CS 350
Operating Systems
Course Notes

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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

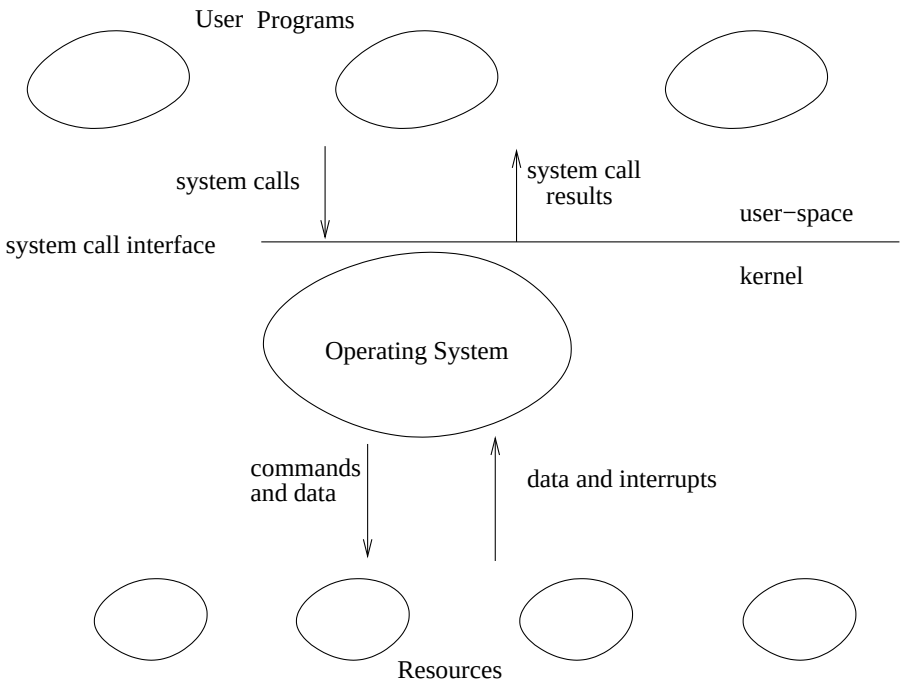
System View: The OS manages the hardware resources of a computer system.

- 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.

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
- Simple C Primer
- Processes and Threads
- Concurrency and Synchronization
- The Kernel and System Calls
- Address Spaces and Virtual Memory
- Scheduling
- Devices and Device Management
- File Systems
- Interprocess Communication and Networking
- Security

Using Memory

```
#include <stdio.h>
#include <stdlib.h>

struct foo_struct {
  int x;
  char a; char b; char c; char d;
};

int
main()
{
   int i;
   char a[40];
   int *iptr = (int *) a;
   struct foo_struct *sptr = (struct foo_struct *) a;
```


Using Memory

```
   for (i=0; i<40; i++) {
     a[i] = (char) i;
   }

   for (i=0; i<10; i++) {
     printf("%2d = 0x%08x\n", i, iptr[i]);
   }

   printf("x = 0x%08x  a = %d  b = %d c = %d d = %d\n",
     sptr[0].x, (int) sptr[0].a, (int) sptr[0].b,
     (int) sptr[0].c, (int) sptr[0].d);

   exit(0);
}
```

Using Memory: Example Output (OS/161)

```
 0 = 0x00010203
 1 = 0x04050607
 2 = 0x08090a0b
 3 = 0x0c0d0e0f
 4 = 0x10111213
 5 = 0x14151617
 6 = 0x18191a1b
 7 = 0x1c1d1e1f
 8 = 0x20212223
 9 = 0x24252627
x = 0x00010203  a = 4  b = 5 c = 6 d = 7
```


Arrays and Addresses

```
#include <stdio.h>
#include <stdlib.h>

static char *alpha = "abcdefghijklmnopqrstuvwxyz";

int
main()
{
   char array[12];
   char *value = 0;
   int i;
```

Arrays and Addresses

```
   for (i=0; i<12; i++) {
     array[i] = alpha[i];
   }

   printf("addr of array = %p\n", &array);
   printf("addr of array[0] = %p\n", &array[0]);
   printf("*array = %c\n", *array);
   printf("addr of value = %p\n", &value);
   printf("addr of value[0] = %p\n", &value[0]);
   printf("value = %p\n", value);
   printf("\n");
```


Arrays and Addresses

```
   value = array;
   printf("addr of value = %p\n", &value);
   printf("addr of value[0] = %p\n", &value[0]);
   printf("value = %p\n", value);
   printf("*value = %c\n", *value);
   printf("\n");

   value = &array[4];
   printf("addr of value = %p\n", &value);
   printf("addr of value[0] = %p\n", &value[0]);
   printf("value = %p\n", value);
   printf("*value = %c\n", *value);
   printf("\n");

   exit(0);
}
```

Arrays and Addresses: Example Output (OS/161)

```
addr of array = 0x7fffffd0
addr of array[0] = 0x7fffffd0
*array = a
addr of value = 0x7fffffe0
addr of value[0] = 0x0
value = 0x0

addr of value = 0x7fffffe0
addr of value[0] = 0x7fffffd0
value = 0x7fffffd0
*value = a

addr of value = 0x7fffffe0
addr of value[0] = 0x7fffffd4
value = 0x7fffffd4
*value = e
```


Writing to a File

```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>

int
main()
{
   int i, rc, fd;
   int array[40];
```

Writing to a File

```
for (i=0; i<40; i++) {
  array[i] = i;
}

fd = open("test-output", O_WRONLY | O_CREAT);

if (fd < 0) {
  exit(1);
}
```


Writing to a File

```
rc = write(fd, array, sizeof(array));

if (rc < 0) {
  exit(1);
}

close(fd);
exit(0);
}
```

Writing to a File: Example Output

```
% cat test-output
#@u
   !$%
```


Writing to a File: Running on OS/161 (viewing on SPARC)

```
# Print offsets and values in Hex (x)
% od -x test-output
0000000 0000 0000 0000 0001 0000 0002 0000 0003
0000020 0000 0004 0000 0005 0000 0006 0000 0007
0000040 0000 0008 0000 0009 0000 000a 0000 000b
0000060 0000 000c 0000 000d 0000 000e 0000 000f
0000100 0000 0010 0000 0011 0000 0012 0000 0013
0000120 0000 0014 0000 0015 0000 0016 0000 0017
0000140 0000 0018 0000 0019 0000 001a 0000 001b
0000160 0000 001c 0000 001d 0000 001e 0000 001f
0000200 0000 0020 0000 0021 0000 0022 0000 0023
0000220 0000 0024 0000 0025 0000 0026 0000 0027
0000240
```

Writing to a File: Running on OS/161 (viewing on Linux/x86)

```
# Print offsets and values in Hex (x)
% od -x test-output
0000000 0000 0000 0000 0100 0000 0200 0000 0300
0000020 0000 0400 0000 0500 0000 0600 0000 0700
0000040 0000 0800 0000 0900 0000 0a00 0000 0b00
0000060 0000 0c00 0000 0d00 0000 0e00 0000 0f00
0000100 0000 1000 0000 1100 0000 1200 0000 1300
0000120 0000 1400 0000 1500 0000 1600 0000 1700
0000140 0000 1800 0000 1900 0000 1a00 0000 1b00
0000160 0000 1c00 0000 1d00 0000 1e00 0000 1f00
0000200 0000 2000 0000 2100 0000 2200 0000 2300
0000220 0000 2400 0000 2500 0000 2600 0000 2700
0000240
```


Endianness

- Some architectures can be started to use either endianness (bi-endian).
- System/161 & OS/161 : big-endian
- Intel x86 : little-endian
- SPARC : historically big-endian Version 9 is bi-endian

```
E.g, x = 0xdeadbeef /* 3735928559 */
Little endian:
Least significant byte at lowest address
Word addressed by address of least significant byte
    0 .. 7 8.. 15 16..23 24..31
    [ ef ] [ be ] [ ad ] [ de ]

Big Endian: Most significant byte at lowest address
Word addressed by address of most significant byte
    0 .. 7 8 ..15 16..23 24..31
    [ de ] [ ad ] [ be ] [ ef ]
```

What is a Process?

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

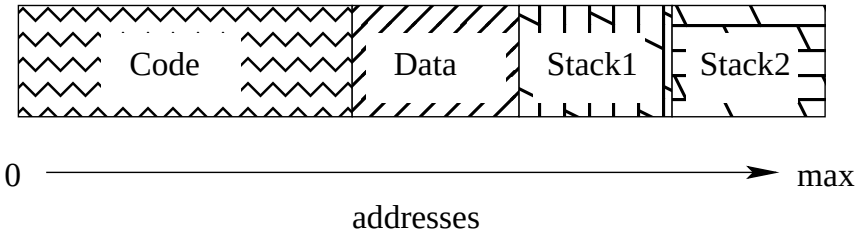
Answer 2: a process consists of

- an address space
- 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.

What is an Address Space?

- For now, think of an address space as a portion of the primary memory of the machine that is used to hold the code, data, and stack(s) of the running program.
- For example:



- We will elaborate on this later.

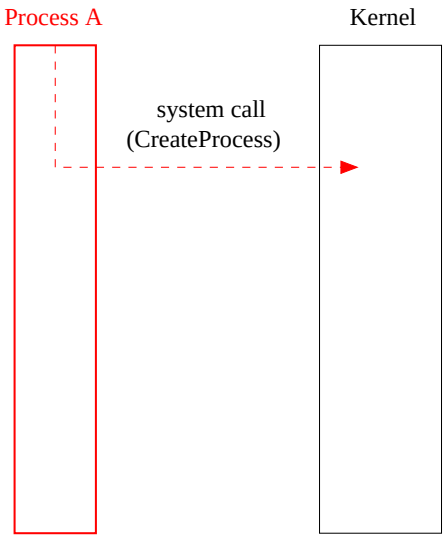
What is a Thread?

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

Implementation of Processes

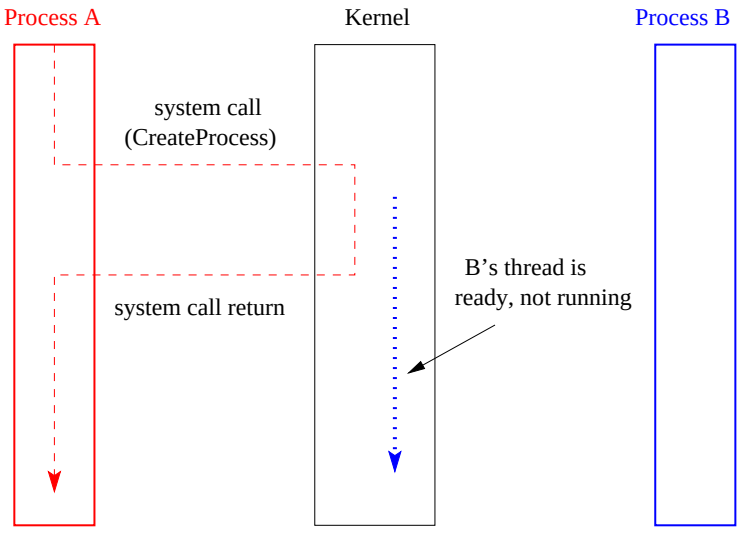
- The kernel maintains information about all of the processes in the system in a data structure often called the process table.
- Information about individual processes is stored in a structure that is sometimes called a *process control block (PCB)*. In practice, however, information about a process may not all be located in a single data structure.
- Per-process information may include:
  - process identifier and owner
  - current process state and other scheduling information
  - lists of available resources, such as open files
  - accounting information
  - and more . . ....

Process Creation Example (Part 1)



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

Process Creation Example (Part 2)

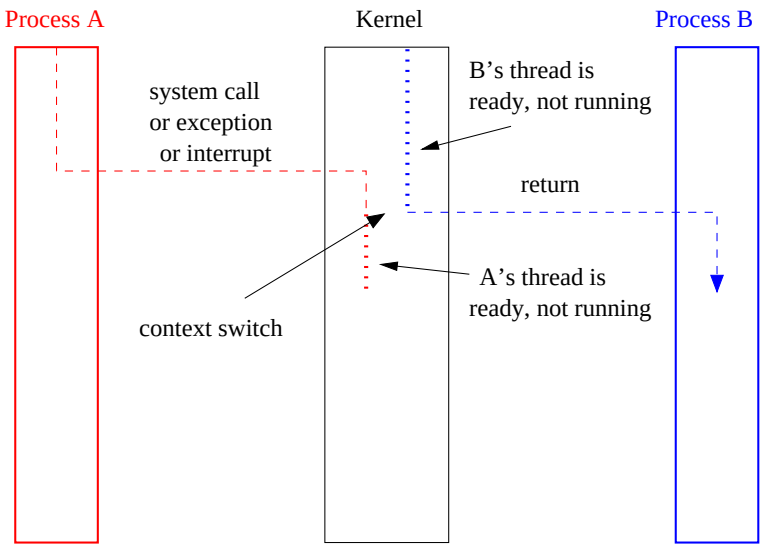


Kernel creates new process (Process B)

Multiprogramming

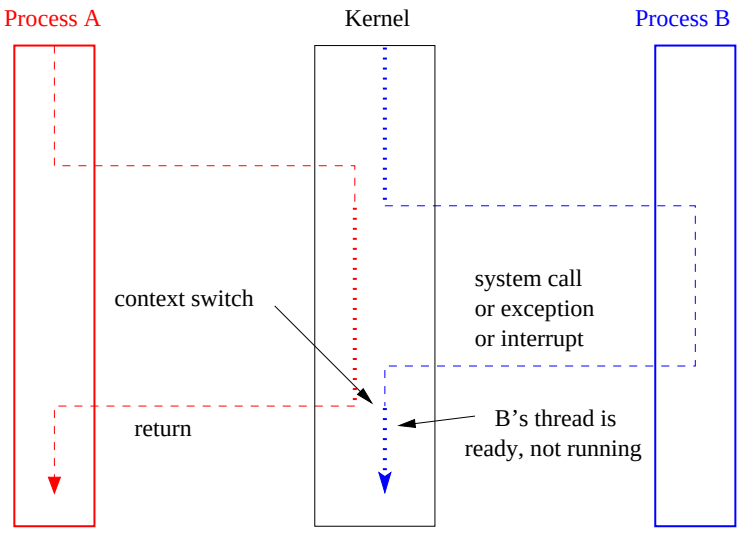
- multiprogramming means having multiple processes existing at the same time
- most modern, general purpose operating systems support multiprogramming
- all processes share the available hardware resources, with the sharing coordinated by the operating system:
  - Each process uses some of the available 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.

Timesharing Example (Part 1)



Kernel switches execution context to Process B.

Timesharing Example (Part 2)



Kernel switches execution context back to process A.

Process Interface

- A running program may use process-related system calls to manipulate its own process, or other processes in the system.
- The process interface will usually include:

  Creation: make new processes, e.g., `fork/exec/execv`

  Destruction: terminate a process, e.g., `exit`

  Synchronization: wait for some event, e.g., `wait/waitpid`

  Attribute Mgmt: read or change process attributes, such as the process identifier or owner or scheduling priority

The Process Model

- Although the general operations supported by the process interface are straightforward, there are some less obvious aspects of process behaviour that must be defined by an operating system.

  Process Initialization: When a new process is created, how is it initialized? What is in the address space? What is the initial thread context? Does it have any other resources?

  Multithreading: Are concurrent processes supported, or is each process limited to a single thread?

  Inter-Process Relationships: Are there relationships among processes, e.g, parent/child? If so, what do these relationships mean?

Processor Scheduling Basics

- Only one thread at a time can run on a processor.
- Processor scheduling means deciding how threads should share the available processor(s)
- Round-robin is a simple *preemptive* scheduling policy:
  - the kernel maintains a list of *ready* threads
  - the first thread on the list is *dispatched* (allowed to run)
  - when the running thread has run for a certain amount of time, called the scheduling quantum, it is *preempted*
  - the preempted thread goes to the back of the ready list, and the thread at the front of the list is dispatched.
- More on scheduling policies later.

Dispatching: Context Switching

```
mips_switch:
    /* a0/a1 points to old/new thread's struct pcb. */

   /* Allocate stack space for saving 11 registers. 11*4 = 44 */
   addi sp, sp, -44

   /* Save the registers */
   sw ra, 40(sp)
   sw gp, 36(sp)
   sw s8, 32(sp)
   sw s7, 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 pcb */
   sw sp, 0(a0)
```

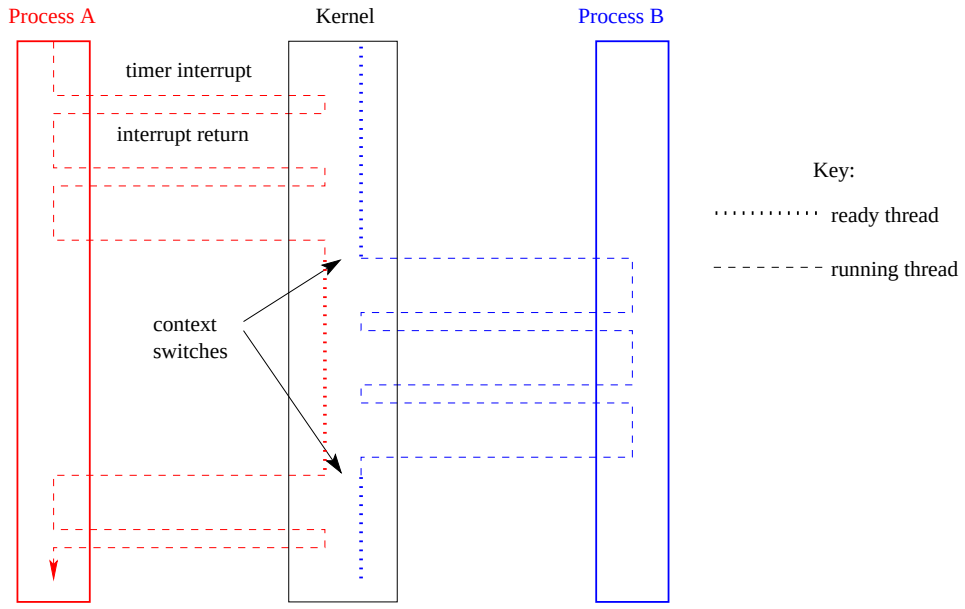

Dispatching: Context Switching

```
   /* Get the new stack pointer from the new pcb */
   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 s7, 28(sp)
   lw s8, 32(sp)
   lw gp, 36(sp)
   lw ra, 40(sp)
   nop /* delay slot for load */

   j ra             /* and return. */
   addi sp, sp, 44 /* in delay slot */
   .end mips_switch
```

Implementing Preemptive Scheduling

- 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.
- All interrupts transfer control from the running program to the kernel.
- In the case of a timer interrupt, this transfer of control gives the kernel the opportunity to preempt the running thread and dispatch a new one.

Preemptive Multiprogramming Example



Blocked Threads

- Sometimes a thread will need to wait for an event. Examples:
  - wait for data from a (relatively) slow disk
  - wait for input from a keyboard
  - wait for another thread to leave a critical section
  - wait for busy device to become idle
- The OS scheduler should only allocate the processor to threads that are not blocked, since blocked threads have nothing to do while they are blocked.

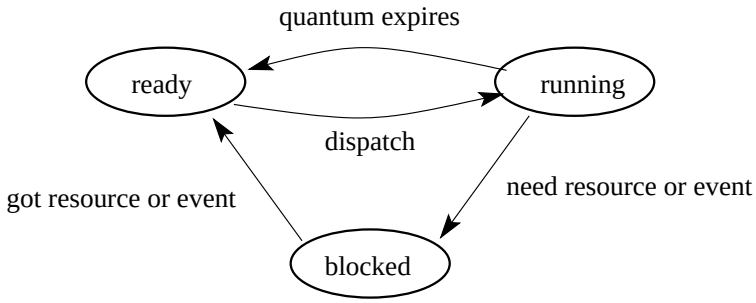
> Multiprogramming makes it easier to keep the processor busy even though individual threads are not always ready.

Implementing Blocking

- The need for waiting normally arises during the execution of a system call by the thread, since programs use devices through the kernel (by making system calls).
- When the kernel recognizes that a thread faces a delay, it can *block* that thread. This means:
  - mark the thread as blocked, don't put it on the ready queue
  - choose a ready thread to run, and dispatch it
  - when the desired event occurs, put the blocked thread back on the ready queue so that it will (eventually) be chosen to run

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.

User-Level Threads

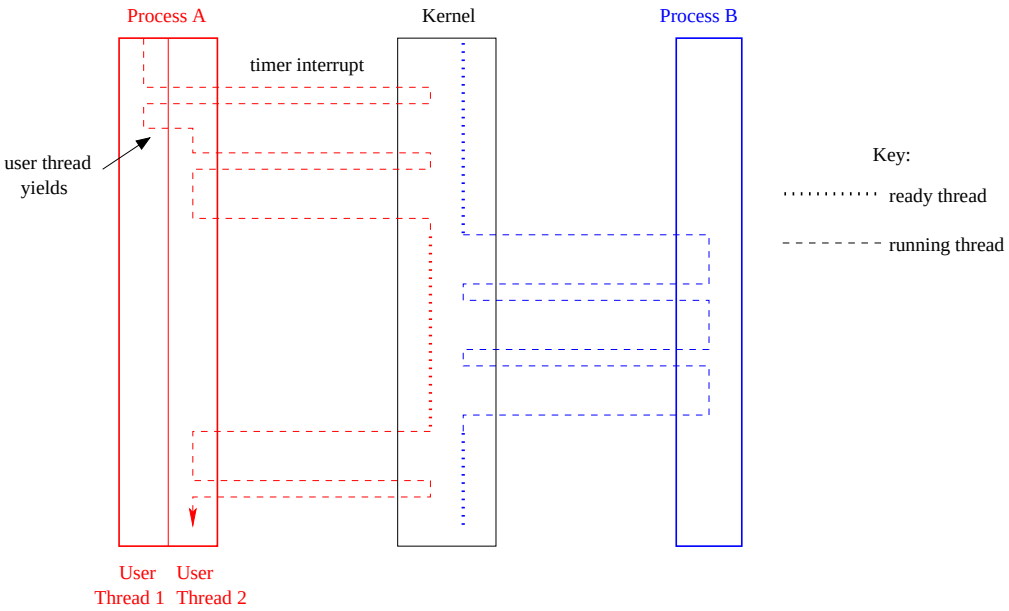
- It is possible to implement threading at the user level.
- This means threads are implemented outside of the kernel, within a process.
- Call these *user-level threads* to distinguish them from *kernel threads*, which are those implemented by the kernel.
- A user-level thread library will include procedures for
  - creating threads
  - terminating threads
  - yielding (voluntarily giving up the processor)
  - synchronization

  In other words, similar operations to those provided by the operating system for kernel threads.

User-Level and Kernel Threads

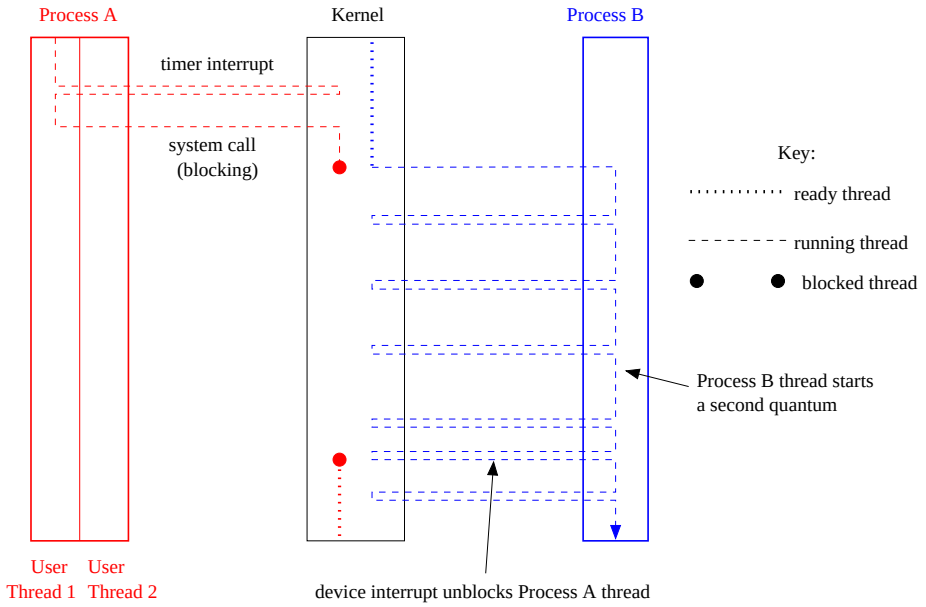
- There are two general ways to implement user-level threads
  1. Multiple user-level thread contexts in a process with one kernel thread. (N:1)
     - Kernel thread can "use" only one user-level thread context at a time.
     - Switching between user threads in the same process is typically non-preemptive.
     - Blocking system calls block the kernel thread, and hence all user threads in that process.
     - Can only use one CPU.
  2. Multiple user-level thread contexts in a process with multiple kernel threads. (N:M)
     - Each kernel thread "uses" one user-level thread context.
     - Switching between threads in the same process can be preemptive.
     - Process can make progress if at least one of its kernel threads is not blocked.
     - Can use multiple CPUs.

Two User Threads, One Kernel Thread (Part 1)



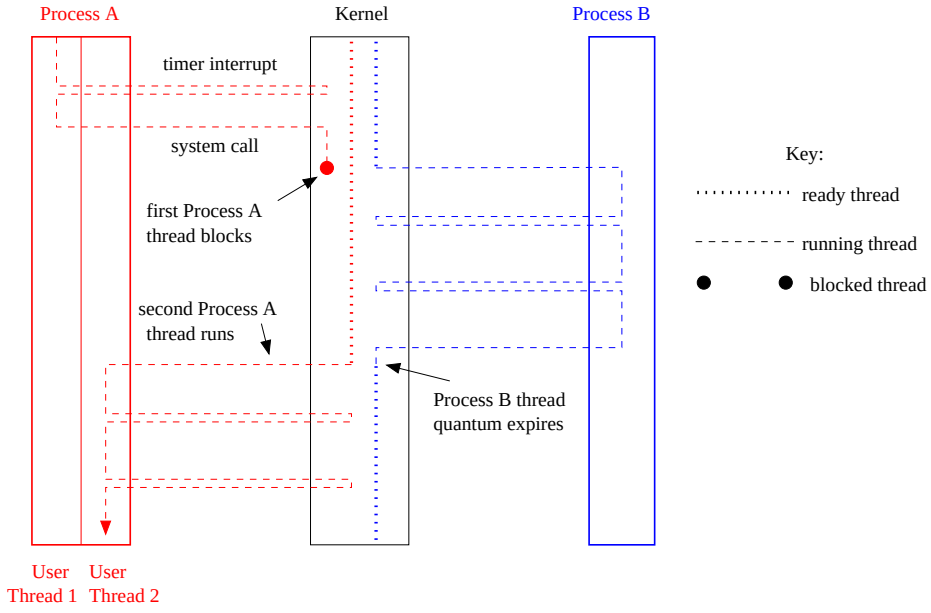
Process A has two user-level threads, but only one kernel thread.

Two User Threads, One Kernel Thread (Part 2)



Once Process A's thread blocks, only Process B's thread can run.

Two User Threads, Two Kernel Threads



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 (though the operating system) to system devices.
  - Threads in the same process share access to program variables in their process's address space.
- 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 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?)

Critical Section Example (Part 2)

```
void list_append(list *lp, int new_item) {
   list_element *element = malloc (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`

Peterson's Mutual Exclusion Algorithm

```
boolean flag[2];  /* shared, initially false */
int turn;         /* shared */

flag[i] = true;   /* in one process, i = 0 and j = 1 */
turn = j;         /* in the other, i = 1 and j = 0 */
while (flag[j] && turn == j) { }  /* busy wait */

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

flag[i] = false;
```

Ensures mutual exclusion and avoids starvation, but works only for two processes. (Why?)

Mutual Exclusion Using Special Instructions

- Software solutions to the critical section problem (e.g., Peterson's algorithm) assume only atomic load and atomic store.
- Simpler algorithms are possible if more complex *atomic* operations are supported by the hardware. For example:

  Test and Set: set the value of a variable, and return the old value

  Swap: swap the values of two variables
- On uniprocessors, mutual exclusion can also be achieved by disabling interrupts during the critical section. (Normally, user programs cannot do this, but the kernel can.)

Mutual Exclusion with Test and Set

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

while (TestAndSet(&lock,true)) { }  /* busy wait */

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

lock = false;
```

Works for any number of threads, but starvation is a possibility.

Semaphores

- A semaphore is a synchronization primitive that can be used to solve the critical section problem, and many other synchronization problems too
- 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*.

Mutual Exclusion Using a Binary Semaphore

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

P(s);

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

V(s);
```


Producer/Consumer Using a Counting Semaphore

```
struct semaphore *s;
s = sem_create("MySem2", 0); /* initial value is 0 */
item buffer[infinite];  /* huge buffer, initially empty */

Producer's Pseudo-code:
  add item to buffer
  V(s);

Consumer's Pseudo-code:
  P(s);
  remove item from buffer
```

If mutual exclusion is required for adding and removing items from the buffer, this can be provided using a second semaphore. (How?)

Producer/Consumer with a Bounded Buffer

```
struct semaphore *full;
struct semaphore *empty;
full = sem_create("FullSem", 0);   /* init value = 0 */
empty = sem_create("EmptySem", N); /* init value = N */
item buffer[N];                    /* buffer of capacity N */

Producer's Pseudo-code:
  P(empty);
      add item to buffer
  V(full);

Consumer's Pseudo-code:
  P(full);
      remove item from buffer
  V(empty);
```


Implementing Semaphores

```
void P(s) {
   start critical section
   while (s == 0) {   /* busy wait */
       end critical section
       start critical section
   }
   s = s - 1;
   end critical section
}

void V(s) {
   start critical section
   s = s + 1;
   end critical section
}
```

Any mutual exclusion technique can be used to protect the critical sections. However, starvation is possible with this implementation.

Implementing Semaphores in the Kernel

- Semaphores can be implemented at user level, e.g., as part of a user-level thread library.
- Semaphores can also be implemented by the kernel:
  - for its own use, for synchronizing threads in the kernel
  - for use by application programs, if a semaphore system call interface is provided
- As an optimization, semaphores can be integrated with the thread scheduler (easy to do for semaphores implemented in the kernel):
  - threads can be made to block, rather than busy wait, in the P operation
  - the V operation can make blocked threads ready

OS/161 Semaphores: kern/include/synch.h

```
struct semaphore {
  char *name;
  volatile int count;
};

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

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

```
void
P(struct semaphore *sem)
{
  int spl;
  assert(sem != NULL);

  /*
   * May not block in an interrupt handler.
   * For robustness, always check, even if we can actually
   * complete the P without blocking.
   */
  assert(in_interrupt==0);

  spl = splhigh();
  while (sem->count==0) {
    thread_sleep(sem);
  }
  assert(sem->count>0);
  sem->count--;
  splx(spl);
}
```


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

```
void
V(struct semaphore *sem)
{
  int spl;
  assert(sem != NULL);
  spl = splhigh();
  sem->count++;
  assert(sem->count>0);
  thread_wakeup(sem);
  splx(spl);
}
```

Locks

```
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 initial value of 1 (except locks ensure that only the acquiring thread can release the lock)

Reader/Writer Locks

- Reader/Writer (or a shared) locks can be acquired in either of read (shared) or write (exclusive) mode
- In OS/161 reader/writer locks might look like this:

```
struct rwlock *rwlock = rw_lock_create("RWLock");

rwlock_aquire(rwlock, READ_MODE);
    can only read shared resources
   /* access is shared by readers */
rwlock_release(rwlock);

rwlock_aquire(rwlock, WRITE_MODE);
    can read and write shared resources
   /* access is exclusive to only one writer */
rwlock_release(rwlock);
```

Monitors

- a monitor is a programming language construct that supports synchronized access to data
- a monitor is essentially an object for which
  - object state is accessible only through the object's methods
  - only one method may be active at a time
- if two threads attempt to execute methods at the same time, one will be blocked until the other finishes
- inside a monitor, so called *condition variables* can be declared and used

Condition Variable

- a condition variable is an object that support two operations:

  wait: causes the calling thread to block, and to release the monitor

  signal: if threads are blocked on the signaled condition variable then unblock one of them, otherwise do nothing

- a thread that has been unblocked by *signal* is outside of the monitor and it must wait to re-enter the monitor before proceeding.
- in particular, it must wait for the thread that signalled it

> This describes Mesa-type monitors. There are other types on monitors, notably Hoare monitors, with different semantics for `wait` and `signal`.

- some implementations (e.g., OS/161) support a **broadcast** operation. If threads are blocked on the signaled condition variable then unblock all of them, otherwise do nothing.

Bounded Buffer Using a Monitor

```
item buffer[N]; /* buffer with capacity N */
int count; /* initially 0 */
cv *notfull, *notempty;  /* Condition variables */

Produce(item) {
  while (count == N) {
     wait(notfull);
  }
  add item to buffer
  count = count + 1;
  signal(notempty);
}
```

`Produce` is implicitly executed atomically, because it is a monitor method.

Bounded Buffer Using a Monitor (cont'd)

```
Consume(item) {
  while (count == 0) {
     wait(notempty);
  }
  remove item from buffer
  count = count - 1;
  signal(notfull);
}
```

`Consume` is implicitly executed atomically, because it is a monitor method. Notice that `while`, rather than `if`, is used in both `Produce` and `Consume`. This is important. (Why?)

Simulating Monitors with Semaphores and Condition Variables

- Use a single binary semaphore (or OS/161 “lock”) to provide mutual exclusion.
- Each method must start by acquiring the mutex semaphore, and must release it on all return paths.
- Signal only while holding the mutex semaphore.
- Re-check the wait condition after each wait.
- Return only (the values of) variables that are local to the method.

Producer Implemented with Locks and Condition Variables (Example)

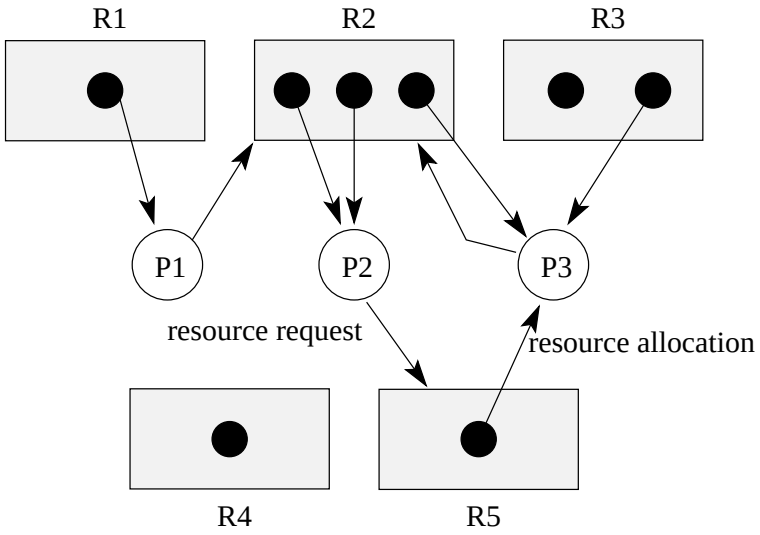
```
item buffer[N]; /* buffer with capacity N */
int count = 0; /* must initially be 0 */
lock mutex;     /* for mutual exclusion */
cv *notfull,*notempty;

notfull = cv_create("NotFull");
notempty = cv_create("NotEmpty");

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

Deadlocks

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

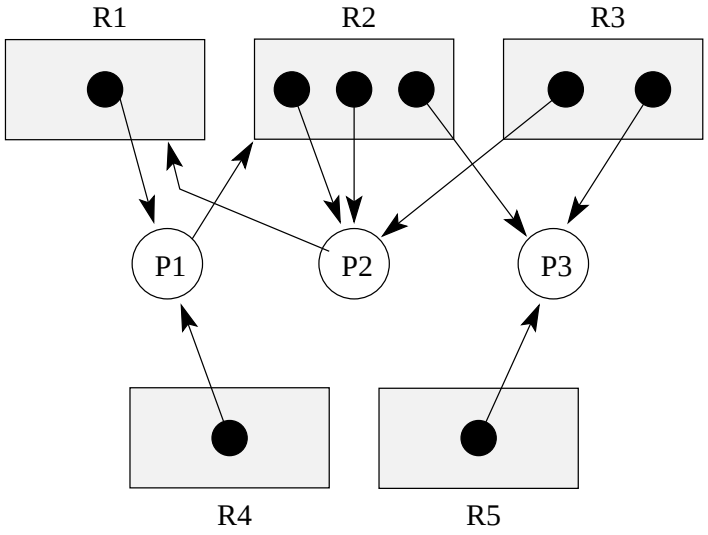
These two processes are *deadlocked* - neither process can make progress. Waiting will not resolve the deadlock. The processes are permanently stuck.

Resource Allocation Graph (Example)



Is there a deadlock in this system?

Resource Allocation Graph (Another Example)



Is there a deadlock in this system?

Deadlock Prevention

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

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

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

Detecting Deadlock in a Resource Allocation Graph

- System State Notation:
  - R_i: request vector for process P_i
  - A_i: current allocation vector for process P_i
  - U: unallocated (available) resource vector
- Additional Algorithm Notation:
  - T: scratch resource vector
  - f_i: algorithm is finished with process P_i? (boolean)

Detecting Deadlock (cont'd)

```
/* initialization */
T = U
f_i is false if A_i > 0, else true
/* can each process finish? */
while ∃ i ( ¬ f_i ∧ (R_i ≤ T) ) {
      T = T + A_i;
      f_i = true
}
/* if not, there is a deadlock */
if ∃ i ( ¬ f_i ) then report deadlock
else report no deadlock
```


Deadlock Detection, Positive Example

- $R_1 = (0, 1, 0, 0, 0)$
- $R_2 = (0, 0, 0, 0, 1)$
- $R_3 = (0, 1, 0, 0, 0)$
- $A_1 = (1, 0, 0, 0, 0)$
- $A_2 = (0, 2, 0, 0, 0)$
- $A_3 = (0, 1, 1, 0, 1)$
- $U = (0, 0, 1, 1, 0)$

The deadlock detection algorithm will terminate with $f_1 == f_2 == f_3 ==$ `false`, so this system is deadlocked.

Deadlock Detection, Negative Example

- $R_1 = (0, 1, 0, 0, 0)$
- $R_2 = (1, 0, 0, 0, 0)$
- $R_3 = (0, 0, 0, 0, 0)$
- $A_1 = (1, 0, 0, 1, 0)$
- $A_2 = (0, 2, 1, 0, 0)$
- $A_3 = (0, 1, 1, 0, 1)$
- $U = (0, 0, 0, 0, 0)$

This system is not in deadlock. It is possible that the processes will run to completion in the order P_3, P_1, P_2.

The Operating System and the Kernel

- We will use the following terminology:

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

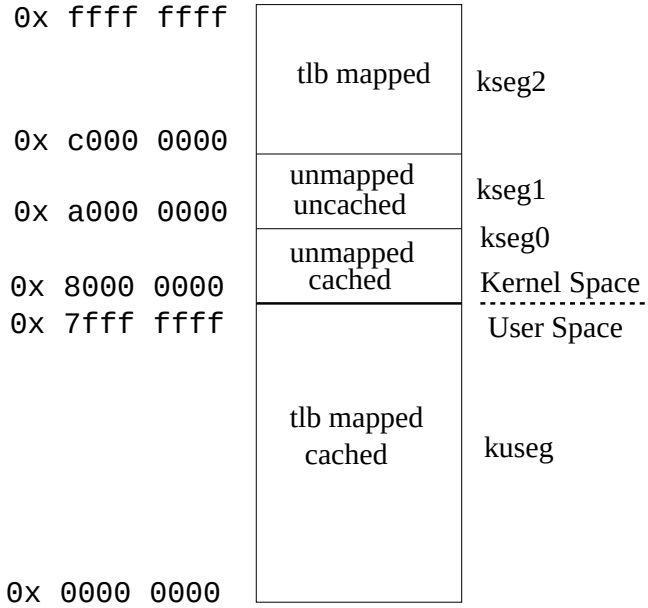
  operating system: The operating system as a whole includes the kernel, and may include other related programs that provide services for applications. This may include things like:
  - utility programs
  - command interpreters
  - programming libraries

The OS Kernel

- Usually kernel code runs in a privileged execution mode, while the rest of the operating system does not.
- The kernel is a program. It has code and data like any other program.
- For now, think of the kernel as a program that resides in its own address space, separate from the address spaces of processes that are running on the system. Later, we will elaborate on the relationship between the kernel's address space and process address spaces.

MIPS Address Spaces and Protection

- On 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



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 virtual 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 the interface between processes and the kernel.
- A process uses system calls to request operating system services.
- From point of view of the process, these services are used to manipulate the abstractions that are part of its execution environment. For example, a process might use a system call to
  - open a file
  - send a message over a pipe
  - create another process
  - increase the size of its address space

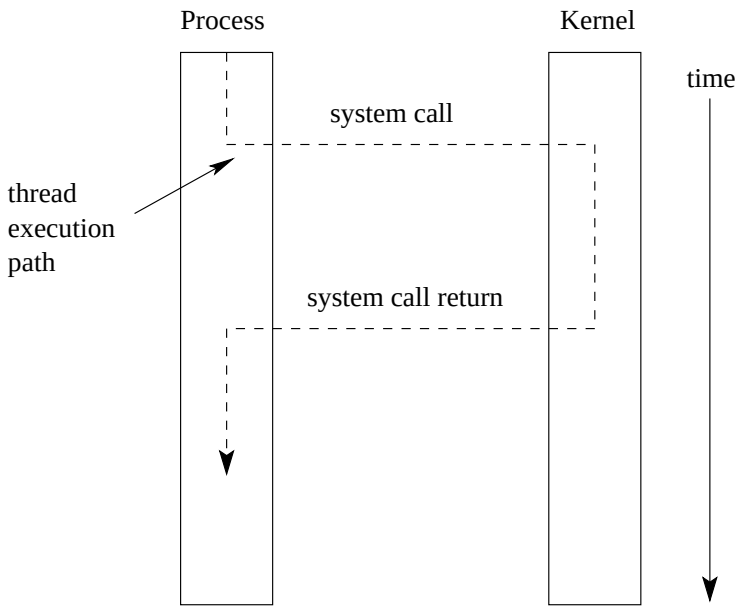
How System Calls Work

- 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, like the program counter and the stack pointer, are saved
  - the thread context is changed so that:
    - the program counter is set to a fixed (determined by the hardware) memory address, which is within the kernel's address space
    - the stack pointer is pointed at a stack in 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 system 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.

System Call Diagram



How a System Call Works

- Review: MIPS Register Usage

```
See also: kern/arch/mips/include/asmdefs.h
R0 =
R1 =
R2 =
R3 =
R4 =
R5 =
R6 =
R7 =
```


How a System Call Works

- Review: MIPS Register Usage

```
R08-R15 =
R24-R25 =

R16-R23 =

R26-27  =
R28     =

R29     =
R30     =
R31     =
```

How a System Call Works: User Code

```
004000b0 <__start>:
  4000b0: 3c1c1000  lui gp,0x1000
  4000b4: 279c7ff0  addiu gp,gp,32752
  4000b8: 3c08ffff  lui t0,0xffff
  4000bc: 3508fff8  ori t0,t0,0xfff8
  4000c0: 03a8e824  and sp,sp,t0
  4000c4: 27bdfff0  addiu sp,sp,-16
  4000c8: 3c011000  lui at,0x1000
  4000cc: ac250004  sw  a1,4(at)
```


How a System Call Works: User Code

```
  4000d0: 0c100040  jal 400100 <main>   # Call main
  4000d4: 00000000  nop
  4000d8: 00408021  move  s0,v0
  4000dc: 0c100050  jal 400140 <exit>
  4000e0: 02002021  move  a0,s0
  4000e4: 0c100069  jal 4001a4 <_exit>
  4000e8: 02002021  move  a0,s0
  4000ec: 02002021  move  a0,s0
  4000f0: 24020000  li  v0,0
  4000f4: 0000000c  syscall
  4000f8: 0810003b  j 4000ec <__start+0x3c>
  4000fc: 00000000  nop
```

How a System Call Works: User Code

```
/* See how a function/system call happens. */
#include <unistd.h>
#include <errno.h>

int
main()
{
  int x;
  int y;
  x = close(999);
  y = errno;

  return x;
}
```


How a System Call Works: User Code

```
% cs350-objdump -d syscall > syscall.out
% cat syscall.out

00400100 <main>:
  400100:     27bdffe0     addiu   sp,sp,-32
  400104:     afbf001c     sw      ra,28(sp)
  400108:     afbe0018     sw      s8,24(sp)
  40010c:     03a0f021     move    s8,sp
  400110:     0c10007b     jal     4001ec <close>
  400114:     240403e7     li      a0,999
  400118:     afc20010     sw      v0,16(s8)
  40011c:     3c021000     lui     v0,0x1000
  400120:     8c420000     lw      v0,0(v0)
  400124:     00000000     nop
```

How a System Call Works: User Code

```
<main> continued

  400128:     afc20014     sw      v0,20(s8)
  40012c:     8fc20010     lw      v0,16(s8)
  400130:     03c0e821     move    sp,s8
  400134:     8fbf001c     lw      ra,28(sp)
  400138:     8fbe0018     lw      s8,24(sp)
  40013c:     03e00008     jr      ra
  400140:     27bd0020     addiu   sp,sp,32
```


How a System Call Works: User Code

```
## See lib/libc/syscalls.S for details/comments */
## At bit easier to understand from disassembled code.

% cs350-objdump -d syscall > syscall.S
% cat syscall.S
...
0040022c <close>:
  40022c: 08100074  j 4001d0 <__syscall>
  400230: 24020007  li  v0,7

00400234 <reboot>:
  400234: 08100074  j 4001d0 <__syscall>
  400238: 24020008  li  v0,8
...
```

How a System Call Works: User Code

From lib/libc/syscalls.S

```
   .set noreorder
   .text
   .type __syscall,@function
   .ent __syscall

__syscall:
   syscall         /* make system call */
   beq a3, $0, 1f  /* if a3 is zero, call succeeded */
   nop             /* delay slot */
   sw v0, errno    /* call failed: store errno */
   li v1, -1       /* and force return value to -1 */
   li v0, -1
1:
   j ra            /* return */
   nop             /* delay slot */
   .end __syscall
   .set reorder
```


How a System Call Works: User Code

From lib/libc/syscalls.S

```
SYSCALL(close, 7)
SYSCALL(reboot, 8)
SYSCALL(sync, 9)
SYSCALL(sbrk, 10)
SYSCALL(getpid, 11)
```

How a System Call Works: Kernel Code

```
syscall instruction generates an exception.
Processor begins execution at virtual address 0x8000 0080
From: kern/arch/mips/mips/exception.S
## Q: where does this address live?

exception:
  move k1, sp       /* Save previous stack pointer in k1 */
  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 stac
  nop                  /* delay slot */

  /* Coming from user mode - load kernel stack into sp */
  la k0, curkstack     /* get address of "curkstack" */
  lw sp, 0(k0)         /* get its value */
  nop                  /* delay slot for the load */

1:
  mfc0 k0, c0_cause    /* Now, load the exception cause. */
  j common_exception   /* Skip to common code */
  nop                  /* delay slot */
```


How a System Call Works: Kernel Code

```
From: kern/arch/mips/mips/exception.S
common_exception:
 o saves the contents of the registers
 o calls mips_trap (C code in kern/arch/mips/mips/trap.c)
 o restores the contents of the saved registers
 o rfe (return from exception)

From: kern/arch/mips/mips/trap.c
mips_trap:
  o figures out the exception type/cause
  o calls the appropriate handing function
    (for system call this is mips_syscall).
```

How a System Call Works: Kernel Code

From: kern/arch/mips/mips/syscall.c

```
mips_syscall(struct trapframe *tf)
{
  assert(curspl==0);
  callno = tf->tf_v0; retval = 0;

  switch (callno) {
    case SYS_reboot:
      /* is in kern/main/main.c */
      err = sys_reboot(tf->tf_a0);
      break;

    /* Add stuff here */

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


How a System Call Works: Kernel Code

```
  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 *
  assert(curspl==0);
}
```

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 error, e.g, overflow
  - illegal instruction
  - memory protection violation
  - page fault (to be discussed later)
- exceptions are detected by the hardware

Exceptions (cont'd)

- when an exception occurs, control is transferred (by the hardware) to a fixed address in the kernel (0x8000 0080 on MIPS & OS/161)
- transfer of control happens in much the same way as it does for a system call. In fact, a system call can be thought of as a type of exception, and they are sometimes implemented that way (e.g., on the MIPS).
- in the kernel, an exception handler determines which exception has occurred and what to do about it. For example, it may choose to destroy a process that attempts to execute an illegal instruction.

Interrupts

- 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.

Summary of Hardware Features Used by the Kernel

Interrupts and Exceptions, such as timer interrupts, give the kernel the opportunity to regain control from user programs.

Memory management features, such as memory protection, allow the kernel to protect its address space from user programs.

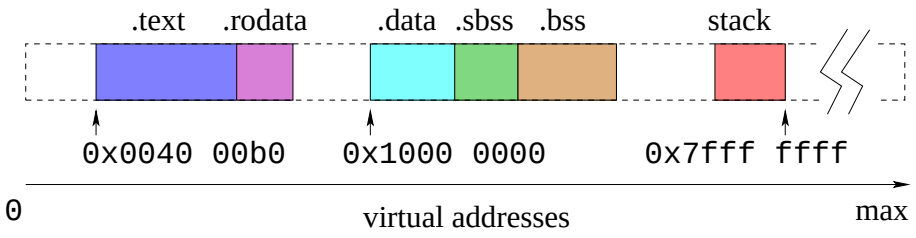
Privileged execution mode allows the kernel to reserve critical machine functions (e.g, halt) for its own use.

Independent I/O devices allow the kernel to schedule other work while I/O operations are on-going.

Virtual and Physical Addresses

- Physical addresses are provided directly by the machine.
  - one physical address space per machine
  - addresses typically range from some minumum (sometimes 0) to some maximum, though some portions of this range are usually used by the OS and/or devices, and are not available for user processes
- Virtual addresses (or logical addresses) are addresses provided by the OS to processes.
  - one virtual address space per process
  - addresses typically start at zero, but not necessarily
  - space may consist of several *segments*
- Address translation (or address binding) means mapping virtual addresses to physical addresses.

Address Space Layout



- Size of each section except stack is specified in ELF file
- Code (i.e., text), read-only data and initialized data segments are initialized from the ELF file. Remaining sections are initially zero-filled.
- Sections have their own specified alignment and segments are page aligned.
- 3 segments = (.text + .rodata), (.data + .sbss + .bss), (stack)
- Note: not all programs contain this many segments and sections.

C Code for Sections and Segments Example

```
#include <unistd.h>

#define N   (200)

int x = 0xdeadbeef;
int y1;
int y2;
int y3;
int array[4096];
char const *str = "Hello World\n";
const int z = 0xabcddcba;

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


C Code for Sections and Segments Example (cont'd)

```
int
main()
{
  int count = 0;
  const int value = 1;
  y1 = N;
  y2 = 2;
  count = x + y1;
  y2 = z + y2 + value;

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

cs350-readelf Output: Sections and Segments

```
% cs350-readelf -a segments > readelf.out
% cat readelf.out

Section Headers:
[Nr] Name       Type         Addr     Off    Size   ES Flg  ... Al
[ 0]            NULL         00000000 000000 000000 00      ...  0
[ 1] .reginfo   MIPS_REGINFO 00400094 000094 000018 18   A  ...  4
[ 2] .text      PROGBITS     004000b0 0000b0 000250 00  AX  ... 16
[ 3] .rodata    PROGBITS     00400300 000300 000020 00   A  ... 16
[ 4] .data      PROGBITS     10000000 001000 000010 00  WA  ... 16
[ 5] .sbss      NOBITS       10000010 001010 000014 00 WAp  ...  4
[ 6] .bss       NOBITS       10000030 00101c 004000 00  WA  ... 16
[ 7] .comment   PROGBITS     00000000 00101c 000036 00      ...  1
...
Key to Flags:
  W (write), A (alloc), X (execute), M (merge), S (strings)
  I (info), L (link order), G (group), x (unknown)
  O (extra OS processing required) o (OS specific), p (processor s

## Size = number of bytes (e.g., .text is 0x250 = 592 bytes
## Off  = offset into the ELF file
## Addr = virtual address
```


cs350-readelf Output: Sections and Segments

```
Program Headers:
Type     Offset   VirtAddr   PhysAddr   FileSiz MemSiz  Flg Align
REGINFO  0x000094 0x00400094 0x00400094 0x00018 0x00018 R   0x4
LOAD     0x000000 0x00400000 0x00400000 0x00320 0x00320 R E 0x1000
LOAD     0x001000 0x10000000 0x10000000 0x00010 0x04030 RW  0x1000

 Section to Segment mapping:
  Segment Sections...
   00     .reginfo
   01     .reginfo .text .rodata
   02     .data .sbss .bss

## .reginfo = register info (not used)
## .text    = code/machine instructions
## .rodata  = read-only data (e.g., string literals, consts)
## .data    = data (i.e., global variables)
## .bss     = Block Started by Symbol
##            has a symbol but no value (i.e, uninitialized data)
## .sbss    = ?small bss?
```

cs350-objdump -s output: Sections and Segments

```
% cs350-objdump -s segments > objdump.out
% cat objdump.out
...

Contents of section .text:
 4000b0 3c1c1001 279c8000 3c08ffff 3508fff8  <...'...<...5...
...

## Decoding 3c1c1001 to determine instruction
## 0x3c1c1001 = binary 11110000011100000100000000001
## 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 unsigned immediate into rt (register target)
## lui gp, 0x1001
```


cs350-objdump -s output: Sections and Segments

```
Contents of section .rodata:
 400300 48656c6c 6f20576f 726c640a 00000000  Hello World.....
 400310 abcddcba 00000000 00000000 00000000  ................
...
## 0x48 = 'H' 0x65 = 'e' 0x0a = '\n' 0x00 = '\0'
## Align next int to 4 byte boundary
## const int z = 0xabcddcba
## If compiler doesn't prevent z from being written/hardware could
## Size = 0x20 = 32 bytes "Hello World\n\0" = 13 + 3 padding = 16
##               +  const int z = 4 = 20
## Then align to the next 16 byte boundry at 32 bytes.
```

cs350-objdump -s output: Sections and Segments

```
Contents of section .data:
 10000000 deadbeef 00400300 00000000 00000000  .....@.........
...
## Size = 0x10 bytes = 16 bytes
## int x = deadbeef (4 bytes)
## char const *str = "Hello World\n"; (4 bytes)
## value stored in str = 0x00400300.
## NOTE: this is the address of the start
## of the .rodata section (i.e., address of 'H').
```

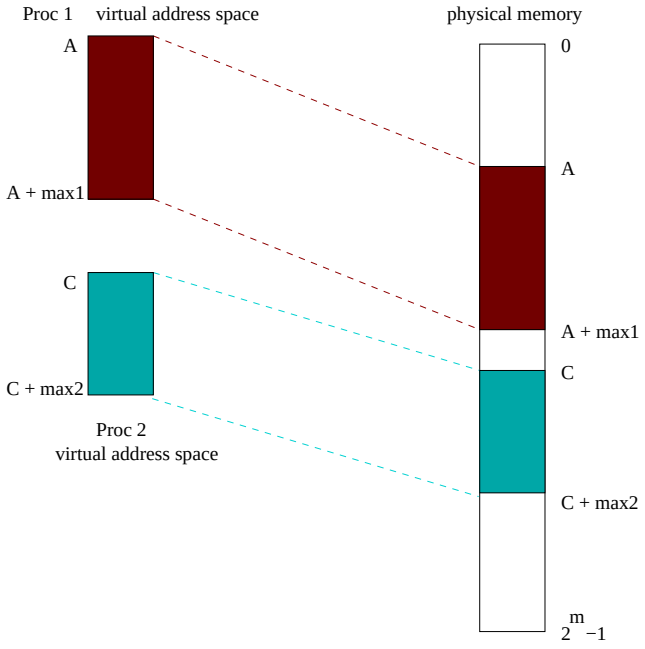

cs350-objdump -s output: Sections and Segments

```
% cs350-nm -n segments > nm.out
% cat nm.out
...
10000010 A __bss_start
10000010 A _edata
10000010 A _fbss
10000010 S y3
10000014 S y2
10000018 S y1
1000001c S errno
10000020 S __argv
...
## .bss  Size = 0x4000 = 16384 = 4096 * sizeof(int)
10000030 B array
10004030 A _end
```

Example 1: A Simple Address Translation Mechanism

- OS divides physical memory into partitions of different sizes.
- Each partition is made available by the OS as a possible virtual address space for processes.
- Properties:
  - virtual addresses are identical to physical addresses
  - address binding is performed by compiler, linker, or loader, not the OS
  - changing partitions means changing the virtual addresses in the application program
    - by recompiling
    - or by *relocating* if the compiler produces relocatable output
  - degree of multiprogramming is limited by the number of partitions
  - size of programs is limited by the size of the partitions

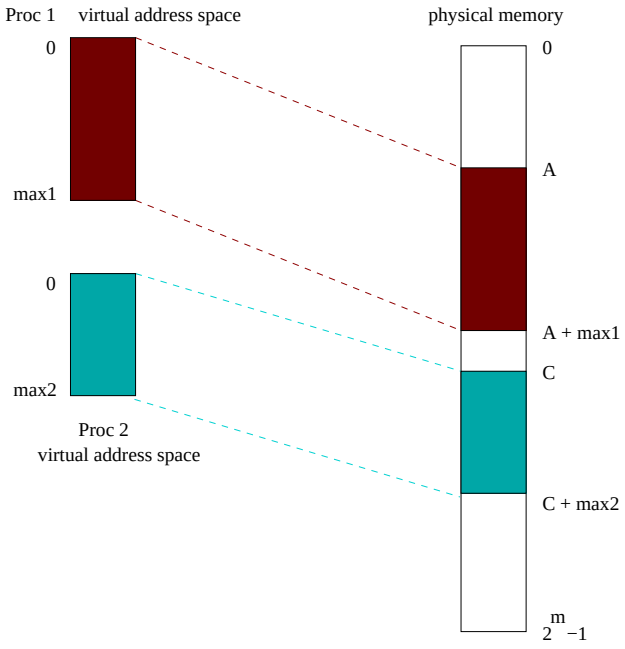
Example 1: Address Space Diagram



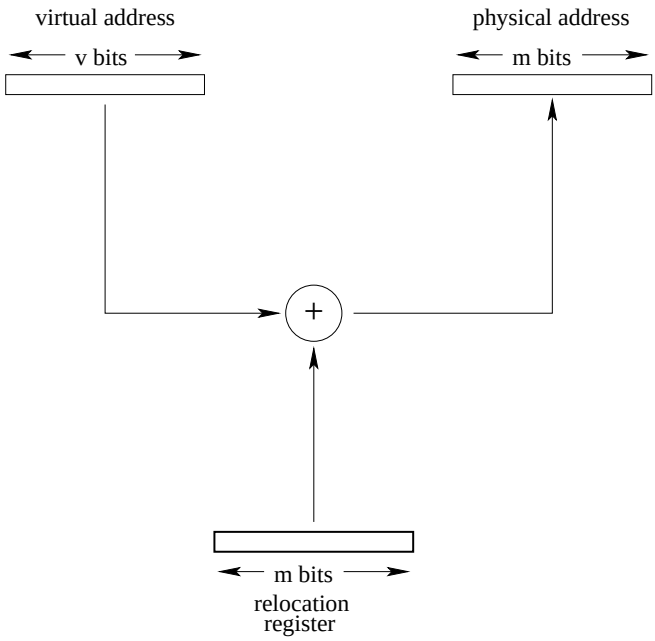
Example 2: Dynamic Relocation

- hardware provides a *memory management unit* which includes a *relocation register*
- *dynamic binding:* at run-time, the contents of the relocation register are added to each virtual address to determine the corresponding physical address
- OS maintains a separate relocation register value for each process, and ensures that relocation register is reset on each context switch
- Properties
  - all programs can have address spaces that start with address 0
  - OS can relocate a process without changing the process's program
  - OS can allocate physical memory dynamically (physical partitions can change over time), again without changing user programs
  - each virtual address space still corresponds to a contiguous range of physical addresses

Example 2: Address Space Diagram



Example 2: Relocation Mechanism



Address Spaces

- OS/161 starts with a dumb/simple address space (`addrspace`)
- `addrspace` maintains the mappings from virtual to physical addresses

```
struct addrspace {
#if OPT_DUMBVM
  vaddr_t as_vbase1;
  paddr_t as_pbase1;
  size_t as_npages1;
  vaddr_t as_vbase2;
  paddr_t as_pbase2;
  size_t as_npages2;
  paddr_t as_stackpbase;
#else
  /* Put stuff here for your VM system */
#endif
};
```

Address Spaces

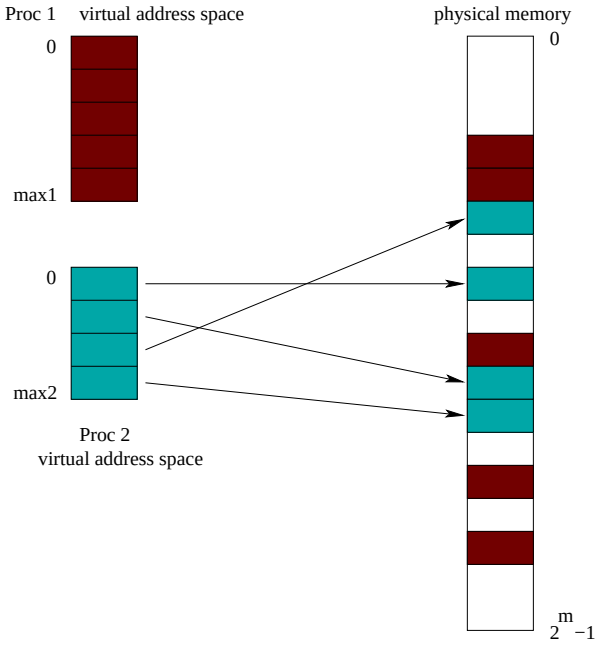
- Think of an address space as ALL of the virtual addresses that can be legally accessed by a thread.
  - .text, .rodata, .data, .sbss, .bss, and stack (if all sections are present).
- kern/arch/mips/mips/dumbvm.c contains functions for creating and managing address spaces
  - `as_create, as_destroy, as_copy, vm_fault`
- kern/lib/copyinout.c contains functions for copying data between kernel and user address spaces
  - `copyin, copyout, copyinstr, copyoutstr`

Why do we need `copyin`, `copyout`, etc.?

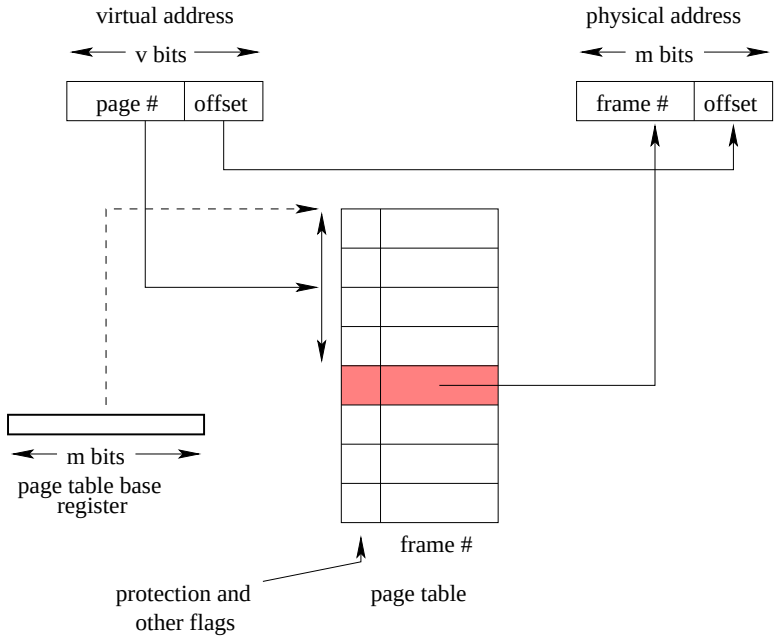
Example 3: Paging

- 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.
- Properties
  - simple physical memory management
  - virtual address space need not be physically contiguous in physical space after translation.

Example 3: Address Space Diagram



Example 3: Page Table Mechanism



Summary of Binding and Memory Management Properties

address binding time:

- compile time: relocating program requires recompilation
- load time: compiler produces relocatable code
- dynamic (run time): hardware MMU performs translation

physical memory allocation:

- fixed or dynamic partitions
- fixed size partitions (frames) or variable size partitions

physical contiguity:

- virtual space is contiguous or uncontiguous in physical space

Physical Memory Allocation

fixed allocation size:

- space tracking and placement are simple
- *internal* fragmentation

variable allocation size:

- space tracking and placement more complex
  - placement heuristics: first fit, best fit, worst fit
- *external* fragmentation

Memory Protection

- ensure that each process accesses only the physical memory that its virtual address space is bound to.
  - threat: virtual address is too large
  - solution: MMU *limit register* checks each virtual address
    - for simple dynamic relocation, limit register contains the maximum virtual address of the running process
    - for paging, limit register contains the maximum page number of the running process
  - MMU generates exception if the limit is exceeded
- restrict the use of some portions of an address space
  - example: read-only memory
  - approach (paging):
    - include read-only flag in each page table entry
    - MMU raises exception on attempt to write to a read-only page

Roles of the Operating System and the MMU (Summary)

- operating system:
  - save/restore MMU state on context switches
  - handle exceptions raised by the MMU
  - manage and allocate physical memory
- MMU (hardware):
  - translate virtual addresses to physical addresses
  - check for protection violations
  - 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, plus copies of some or all of the page's protection bits, use bit, and dirty bit.
- If address translation can be accomplished using a TLB entry, access to the page table is avoided.
- 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 (10^2 to 10^3 entries).
- Otherwise, translate through the page table, and add the resulting translation to the TLB, replacing an existing entry if necessary. In a *hardware controlled* TLB, this is done by the MMU. In a *software controlled* TLB, it is done by the kernel.
- On a context switch, the kernel must clear or invalidate the TLB. (Why?)

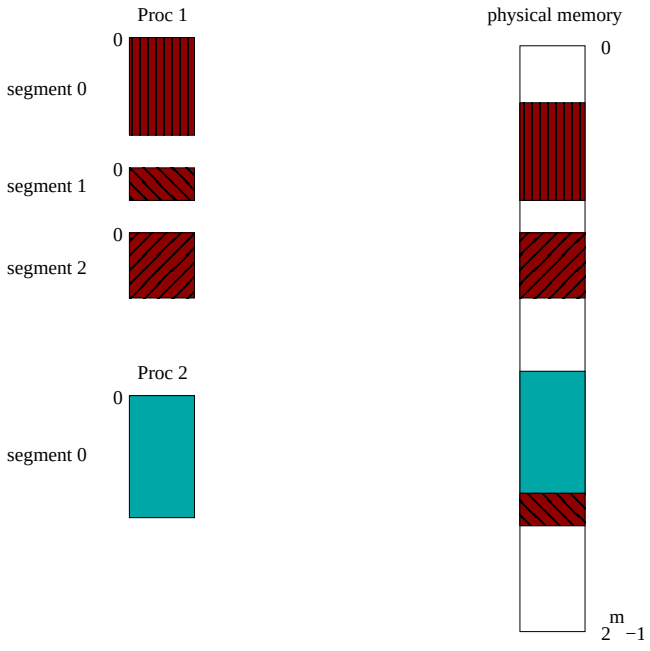
Segmentation

- An OS that supports segmentation (e.g., Multics, OS/2) can provide more than one address space to each process.
- The individual address spaces are called *segments*.
- A logical address consists of two parts:

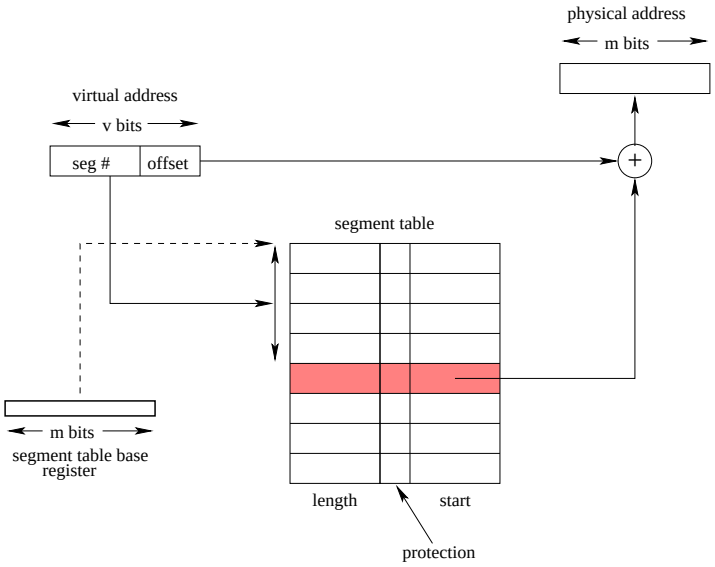
  (segment ID, address within segment)

- Each segment:
  - can grow or shrink independently of the other segments
  - has its own memory protection attributes
- For example, process could use separate segments for code, data, and stack.

Segmented Address Space Diagram

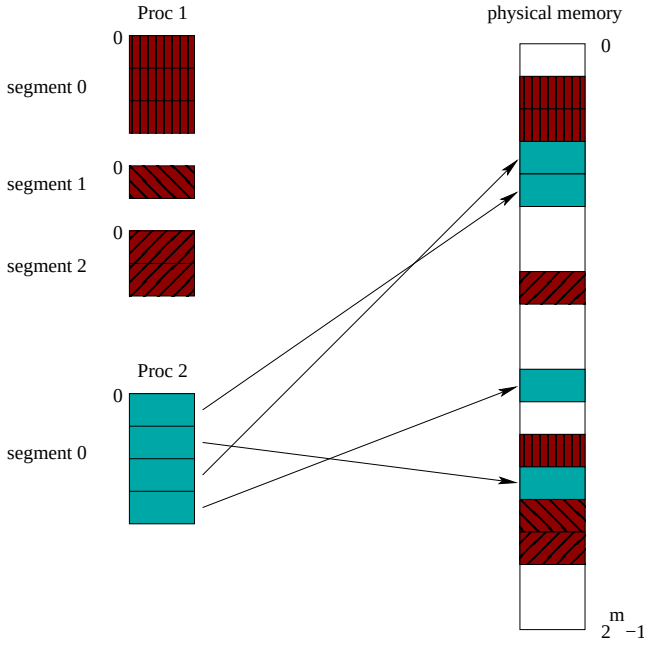


Mechanism for Translating Segmented Addresses

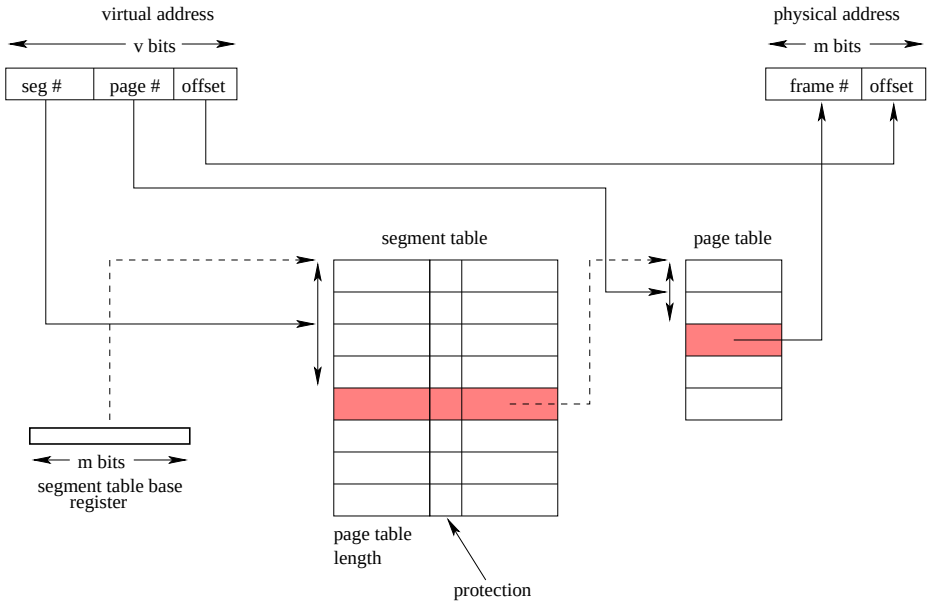


This translation mechanism requires physically contiguous allocation of segments.

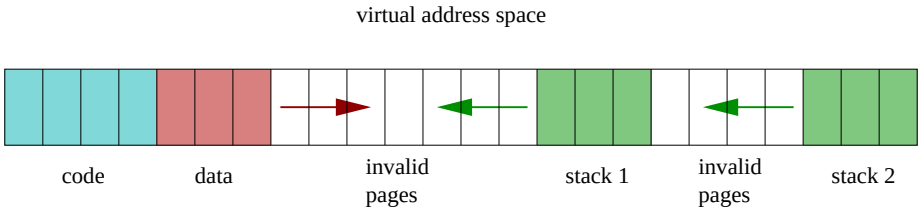
Combining Segmentation and Paging



Combining Segmentation and Paging: Translation Mechanism



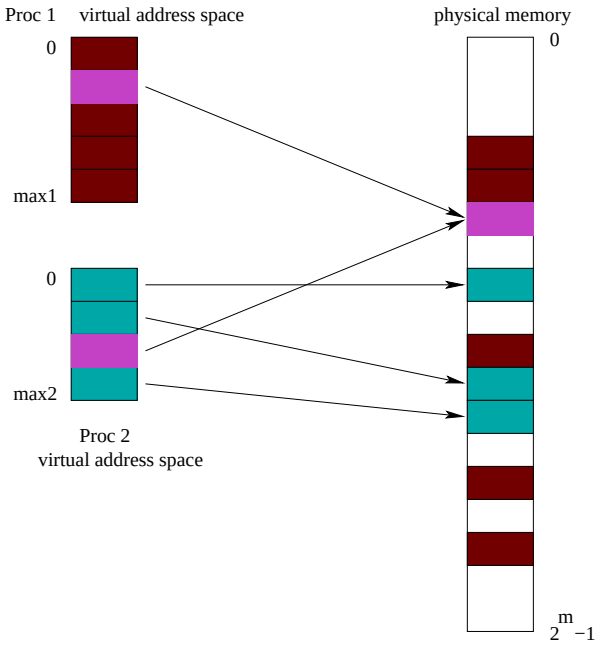
Simulating Segmentation with Paging



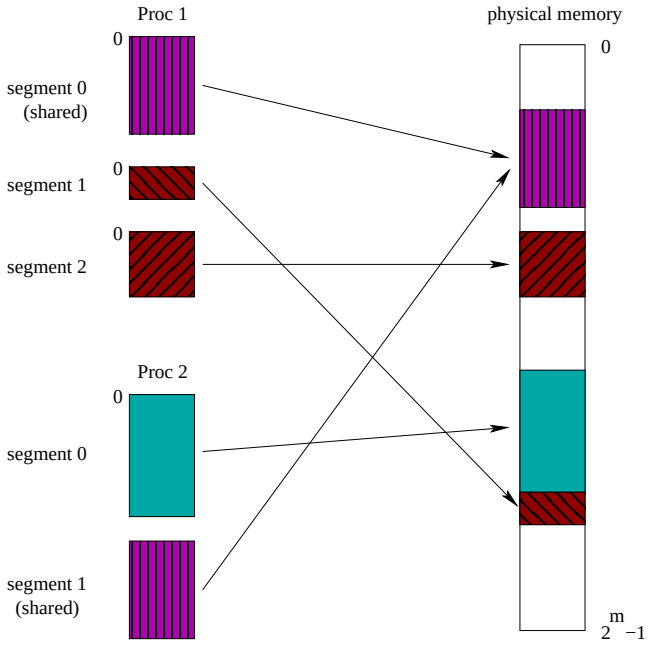
Shared Virtual Memory

- virtual memory sharing allows parts of two or more address spaces to overlap
- shared virtual memory is:
  - a way to use physical memory more efficiently, e.g., one copy of a program can be shared by several processes
  - a mechanism for interprocess communication
- sharing is accomplished by mapping virtual addresses from several processes to the same physical address
- unit of sharing can be a page or a segment

Shared Pages Diagram



Shared Segments Diagram



An Address Space for the Kernel

Option 1: Kernel in physical space

- mechanism: disable MMU in system mode, enable it in user mode
- accessing process address spaces: OS must interpret process page tables
- OS must be entirely memory resident

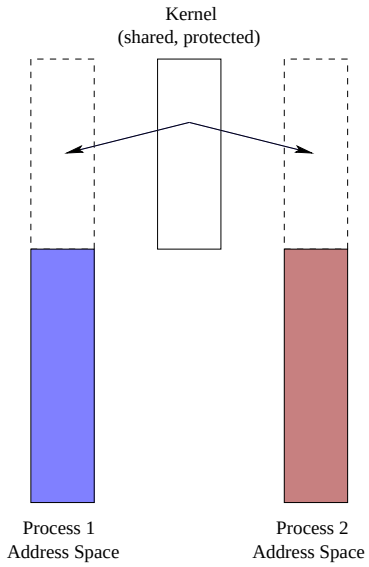
Option 2: Kernel in separate logical address space

- mechanism: MMU has separate state for user and system modes
- accessing process address spaces: difficult
- portions of the OS may be non-resident

Option 3: Kernel shares logical space with each process

- memory protection mechanism is used to isolate the OS
- accessing process address space: easy (process and kernel share the same address space)
- portions of the OS may be non-resident

The Kernel in Process' Address Spaces



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

Memory Management Interface

- much memory allocation is implicit, e.g.:
  - allocation for address space of new process
  - implicit stack growth on overflow
- OS may support explicit requests to grow/shrink address space, e.g., Unix `brk` system call.
- shared virtual memory (simplified Solaris example):

  Create: `shmid = shmget(key,size)`

  Attach: `vaddr = shmat(shmid, vaddr)`

  Detach: `shmdt(vaddr)`

  Delete: `shmctl(shmid,IPC_RMID)`

Virtual Memory

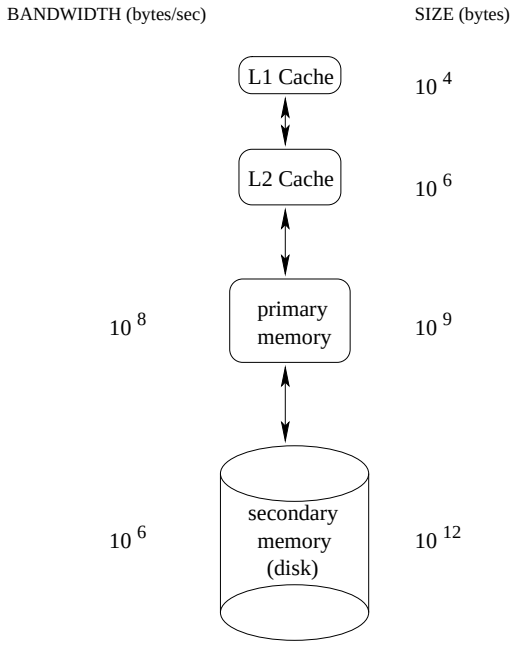
Goals:

- 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 memory, as well as primary memory.
- Move pages (or segments) between secondary and primary memory so that they are in primary memory when they are needed.

The Memory Hierarchy



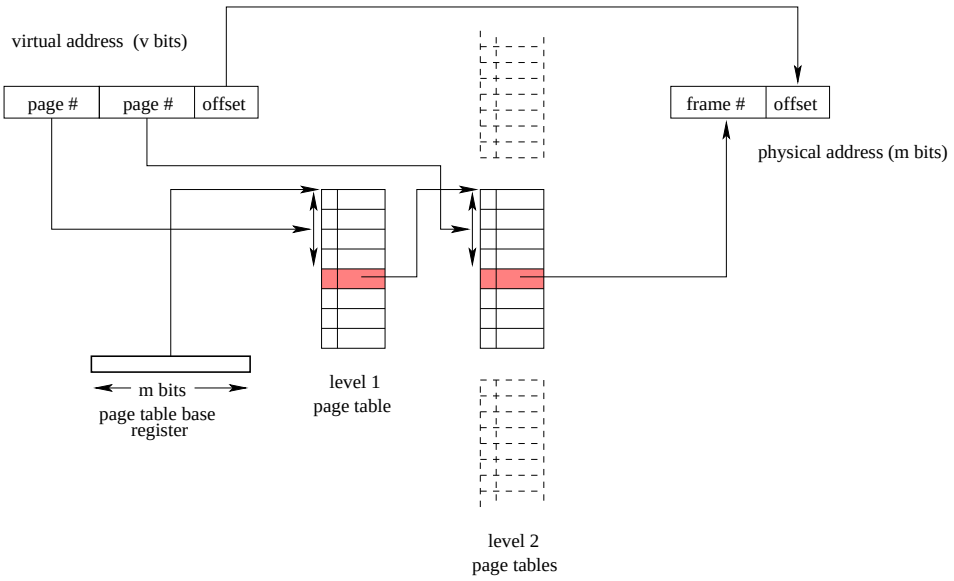
Large Virtual Address Spaces

- Virtual memory allows for very large virtual address spaces, and very large virtual address spaces require large page tables.
- example: 2^{48} byte virtual address space, 8Kbyte (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 must be in memory and physically contiguous
- some solutions:
  - multi-level page tables - page the page tables
  - inverted page tables

Two-Level Paging



Inverted Page Tables

- A normal page table maps virtual pages to physical frames. An inverted page table maps physical frames to virtual pages.
- Other key differences between normal and inverted page tables:
  - there is only one inverted page table, not one table per process
  - entries in an inverted page table must include a process identifier
- An inverted page table only specifies the location of virtual pages that are located in memory. Some other mechanism (e.g., regular page tables) must be used to locate pages that are not in memory.

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.

Global vs. Local Page Replacement

- When the system's page reference string is generated by more than one process, should the replacement policy take this into account?

  Global Policy: A global policy is applied to all in-memory pages, regardless of the process to which each one "belongs". A page requested by process X may replace a page that belongs another process, Y.

  Local Policy: Under a local policy, the available frames are allocated to processes according to some memory allocation policy. A replacement policy is then applied separately to each process's allocated space. A page requested by process X replaces another page that "belongs" to process X.

Paging Mechanism

- A *valid* bit (V) in each page table entry is used to track which pages are in (primary) memory, and which are not.

  $V = 1$**:** valid entry which can be used for translation

  $V = 0$**:** invalid entry. If the MMU encounters an invalid page table entry, it raises a *page fault* exception.

- To handle a page fault exception, the operating system must:
  - Determine which page table entry caused the exception. (In SYS/161, and in real MIPS processors, MMU puts the offending virtual address into a register on the CP0 co-processor (register 8, BadVaddr). The kernel can read that register.
  - Ensure that that page is brought into memory.

  On return from the exception handler, the instruction that resulted in the page fault will be retried.

- If (pure) segmentation is being used, there will a valid bit in each segment table entry to indicate whether the segment is in memory.

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?

Frequency-based Page Replacement

- Another approach to page replacement is to count references to pages. The counts can form the basis of a page replacement decision.
- Example: LFU (Least Frequently Used)
  Replace the page with the smallest reference count.
- Any frequency-based policy requires a reference counting mechanism, e.g., MMU increments a counter each time an in-memory page is referenced.
- Pure frequency-based policies have several potential drawbacks:
  - Old references are never forgotten. This can be addressed by periodically reducing the reference count of every in-memory page.
  - Freshly loaded pages have small reference counts and are likely victims - ignores temporal locality.

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, LRU is often considered to be impractical for use as a replacement policy 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 updated by the operating system
- Note: Page table entries in SYS/161 do not include a use bit.

> 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 the page table entry when the contents of the page change. Operating system clears 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.
- Note: page table entries in SYS/161 do not include a modified bit.

Enhanced Second Chance Replacement Algorithm

- Classify pages according to their use and modified bits:

  (0,0): not recently used, clean.

  (0,1): not recently used, modified.

  (1,0): recently used, clean

  (1,1): recently used, modified

- Algorithm:
  1. Sweep once looking for (0,0) page. Don't clear use bits while looking.
  2. If none found, look for (0,0) or (0,1) page, this time clearing "use" bits while looking.

Page Cleaning

- A modified page must be cleaned before it can be replaced, otherwise changes on that page will be lost.
- *Cleaning* a page means copying the page to secondary storage.
- Cleaning is distinct from replacement.
- Page cleaning may be *synchronous* or *asynchronous*:

  synchronous cleaning: happens at the time the page is replaced, during page fault handling. Page is first cleaned by copying it to secondary storage. Then a new page is brought in to replace it.

  asynchronous cleaning: happens before a page is replaced, so that page fault handling can be faster.

  – asynchronous cleaning may be implemented by dedicated OS *page cleaning threads* that sweep through the in-memory pages cleaning modified pages that they encounter.

What if Hardware Doesn't Have a "Modified" Bit?

- Can emulate it. Track two sets of pages:
  1. Pages user program can access without taking a fault (call them valid or mapped pages)
  2. Pages in memory
- Set 1. is a subset of set 2.
- Initially, mark all pages as read-only, even data page (i.e., all pages are unmapped).
- On write, trap to OS. If page isn't actually read-only (e.g., code / text page) set modified bit in page table and now make page read-write.
- When page is brought back in from disk, mark it read-only.

What if Hardware Doesn't Have a "Use" Bit?

- Can emulate it in similar fashion to modified bit (assume no modified or use bit).
  1. Mark all pages as invalid, even if in memory.
  2. On read to invalid page, trap to OS.
  3. OS sets use bit (in page table) and marks page read-only.
  4. On write, set use and modified bit, and mark page read-write.
  5. When clock hand passes by, reset use bit and mark page as invalid.

Belady's Anomaly

- FIFO replacement, 4 frames

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	e	e	e	e	d	d
Frame 2		b	b	b	b	b	b	a	a	a	a	e
Frame 3			c	c	c	c	c	c	b	b	b	b
Frame 4				d	d	d	d	d	d	c	c	c
Fault?	x	x	x	x			x	x	x	x	x	x

- FIFO example on Slide 9 with same reference string had 3 frames and only 9 faults.

More memory does not necessarily mean fewer page faults.

Stack Policies

- Let $B(m, t)$ represent the set of pages in a memory of size m at time t under some given replacement policy, for some given reference string.
- A replacement policy is called a *stack policy* if, for all reference strings, all m and all t:

$$B(m, t) \subseteq B(m + 1, t)$$

- If a replacement algorithm imposes a total order, independent of memory size, on the pages and it replaces the largest (or smallest) page according to that order, then it satisfies the definition of a stack policy.
- Examples: LRU is a stack algorithm. FIFO and CLOCK are not stack algorithms. (Why?)

Stack algorithms do not suffer from Belady's anomaly.

Prefetching

- Prefetching means moving virtual pages into memory before they are needed, i.e., before a page fault results.
- The goal of prefetching is *latency hiding*: do the work of bringing a page into memory in advance, not while a process is waiting.
- To prefetch, the operating system must guess which pages will be needed.
- Hazards of prefetching:
  - guessing wrong means the work that was done to prefetch the page was wasted
  - guessing wrong means that some other potentially useful page has been replaced by a page that is not used
- most common form of prefetching is simple sequential prefetching: if a process uses page x, prefetch page $x + 1$.
- sequential prefetching exploits spatial locality of reference

Page Size Tradeoffs

- larger pages mean:
  + smaller page tables
  + better TLB "coverage"
  + more efficient I/O
  - greater internal fragmentation
  - increased chance of paging in unnecessary data

How Much 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 process 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
```

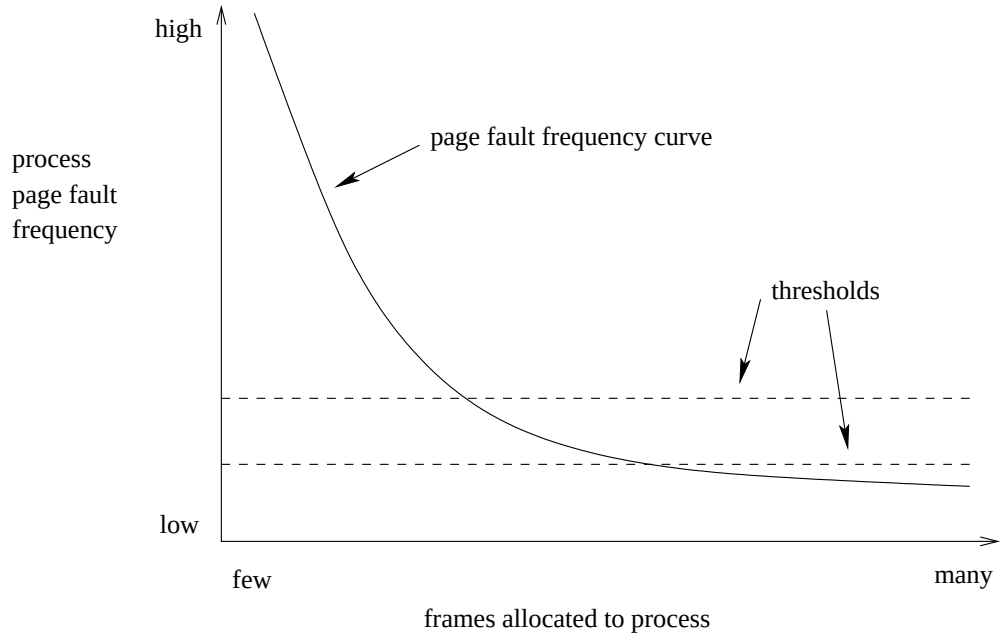
Refining the Working Set Model

- Define $WS(t, \Delta)$ to be the set of pages referenced by a given process during the time interval $(t - \Delta, t)$. $WS(t, \Delta)$ is the working set of the process at time t.
- Define $|WS(t, \Delta)|$ to be the size of $WS(t, \Delta)$, i.e., the number of *distinct* pages referenced by the process.
- If the operating system could track $WS(t, \Delta)$, it could:
  - use $|WS(t, \Delta)|$ to determine the number of frames to allocate to the process under a local page replacement policy
  - use $WS(t, \Delta)$ directly to implement a working-set based page replacement policy: any page that is no longer in the working set is a candidate for replacement

Page Fault Frequency

- A more direct way to allocate memory to processes is to measure their *page fault frequencies* - the number of page faults they generate per unit time.
- If a process's page fault frequency is too high, it needs more memory. If it is low, it may be able to surrender memory.
- The working set model suggests that a page fault frequency plot should have a sharp "knee".

A Page Fault Frequency Plot



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.

Scheduling Criteria

CPU utilization: keep the CPU as busy as possible

throughput: rate at which tasks are completed

response time/turnaround time: time required to finish a task

fairness

A "task" might be a single CPU burst, a thread, or an application-level service request.

The Nature of Program Executions

- A running thread can be modeled as alternating series of *CPU bursts* and *I/O bursts*
  - during a CPU burst, a thread is executing instructions
  - during an I/O burst, a thread is waiting for an I/O operation to be performed and is not executing instructions

Preemptive vs. Non-Preemptive

- A *non-preemptive* scheduler runs only when the running thread gives up the processor through its own actions, e.g.,
  - the thread terminates
  - the thread blocks because of an I/O or synchronization operation
  - the thread performs a Yield system call (if one is provided by the operating system)
- A *preemptive* scheduler may, in addition, force a running thread to stop running
  - typically, a preemptive scheduler will be invoked periodically by a timer interrupt handler, as well as in the circumstances listed above
  - a running thread that is preempted is moved to the ready state

FCFS and Round-Robin Scheduling

First-Come, First-Served (FCFS):

- non-preemptive - each thread runs until it blocks or terminates
- FIFO ready queue

Round-Robin:

- preemptive version of FCFS
- running thread is preempted after a fixed time quantum, if it has not already blocked
- preempted thread goes to the end of the FIFO ready queue

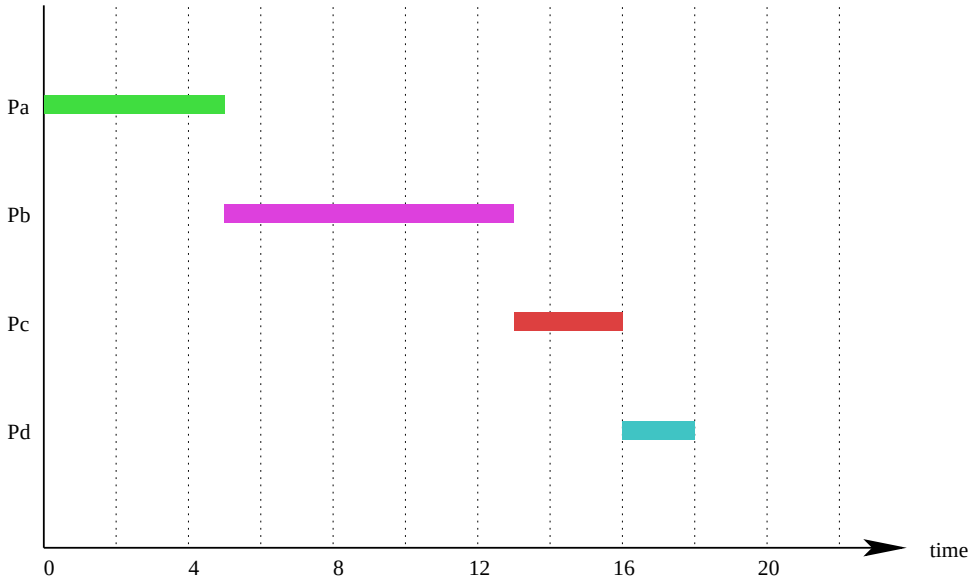
Shortest Job First (SJF) Scheduling

- non-preemptive
- ready threads are scheduled according to the length of their next CPU burst - thread with the shortest burst goes first
- SJF minimizes average waiting time, but can lead to starvation
- SJF requires knowledge of CPU burst lengths
  - Simplest approach is to estimate next burst length of each thread based on previous burst length(s). For example, exponential average considers all previous burst lengths, but weights recent ones most heavily:

    $$B_{i+1} = \alpha b_i + (1 - \alpha) B_i$$

    where B_i is the predicted length of the ith CPU burst, and b_i is its actual length, and $0 \leq \alpha \leq 1$.
- Shortest Remaining Time First is a preemptive variant of SJF. Preemption may occur when a new thread enters the ready queue.

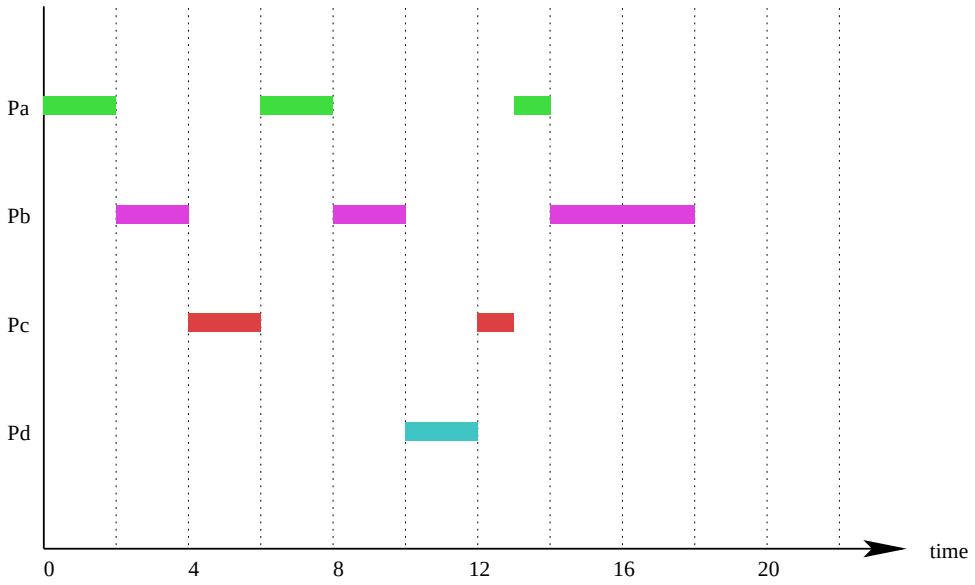
FCFS Gantt Chart Example



Initial ready queue: Pa = 5 Pb = 8 Pc = 3

Thread Pd (=2) "arrives" at time 5

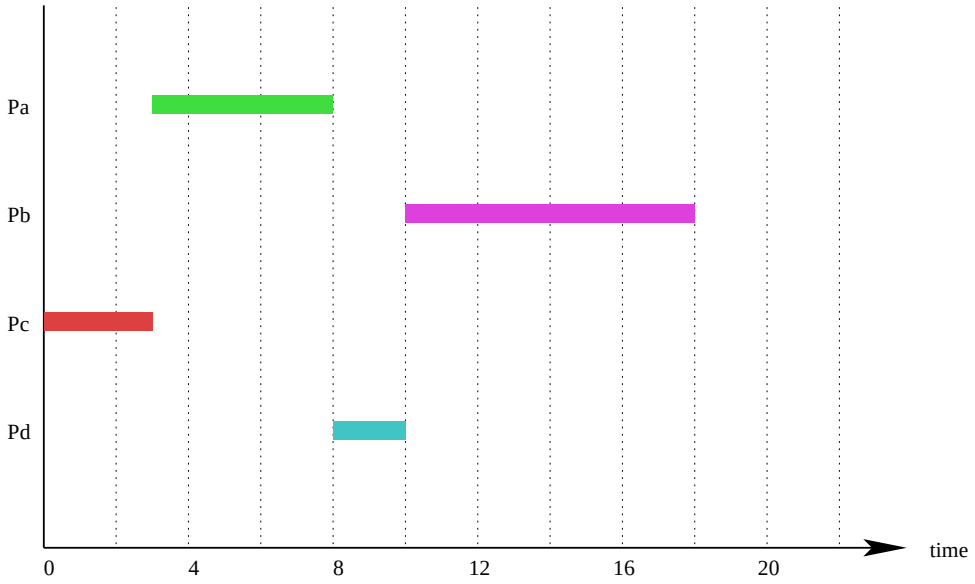
Round Robin Example



Initial ready queue: Pa = 5 Pb = 8 Pc = 3 Quantum = 2

Thread Pd (=2) "arrives" at time 5

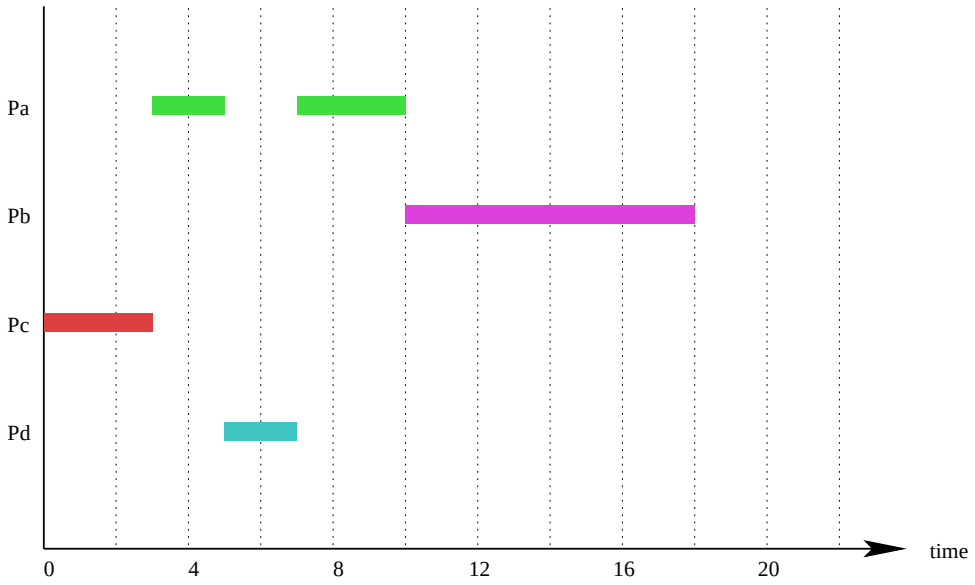
SJF Example



Initial ready queue: Pa = 5 Pb = 8 Pc = 3

Thread Pd (=2) "arrives" at time 5

SRTF Example



Initial ready queue: Pa = 5 Pb = 8 Pc = 3

Thread Pd (=2) "arrives" at time 5

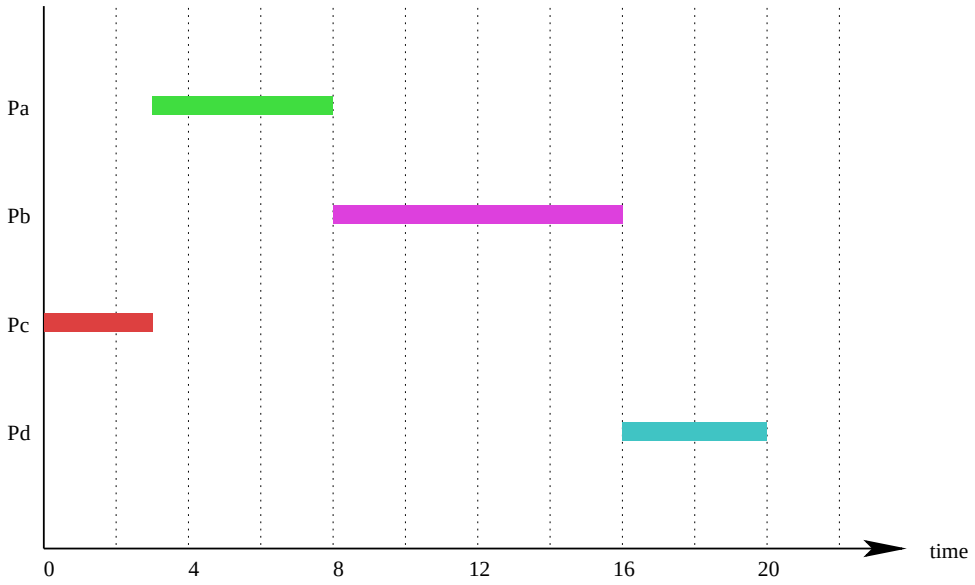
Highest Response Ratio Next

- non-preemptive
- response ratio is defined for each ready thread as:

$$\frac{w+b}{b}$$

  where b is the estimated CPU burst time and w is the actual waiting time
- scheduler chooses the thread with the highest response ratio (choose smallest b in case of a tie)
- HRRN is an example of a heuristic that blends SJF and FCFS

HRRN Example



Initial ready queue: Pa = 5 Pb = 8 Pc = 3

Thread Pd (=4) "arrives" at time 5

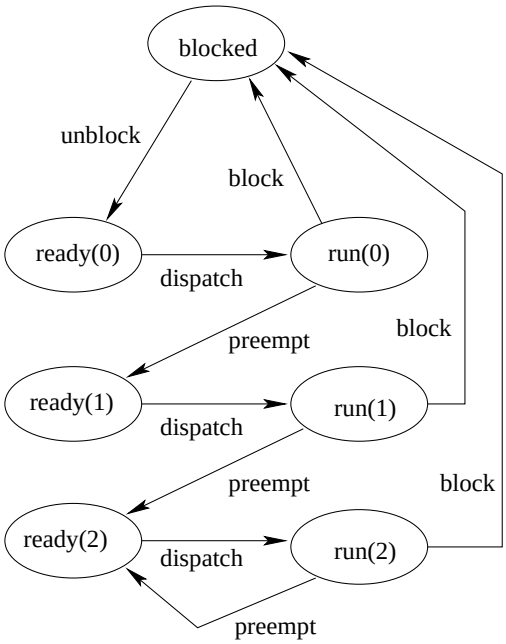
Prioritization

- a scheduler may be asked to take process or thread priorities into account
- for example, priorities could be based on
  - user classification
  - application classification
  - application specification
    (e.g., Linux `setpriority/sched_setscheduler`)
- scheduler can:
  - always choose higher priority threads over lower priority thread
  - use any scheduling heuristic to schedule threads of equal priority
- low priority threads risk starvation. If this is not desired, scheduler must have a mechanism for elevating the priority of low priority threads that have waited a long time

Multilevel Feedback Queues

- gives priority to interactive threads (those with short CPU bursts)
- scheduler maintains several ready queues
- scheduler never chooses a thread in queue i if there are threads in any queue $j < i$.
- threads in queue i use quantum q_i, and $q_i < q_j$ if $i < j$
- newly ready threads go in to queue 0
- a level i thread that is preempted goes into the level $i + 1$ ready queue

3 Level Feedback Queue State Diagram



Lottery Scheduling

- randomized proportional share resource allocation
- resource rights represented by lottery tickets, allocation determined by lottery
  - resource granted to holder of winning ticket
- probabilistically fair with $p = t/T$
  - p = probability of allocation, t = tickets held, T = total tickets
  - avoid starvation by ensuring $t > 0$
- uniformly-distributed pseudo-random number generator (10 lines on MIPS)
- can proportionally assign other resources (e.g., memory, bandwidth)
- "Lottery Scheduling: Flexible Proportional-Share Resource Management", Waldspurger and Weihl, Operating System Design and Implementation, 1994.

Processor Scheduling Summary

FCFS:

+ simple, low overhead
+ no starvation
- can give poor response times for interactive processes

RR:

+ no starvation
+ reduced waiting time variance
+ good response times for interactive processes

SJF and SRTF:

+ best response times
- depends on burst length estimates
- starvation is possible

Processor Scheduling Summary

HRRN:

+ no starvation
+ good response times
- depends on burst length estimates

Multilevel Feedback Queues:

+ flexible
+ good response times for interactive processes
- compute-intensive processes can starve

Other Scheduling Issues

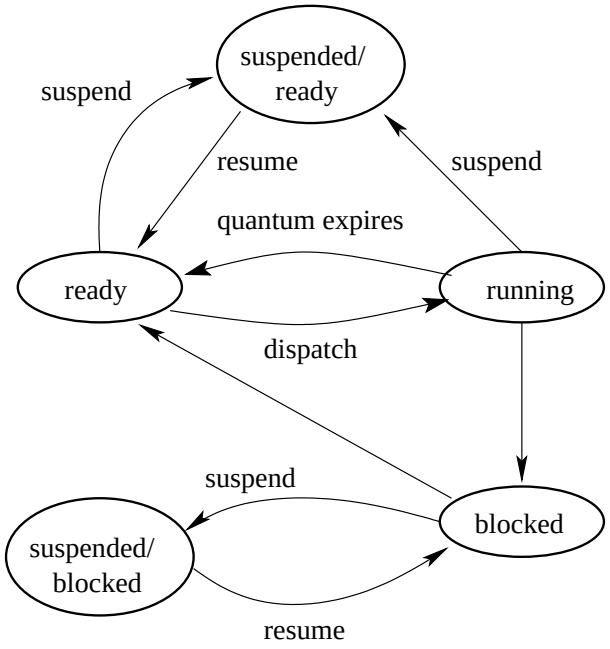
short term scheduling: what has been covered so far

medium term scheduling: suspension/resumption of partially executed processes

- usually because a resource, especially memory, is overloaded
- suspended process releases resources
- operating system may also provide mechanisms for applications or users to request suspension/resumption of processes

long term scheduling: process admission control to limit the degree of multiprogramming

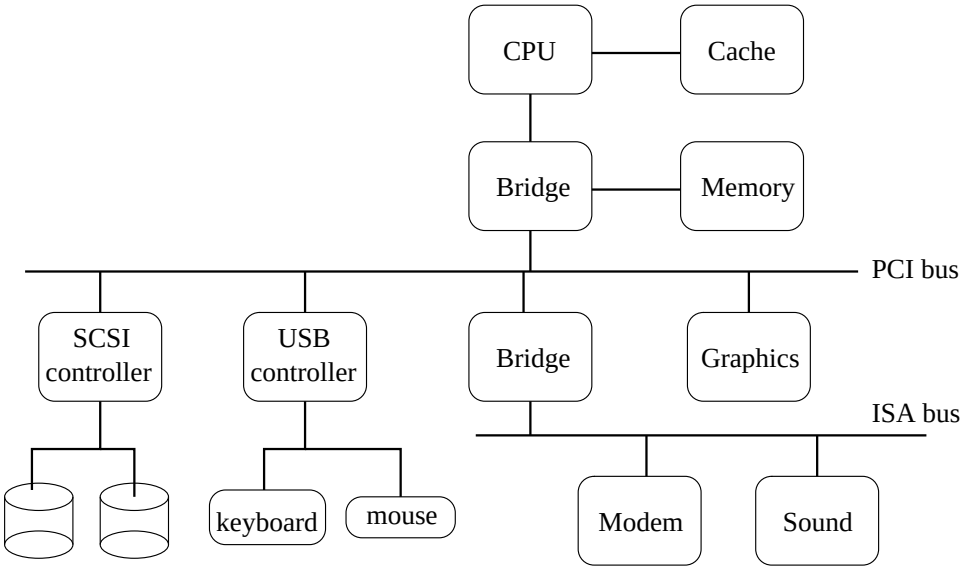
Scheduling States Including Suspend/Resume



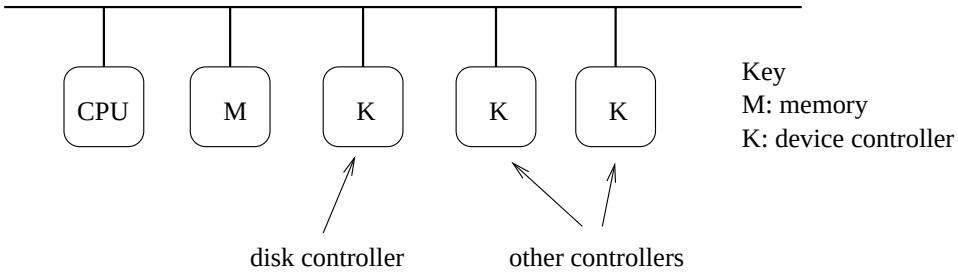
Devices and Device Controllers

- network interface
- graphics adapter
- secondary storage (disks, tape) and storage controllers
- serial (e.g., mouse, keyboard)
- sound
- co-processors
- . . .

Bus Architecture Example



Simplified Bus Architecture



Device Interactions

- device registers
  - command, status, and data registers
  - CPU accesses register access via:
    - special I/O instructions
    - memory mapping
- interrupts
  - used by device for asynchronous notification (e.g., of request completion)
  - handled by interrupt handlers in the operating system

Device Interactions: OS/161 Example

```
/* LAMEbus mapping size per slot */
#define LB_SLOT_SIZE         65536
#define MIPS_KSEG1  0xa0000000
#define LB_BASEADDR  (MIPS_KSEG1 + 0x1fe00000)

/* Generate the memory address (in the uncached segment)   *
/* for specified offset into slot's region of the LAMEbus. *
void *
lamebus_map_area(struct lamebus_softc *bus, int slot, u_int3
{
    u_int32_t address;
    (void)bus;   // not needed

    assert(slot>=0 && slot<LB_NSLOTS);

    address = LB_BASEADDR + slot*LB_SLOT_SIZE + offset;
    return (void *)address;
}
```


Device Interactions: OS/161 Example

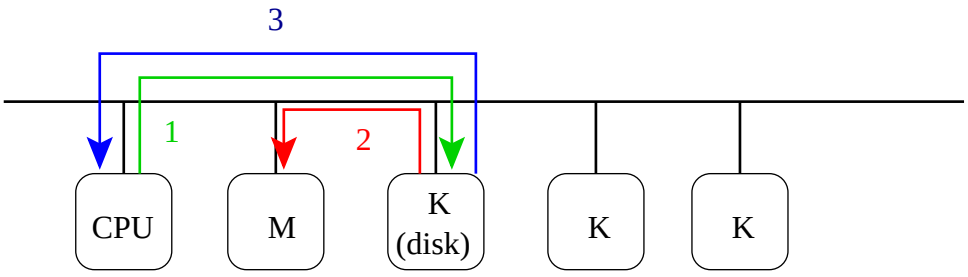
```
/* FROM: kern/arch/mips/mips/lamebus_mips.c */
/* Read 32-bit register from a LAMEbus device. */
u_int32_t
lamebus_read_register(struct lamebus_softc *bus,
    int slot, u_int32_t offset)
{
    u_int32_t *ptr = lamebus_map_area(bus, slot, offset);
    return *ptr;
}

/* Write a 32-bit register of a LAMEbus device. */
void
lamebus_write_register(struct lamebus_softc *bus,
    int slot, u_int32_t offset, u_int32_t val)
{
    u_int32_t *ptr = lamebus_map_area(bus, slot, offset);
    *ptr = val;
}
```

Device Interactions: OS/161 Example

```
/* Registers (offsets within slot) */
#define LT_REG_SEC   0  /* time of day: seconds */
#define LT_REG_NSEC  4  /* time of day: nanoseconds */
#define LT_REG_ROE   8  /* Restart On countdown-timer Expiry flag
#define LT_REG_IRQ   12 /* Interrupt status register */
#define LT_REG_COUNT 16 /* Time for countdown timer (usec) */
#define LT_REG_SPKR  20 /* Beep control */

/* Get the number of seconds from the lamebus timer */
secs = bus_read_register(lt->lt_bus, lt->lt_buspos,
    LT_REG_SEC);

/* Get the timer to beep. Doesn't matter what value is sent */
bus_write_register(lt->lt_bus, lt->lt_buspos,
    LT_REG_SPKR, 440);
```


Direct Memory Access (DMA)

- used for block data transfers between devices (e.g., disk controller) and memory
- CPU initiates DMA, but can do other work while the transfer occurs



1. CPU issues DMA request to controller
2. controller directs data transfer
3. controller interrupts CPU

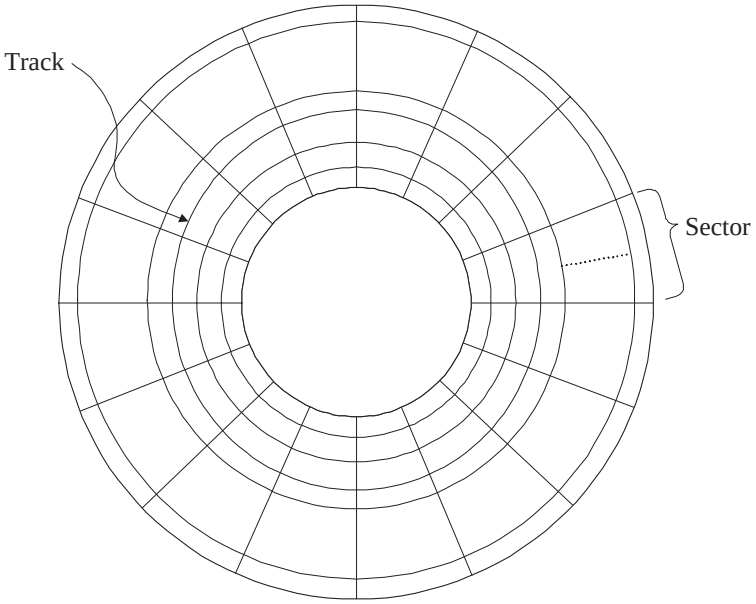
Applications and Devices

- interaction with devices is normally accomplished by device drivers in the OS, so that the OS can control how the devices are used
- applications see a simplified view of devices through a system call interface (e.g., block vs. character devices in Unix)
  - the OS may provide a system call interface that permits low level interaction between application programs and a device
- operating system often *buffers* data that is moving between devices and application programs' address spaces
  - benefits: solve timing, size mismatch problems
  - drawback: performance

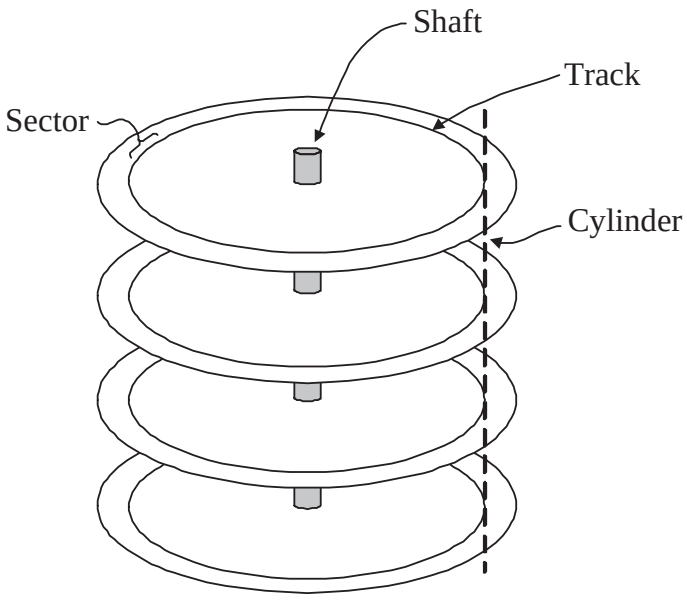
Logical View of a Disk Drive

- disk is an array of numbered blocks (or sectors)
- each block is the same size (e.g., 512 bytes)
- blocks are the unit of transfer between the disk and memory
  - typically, one or more contiguous blocks can be transferred in a single operation
- storage is *non-volatile*, i.e., data persists even when the device is without power

A Disk Platter's Surface



Physical Structure of a Disk Drive



Simplified Cost Model for Disk Block Transfer

- moving data to/from a disk involves:

  seek time: move the read/write heads to the appropriate cylinder

  rotational latency: wait until the desired sectors spin to the read/write heads

  transfer time: wait while the desired sectors spin past the read/write heads

- request service time is the sum of seek time, rotational latency, and transfer time

$$t_{service} = t_{seek} + t_{rot} + t_{transfer}$$

- note that there are other overheads but they are typically small relative to these three

Rotational Latency and Transfer Time

- rotational latency depends on the rotational speed of the disk
- if the disk spins at ω rotations per second:

$$0 \leq t_{rot} \leq \frac{1}{\omega}$$

- expected rotational latency:

$$\bar{t}_{rot} = \frac{1}{2\omega}$$

- transfer time depends on the rotational speed and on the amount of data transferred
- if k sectors are to be transferred and there are T sectors per track:

$$t_{transfer} = \frac{k}{T\omega}$$

Seek Time

- seek time depends on the speed of the arm on which the read/write heads are mounted.
- a simple linear seek time model:
  - $t_{maxseek}$ is the time required to move the read/write heads from the innermost cylinder to the outermost cylinder
  - C is the total number of cylinders
- if k is the required *seek distance* ($k > 0$):

$$t_{seek}(k) = \frac{k}{C} t_{maxseek}$$

Disk Head Scheduling

- goal: reduce seek times by controlling the order in which requests are serviced
- disk head scheduling may be performed by the controller, by the operating system, or both
- for disk head scheduling to be effective, there must be a queue of outstanding disk requests (otherwise there is nothing to reorder)
- an on-line approach is required: the disk request queue is not static

FCFS Disk Head Scheduling

- handle requests in the order in which they arrive
  - **+:** fair, simple
  - **-:** no optimization of seek times

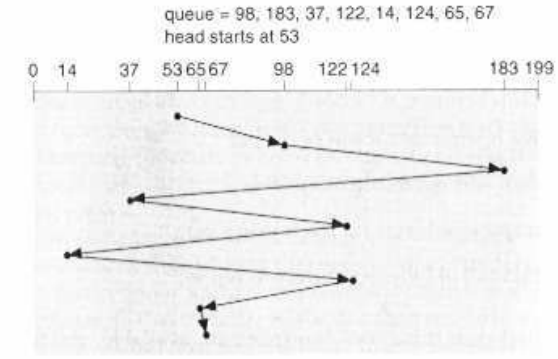


Figure 14.1 FCFS disk scheduling.

Figure from *Operating Systems Concepts, 6th Ed.*, Silberschatz, Galvin, Gagne. Wiley. 2003

Shortest Seek Time First (SSTF)

- choose closest request (a greedy approach)
  - **+:** seek times are reduced
  - **-:** starvation of distant requests

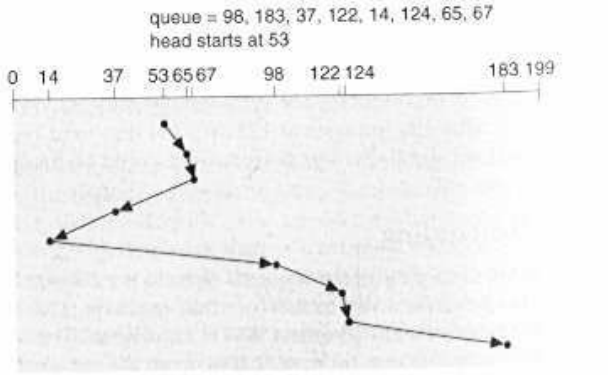


Figure 14.2 SSTF disk scheduling.

Figure from *Operating Systems Concepts, 6th Ed.*, Silberschatz, Galvin, Gagne. Wiley. 2003

SCAN and LOOK

- LOOK is the commonly-implemented variant of SCAN. Also known as the "elevator" algorithm.
- Under LOOK, the disk head moves in one direction until there are no more requests in front of it, then reverses direction.
- seek time reduction without starvation
- SCAN is like LOOK, except the read/write heads always move all the way to the edge of the disk in each direction.

SCAN Example

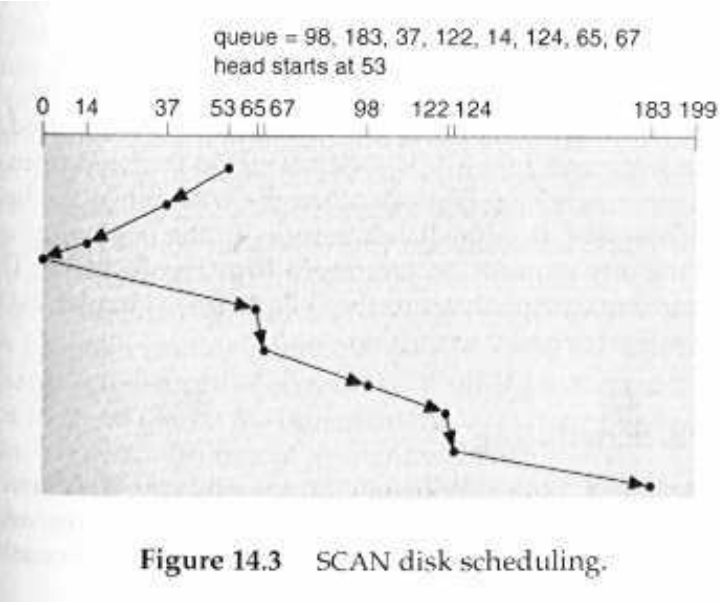


Figure 14.3 SCAN disk scheduling.

Figure from *Operating Systems Concepts, 6th Ed.*, Silberschatz, Galvin, Gagne. Wiley. 2003

Circular SCAN (C-SCAN) and Circular LOOK (C-LOOK)

- C-LOOK is the commonly-implemented variant of C-SCAN
- Under C-LOOK, the disk head moves in one direction until there are no more requests in front of it, then it jumps back and begins another scan in the same direction as the first.
- C-LOOK avoids bias against "edge" cylinders

C-LOOK Example

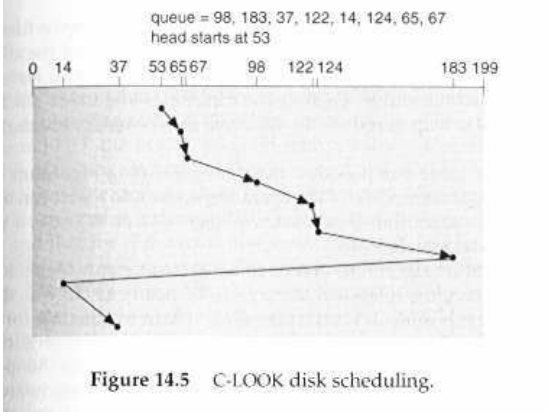


Figure 14.5 C-LOOK disk scheduling.

Figure from *Operating Systems Concepts, 6th Ed.*, Silberschatz, Galvin, Gagne. Wiley. 2003

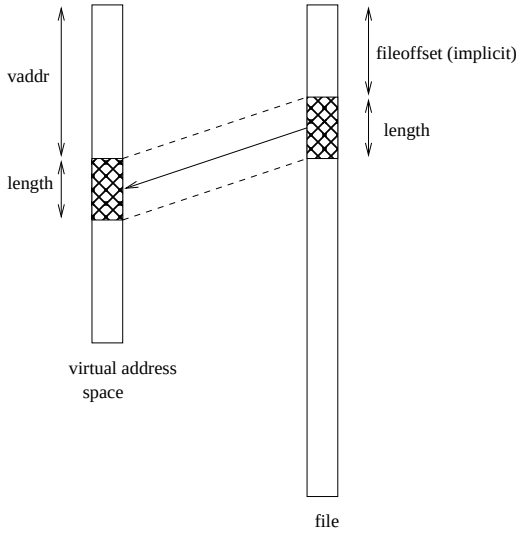
Files and File Systems

- files: persistent, named data objects
  - data consists of a sequence of numbered bytes
  - alternatively, a file may have some internal structure, e.g., a file may consist of sequence of numbered records
  - file may change size over time
  - file has associated meta-data (attributes), in addition to the file name
    - examples: owner, access controls, file type, creation and access timestamps
- file system: a collection of files which share a common name space
  - allows files to be created, destroyed, renamed, . . .

File Interface

- open, close
  - open returns a file identifier (or handle or descriptor), which is used in subsequent operations to identify the file. (Why is this done?)
- read, write
  - must specify which file to read, which part of the file to read, and where to put the data that has been read (similar for write).
  - often, file position is implicit (why?)
- seek
- get/set file attributes, e.g., Unix `fstat, chmod`

File Read




```
read(fileID, vaddr, length)
```


File Position

- may be associated with the file, with a process, or with a file descriptor (Unix style)
- read and write operations
  - start from the current file position
  - update the current file position
- this makes sequential file I/O easy for an application to request
- for non-sequential (random) file I/O, use:
  - `seek`, to adjust file position before reading or writing
  - a positioned read or write operation, e.g., Unix `pread, pwrite`: `pread(fileId,vaddr,length,filePosition)`

Sequential File Reading Example (Unix)

```
char buf[512];
int i;
int f = open("myfile",O_RDONLY);
for(i=0; i<100; i++) {
  read(f,(void *)buf,512);
}
close(f);
```

Read the first $100 * 512$ bytes of a file, 512 bytes at a time.

File Reading Example Using Seek (Unix)

```
char buf[512];
int i;
int f = open("myfile",O_RDONLY);
lseek(f,99*512,SEEK_SET);
for(i=0; i<100; i++) {
  read(f,(void *)buf,512);
  lseek(f,-1024,SEEK_CUR);
}
close(f);
```

Read the first $100 * 512$ bytes of a file, 512 bytes at a time, in reverse order.

File Reading Example Using Positioned Read

```
char buf[512];
int i;
int f = open("myfile",O_RDONLY);
for(i=0; i<100; i+=2) {
  pread(f,(void *)buf,512,i*512);
}
close(f);
```

Read every second 512 byte chunk of a file, until 50 have been read.

Memory-Mapped Files

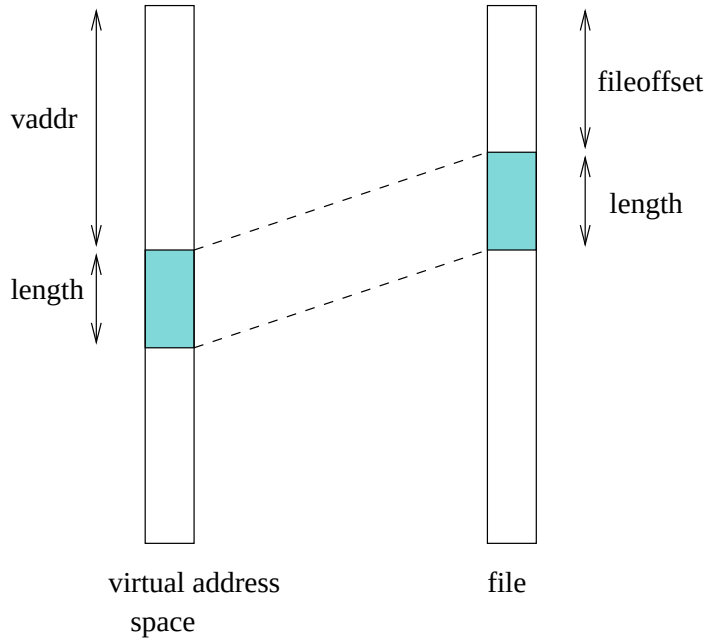
- generic interface:

  `vaddr ← mmap(file descriptor,fileoffset,length)`
  `munmap(vaddr,length)`

- `mmap` call returns the virtual address to which the file is mapped
- `munmap` call unmaps mapped files within the specified virtual address range

Memory-mapping is an alternative to the read/write file interface.

Memory Mapping Illustration



Memory Mapping Update Semantics

- what should happen if the virtual memory to which a file has been mapped is updated?
- some options:
  - prohibit updates (read-only mapping)
  - eager propagation of the update to the file (too slow!)
  - lazy propagation of the update to the file
    - user may be able to request propagation (e.g., Posix `msync()`
    - propagation may be guaranteed by `munmap()`
  - allow updates, but do not propagate them to the file

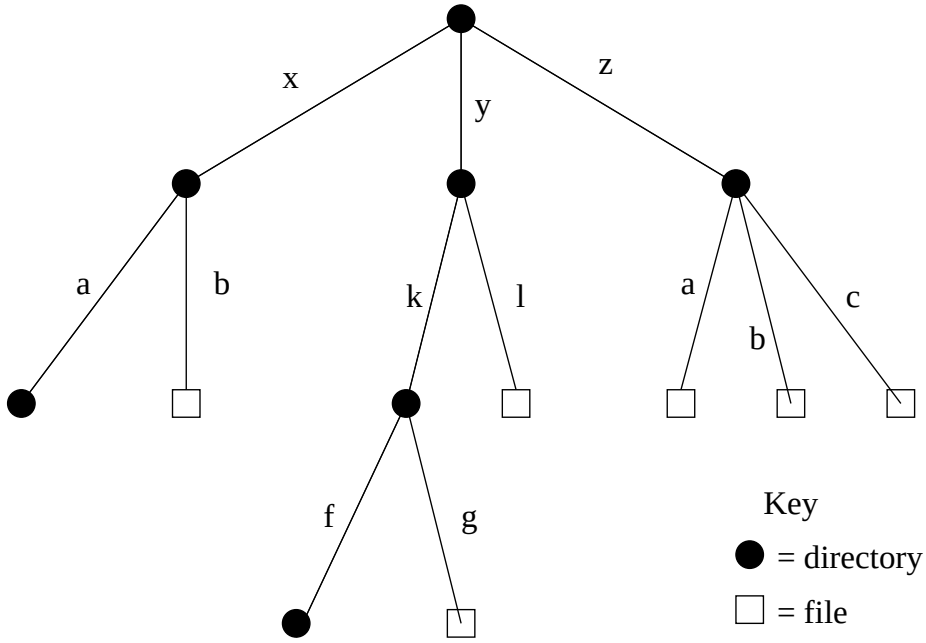
Memory Mapping Concurrency Semantics

- what should happen if a memory mapped file is updated?
  - by a process that has mmapped the same file
  - by a process that is updating the file using a `write()` system call
- options are similar to those on the previous slide. Typically:
  - propagate lazily: processes that have mapped the file *may* eventually see the changes
  - propagate eagerly: other processes will see the changes
    - typically implemented by invalidating other process's page table entries

File Names

- flat namespace
  - file names are simple strings
- hierarchical namespace
  - directories (folders) can be used to organize files and/or other directories
  - directory inclusion graph is a tree
  - pathname: file or directory is identified by a *path* in the tree
    Unix: `/home/kmsalem/courses/cs350/notes/filesys.ps`
    Windows: `c:\kmsalem\cs350\schedule.txt`

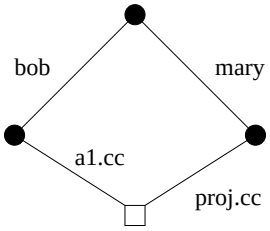
Hierarchical Namespace Example



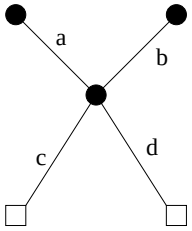
Acyclic File Namespaces

- directory inclusion graph can be a (rooted) DAG
- allows files/directories to have more than one pathname
  - increased flexibility for file sharing and file organization
  - file removal and some other file system operations are more complicated
- examples:

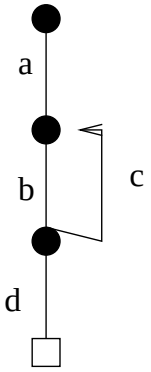
Rooted Acyclic Namespace



An Unrooted DAG



General File Namespaces



- no restriction on inclusion graph (except perhaps that it should have a designated root node)
- maximum flexibility
- additional complications, e.g.:
  - reference counts are no longer sufficient for implementing file deletion
  - pathnames can have an infinite number of components

File Links

- typically, a new file or directory is linked to a single "parent" directory when it is created. This gives a hierarchical namespace.
- another mechanism can then be used to create additional links to existing files or directories, introducing non-hierarchical structure in the namespace.
- hard links
  - "first class" links, like the original link to a file
  - *referential integrity* is maintained (no "dangling" hard links)
  - scope usually restricted to a single file system
  - Unix: hard links can be made to files, but not to directories. This restriction is sufficient to avoid cycles. (Why?)
- soft links (a.k.a. "symbolic links", "shortcuts")
  - referential integrity is *not* maintained
  - flexible: may be allowed to span file systems, may link to directories and (possibly) create cycles

Link Examples

```
tiger % cat > file1
This is file1.

tiger % ls -al
total 8
 2 drwx------   2 cs350 group   512 Nov 20 13:45 ./
 4 drwxr-xr-x  30 cs350 group  2048 Nov 20 13:43 ../
 2 -rw-------   1 cs350 group    15 Nov 20 13:46 file1

tiger % ln file1 link1

tiger % ls -al
total 10
 2 drwx------   2 cs350 group   512 Nov 20 13:46 ./
 4 drwxr-xr-x  30 cs350 group  2048 Nov 20 13:43 ../
 2 -rw-------   2 cs350 group    15 Nov 20 13:46 file1
 2 -rw-------   2 cs350 group    15 Nov 20 13:46 link1
```

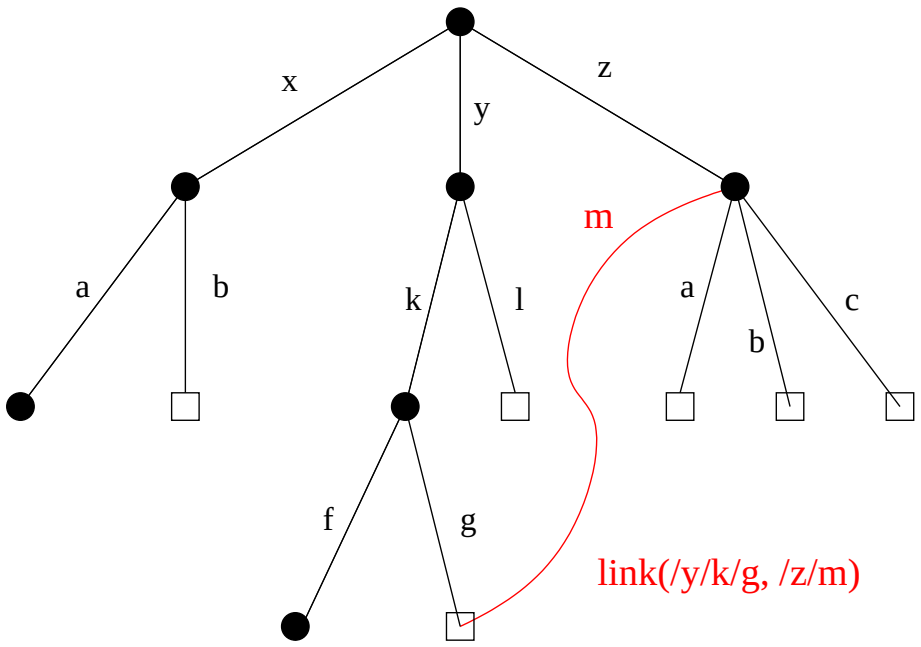

Link Examples

```
tiger % ln -s file1 sym1

tiger % ls -al
total 10
 2 drwx------  2 cs350 group  512 Nov 20 13:46 ./
 4 drwxr-xr-x 30 cs350 group 2048 Nov 20 13:43 ../
 2 -rw-------  2 cs350 group   15 Nov 20 13:46 file1
 2 -rw-------  2 cs350 group   15 Nov 20 13:46 link1
 0 lrwxrwxrwx  1 cs350 group    5 Nov 20 13:46 sym1 -> file1

tiger % pwd
/cs/home/fac1/cs350/links

tiger % cat file1
This is file1.

tiger % cat link1
This is file1.

tiger % cat sym1
This is file1.
```

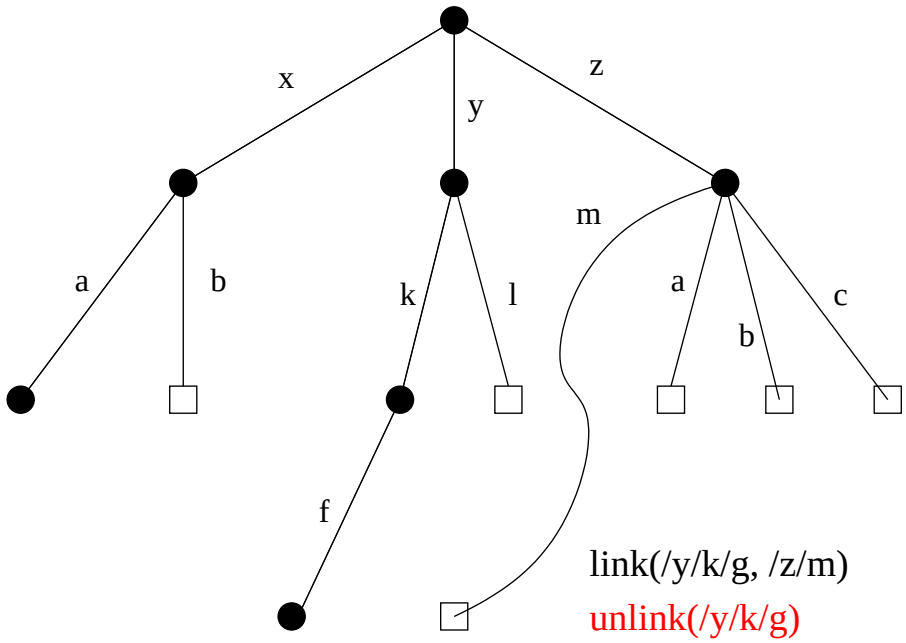
Link Examples

```
tiger % rm file1
rm: remove file1 (yes/no)? y

tiger % ls -al
total 8
 2 drwx------  2 brecht brecht  512 Nov 20 13:47 ./
 4 drwxr-xr-x 30 brecht brecht 2048 Nov 20 13:43 ../
 2 -rw-------  1 brecht brecht   15 Nov 20 13:46 link1
 0 lrwxrwxrwx  1 brecht brecht    5 Nov 20 13:46 sym1 -> file1

tiger % cat link1
This is file1.

tiger % cat sym1
cat: cannot open sym1
```

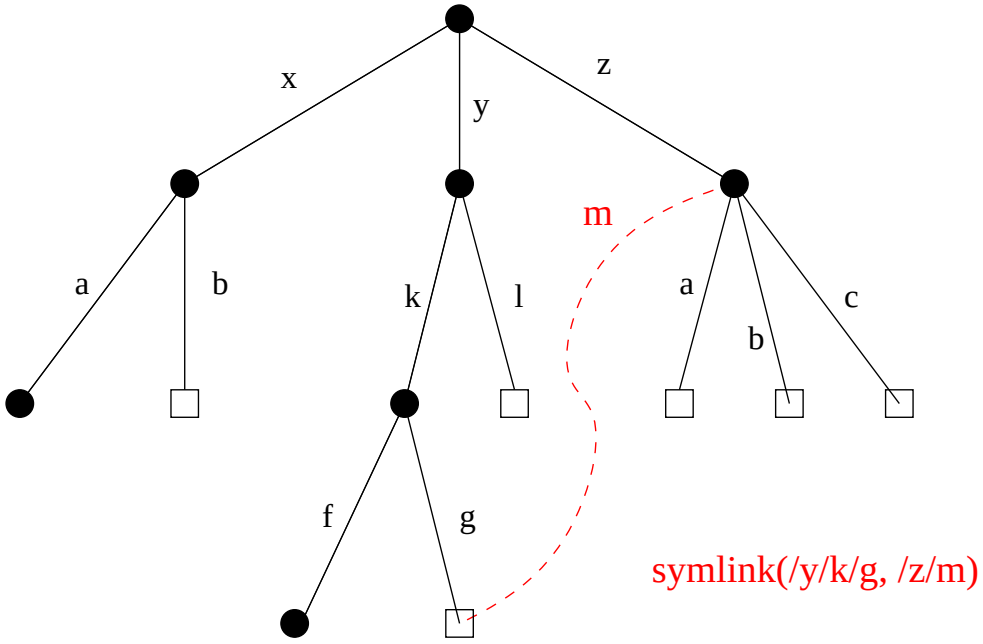

Hard Link Example (Part 1)



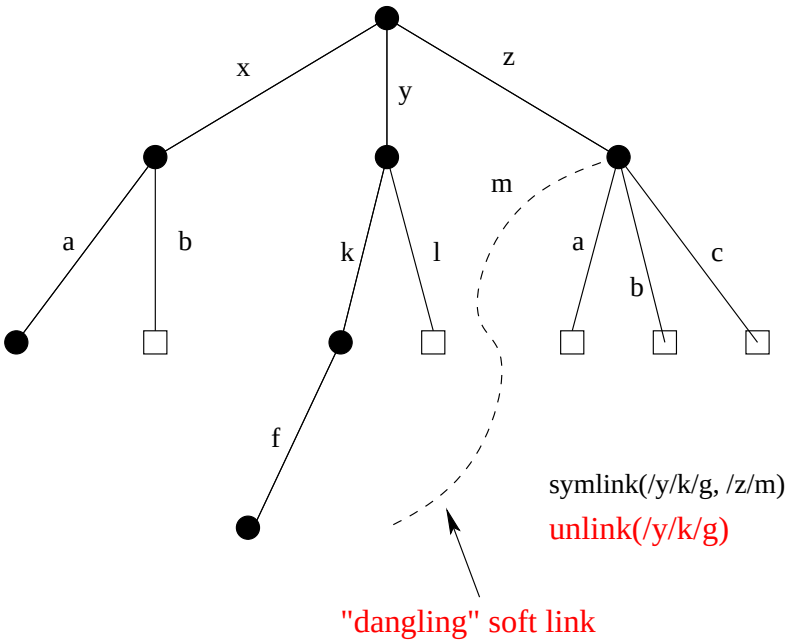
Hard Link Example (Part 2)



Soft Link Example (Part 1)



Soft Link Example (Part 2)



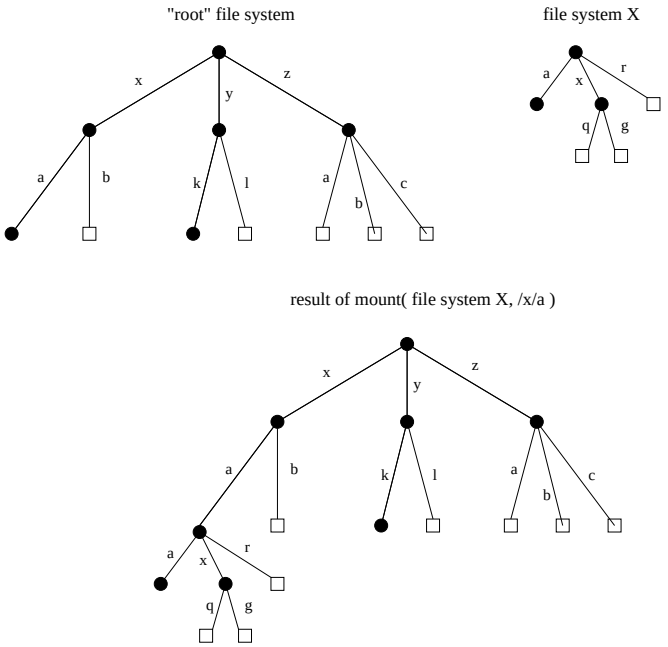
Multiple File Systems

- it is not uncommon for a system to have multiple file systems
- some kind of global file namespace is required
- two examples:

  DOS: use two-part file names: file system name,pathname
  - example: `C:\kmsalem\cs350\schedule.txt`

  Unix: merge file graphs into a single graph
  - Unix `mount` system call does this

Unix `mount` Example



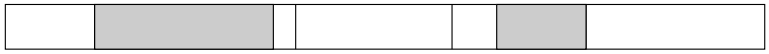
File System Implementation

- space management
- file indexing (how to locate file data and meta-data)
- directories
- links
- buffering, in-memory data structures
- persistence

Space Allocation

- space may be allocated in fixed-size chunks, or in chunks of varying size
- fixed-size chunks
  - simple space management
  - internal fragmentation
- variable-size chunks
  - external fragmentation

fixed−size allocation



variable−size allocation

Space Allocation (continued)

- differences between primary and secondary memory
  - larger transfers are cheaper (per byte) than smaller transfers
  - sequential I/O is faster than random I/O
- both of these suggest that space should be allocated to files in large chunks, sometimes called *extents*

File Indexing

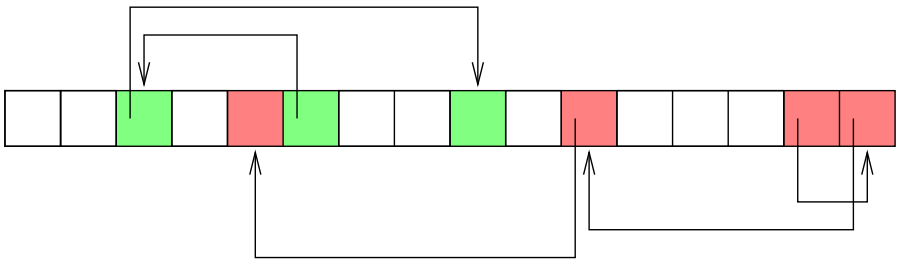
- in general, a file will require more than one chunk of allocated space (extent)
- this is especially true because files can grow
- how to find all of a file's data?

  chaining:
  - each chunk includes a pointer to the next chunk
  - OK for sequential access, poor for random access

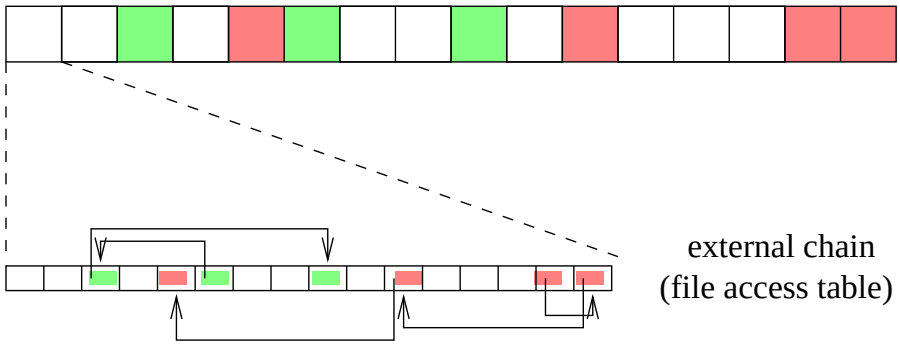
  external chaining: DOS file allocation table (FAT), for example
  - like chaining, but the chain is kept in an external structure

  per-file index: Unix i-node, for example
  - for each file, maintain a table of pointers to the file's blocks or extents

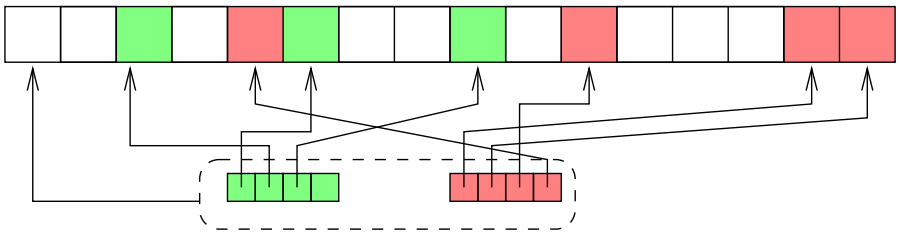
Chaining



External Chaining (File Access Table)



Per-File Indexing



File Meta-Data and Other Information

- where to store file meta-data?
  - immediately preceding the file data
  - with the file index (if per-file indexing is being used)
  - with the directory entry for the file
    - this is a problem if a file can have multiple names, and thus multiple directory entries

Unix i-nodes

- an i-node is a particular implementation of a per-file index
- each i-node is uniquely identified by an i-number, which determines its physical location on the disk
- an i-node is a fixed size record containing:

  file attribute values
  - file type
  - file owner and group
  - access controls
  - creation, reference and update timestamps
  - file size

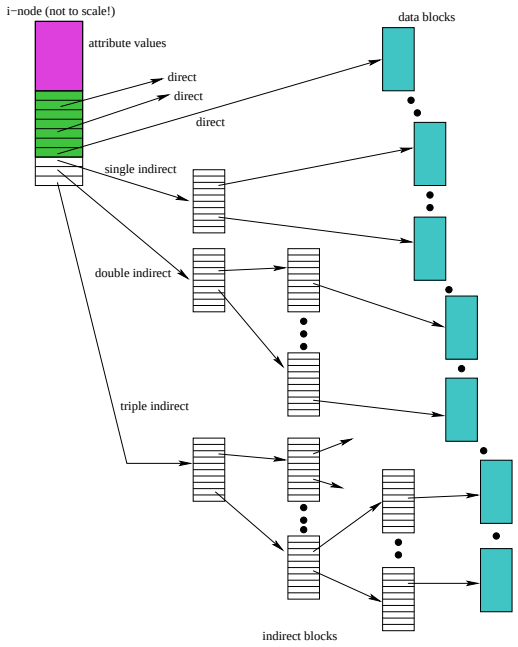
  direct block pointers: approximately 10 of these

  single indirect block pointer

  double indirect block pointer

  triple indirect block pointer

i-node Diagram



Directories

- A directory consists of a set of entries, where each entry is a record that includes:
  - a file name (component of a path name)
  - a file "locator"
    - location of the first block of the file, if chaining or external chaining is used
    - location of the file index, if per-file indexing is being used
- A directory can be implemented like any other file, except:
  - interface should allow reading of records (can be provided by a special system call or a library)
  - file should not be writable directly by application programs
  - directory records are updated by the kernel as files are created and destroyed

Implementing Hard Links (Unix)

- hard links are simply directory entries
- for example, consider:

  `link(/y/k/g,/z/m)`
- to implement this:
  - create a new entry in directory `/z`
    - file name in new entry is `m`
    - file locator (i-number) in the new entry is the same as the i-number for entry `g` in directory `/y/k`

Implementing Soft Links (Unix)

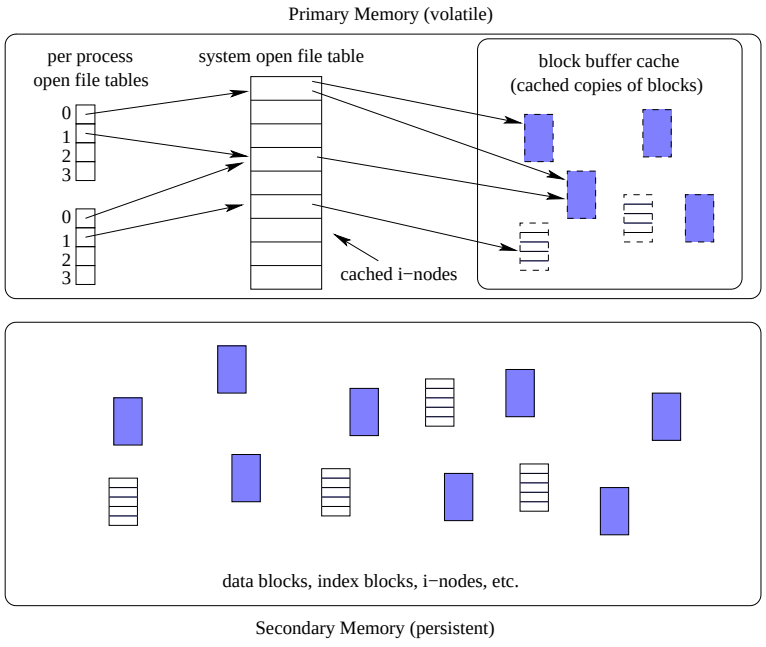
- soft links are implemented as a special type of file
- for example, consider:

  `symlink(/y/k/g,/z/m)`
- to implement this:
  - create a new *symlink* file
  - add a new entry in directory `/z`
    - file name in new entry is `m`
    - i-number in the new entry is the i-number of the new symlink file
  - store the pathname string "/y/k/g" as the contents of the new symlink file
- change the behaviour of the `open` system call so that when the symlink file is encountered during `open(/z/m)`, the file `/y/k/g` will be opened instead.

File System Meta-Data

- file system must record:
  - location of file indexes or file allocation table
  - location of free list(s) or free space index
  - file system parameters, e.g., block size
  - file system identifier and other attributes
- example: Unix *superblock*
  - located at fixed, predefined location(s) on the disk

Main Memory Data Structures



A Simple Exercise

- Walk through the steps that the file system must take to implement `Open`.
  - which data structures (from the previous slide) are updated?
  - how much disk I/O is involved?

Problems Caused by Failures

- a single logical file system operation may require several disk I/O operations
- example: deleting a file
  - remove entry from directory
  - remove file index (i-node) from i-node table
  - mark file's data blocks free in free space index
- what if, because a failure, some but not all of these changes are reflected on the disk?

Fault Tolerance

- special-purpose consistency checkers (e.g., Unix `fsck` in Berkeley FFS, Linux ext2)
  - runs after a crash, before normal operations resume
  - find and attempt to repair inconsistent file system data structures, e.g.:
    - file with no directory entry
    - free space that is not marked as free
- journaling (e.g., Veritas, NTFS, Linux ext3)
  - record file system meta-data changes in a journal (log), so that sequences of changes can be written to disk in a single operation
  - *after* changes have been journaled, update the disk data structures (*write-ahead logging*)
  - after a failure, redo journaled updates in case they were not done before the failure

Interprocess Communication Mechanisms

- shared storage
  - These mechanisms have already been covered. examples:
    - shared virtual memory
    - shared files
  - processes must agree on a name (e.g., a file name, or a shared virtual memory key) in order to establish communication
- message based
  - signals
  - sockets
  - pipes
  - . . .

Signals

- signals permit asynchronous one-way communication
  - from a process to another process, or to a group of processes
  - from the kernel to a process, or to a group of processes
- there are many types of signals
- the arrival of a signal may cause the execution of a *signal handler* in the receiving process
- there may be a different handler for each type of signal

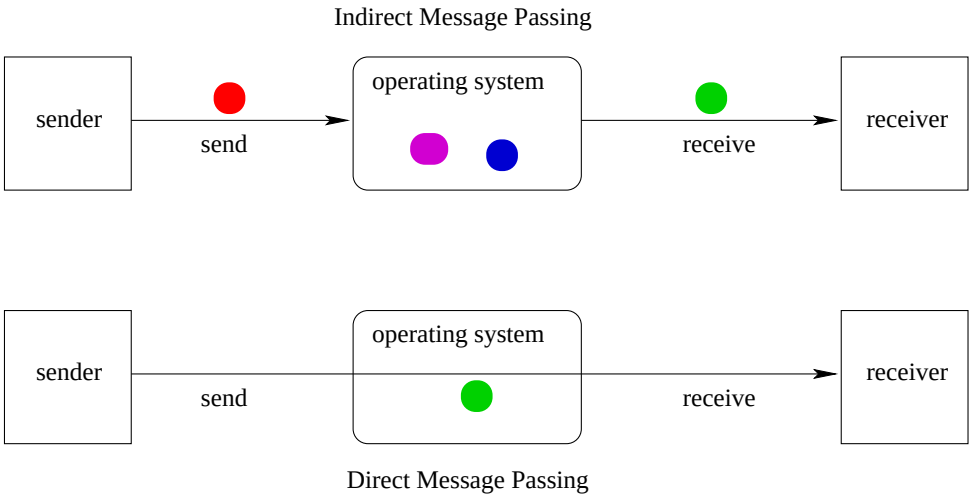
Examples of Signal Types

Signal	Value	Action	Comment
SIGINT	2	Term	Interrupt from keyboard
SIGILL	4	Core	Illegal Instruction
SIGKILL	9	Term	Kill signal
SIGCHLD	20,17,18	Ign	Child stopped or terminated
SIGBUS	10,7,10	Core	Bus error
SIGXCPU	24,24,30	Core	CPU time limit exceeded
SIGSTOP	17,19,23	Stop	Stop process

Signal Handling

- operating system determines default signal handling for each new process
- example default actions:
  - ignore (do nothing)
  - kill (terminate the process)
  - stop (block the process)
- a running process can change the default for some types of signals
- signal-related system calls
  - calls to set non-default signal handlers, e.g., Unix `signal`, `sigaction`
  - calls to send signals, e.g., Unix `kill`

Message Passing



If message passing is indirect, the message passing system must have some capacity to buffer (store) messages.

Properties of Message Passing Mechanisms

Addressing: how to identify where a message should go

Directionality:

- simplex (one-way)
- duplex (two-way)
- half-duplex (two-way, but only one way at a time)

Message Boundaries:

datagram model: message boundaries

stream model: no boundaries

Properties of Message Passing Mechanisms (cont'd)

Connections: need to connect before communicating?

- in connection-oriented models, recipient is specified at time of connection, not by individual send operations. All messages sent over a connection have the same recipient.
- in connectionless models, recipient is specified as a parameter to each send operation.

Reliability:

- can messages get lost?
- can messages get reordered?
- can messages get damaged?

Sockets

- a socket is a communication *end-point*
- if two processes are to communicate, each process must create its own socket
- two common types of sockets

  stream sockets: support connection-oriented, reliable, duplex communication under the stream model (no message boundaries)

  datagram sockets: support connectionless, best-effort (unreliable), duplex communication under the datagram model (message boundaries)

- both types of sockets also support a variety of address domains, e.g.,

  Unix domain: useful for communication between processes running on the same machine

  INET domain: useful for communication between process running on different machines that can communicate using IP protocols.

Using Datagram Sockets (Receiver)

```
s = socket(addressType, SOCK_DGRAM);
bind(s,address);
recvfrom(s,buf,bufLength,sourceAddress);
...
close(s);
```

- `socket` creates a socket
- `bind` assigns an address to the socket
- `recvfrom` receives a message from the socket
  - `buf` is a buffer to hold the incoming message
  - `sourceAddress` is a buffer to hold the address of the message sender
- both `buf` and `sourceAddress` are filled by the `recvfrom` call

Using Datagram Sockets (Sender)

```
s = socket(addressType, SOCK_DGRAM);
sendto(s,buf,msgLength,targetAddress)
...
close(s);
```

- `socket` creates a socket
- `sendto` sends a message using the socket
  - `buf` is a buffer that contains the message to be sent
  - `msgLength` indicates the length of the message in the buffer
  - `targetAddress` is the address of the socket to which the message is to be delivered

More on Datagram Sockets

- `sendto` and `recvfrom` calls *may* block
  - `recvfrom` blocks if there are no messages to be received from the specified socket
  - `sendto` blocks if the system has no more room to buffer undelivered messages
- datagram socket communications are (in general) unreliable
  - messages (datagrams) may be lost
  - messages may be reordered
- The sending process must know the address of the receive process's socket. How does it know this?

A Socket Address Convention

```
Service         Port       Description
-----------------------------------------------------
echo            7/udp
systat          11/tcp
netstat         15/tcp
chargen         19/udp
ftp             21/tcp
ssh             22/tcp     # SSH Remote Login Protocol
telnet          23/tcp
smtp            25/tcp
time            37/udp
gopher          70/tcp     # Internet Gopher
finger          79/tcp
www             80/tcp     # WorldWideWeb HTTP
pop2            109/tcp    # POP version 2
imap2           143/tcp    # IMAP
```

Using Stream Sockets (Passive Process)

```
s = socket(addressType, SOCK_STREAM);
bind(s,address);
listen(s,backlog);
ns = accept(s,sourceAddress);
recv(ns,buf,bufLength);
send(ns,buf,bufLength);
...
close(ns); // close accepted connection
close(s);  // don't accept more connections
```

- `listen` specifies the number of connection requests for this socket that will be queued by the kernel
- `accept` accepts a connection request and creates a new socket (`ns`)
- `recv` receives up to `bufLength` bytes of data from the connection
- `send` sends `bufLength` bytes of data over the connection.

Notes on Using Stream Sockets (Passive Process)

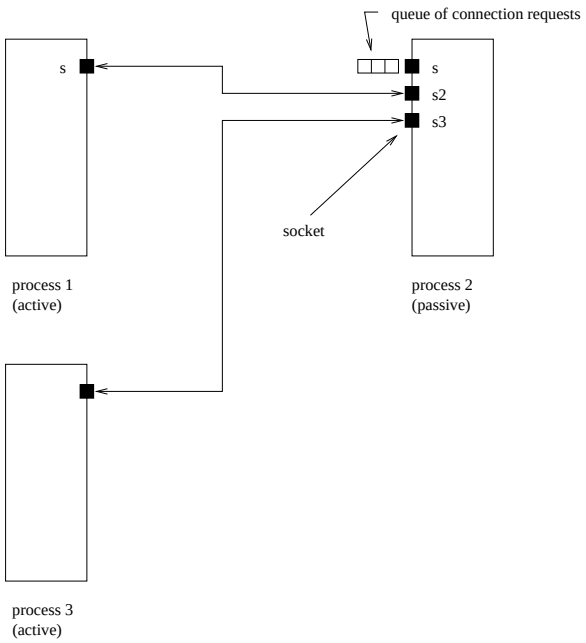
- `accept` creates a new socket (`ns`) for the new connection
- `sourceAddress` is an address buffer. `accept` fills it with the address of the socket that has made the connection request
- additional connection requests can be accepted using more `accept` calls on the original socket (`s`)
- `accept` blocks if there are no pending connection requests
- connection is duplex (both `send` and `recv` can be used)

Using Stream Sockets (Active Process)

```
s = socket(addressType, SOCK_STREAM);
connect(s,targetAddress);
send(s,buf,bufLength);
recv(s,buf,bufLength);
...
close(s);
```

- `connect` sends a connection request to the socket with the specified address
  - `connect` blocks until the connection request has been accepted
- active process may (optionally) bind an address to the socket (using `bind`) before connecting. This is the address that will be returned by the `accept` call in the passive process
- if the active process does not choose an address, the system will choose one

Illustration of Stream Socket Connections



Socket Example: Client

```
#include "defs.h"

#define USAGE "client serverhost port#\n"
#define ERROR_STR_LEN  (80)

int
main(int argc, char *argv[])
{
  struct hostent *hostp;
  int socketfd, server_port, num;

  char error_str[ERROR_STR_LEN];
  char read_buf[BUF_LEN];
  char *hostname;
  struct sockaddr_in server_addr;
  struct in_addr tmp_addr;

  if (argc != 3) {
    fprintf(stderr, "%s", USAGE);
    exit(-1);
  }
```


Socket Example: Client (continued)

```
  /* get hostname and port for the server */
  hostname = argv[1];
  server_port = atoi(argv[2]);

  /* get the server hosts address */
  if ((hostp = (struct hostent *)
       gethostbyname(hostname)) ==
       (struct hostent *) NULL) {
    sprintf(error_str,
       "client: gethostbyname fails for host  %s",
        hostname);
    /* gethostbyname sets h_errno */
    herror(error_str);
    exit(-1);
  }

  /* create a socket to connect to server */
  if ((socketfd = socket(DOMAIN, SOCK_STREAM, 0)) < 0) {
    perror("client: can't create socket ");
    exit(1);
  }
```

Socket Example: Client (continued)

```
/* zero the socket address structure */
memset((char *) &server_addr, 0, sizeof(server_addr));

/* start constructing the server socket addr */
memcpy(&tmp_addr, hostp->h_addr_list[0],
       hostp->h_length);

printf("Using server IP addr = %s\n",
        inet_ntoa(tmp_addr));

/* set servers address field, port number and family */
memcpy((char *) &server_addr.sin_addr,
       (char *) &tmp_addr,
       (unsigned int) hostp->h_length);
server_addr.sin_port = htons(server_port);
server_addr.sin_family = DOMAIN;
```


Socket Example: Client (continued)

```
/* connect to the server */
if (connect(socketfd, (struct sockaddr  *) &server_addr,
  sizeof(server_addr)) < 0) {
  perror("client: can't connect socket ");
  exit(1);
}

/* send from the client to the server */
num = write(socketfd, CLIENT_STR, CLIENT_BYTES);
if (num < 0) {
  perror("client: write to socket failed\n");
  exit(1);
}
assert(num == CLIENT_BYTES);
```

Socket Example: Client (continued)

```
  /* receive data sent back by the server */
  total_read = 0;
  while (total_read < SERVER_BYTES) {
    num = read(socketfd, &read_buf[total_read],
       SERVER_BYTES - total_read);
    if (num < 0) {
      perror("client: read from socket failed\n");
      exit(1);
    }
    total_read += num;
  }

  printf("sent %s\n", CLIENT_STR);
  printf("received %s\n", read_buf);

  close(socketfd);
  exit(0);
} /* main */
```


Socket Example: Server

```
#include "defs.h"

int
main()
{
  int serverfd, clientfd;
  struct sockaddr_in server_addr, client_addr;
  int size, num;
  char read_buf[BUF_LEN];
  struct sockaddr_in bound_addr;

  serverfd = socket(DOMAIN, SOCK_STREAM, 0);

  if (serverfd < 0) {
    perror("server: unable to create socket ");
    exit(1);
  }
```

Socket Example: Server (continued)

```
/* zero the server_addr structure */
memset((char *) &server_addr, 0, sizeof (server_addr));

/* set up addresses server will accept connections on */
server_addr.sin_addr.s_addr = htonl(INADDR_ANY);
server_addr.sin_port = htons(PORT);
server_addr.sin_family = DOMAIN;

/* assign address to the socket */
if (bind (serverfd, (struct sockaddr *) &server_addr,
  sizeof(server_addr)) < 0) {
  perror("server: unable to bind socket ");
  exit(1);
}

/* Willing to accept connections on this socket. */
/* Maximum backlog of 5 clients can be queued */
listen(serverfd, 5);
```


Socket Example: Server (continued)

```
for (;;) {
  /* wait for and return next completed connection */
  size = sizeof(client_addr);
  if ((clientfd = accept(serverfd,
       (struct sockaddr *) &client_addr, &size)) < 0) {
    perror("server: accept failed ");
    exit(1);
  }

  /* get the data sent by the client */
  total_read = 0;
  while (total_read < CLIENT_BYTES) {
    num = read(clientfd, &read_buf[total_read],
          CLIENT_BYTES - total_read);
    if (num < 0) {
      perror("server: read from client socket failed ");
      exit(1);
    }
    total_read += num;
  }
```

Socket Example: Server (continued)

```
    /* process the client info / request here */
    printf("client sent %s\n", read_buf);
    printf("server sending %s\n", SERVER_STR);

    /* send the data back to the client */
    num = write(clientfd, SERVER_STR, SERVER_BYTES);
    if (num < 0) {
      perror("server: write to client socket failed ");
      exit(1);
    }
    assert(num == SERVER_BYTES);

    close(clientfd);
  } /* for */
  exit(0);
} /* main */
```

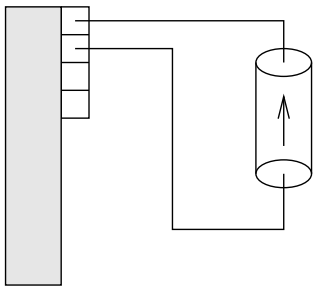

Pipes

- pipes are communication objects (not end-points)
- pipes use the stream model and are connection-oriented and reliable
- some pipes are simplex, some are duplex
- pipes use an implicit addressing mechanism that limits their use to communication between *related* processes, typically a child process and its parent
- a `pipe()` system call creates a pipe and returns two descriptors, one for each end of the pipe
  - for a simplex pipe, one descriptor is for reading, the other is for writing
  - for a duplex pipe, both descriptors can be used for reading and writing

One-way Child/Parent Communication Using a Simplex Pipe

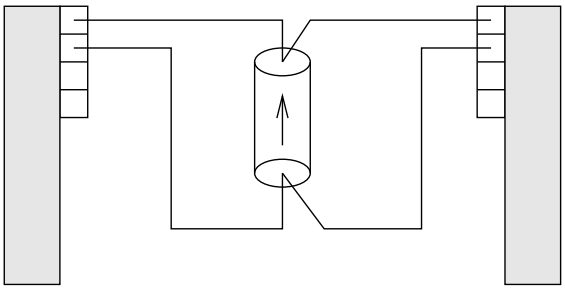
```
int fd[2];
char m[] = "message for parent";
char y[100];
pipe(fd); // create pipe
pid = fork(); // create child process
if (pid == 0) {
  // child executes this
  close(fd[0]); // close read end of pipe
  write(fd[1],m,19);
  ...
} else {
  // parent executes this
  close(fd[1]); // close write end of pipe
  read(fd[0],y,100);
  ...
}
```


Illustration of Example (after `pipe()`)



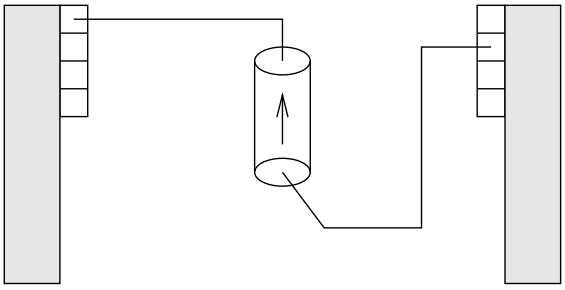
parent process

Illustration of Example (after `fork()`)



parent process child process

Illustration of Example (after `close()`)



parent process child process

Examples of Other Interprocess Communication Mechanisms

named pipe:

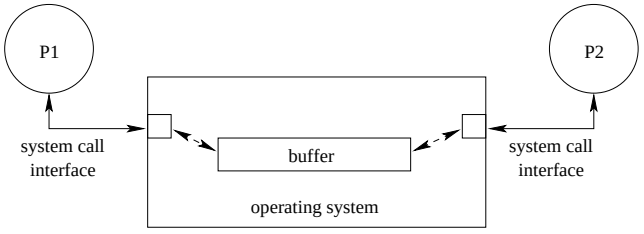
- similar to pipes, but with an associated name (usually a file name)
- name allows arbitrary processes to communicate by opening the same named pipe
- must be explicitly deleted, unlike an unnamed pipe

message queue:

- like a named pipe, except that there are message boundaries
- `msgsend` call sends a message into the queue, `msgrecv` call receives the next message from the queue

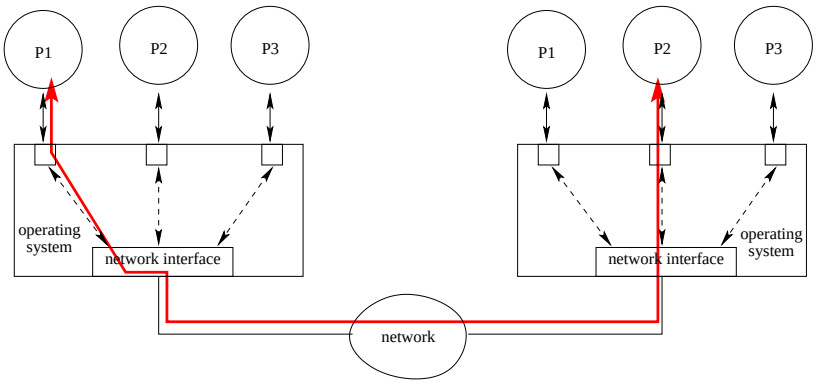
Implementing IPC

- application processes use descriptors (identifiers) provided by the kernel to refer to specific sockets and pipes, as well as files and other objects
- kernel *descriptor tables* (or other similar mechanism) are used to associate descriptors with kernel data structures that implement IPC objects
- kernel provides bounded buffer space for data that has been sent using an IPC mechanism, but that has not yet been received
  - for IPC objects, like pipes, buffering is usually on a per object basis
  - IPC end points, like sockets, buffering is associated with each endpoint



Network Interprocess Communication

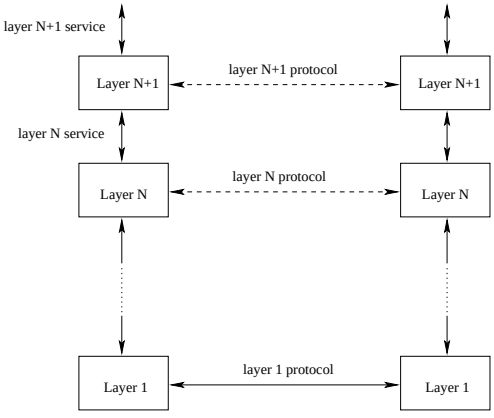
- some sockets can be used to connect processes that are running on different machine
- the kernel:
  - controls access to network interfaces
  - multiplexes socket connections across the network



Networking Reference Models

- ISO/OSI Reference Model

7	Application Layer
6	Presentation Layer
5	Session Layer
4	Transport Layer
3	Network Layer
2	Data Link Layer
1	Physical Layer



- Internet Model
  - layers 1-4 and 7

Internet Protocol (IP): Layer 3

- every machine has one (or more) IP address, in addition to its data link layer address(es)
- In IPv4, addresses are 32 bits, and are commonly written using "dot" notation, e.g.:
  - cpu06.student.cs = 129.97.152.106
  - www.google.ca = 216.239.37.99 or 216.239.51.104 or ...
- IP moves packets (datagrams) from one machine to another machine
- principal function of IP is *routing*: determining the network path that a packet should take to reach its destination
- IP packet delivery is "best effort" (unreliable)

IP Routing Table Example

- Routing table for zonker.uwaterloo.ca, which is on three networks, and has IP addresses 129.97.74.66, 172.16.162.1, and 192.168.148.1 (one per network):

Destination	Gateway	Interface
172.16.162.*	-	vmnet1
129.97.74.*	-	eth0
192.168.148.*	-	vmnet8
default	129.97.74.1	eth0

- routing table key:

  destination: ultimate destination of packet

  gateway: next hop towards destination (or "-" if destination is directly reachable)

  interface: which network interface to use to send this packet

Internet Transport Protocols

TCP: transport control protocol

- connection-oriented
- reliable
- stream
- congestion control
- used to implement INET domain stream sockets

UDP: user datagram protocol

- connectionless
- unreliable
- datagram
- no congestion control
- used to implement INET domain datagram sockets

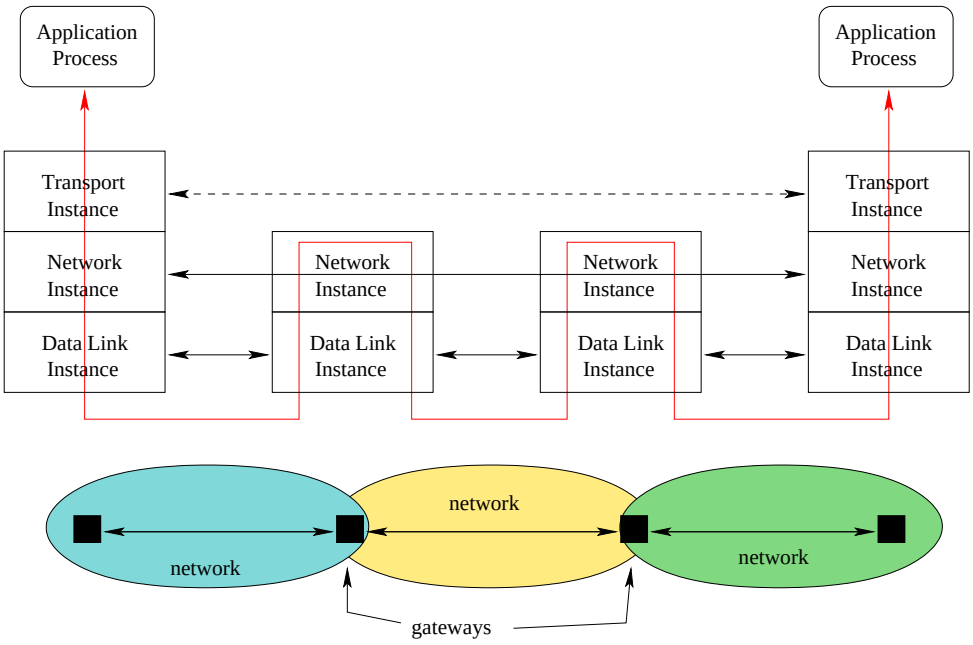
TCP and UDP Ports

- since there can be many TCP or UDP communications end points (sockets) on a single machine, there must be a way to distinguish among them
- each TCP or UDP address can be thought of as having two parts:

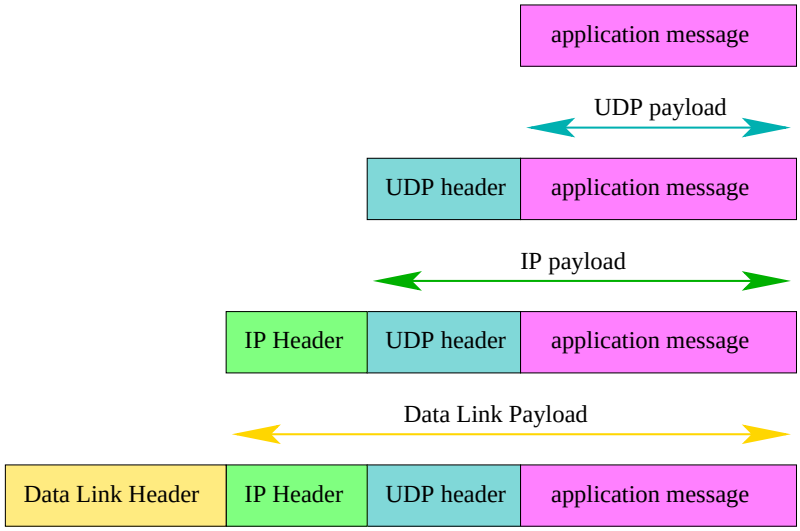
  (machine name, port number)

- The machine name is the IP address of a machine, and the port number serves to distinguish among the end points on that machine.
- INET domain socket addresses are TCP or UDP addresses (depending on whether the socket is a stream socket or a datagram socket).

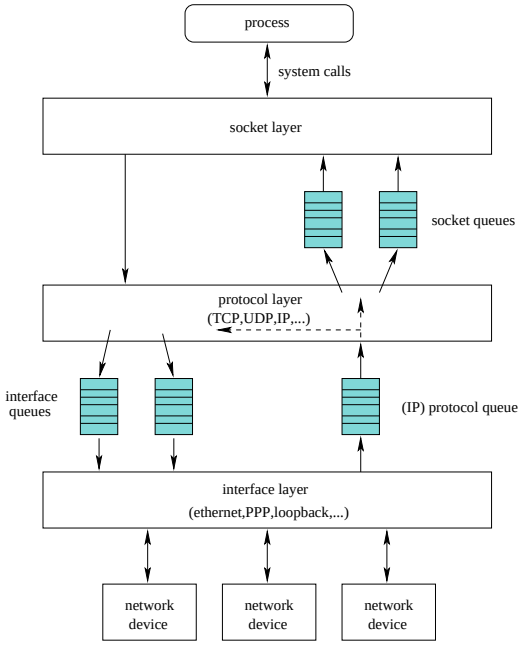
Example of Network Layers



Network Packets (UDP Example)



BSD Unix Networking Layers



Protection and Security

Protection: ensure controlled access to resources *internally* within a system

- OS provides mechanisms for policy enforcement
- Principle of least privilege: grant only enough privileges to complete task

Security: need to have adequate protection and consider *external* environment

- Security is hard because so many people try to break it.

Protection Domains

- Process should have access to specific objects and have the right to do specific things with each
- Rights should change to reflect what is needed at the time
- At any time, a process is operating in a protection domain that determines its access rights
- The domains should change to reflect actual needs
  (principle of least privilege)
- In most systems
  - domain changes are rare
  - more rights are granted than are needed

Protection Domains: Examples

- When you compile, should the compiler have access to all of your files? E.g., mail, mp3 files, video
  - what is stopping it from transferring these files to another host
  - what is stopping it from deleting these files
- Often protection domain == user

  All processes belonging to a user have the same rights
- Changing protection domains

  UNIX setuid, effective user id becomes the same as file owner

  Windows Server "execute as"
- Grant additional rights to specific programs, but not a solution to the first problem above

Protection: The Access Control Matrix

		Objects				
		1	2	3	4	5
Subjects	1		R		R	
	2			R,W		R,W
	3	R,X	R,W	R,W		
	4			R		

objects: the things to be protected, e.g., files, printers, etc.

subjects: users, groups, roles

matrix entries: access rights, i.e., operations allowed by a subject on an object

A common implementation is an *access control list* for each object.

Protection: Access Control Administration

- there must be a mechanism for changing the access rights described in the access control matrix
  - set of subjects is dynamic
  - set of objects is dynamic
  - access rights may need to change
- some approaches
  - encode access control change rights in the access control matrix
    - add "owner" as a possible access right. Subject with owner rights on object x can change access rights in x's column.
  - new users/subjects can inherit rights from others

Protection: Example – Access Rights in Unix

- subjects are users and groups (group membership is maintained separately)
- each object has an owner and a group
- access rights are specified for the owner, for the group, and for everyone else
- object access rights can be modified by the object owner
- major access rights are read, write, and execute
- access controls can be applied to files, devices, shared memory segments, and more.

Protection: Authentication

- object access is performed by processes
- to apply access controls, it is necessary to associate processes with users
- this requires user *authentication*
- some authentication techniques:
  - passwords
  - cryptographic (e.g., public key methods)
  - physical tokens (e.g., smart cards)
  - biometrics

Security

OS / Network threats:

- Trojan Horses
- Trap Doors
- Buffer Overflows
- Worms
- Viruses
- Other (specific examples)

Even Worse:

- Physical
- Human

Trojan Horses

- Two different meanings:
  1. A programs that intends to run and do something undesirable
     E.g., download a program/game that also erases all of your files
  2. User tricked into running it
     Unix PATH variable includes "." as first entry
     `% cd /home/username; ls` BUT
     `/home/username/ls` is actually
     `cd $HOME; /bin/rm -rf *`

     Fundamental problem: privilege of command determined by user

Trap Doors / Back Doors

Lets perpetrator do things they wouldn't normally be allowed to do.
For example,

- when run by root
- surprise/undocumented response to a special input
  game cheats (type sequence of characters that make you invincible)
- special/alternate login program allows author access via special user name

Usually obscure, casual examination of source would miss it

Buffer Overflows

Send more data than is expected by executing program

Many programs have fixed-sized input buffers but don't limit input length

Data contains executable code

Consequences:

- Crash
- Much worse when buffer is on the stack (execute arbitrary code)

Very machine dependent but the X86 family is very wide-spread

Worms

- Program that replicates itself from one system to another (usually via Internet)
- Tend to consume resources leading to a Denial of Service (DOS) attack
- Arbitrarily bad behaviour
- Often use buffer overflows to compromise systems/users

  Morris Worm:
  - Spread using legitimate access of compromised users (e.g., .rhosts)
  - 1988 – 3 yrs probation, 400 hrs community service, $10K

  Sobig:
  - Mail to all users in the address book
  - Modifies system parameters to restart worm when rebooted (registry)

Viruses

- Not a free standing program, but a fragment attached to a legitimate program
- Essentially a dynamic Trojan horse or trap door.
- Especially a problem on single user systems with weak or non-existent protection

  Makes it easy to infect file systems
- Microsoft Office Macros and/or Active X lead to problems with Word files, email and web content
  - no need to reboot
  - execution not even expected
- Denial of Service often occurs at the same time (as a result of rapid spreading)

Specific Examples / Hacks

- Allocate virtual memory and look for data
- Illegal system calls or calls with invalid number of parameters or types
- Modify any OS data structures stored in user data e.g., `open()` call
- Look for don't do XXX in the documentation
- Social Engineering

Additional Notes:

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