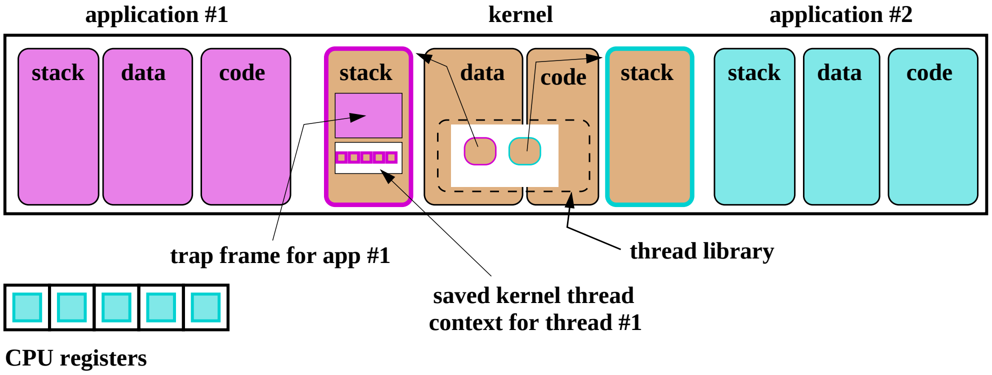
```
/* From kern/include/proc.h */
/* Create a fresh process for use by runprogram() */
struct proc *proc_create_runprogram(const char *name);

/* 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

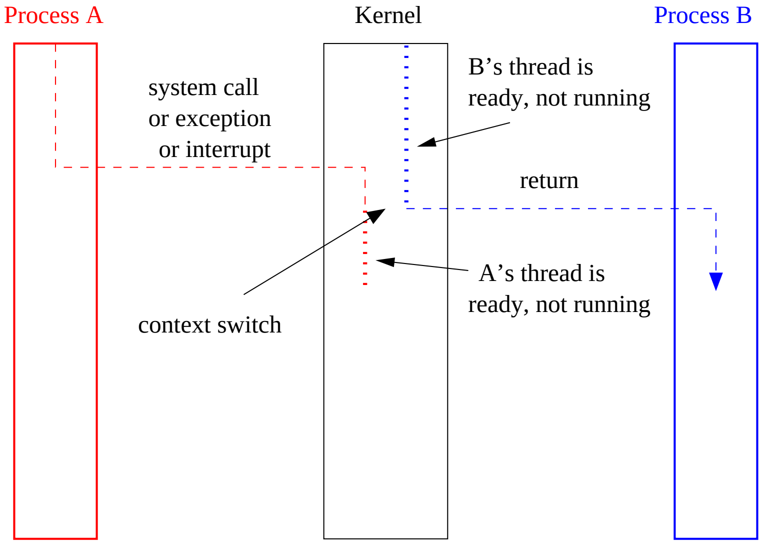
- whenever a system call, exception, or interrupt occurs, control is transferred from the running program to the kernel
- at these points, the kernel has the ability to cause a context switch from the running process' thread to another process' thread
- notice that these context switches always occur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

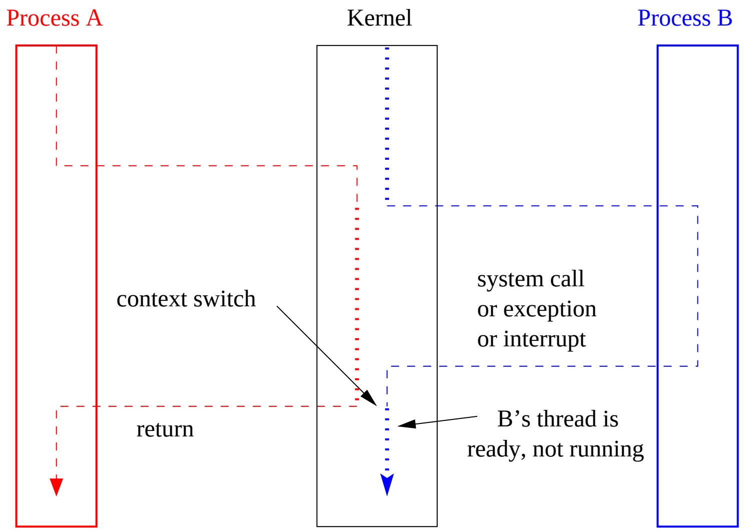


Timesharing Example (Part 1)



Kernel switches execution context to Process B.

Timesharing Example (Part 2)

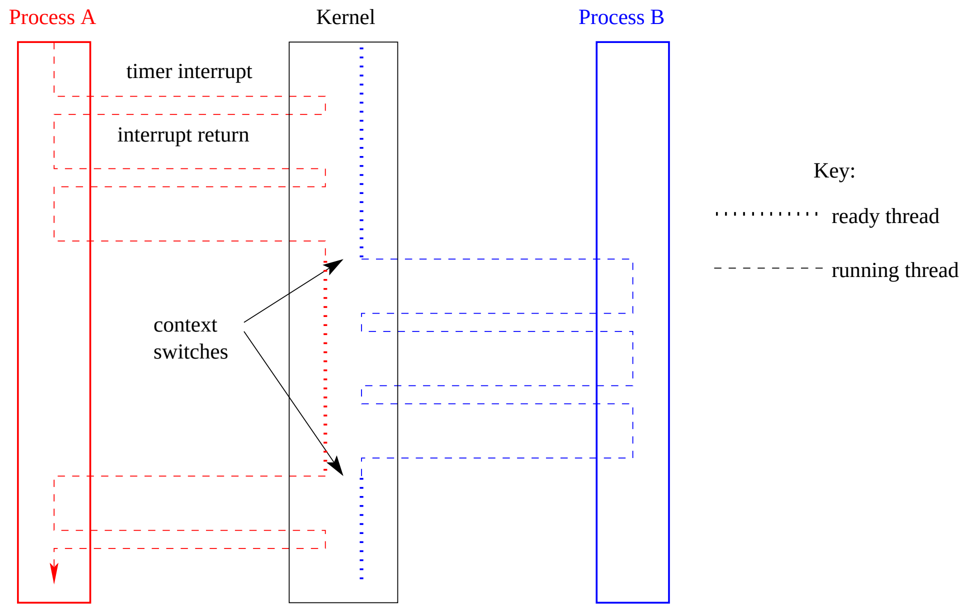


Kernel switches execution context back to process A.

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



Virtual and Physical Addresses

- Physical addresses are provided directly by the machine.
  - one physical address space per machine
  - the size of a physical address determines the maximum amount of addressable physical memory
- Virtual addresses (or logical addresses) are addresses provided by the OS to processes.
  - one virtual address space *per process*
- Programs use virtual addresses. As a program runs, the hardware (with help from the operating system) converts each virtual address to a physical address.
- The conversion of a virtual address to a physical address is called *address translation*.

On the MIPS, virtual addresses and physical addresses are 32 bits long. This limits the size of virtual and physical address spaces.

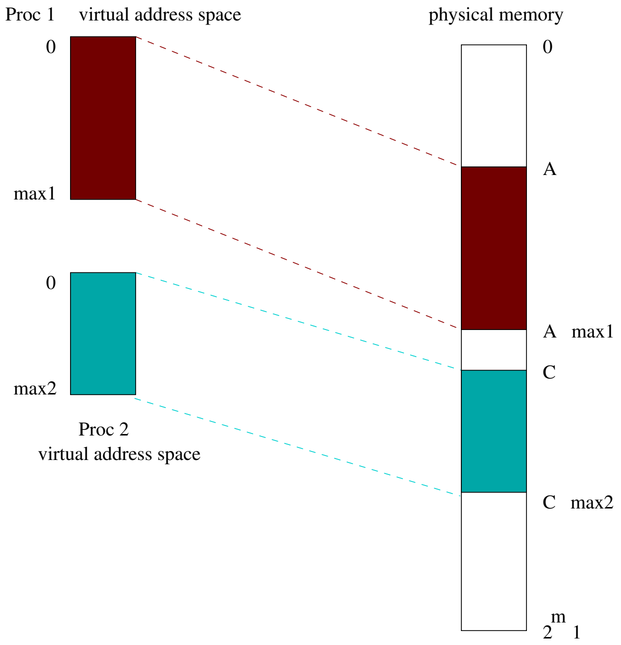
Simple Address Translation: Dynamic Relocation

- hardware provides a *memory management unit (MMU)* which includes a *relocation register* and a *limit register* (or *bound register*).
- to translate a virtual address to a physical address, the MMU:
  - checks whether the virtual address is larger than the limit in the limit register
  - if it is, the MMU raises an *exception*
  - otherwise, the MMU adds the base address (stored in the relocation register) to the virtual address to produce the physical address
- The OS maintains a separate base address and limit for each process, and ensures that the relocation and limit registers in the MMU always contain the base address and limit of the currently-running process.
- To ensure this, the OS must normally change the values in the MMU's registers during each context switch.

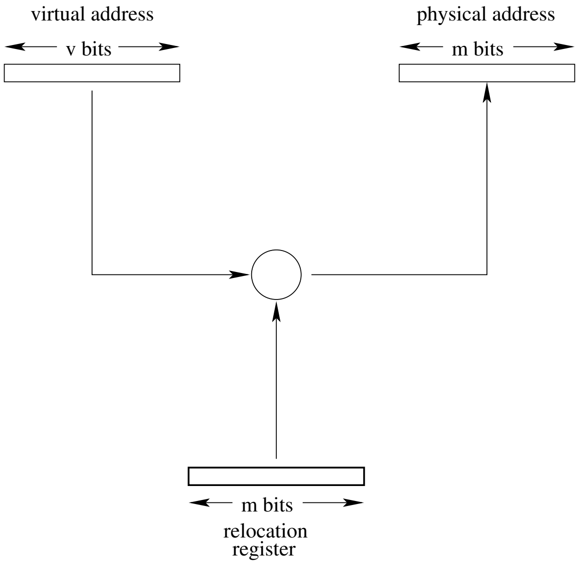
Properties of Dynamic Relocation

- each virtual address space corresponds to a *contiguous range of physical addresses*
- the OS is responsible for deciding *where* each virtual address space should map to in physical memory
  - the OS must track which parts of physical memory are in use, and which parts are free
  - since different address spaces may have different sizes, the OS must allocate/deallocate variable-sized chunks of physical memory
  - this creates the potential for *external fragmentation* of physical memory: wasted, unallocated space
- the MMU is responsible for performing all address translations, using base and limit information provided to it by the the OS

Dynamic Relocation: Address Space Diagram



Dynamic Relocation Mechanism

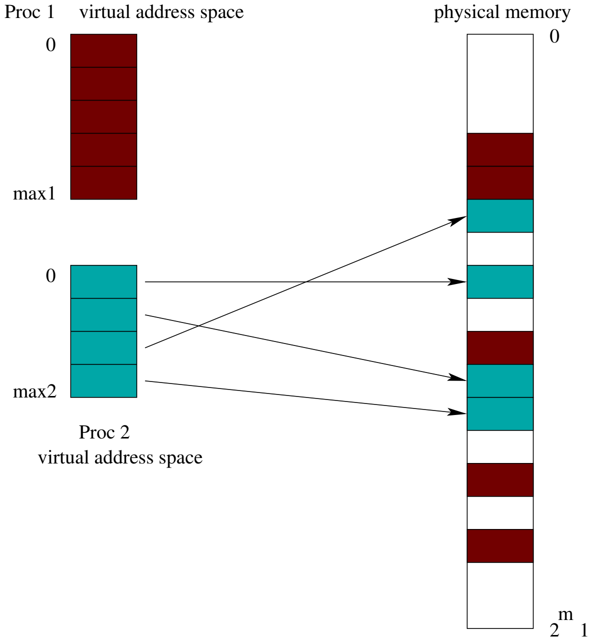


This diagram shows only the address translation, not the limit check.

Address Translation: Paging

- Each virtual address space is divided into fixed-size chunks called *pages*
- The physical address space is divided into *frames*. Frame size matches page size.
- OS maintains a *page table* for each process. Page table specifies the frame in which each of the process's pages is located.
- At run time, MMU translates virtual addresses to physical using the page table of the running process.

Address Space Diagram for Paging



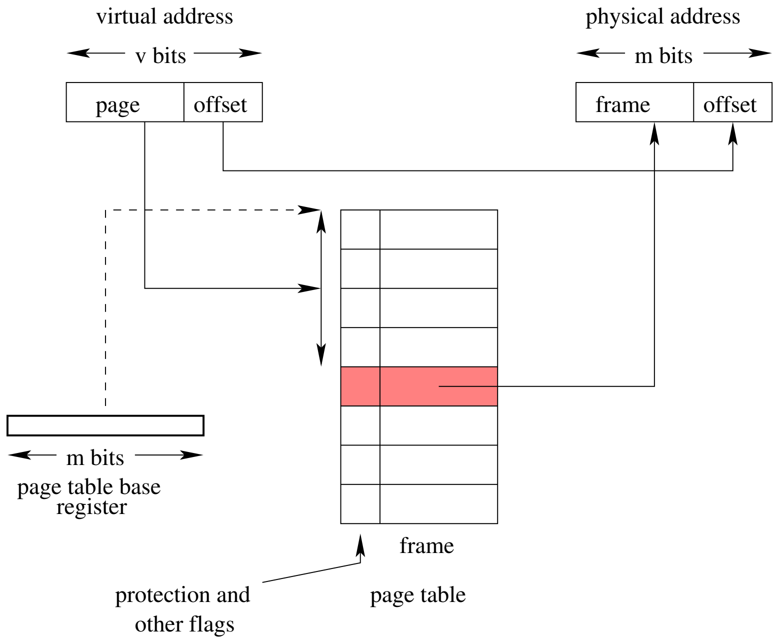
Properties of Paging

- OS is responsible for deciding which frame will hold each page
  - simple physical memory management
  - potential for *internal fragmentation* of physical memory: wasted, allocated space
  - virtual address space need not be physically contiguous in physical space after translation.
- MMU is responsible for performing all address translations using the page table that is created and maintained by the OS.
- The OS must normally change the values in the MMU registers on each context switch, so that they refer to the page table of the currently-running process.

How the MMU Translates Virtual Addresses

- The MMU includes a *page table base register* and a *page table length register*.
  - the base register contains the (physical) address of the first page table entry for the currently-running process
  - the length register contains the number of entries in the page table of the currently running process.
- To translate a virtual address, the MMU:
  - determines the *page number* and *offset* of the virtual address
  - checks whether the page number is larger than the value in the page table length register
  - if it is, the MMU raises an exception
  - otherwise, the MMU uses the page table to determine the *frame number* of the frame that holds the virtual page, and combines the frame number and offset to determine the physical address

Paging Mechanism



Page Table Entries

- the primary payload of each page table entry (PTE) is a frame number
- PTEs typically contain other information as well, such as
  - information provided by the kernel to control address translation by the MMU, such as:
    - valid bit: is the process permitted to use this part of the address space?
    - present bit: is this page mapped into physical memory (useful with page replacement, to be discussed later)
    - protection bits: to be discussed
  - information provided by the MMU to help the kernel manage address spaces, such as:
    - reference (use) bit: has the process used this page recently?
    - dirty bit: has the process changed the contents of this page?

Validity and Protection

- during address translation, the MMU checks that the page being used by the process has a *valid* page table entry
  - typically, each PTE contains a *valid bit*
  - invalid PTEs indicate pages that the process is not permitted to use
- the MMU may also enforce other protection rules, for example
  - each PTE may contain a *read-only* bit that indicates whether the corresponding page is read-only, or can be modified by the process
- if a process attempts to access an invalid page, or violates a protection rule, the MMU raises an exception, which is handled by the kernel

The kernel controls which pages are valid and which are protected by setting the contents of PTEs and/or MMU registers.

Summary: Roles of the Kernel and the MMU

- Kernel:
  - manage MMU state on address space switches (context switch from thread in one process to thread in a different process)
  - create and manage page tables
  - manage (allocate/deallocate) physical memory
  - handle exceptions raised by the MMU
- MMU (hardware):
  - translate virtual addresses to physical addresses
  - check for and raise exceptions when necessary

Speed of Address Translation

- Execution of each machine instruction may involve one, two or more memory operations
  - one to fetch instruction
  - one or more for instruction operands
- Address translation through a page table adds one extra memory operation (for page table entry lookup) for each memory operation performed during instruction execution
  - Simple address translation through a page table can cut instruction execution rate in half.
  - More complex translation schemes (e.g., multi-level paging) are even more expensive.
- Solution: include a Translation Lookaside Buffer (TLB) in the MMU
  - TLB is a fast, fully associative address translation cache
  - TLB hit avoids page table lookup

TLB

- Each entry in the TLB contains a (page number, frame number) pair.
- If address translation can be accomplished using a TLB entry, access to the page table is avoided.
  - This is called a *TLB hit*.
- Otherwise, translate through the page table.
  - This is called a *TLB miss*.
- TLB lookup is much faster than a memory access. TLB is an associative memory - page numbers of all entries are checked simultaneously for a match. However, the TLB is typically small (typically hundreds, e.g. 128, or 256 entries).
- If the MMU cannot distinguish TLB entries from different address spaces, then the kernel must clear or invalidate the TLB on each context switch. (Why?)

TLB Management

- An TLB may be *hardware-controlled* or *software-controlled*
- In a hardware-controlled TLB, when there is a TLB miss:
  - The MMU (hardware) finds the frame number by performing a page table lookup, translates the virtual address, and adds the transalation (page number, frame number pair) to the TLB.
  - If the TLB is full, the MMU evicts an entry to make room for the new one.
- In a software-controlled TLB, when there is a TLB miss:
  - the MMU simply causes an exception, which triggers the kernel exception handler to run
  - the kernel must determine the correct page-to-frame mapping and load the mapping into the TLB (evicting an entry if the TLB is full), before returning from the exception
  - after the exception handler runs, the MMU retries the instruction that caused the exception.

The MIPS R3000 TLB

- The MIPS has a software-controlled TLB that can hold 64 entries.
- Each TLB entry includes a virtual page number, a physical frame number, an address space identifier (not used by OS/161), and several flags (valid, read-only).
- OS/161 provides low-level functions for managing the TLB:

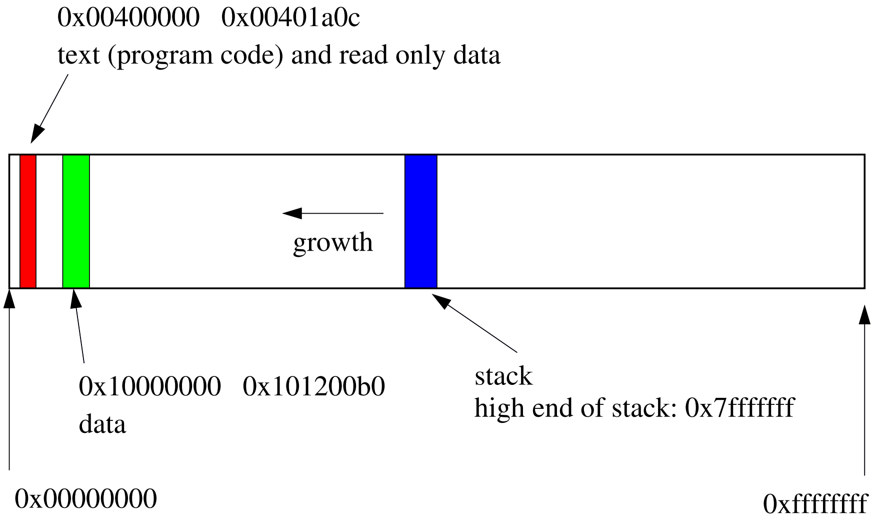
  TLB_Write: modify a specified TLB entry

  TLB_Read: read a specified TLB entry

  TLB_Probe: look for a page number in the TLB
- If the MMU cannot translate a virtual address using the TLB it raises an exception, which must be handled by OS/161.

See `kern/arch/mips/include/tlb.h`

What is in a Virtual Address Space?



0x00400000 0x00401a0c
text (program code) and read only data

growth

0x10000000 0x101200b0
data

stack
high end of stack: 0x7fffffff

0x00000000

0xffffffff

This diagram illustrates the layout of the virtual address space for the OS/161 test application `user/testbin/sort`

Address Translation In OS/161: dumbvm

- OS/161 starts with a very simple virtual memory implementation
- virtual address spaces are described by `addrspace` objects, which record the mappings from virtual to physical addresses

```
struct addrspace {
#if OPT_DUMBVM
  vaddr_t as_vbase1; /* base virtual address of code segment */
  paddr_t as_pbase1; /* base physical address of code segment */
  size_t as_npages1; /* size (in pages) of code segment */
  vaddr_t as_vbase2; /* base virtual address of data segment */
  paddr_t as_pbase2; /* base physical address of data segment */
  size_t as_npages2; /* size (in pages) of data segment */
  paddr_t as_stackpbase; /* base physical address of stack */
#else
  /* Put stuff here for your VM system */
#endif
};
```

- Notice that each segment must be mapped contiguously into physical memory.

Address Translation Under `dumbvm`

- the MIPS MMU tries to translate each virtual address using the entries in the TLB
- If there is no valid entry for the page the MMU is trying to translate, the MMU generates a TLB fault (called an *address exception*)
- The `vm_fault` function (see `kern/arch/mips/vm/dumbvm.c`) handles this exception for the OS/161 kernel. It uses information from the current process' `addrspace` to construct and load a TLB entry for the page.
- On return from exception, the MIPS retries the instruction that caused the exception. This time, it may succeed.

`vm_fault` is not very sophisticated. If the TLB fills up, OS/161 will crash!

Initializing an Address Space

- When the kernel creates a process to run a particular program, it must create an address space for the process, and load the program's code and data into that address space

> OS/161 *pre-loads* the address space before the program runs. Many other OS load pages *on demand*. (Why?)

- A program's code and data is described in an *executable file*, which is created when the program is compiled and linked
- OS/161 (and some other operating systems) expect executable files to be in ELF (**E**xecutable and **L**inking **F**ormat) format
- The OS/161 `execv` system call re-initializes the address space of a process

  ```
  int execv(const char *program, char **args)
  ```

- The `program` parameter of the `execv` system call should be the name of the ELF executable file for the program that is to be loaded into the address space.

ELF Files

- ELF files contain address space segment descriptions, which are useful to the kernel when it is loading a new address space
- the ELF file identifies the (virtual) address of the program's first instruction
- the ELF file also contains lots of other information (e.g., section descriptors, symbol tables) that is useful to compilers, linkers, debuggers, loaders and other tools used to build programs

Address Space Segments in ELF Files

- The ELF file contains a header describing the segments and segment *images*.
- Each ELF segment describes a contiguous region of the virtual address space.
- The header includes an entry for each segment which describes:
  - the virtual address of the start of the segment
  - the length of the segment in the virtual address space
  - the location of the start of the segment image in the ELF file (if present)
  - the length of the segment image in the ELF file (if present)
- the image is an exact copy of the binary data that should be loaded into the specified portion of the virtual address space
- the image may be smaller than the address space segment, in which case the rest of the address space segment is expected to be zero-filled

To initialize an address space, the OS/161 kernel copies segment images from the ELF file to the specifed portions of the virtual address space.

ELF Files and OS/161

- OS/161's `dumbvm` implementation assumes that an ELF file contains two segments:
  - a *text segment*, containing the program code and any read-only data
  - a *data segment*, containing any other global program data
- the ELF file does not describe the stack (why not?)
- `dumbvm` creates a *stack segment* for each process. It is 12 pages long, ending at virtual address `0x7fffffff`

Look at `kern/syscall/loadelf.c` to see how OS/161 loads segments from ELF files

ELF Sections and Segments

- In the ELF file, a program's code and data are grouped together into *sections*, based on their properties. Some sections:

  .text: program code

  .rodata: read-only global data

  .data: initialized global data

  .bss: uninitialized global data (Block Started by Symbol)

  .sbss: small uninitialized global data
- not all of these sections are present in every ELF file
- normally
  - the `.text` and `.rodata` sections together form the text segment
  - the `.data`, `.bss` and `.sbss` sections together form the data segement
- space for *local* program variables is allocated on the stack when the program runs

The `user/uw-testbin/segments.c` Example Program (1 of 2)

```
#include <unistd.h>

#define N   (200)

int x = 0xdeadbeef;
int t1;
int t2;
int t3;
int array[4096];
char const *str = "Hello World\n";
const int z = 0xabcddcba;

struct example {
  int ypos;
  int xpos;
};
```

The `user/uw-testbin/segments.c` Example Program (2 of 2)

```
int
main()
{
  int count = 0;
  const int value = 1;
  t1 = N;
  t2 = 2;
  count = x + t1;
  t2 = z + t2 + value;

  reboot(RB_POWEROFF);
  return 0; /* avoid compiler warnings */
}
```

ELF Sections for the Example Program

```
Section Headers:
[Nr] Name         Type             Addr     Off    Size   Flg
[ 0]              NULL             00000000 000000 000000
[ 1] .text        PROGBITS         00400000 010000 000200  AX
[ 2] .rodata      PROGBITS         00400200 010200 000020   A
[ 3] .reginfo     MIPS_REGINFO     00400220 010220 000018   A
[ 4] .data        PROGBITS         10000000 020000 000010  WA
[ 5] .sbss        NOBITS           10000010 020010 000014 WAp
[ 6] .bss         NOBITS           10000030 020010 004000  WA
...
Flags: W (write), A (alloc), X (execute), p (processor specific)

## Size = number of bytes (e.g., .text is 0x200 = 512 bytes
## Off  = offset into the ELF file
## Addr = virtual address
```

The `cs350-readelf` program can be used to inspect OS/161 MIPS ELF files: `cs350-readelf -a segments`

ELF Segments for the Example Program

```
Program Headers:
Type     Offset   VirtAddr   PhysAddr   FileSiz MemSiz  Flg Align
REGINFO 0x010220 0x00400220 0x00400220 0x00018 0x00018 R   0x4
LOAD    0x010000 0x00400000 0x00400000 0x00238 0x00238 R E 0x10000
LOAD    0x020000 0x10000000 0x10000000 0x00010 0x04030 RW  0x10000
```

- segment info, like section info, can be inspected using the `cs350-readelf` program
- the REGINFO section is not used
- the first LOAD segment includes the .text and .rodata sections
- the second LOAD segment includes .data, .sbss, and .bss

Contents of the Example Program’s `.text` Section

```
Contents of section .text:
 400000 3c1c1001 279c8000 2408fff8 03a8e824  <...’...$......$
...
## Decoding 3c1c1001 to determine instruction
## 0x3c1c1001 = binary 111100000111000001000000000001
## 0011 1100 0001 1100 0001 0000 0000 0001
## instr  | rs    | rt    |   immediate
## 6 bits | 5 bits| 5 bits|   16 bits
## 001111 | 00000 | 11100 |  0001 0000 0000 0001
## LUI    | 0     | reg 28|   0x1001
## LUI    | unused| reg 28|   0x1001
## Load upper immediate into rt (register target)
## lui gp, 0x1001
```

The `cs350-objdump` program can be used to inspect OS/161 MIPS ELF file section contents: `cs350-objdump -s segments`

Contents of the Example Program’s `.rodata` Section

```
Contents of section .rodata:
 400200 abcddcba 00000000 00000000 00000000  ................
 400210 48656c6c 6f20576f 726c640a 00000000  Hello World.....
...
## const int z = 0xabcddcba
## If compiler doesn’t prevent z from being written,
##    then the hardware could.
## 0x48 = ’H’ 0x65 = ’e’ 0x0a = ’\n’ 0x00 = ’\0’
```

The `.rodata` section contains the “Hello World” string literal and the constant integer variable `z`.

Contents of the Example Program’s `.data` Section

```
Contents of section .data:
 10000000 deadbeef 00400210 00000000 00000000  .....@..........
...
## Size = 0x10 bytes = 16 bytes (padding for alignment)
## int x = deadbeef (4 bytes)
## char const *str = "Hello World\n"; (4 bytes)
## address of str = 0x10000004
## value stored in str = 0x00400210.
## NOTE: this is the address of the start
## of the string literal in the .rodata section
```

The `.data` section contains the initialized global variables `str` and `x`.

Contents of the Example Program's `.bss` and `.sbss` Sections

```
...
10000000 D x
10000004 D str
10000010 S t3       ## S indicates sbss section
10000014 S t2
10000018 S t1
1000001c S errno
10000020 S __argv
10000030 B array    ## B indicates bss section
10004030 A _end
10008000 A _gp
```

The `t1`, `t2`, and `t3` variables are in the `.sbss` section. The `array` variable is in the `.bss` section. There are no values for these variables in the ELF file, as they are uninitialized. The `cs350-nm` program can be used to inspect symbols defined in ELF files: `cs350-nm -n <filename>`, in this case `cs350-nm -n segments`.

An Address Space for the Kernel

- Each process has its own address space. What about the kernel?
- Three possibilities:

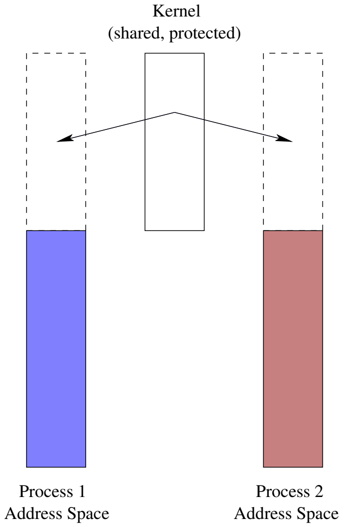
Kernel in physical space: disable address translation in privileged system execution mode, enable it in unprivileged mode

Kernel in separate virtual address space: need a way to change address translation (e.g., switch page tables) when moving between privileged and unprivileged code

Kernel mapped into portion of address space of *every process*: OS/161, Linux, and other operating systems use this approach

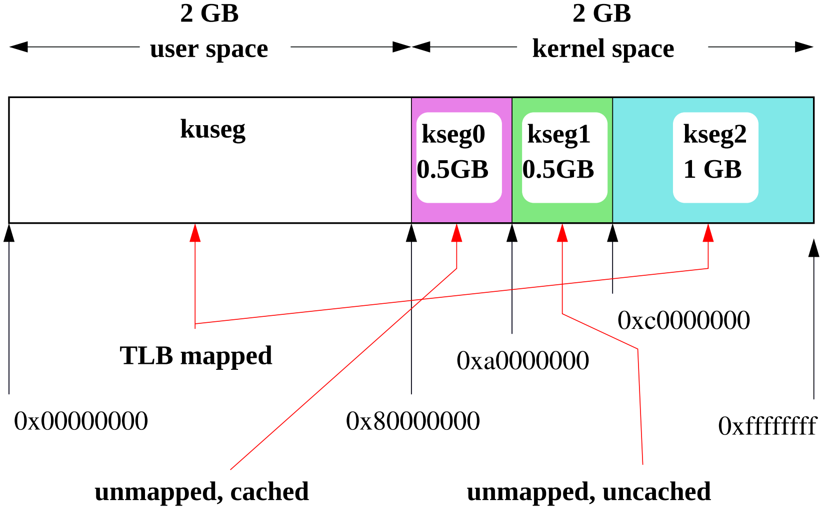
- memory protection mechanism is used to isolate the kernel from applications
- one advantage of this approach: application virtual addresses (e.g., system call parameters) are easy for the kernel to use

The Kernel in Process' Address Spaces



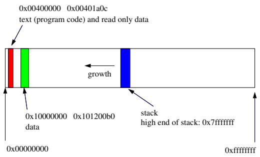
Attempts to access kernel code/data in user mode result in memory protection exceptions, not invalid address exceptions.

Address Translation on the MIPS R3000



In OS/161, user programs live in kuseg, kernel code and data structures live in kseg0, devices are accessed through kseg1, and kseg2 is not used.

The Problem of Sparse Address Spaces



- Consider the page table for `user/testbin/sort`, assuming a 4 Kbyte page:
  - need 2^{19} page table entries (PTEs) to cover the bottom half of the virtual address space (2GB).
  - the text segment occupies 2 pages, the data segment occupies 289 pages, and OS/161 sets the initial stack size to 12 pages, so there are only 303 *valid* pages (of 2^{19}).
- If dynamic relocation is used, the kernel will need to map a 2GB address space contiguously into physical memory, even though only a tiny fraction of that address space is actually used by the program.
- If paging is used, the kernel will need to create a page table with 2^{19} PTEs, almost all of which are marked as not valid.

Handling Sparse Address Spaces

- Use dynamic relocation, but provide separate base and length for each valid segment of the address space. Do not map the rest of the address space.
  - OS/161 `dumbvm` uses a simple variant of this idea, which depends on having a software-managed TLB.
  - A more general approach is *segmentation*.
- A second approach is to use *multi-level paging*
  - replace the single large linear page table with a hierarchy of smaller page tables
  - a sparse address space can be mapped by a sparse tree hierarchy
  - easier to manage several smaller page tables than one large one (remember: each page table must be continguous in physical memory!)

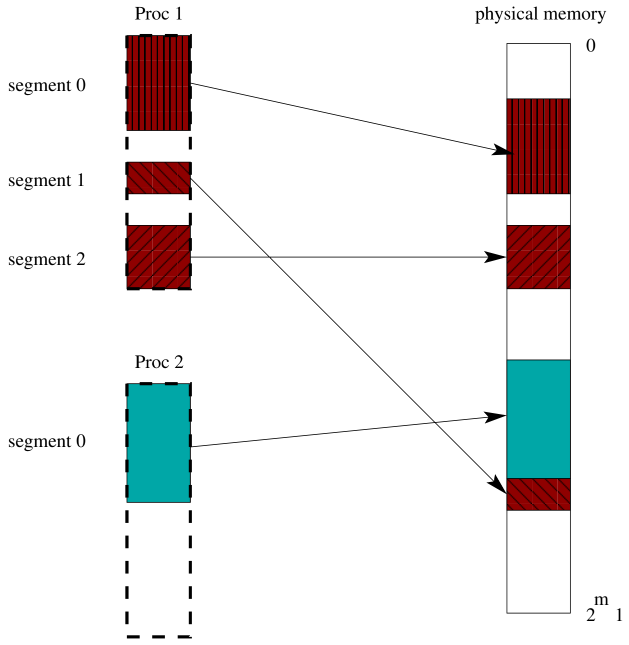
Segmentation

- Often, programs (like `sort`) need several virtual address segments, e.g, for code, data, and stack.
- With segmentation, a virtual address can be thought of as having two parts:

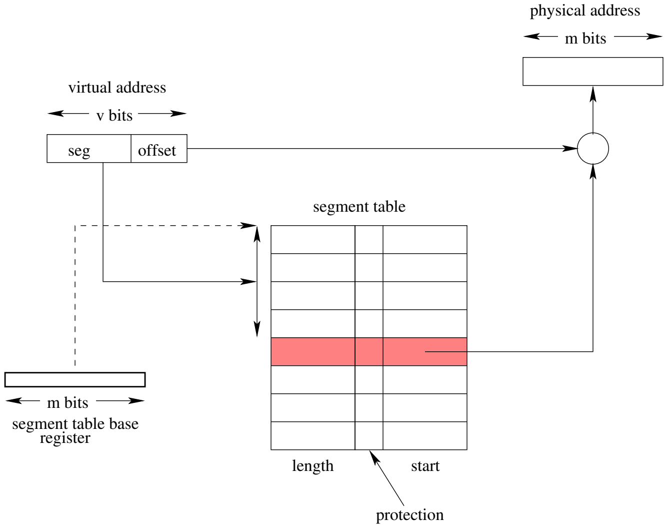
  (segment ID, address within segment)

- Each segment also has a length.

Segmented Address Space Diagram



Mechanism for Translating Segmented Addresses



This translation mechanism requires physically contiguous allocation of segments.

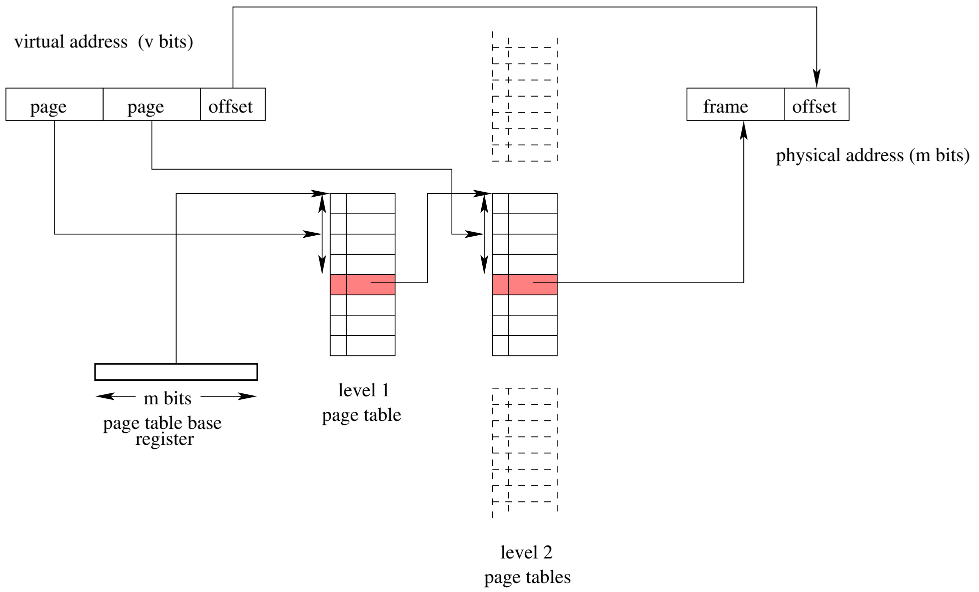
Handling Sparse Paged Virtual Address Spaces

- Large paged virtual address spaces require large page tables.
- example: 2^{48} byte virtual address space, 8 Kbyte (2^{13} byte) pages, 4 byte page table entries means

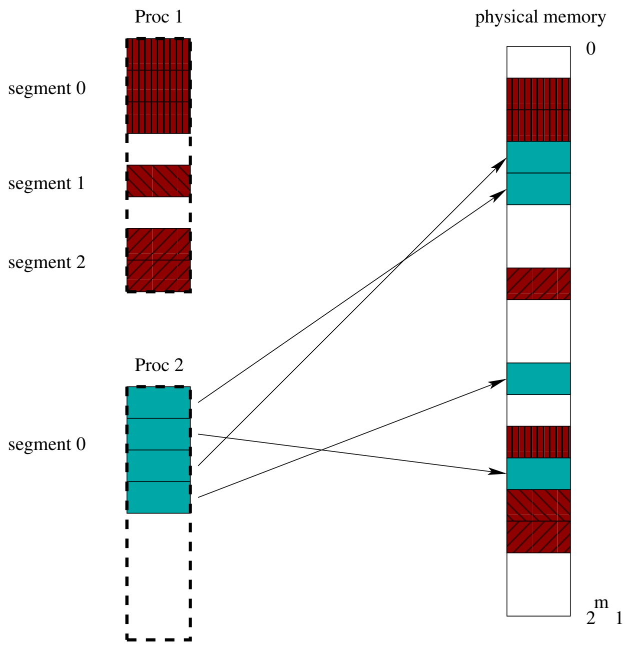
$$\frac{2^{48}}{2^{13}}2^2 = 2^{37} \text{ bytes per page table}$$

- page tables for large address spaces may be very large, and
  - they must be in memory, and
  - they must be physically contiguous

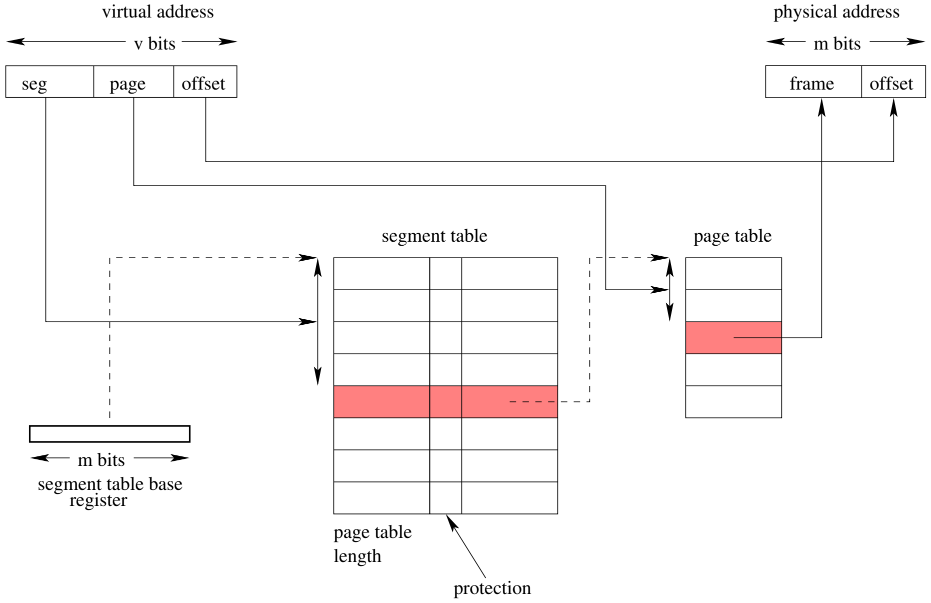
Two-Level Paging



Combining Segmentation and Paging



Combining Segmentation and Paging: Translation Mechanism



Exploiting Secondary Storage

Goals:

- Allow virtual address spaces that are larger than the physical address space.
- Allow greater multiprogramming levels by using less of the available (primary) memory for each process.

Method:

- Allow pages (or segments) from the virtual address space to be stored in secondary storage, e.g., on disks, as well as primary memory.
- Move pages (or segments) between secondary storage and primary memory so that they are in primary memory when they are needed.

Paging Policies

When to Page?:

Demand paging brings pages into memory when they are used. Alternatively, the OS can attempt to guess which pages will be used, and *prefetch* them.

What to Replace?:

Unless there are unused frames, one page must be replaced for each page that is loaded into memory. A *replacement policy* specifies how to determine which page to replace.

Similar issues arise if (pure) segmentation is used, only the unit of data transfer is segments rather than pages. Since segments may vary in size, segmentation also requires a *placement policy*, which specifies where, in memory, a newly-fetched segment should be placed.

Page Faults

- When paging is used, some valid pages may be loaded into memory, and some may not be.
- To account for this, each PTE may contain a *present* bit, to indicate whether the page is or is not loaded into memory
  - $V = 1, P = 1$: page is valid and in memory (no exception occurs)
  - $V = 1, P = 0$: page is valid, but is not in memory (exception!)
  - $V = 0, P = x$: invalid page (exception!)
- If $V = 0$, or if $V = 1$ and $P = 0$, the MMU will generate an exception if a process tries to access the page. This is called a *page fault.*
- To handle a page fault, the kernel operating system must:
  - bring the missing page into memory, set $P = 1$ in the PTE
  - while the missing page is being loaded, the faultin process is *blocked*
  - return from the exception
- the processor will then retry the instrution that caused the page fault

Page Faults in OS/161

- things are a bit different in systems with software-managed TLBs, such as OS/161 on the MIPS processor
- MMUs with software-managed TLBs never check page tables, and thus do not interpret P bits in page table entries
- In an MMU with a software-managed TLB, either there is a valid translation for a page in the TLB, or there is not.
  - If there is not, the MMU generates an exception. It is up to the kernel to determine the reason for the exception. Is this:
    - ∗ an access to a valid page that is not in memory (a page fault)?
    - ∗ an access to a valid page that is in memory?
    - ∗ an access to an invalid page?
  - The kernel should ensure that a page has a translation in the TLB *only* if the page is valid and in memory. (Why?)

A Simple Replacement Policy: FIFO

- the FIFO policy: replace the page that has been in memory the longest
- a three-frame example:

Num	1	2	3	4	5	6	7	8	9	10	11	12
Refs	a	b	c	d	a	b	e	a	b	c	d	e
Frame 1	a	a	a	d	d	d	e	e	e	e	e	e
Frame 2		b	b	b	a	a	a	a	a	c	c	c
Frame 3			c	c	c	b	b	b	b	b	d	d
Fault ?	x	x	x	x	x	x	x			x	x	

Optimal Page Replacement

- There is an optimal page replacement policy for demand paging.
- The OPT policy: replace the page that will not be referenced for the longest time.

Num	1	2	3	4	5	6	7	8	9	10	11	12
Refs	a	b	c	d	a	b	e	a	b	c	d	e
Frame 1	a	a	a	a	a	a	a	a	a	c	c	c
Frame 2		b	b	b	b	b	b	b	b	b	d	d
Frame 3			c	d	d	d	e	e	e	e	e	e
Fault ?	x	x	x	x			x			x	x	

- OPT requires knowledge of the future.

Other Replacement Policies

- FIFO is simple, but it does not consider:

  Frequency of Use: how often a page has been used?

  Recency of Use: when was a page last used?

  Cleanliness: has the page been changed while it is in memory?

- The *principle of locality* suggests that usage ought to be considered in a replacement decision.
- Cleanliness may be worth considering for performance reasons.

Locality

- Locality is a property of the page reference string. In other words, it is a property of programs themselves.
- *Temporal locality* says that pages that have been used recently are likely to be used again.
- *Spatial locality* says that pages "close" to those that have been used are likely to be used next.

In practice, page reference strings exhibit strong locality. Why?

Least Recently Used (LRU) Page Replacement

- LRU is based on the principle of temporal locality: replace the page that has not been used for the longest time
- To implement LRU, it is necessary to track each page's recency of use. For example: maintain a list of in-memory pages, and move a page to the front of the list when it is used.
- Although LRU and variants have many applications, true LRU is difficult to implement in virtual memory systems. (Why?)

Least Recently Used: LRU

- the same three-frame example:

Num	1	2	3	4	5	6	7	8	9	10	11	12
Refs	a	b	c	d	a	b	e	a	b	c	d	e
Frame 1	a	a	a	d	d	d	e	e	e	c	c	c
Frame 2		b	b	b	a	a	a	a	a	a	d	d
Frame 3			c	c	c	b	b	b	b	b	b	e
Fault ?	x	x	x	x	x	x	x			x	x	x

The “Use” Bit

- A *use bit* (or *reference bit*) is a bit found in each page table entry that:
  - is set by the MMU each time the page is used, i.e., each time the MMU translates a virtual address on that page
  - can be read and cleared by the operating system
- The use bit provides a small amount of efficiently-maintainable usage information that can be exploited by a page replacement algorithm.

The Clock Replacement Algorithm

- The clock algorithm (also known as “second chance”) is one of the simplest algorithms that exploits the use bit.
- Clock is identical to FIFO, except that a page is “skipped” if its use bit is set.
- The clock algorithm can be visualized as a victim pointer that cycles through the page frames. The pointer moves whenever a replacement is necessary:

```
while use bit of victim is set
   clear use bit of victim
   victim = (victim + 1) % num_frames
choose victim for replacement
victim = (victim + 1) % num_frames
```

Page Cleanliness: the “Modified” Bit

- A page is *modified* (sometimes called dirty) if it has been changed since it was loaded into memory.
- A modified page is more costly to replace than a clean page. (Why?)
- The MMU identifies modified pages by setting a *modified bit* in page table entry of a page when a process *writes* to a virtual address on that page, i.e., when the page is changed.
- The operating system can clear the modified bit when it cleans the page
- The modified bit potentially has two roles:
  - Indicates which pages need to be cleaned.
  - Can be used to influence the replacement policy.

How Much Physical Memory Does a Process Need?

- Principle of locality suggests that some portions of the process's virtual address space are more likely to be referenced than others.
- A refinement of this principle is the *working set model* of process reference behaviour.
- According to the working set model, at any given time some portion of a program's address space will be heavily used and the remainder will not be. The heavily used portion of the address space is called the *working set* of the process.
- The working set of a process may change over time.
- The *resident set* of a process is the set of pages that are located in memory.

According to the working set model, if a process's resident set includes its working set, it will rarely page fault.

Resident Set Sizes (Example)

```
PID   VSZ  RSS COMMAND
805 13940 5956 /usr/bin/gnome-session
831  2620  848 /usr/bin/ssh-agent
834  7936 5832 /usr/lib/gconf2/gconfd-2 11
838  6964 2292 gnome-smproxy
840 14720 5008 gnome-settings-daemon
848  8412 3888 sawfish
851 34980 7544 nautilus
853 19804 14208 gnome-panel
857  9656 2672 gpilotd
867  4608 1252 gnome-name-service
```

Thrashing and Load Control

- What is a good multiprogramming level?
  - If too low: resources are idle
  - If too high: too few resources per process
- A system that is spending too much time paging is said to be *thrashing*. Thrashing occurs when there are too many processes competing for the available memory.
- Thrashing can be cured by load shedding, e.g.,
  - Killing processes (not nice)
  - Suspending and *swapping out* processes (nicer)

Swapping Out Processes

- Swapping a process out means removing all of its pages from memory, or marking them so that they will be removed by the normal page replacement process. Suspending a process ensures that it is not runnable while it is swapped out.
- Which process(es) to suspend?
  - low priority processes
  - blocked processes
  - large processes (lots of space freed) or small processes (easier to reload)
- There must also be a policy for making suspended processes ready when system load has decreased.