CS162
Operating Systems and Systems Programming
Lecture 10

Synchronization 4: Readers/Writers
Scheduling Intro: Pintos Concurrency, FCFS

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Recall: Bounded Buffer, 3rd cut (coke machine)


```
Semaphore fullSlots = 0;       // Initially, no coke
Semaphore emptySlots = bufSize;
                               // Initially, num empty slots
Semaphore mutex = 1;           // No one using machine

Producer(item) {
    semaP(&emptySlots);        // Wait until space
    semaP(&mutex);             // Wait until machine free
    Enqueue(item);
    semaV(&mutex);
    semaV(&fullSlots);         // Tell consumers there is
                               // more coke
}
Consumer() {
    semaP(&fullSlots);         // Check if there's a coke
    semaP(&mutex);             // Wait until machine free
    item = Dequeue();
    semaV(&mutex);
    semaV(&emptySlots);        // tell producer need more
    return item;
}
```

`fullSlots` signals coke

`emptySlots` signals space

Critical sections using mutex protect integrity of the queue

Recall: Monitors and Condition Variables

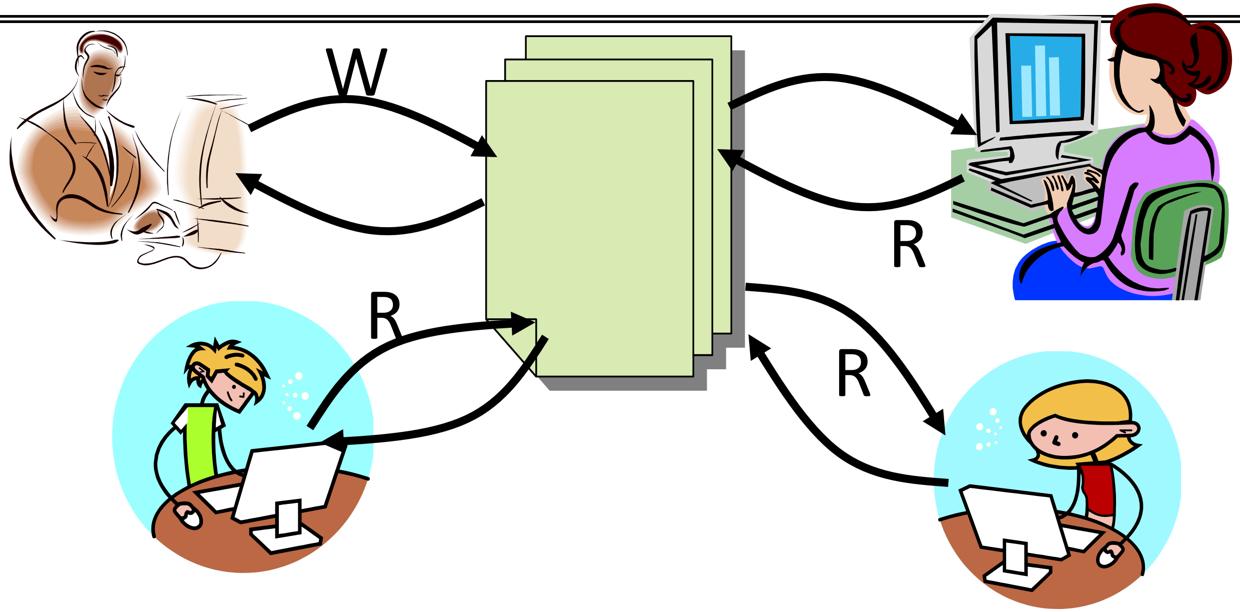
- Monitor: a lock and zero or more condition variables for managing concurrent access to shared data
  – Use of Monitors is a programming paradigm
  – Some languages like Java provide monitors in the language
- Condition Variable: a queue of threads waiting for something *inside* a critical section
  – Key idea: allow sleeping inside critical section by atomically releasing lock at time we go to sleep
  – Contrast to semaphores: Can't wait inside critical section
- Operations:
  – `Wait(&lock)`: Atomically release lock and go to sleep. Re-acquire lock later, before returning.
  – `Signal()`: Wake up one waiter, if any
  – `Broadcast()`: Wake up all waiters
- Rule: Must hold lock when doing condition variable ops!

Recall: Bounded Buffer – 4rd cut (Monitors, pthread-like)

```
lock buf_lock = <initially unlocked>
condition producer_CV = <initially empty>
condition consumer_CV = <initially empty>

Producer(item) {
  acquire(&buf_lock);
  while (buffer full) { cond_wait(&producer_CV, &buf_lock); }
  enqueue(item);
  cond_signal(&consumer_CV);
  release(&buf_lock);
}

Consumer() {
  acquire(buf_lock);
  while (buffer empty) { cond_wait(&consumer_CV, &buf_lock); }
  item = dequeue();
  cond_signal(&producer_CV);
  release(buf_lock);
  return item
}
```

What does thread do when it is waiting?
- Sleep, not busywait!

Readers/Writers Problem



- Motivation: Consider a shared database
  - Two classes of users:
    - » Readers – never modify database
    - » Writers – read and modify database
  - Is using a single lock on the whole database sufficient?
    - » Like to have many readers at the same time
    - » Only one writer at a time

Basic Structure of *Mesa* Monitor Program

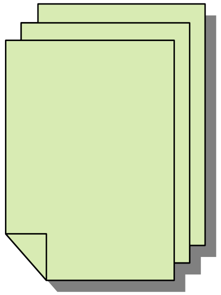
- Monitors represent the synchronization logic of the program
  - Wait if necessary
  - Signal when change something so any waiting threads can proceed
- Basic structure of mesa monitor-based program:

```
lock
while (need to wait) {
    condvar.wait();
}
unlock

do something so no need to wait

lock

condvar.signal();

unlock
```

Check and/or update state variables
Wait if necessary

Check and/or update state variables

Basic Readers/Writers Solution



- Correctness Constraints:
  - Readers can access database when no writers
  - Writers can access database when no readers or writers
  - Only one thread manipulates state variables at a time
- Basic structure of a solution:
  - **Reader()**
    ```
    Wait until no writers
    Access data base
    Check out – wake up a waiting writer
    ```
  - **Writer()**
    ```
    Wait until no active readers or writers
    Access database
    Check out – wake up waiting readers or writer
    ```
  - State variables (Protected by a lock called “lock”):
    - » int AR: Number of active readers; initially = 0
    - » int WR: Number of waiting readers; initially = 0
    - » int AW: Number of active writers; initially = 0
    - » int WW: Number of waiting writers; initially = 0
    - » Condition okToRead = NIL
    - » Condition okToWrite = NIL

Code for a Reader

```
Reader() {
  // First check self into system
  acquire(&lock);
  while ((AW + WW) > 0) { // Is it safe to read?
    WR++;                 // No. Writers exist
    cond_wait(&okToRead,&lock);// Sleep on cond var
    WR--;                 // No longer waiting
  }
  AR++;                   // Now we are active!
  release(&lock);
  // Perform actual read-only access
  AccessDatabase(ReadOnly);
  // Now, check out of system
  acquire(&lock);
  AR--;                   // No longer active
  if (AR == 0 && WW > 0)  // No other active readers
    cond_signal(&okToWrite);// Wake up one writer
  release(&lock);
}
```

Code for a Writer

```
Writer() {
  // First check self into system
  acquire(&lock);
  while ((AW + AR) > 0) { // Is it safe to write?
    WW++;                 // No. Active users exist
    cond_wait(&okToWrite,&lock);  // Sleep on cond var
    WW--;                 // No longer waiting
  }
  AW++;                   // Now we are active!
  release(&lock);
  // Perform actual read/write access
  AccessDatabase(ReadWrite);
  // Now, check out of system
  acquire(&lock);
  AW--;                   // No longer active
  if (WW > 0){            // Give priority to writers
    cond_signal(&okToWrite);// Wake up one writer
  } else if (WR > 0) {    // Otherwise, wake reader
    cond_broadcast(&okToRead); // Wake all readers
  }
  release(&lock);
}
```

Simulation of Readers/Writers Solution

- Use an example to simulate the solution

- Consider the following sequence of operators:
  - R1, R2, W1, R3

- Initially: AR = 0, WR = 0, AW = 0, WW = 0

Simulation of Readers/Writers Solution

- R1 comes along (no waiting threads)
- AR = 0, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock)
    while ((AW + WW) > 0) { // Is it safe to read?
       WR++;               // No. Writers exist
       cond_wait(&okToRead,&lock);// Sleep on cond var
       WR--;               // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
       cond_signal(&okToWrite);
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- R1 comes along (no waiting threads)
- AR = 0, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
      WR++;                  // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                  // No longer waiting
    }
    AR++;                    // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R1 comes along (no waiting threads)
- AR = 1, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R1 comes along (no waiting threads)
- AR = 1, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- R1 accessing dbase (no other threads)
- AR = 1, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R2 comes along (R1 accessing dbase)
- AR = 1, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
        WR++;               // No. Writers exist
        cond_wait(&okToRead,&lock);// Sleep on cond var
        WR--;               // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
        cond_signal(&okToWrite);
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- R2 comes along (R1 accessing dbase)
- AR = 1, WR = 0, AW = 0, WW = 0

```
Reader() {
   acquire(&lock);
   while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                // No longer waiting
   }
   AR++;                   // Now we are active!
   release(&lock);

   AccessDBase(ReadOnly);

   acquire(&lock);
   AR--;
   if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
   release(&lock);
 }
```

Simulation of Readers/Writers Solution

- R2 comes along (R1 accessing dbase)
- AR = 2, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R2 comes along (R1 accessing dbase)
- AR = 2, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R1 and R2 accessing dbase
- AR = 2, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
      WR++;                  // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                  // No longer waiting
    }
    AR++;                    // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
```

Assume readers take a while to access database

Situation: Locks released, only AR is non-zero

Simulation of Readers/Writers Solution

- W1 comes along (R1 and R2 are still accessing dbase)
- AR = 2, WR = 0, AW = 0, WW = 0

```
Writer() {
  acquire(&lock);
  while ((AW + AR) > 0) {  // Is it safe to write?
     WW++;                 // No. Active users exist
     cond_wait(&okToWrite,&lock);// Sleep on cond var
     WW--;                 // No longer waiting
  }
  AW++;
  release(&lock);

  AccessDBase(ReadWrite);

  acquire(&lock);
  AW--;
  if (WW > 0){
     cond_signal(&okToWrite);
  } else if (WR > 0) {
     cond_broadcast(&okToRead);
  }
  release(&lock);
}
```

Simulation of Readers/Writers Solution

- W1 comes along (R1 and R2 are still accessing dbase)
- AR = 2, WR = 0, AW = 0, WW = 0

```
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {   // Is it safe to write?
      WW++;                   // No. Active users exist
      cond_wait(&okToWrite,&lock);// Sleep on cond var
      WW--;                   // No longer waiting
    }
    AW++;
    release(&lock);

    AccessDBase(ReadWrite);

    acquire(&lock);
    AW--;
    if (WW > 0){
      cond_signal(&okToWrite);
    } else if (WR > 0) {
      cond_broadcast(&okToRead);
    }
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- W1 comes along (R1 and R2 are still accessing dbase)
- AR = 2, WR = 0, AW = 0, WW = 1

```
Writer() {
   acquire(&lock);
   while ((AW + AR) > 0) {  // Is it safe to write?
      WW++;                 // No. Active users exist
      cond_wait(&okToWrite,&lock);// Sleep on cond var
      WW--;                 // No longer waiting
   }
   AW++;
   release(&lock);

   AccessDBase(ReadWrite);

   acquire(&lock);
   AW--;
   if (WW > 0){
      cond_signal(&okToWrite);
   } else if (WR > 0) {
      cond_broadcast(&okToRead);
   }
   release(&lock);
}
```

Simulation of Readers/Writers Solution

- R3 comes along (R1 and R2 accessing dbase, W1 waiting)
- AR = 2, WR = 0, AW = 0, WW = 1

```
Reader() {
   acquire(&lock);
   while ((AW + WW) > 0) { // Is it safe to read?
     WR++;                 // No. Writers exist
     cond_wait(&okToRead,&lock);// Sleep on cond var
     WR--;                 // No longer waiting
   }
   AR++;                   // Now we are active!
   release(&lock);

   AccessDBase(ReadOnly);

   acquire(&lock);
   AR--;
   if (AR == 0 && WW > 0)
     cond_signal(&okToWrite);
   release(&lock);
 }
```

Simulation of Readers/Writers Solution

- R3 comes along (R1 and R2 accessing dbase, W1 waiting)
- AR = 2, WR = 0, AW = 0, WW = 1

```
Reader() {
   acquire(&lock);
   while ((AW + WW) > 0) { // Is it safe to read?
     WR++;                 // No. Writers exist
     cond_wait(&okToRead,&lock);// Sleep on cond var
     WR--;                 // No longer waiting
   }
   AR++;                   // Now we are active!
   release(&lock);

   AccessDBase(ReadOnly);

   acquire(&lock);
   AR--;
   if (AR == 0 && WW > 0)
     cond_signal(&okToWrite);
   release(&lock);
 }
```

Simulation of Readers/Writers Solution

- R3 comes along (R1 and R2 accessing dbase, W1 waiting)
- AR = 2, WR = 1, AW = 0, WW = 1

```
Reader() {
   acquire(&lock);
   while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                // No longer waiting
   }
   AR++;                   // Now we are active!
   lock.release();

   AccessDBase(ReadOnly);

   acquire(&lock);
   AR--;
   if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
   release(&lock);
 }
```

Simulation of Readers/Writers Solution

- R3 comes along (R1, R2 accessing dbase, W1 waiting)
- AR = 2, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R1 and R2 accessing dbase, W1 and R3 waiting
- AR = 2, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
```

Status:
- R1 and R2 still reading
- W1 and R3 waiting on okToWrite and okToRead, respectively

Simulation of Readers/Writers Solution

- R2 finishes (R1 accessing dbase, W1 and R3 waiting)
- AR = 2, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
        WR++;                  // No. Writers exist
        cond_wait(&okToRead,&lock);// Sleep on cond var
        WR--;                  // No longer waiting
    }
    AR++;                      // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
        cond_signal(&okToWrite);
    release(&lock);
}
```

Simulation of Readers/Writers Solution

- R2 finishes (R1 accessing dbase, W1 and R3 waiting)
- AR = 1, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) {  // Is it safe to read?
      WR++;                  // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                  // No longer waiting
    }
    AR++;                    // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R2 finishes (R1 accessing dbase, W1 and R3 waiting)
- AR = 1, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R2 finishes (R1 accessing dbase, W1 and R3 waiting)
- AR = 1, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R1 finishes (W1 and R3 waiting)
- AR = 1, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R1 finishes (W1, R3 waiting)
- AR = 0, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R1 finishes (W1, R3 waiting)
- AR = 0, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R1 signals a writer (W1 and R3 waiting)
- AR = 0, WR = 1, AW = 0, WW = 1

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- W1 gets signal (R3 still waiting)
- AR = 0, WR = 1, AW = 0, WW = 1

```
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {  // Is it safe to write?
      WW++;                  // No. Active users exist
      cond_wait(&okToWrite,&lock);// Sleep on cond var
      WW--;                  // No longer waiting
    }
    AW++;
    release(&lock);

    AccessDBase(ReadWrite);

    acquire(&lock);
    AW--;
    if (WW > 0){
      cond_signal(&okToWrite);
    } else if (WR > 0) {
      cond_broadcast(&okToRead);
    }
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- W1 gets signal (R3 still waiting)
- AR = 0, WR = 1, AW = 0, WW = 0

```
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {  // Is it safe to write?
      WW++;                  // No. Active users exist
      cond_wait(&okToWrite,&lock);// Sleep on cond var
      WW--;                  // No longer waiting
    }
    AW++;
    release(&lock);

    AccessDBase(ReadWrite);

    acquire(&lock);
    AW--;
    if (WW > 0){
      cond_signal(&okToWrite);
    } else if (WR > 0) {
      cond_broadcast(&okToRead);
    }
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- W1 gets signal (R3 still waiting)
- AR = 0, WR = 1, AW = 1, WW = 0

```
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {  // Is it safe to write?
      WW++;                  // No. Active users exist
      cond_wait(&okToWrite,&lock);// Sleep on cond var
      WW--;                  // No longer waiting
    }
    AW++;
    release(&lock);

    AccessDBase(ReadWrite);

    acquire(&lock);
    AW--;
    if (WW > 0){
      cond_signal(&okToWrite);
    } else if (WR > 0) {
      cond_broadcast(&okToRead);
    }
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- W1 accessing dbase (R3 still waiting)
- AR = 0, WR = 1, AW = 1, WW = 0

```
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {  // Is it safe to write?
      WW++;                  // No. Active users exist
      cond_wait(&okToWrite,&lock);// Sleep on cond var
      WW--;                  // No longer waiting
    }
    AW++;
    release(&lock);

    AccessDBase(ReadWrite);

    acquire(&lock);
    AW--;
    if (WW > 0){
      cond_signal(&okToWrite);
    } else if (WR > 0) {
      cond_broadcast(&okToRead);
    }
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- W1 finishes (R3 still waiting)
- AR = 0, WR = 1, AW = 1, WW = 0

```
Writer() {
   acquire(&lock);
   while ((AW + AR) > 0) {  // Is it safe to write?
     WW++;                  // No. Active users exist
     cond_wait(&okToWrite,&lock);// Sleep on cond var
     WW--;                  // No longer waiting
   }
   AW++;
   release(&lock);

   AccessDBase(ReadWrite);

   acquire(&lock);
   AW--;
   if (WW > 0){
     cond_signal(&okToWrite);
   } else if (WR > 0) {
     cond_broadcast(&okToRead);
   }
   release(&lock);
 }
```

Simulation of Readers/Writers Solution

- W1 finishes (R3 still waiting)
- AR = 0, WR = 1, AW = 0, WW = 0

```
Writer() {
   acquire(&lock);
   while ((AW + AR) > 0) {  // Is it safe to write?
     WW++;                  // No. Active users exist
     cond_wait(&okToWrite,&lock);// Sleep on cond var
     WW--;                  // No longer waiting
   }
   AW++;
   release(&lock);

   AccessDBase(ReadWrite);

   acquire(&lock);
   AW--;
   if (WW > 0){
     cond_signal(&okToWrite);
   } else if (WR > 0) {
     cond_broadcast(&okToRead);
   }
   release(&lock);
 }
```

Simulation of Readers/Writers Solution

- W1 finishes (R3 still waiting)
- AR = 0, WR = 1, AW = 0, WW = 0

```
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {  // Is it safe to write?
      WW++;                  // No. Active users exist
      cond_wait(&okToWrite,&lock);// Sleep on cond var
      WW--;                  // No longer waiting
    }
    AW++;
    release(&lock);

    AccessDBase(ReadWrite);

    acquire(&lock);
    AW--;
    if (WW > 0){
      cond_signal(&okToWrite);
    } else if (WR > 0) {
      cond_broadcast(&okToRead);
    }
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- W1 signaling readers (R3 still waiting)
- AR = 0, WR = 1, AW = 0, WW = 0

```
Writer() {
    acquire(&lock);
    while ((AW + AR) > 0) {  // Is it safe to write?
      WW++;                  // No. Active users exist
      cond_wait(&okToWrite,&lock);// Sleep on cond var
      WW--;                  // No longer waiting
    }
    AW++;
    release(&lock);

    AccessDBase(ReadWrite);

    acquire(&lock);
    AW--;
    if (WW > 0){
      cond_signal(&okToWrite);
    } else if (WR > 0) {
      cond_broadcast(&okToRead);
    }
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R3 gets signal (no waiting threads)
- AR = 0, WR = 1, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R3 gets signal (no waiting threads)
- AR = 0, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R3 accessing dbase (no waiting threads)
- AR = 1, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R3 finishes (no waiting threads)
- AR = 1, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Simulation of Readers/Writers Solution

- R3 finishes (no waiting threads)
- AR = 0, WR = 0, AW = 0, WW = 0

```
Reader() {
    acquire(&lock);
    while ((AW + WW) > 0) { // Is it safe to read?
      WR++;                 // No. Writers exist
      cond_wait(&okToRead,&lock);// Sleep on cond var
      WR--;                 // No longer waiting
    }
    AR++;                   // Now we are active!
    release(&lock);

    AccessDBase(ReadOnly);

    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
      cond_signal(&okToWrite);
    release(&lock);
  }
```

Questions

- Can readers starve? Consider Reader() entry code:

```
while ((AW + WW) > 0) {  // Is it safe to read?
  WR++;                  // No. Writers exist
  cond_wait(&okToRead,&lock);// Sleep on cond var
  WR--;                  // No longer waiting
}
AR++;                    // Now we are active!
```

- What if we erase the condition check in Reader exit?

```
AR--;                    // No longer active
if (AR == 0 && WW > 0)   // No other active readers
  cond_signal(&okToWrite);// Wake up one writer
```

- Further, what if we turn the signal() into broadcast()

```
AR--;                    // No longer active
cond_broadcast(&okToWrite); // Wake up sleepers
```

- Finally, what if we use only one condition variable (call it "**okContinue**") instead of two separate ones?
  – Both readers and writers sleep on this variable
  – Must use broadcast() instead of signal()

Use of Single CV: `okContinue`

```
Reader() {
    // check into system
    acquire(&lock);
    while ((AW + WW) > 0) {
       WR++;
       cond_wait(&okContinue,&lock);
       WR--;
    }
    AR++;
    release(&lock);

    // read-only access
    AccessDbase(ReadOnly);

    // check out of system
    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
       cond_signal(&okContinue);
    release(&lock);
  }
```

```
Writer() {
    // check into system
    acquire(&lock);
    while ((AW + AR) > 0) {
       WW++;
       cond_wait(&okContinue,&lock);
       WW--;
    }
    AW++;
    release(&lock);

    // read/write access
    AccessDbase(ReadWrite);

    // check out of system
    acquire(&lock);
    AW--;
    if (WW > 0){
       cond_signal(&okContinue);
    } else if (WR > 0) {
       cond_broadcast(&okContinue);
    }
    release(&lock);
  }
```

What if we turn `okToWrite` and `okToRead` into `okContinue`
(i.e. use only one condition variable instead of two)?

Use of Single CV: `okContinue`

```
Reader() {
    // check into system
    acquire(&lock);
    while ((AW + WW) > 0) {
        WR++;
        cond_wait(&okContinue,&lock);
        WR--;
    }
    AR++;
    release(&lock);

    // read-only access
    AccessDbase(ReadOnly);

    // check out of system
    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
        cond_signal(&okContinue);
    release(&lock);
}
```

```
Writer() {
    // check into system
    acquire(&lock);
    while ((AW + AR) > 0) {
        WW++;
        cond_wait(&okContinue,&lock);
        WW--;
    }
    AW++;
    release(&lock);

    // read/write access
    AccessDbase(ReadWrite);

    // check out of system
    acquire(&lock);
    AW--;
    if (WW > 0){
        cond_signal(&okContinue);
    } else if (WR > 0) {
        cond_broadcast(&okContinue);
    }
```

Consider this scenario:
- **R1 arrives**
- **W1, R2 arrive while R1 still reading → W1 and R2 wait for R1 to finish**
- **Assume R1's signal is delivered to R2 (not W1)**

Use of Single CV: okContinue

```
Reader() {
    // check into system
    acquire(&lock);
    while ((AW + WW) > 0) {
       WR++;
        cond_wait(&okContinue,&lock);
       WR--;
    }
    AR++;
    release(&lock);

    // read-only access
    AccessDbase(ReadOnly);

    // check out of system
    acquire(&lock);
    AR--;
    if (AR == 0 && WW > 0)
       cond_broadcast(&okContinue);
    release(&lock);
  }
```

Need to change to broadcast()!

```
Writer() {
    // check into system
    acquire(&lock);
    while ((AW + AR) > 0) {
       WW++;
       cond_wait(&okContinue,&lock);
    WW--;
    }
    AW++;
    release(&lock);

    // read/write access
    AccessDbase(ReadWrite);

    // check out of system
    acquire(&lock);
    AW--;
    if (WW > 0 || WR > 0){
       cond_broadcast(&okContinue);
    }
    release(&lock);
  }
```

Must broadcast() to sort things out!

Administrivia

- Midterm This Thursday, 7-9pm (October 3)!
  - You are responsible for all materials up to lecture 9
    - » Including Semaphores and Monitors
    - » Including DB example in this lecture
- You get one (1) double-side page of *handwritten* notes
  - Hand drawn figures, handwritten notes
  - No copying of figures directly from slides, no microfiche, etc
  - Redraw them if you want them on your notes!

Can we construct Monitors from Semaphores?

- Locking aspect is easy: Just use a mutex
- Can we implement condition variables this way?

```
Wait(Semaphore *thesema)   { semaP(thesema); }
Signal(Semaphore *thesema) { semaV(thesema); }
```

- Does this work better?

```
Wait(Lock *thelock, Semaphore *thesema) {
   release(thelock);
   semaP(thesema);
   acquire(thelock);
}
Signal(Semaphore *thesema) {
  semaV(thesema);
}
```

Construction of Monitors from Semaphores (con't)

- Problem with previous try:
  - P and V are commutative – result is the same no matter what order they occur
  - Condition variables are NOT commutative
- Does this fix the problem?

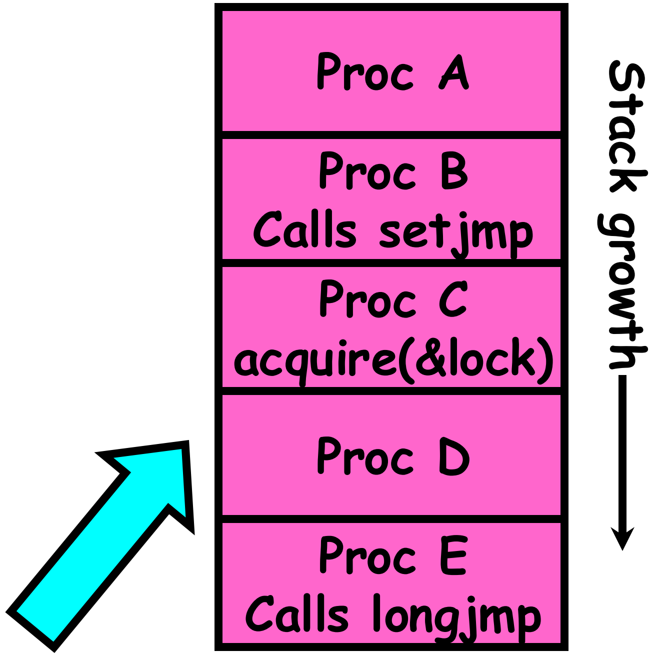
```
Wait(Lock *thelock, Semaphore *thesema) {
   release(thelock);
   semaP(thesema);
   acquire(thelock);
}
Signal(Semaphore *thesema) {
   if semaphore queue is not empty
      semaV(thesema);
}
```

  - Not legal to look at contents of semaphore queue
  - There is a race condition – signaler can slip in after lock release and before waiter executes semaphore.P()
- It is actually possible to do this correctly
  - Complex solution for Hoare scheduling in book
  - Can you come up with simpler Mesa-scheduled solution?

C-Language Support for Synchronization

- C language: Pretty straightforward synchronization
  - Just make sure you know *all* the code paths out of a critical section

```
int Rtn() {
   acquire(&lock);
   …
   if (exception) {
      release(&lock);
      return errReturnCode;
   }
   …
   release(&lock);
   return OK;
}
```



  - Watch out for `setjmp`/`longjmp`!
    - » Can cause a non-local jump out of procedure
    - » In example, procedure E calls longjmp, poping stack back to procedure B
    - » If Procedure C had lock.acquire, problem!

Concurrency and Synchronization in C

- Harder with more locks

```
void Rtn() {
  lock1.acquire();
  …
  if (error) {
    lock1.release();
    return;
  }
  …
  lock2.acquire();
  …
  if (error) {
    lock2.release()
    lock1.release();
    return;
  }
  …
  lock2.release();
  lock1.release();
}
```

- Is goto a solution???

```
void Rtn() {
  lock1.acquire();
  …
  if (error) {
    goto release_lock1_and_return;
  }
  …
  lock2.acquire();
  …
  if (error) {
    goto release_both_and_return;
  }
  …
release_both_and_return:
  lock2.release();
release_lock1_and_return:
  lock1.release();
}
```

C++ Language Support for Synchronization

- Languages with exceptions like C++
  - Languages that support exceptions are problematic (easy to make a non-local exit without releasing lock)
  - Consider:

```
void Rtn() {
   lock.acquire();
   …
   DoFoo();
   …
   lock.release();
}
void DoFoo() {
   …
   if (exception) throw errException;
   …
}
```

  - Notice that an exception in DoFoo() will exit without releasing the lock!

C++ Language Support for Synchronization (con't)

- Must catch all exceptions in critical sections
  - Catch exceptions, release lock, and re-throw exception:

```
void Rtn() {
   lock.acquire();
   try {
      …
      DoFoo();
      …
   } catch (…) {        // catch exception
      lock.release();   // release lock
      throw;            // re-throw the exception
   }
   lock.release();
}
void DoFoo() {
   …
   if (exception) throw errException;
   …
}
```

Much better: C++ Lock Guards

```
#include <mutex>
int global_i = 0;
std::mutex global_mutex;

void safe_increment() {
  std::lock_guard<std::mutex> lock(global_mutex);
  …
  global_i++;
  // Mutex released when ‘lock’ goes out of scope
}
```

Python `with` Keyword

- More versatile than we show here (can be used to close files, database connections, etc.)

```
lock = threading.Lock()
…
with lock: # Automatically calls acquire()
  some_var += 1
  …
# release() called however we leave block
```

Java synchronized Keyword

- Every Java object has an associated lock:
  - Lock is acquired on entry and released on exit from a synchronized method
  - Lock is properly released if exception occurs inside a synchronized method
  - Mutex execution of synchronized methods (beware deadlock)

```
class Account {
   private int balance;

   // object constructor
   public Account (int initialBalance) {
      balance = initialBalance;
   }
   public synchronized int getBalance() {
      return balance;
   }
   public synchronized void deposit(int amount) {
      balance += amount;
   }
}
```

Java Support for Monitors

- Along with a lock, every object has a single condition variable associated with it
- To wait inside a synchronized method:
  - `void wait();`
  - `void wait(long timeout);`
- To signal while in a synchronized method:
  - `void notify();`
  - `void notifyAll();`

Goal for Today

```
if ( readyThreads(TCBs) ) {
        nextTCB = selectThread(TCBs);
        run( nextTCB );
} else {
        run_idle_thread();
}
```

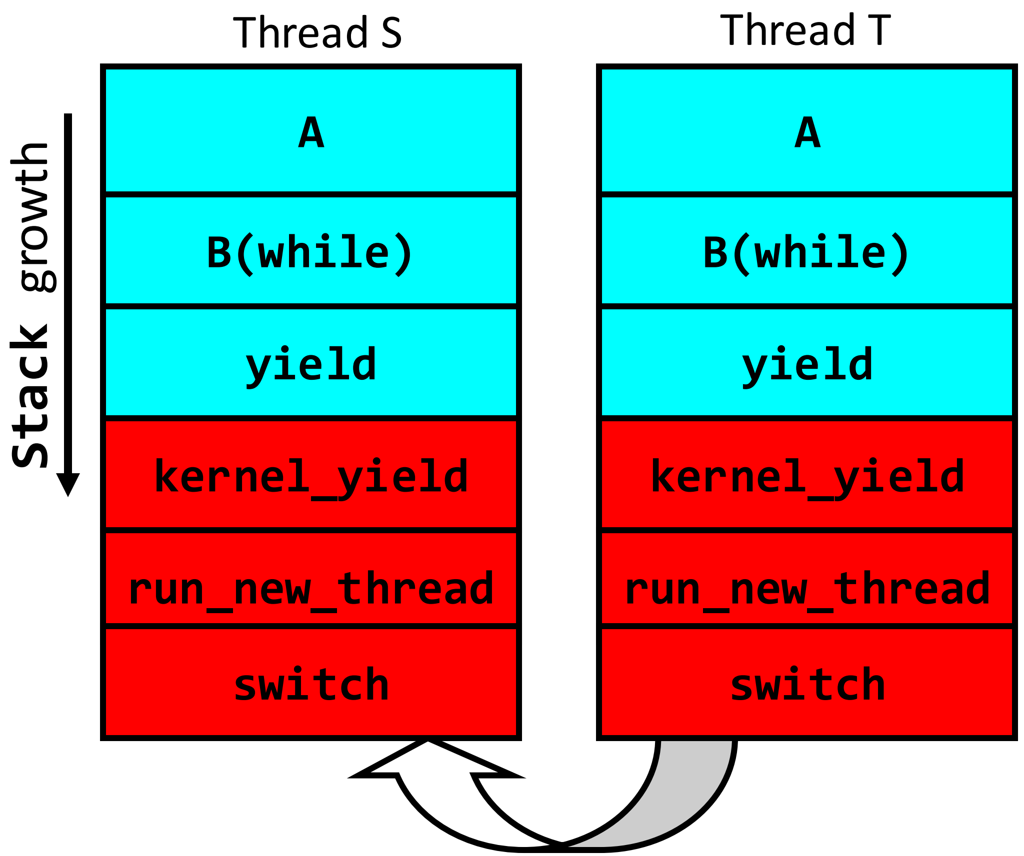
- Discussion of Scheduling:
  - Which thread should run on the CPU next?
- Scheduling goals, policies
- Look at a number of different schedulers

Recall: Stacks for Yield with Multiple Threads

- Consider the following code blocks:

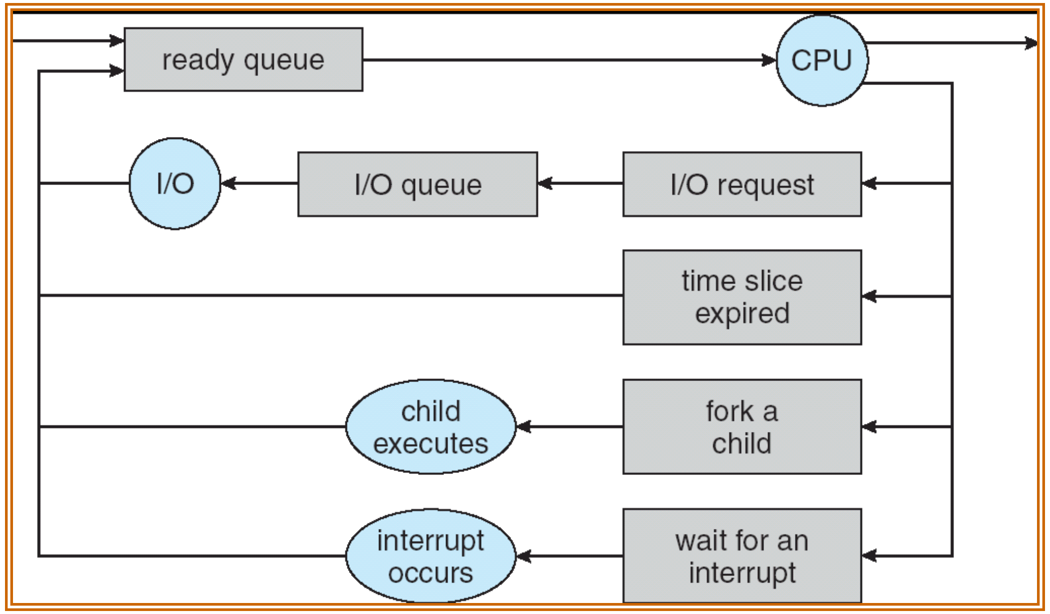
```
proc A() {
    B();
}
proc B() {
    while(TRUE) {
        yield();
    }
}
```

- Suppose we have 2 threads:
  - Threads S and T
  - Assume that both have been running for a while



Thread T's switch returns to Thread S

Recall: Scheduling



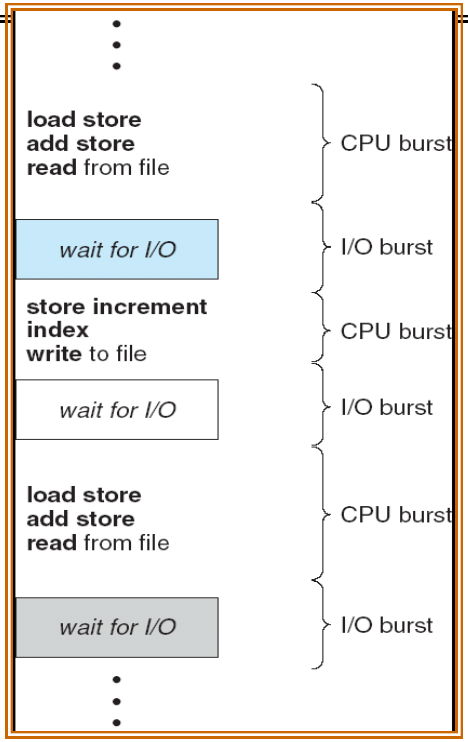
- Question: How is the OS to decide which of several tasks to take off a queue?
- Scheduling: deciding which threads are given access to resources from moment to moment
  – Often, we think in terms of CPU time, but could also think about access to resources like network BW or disk access

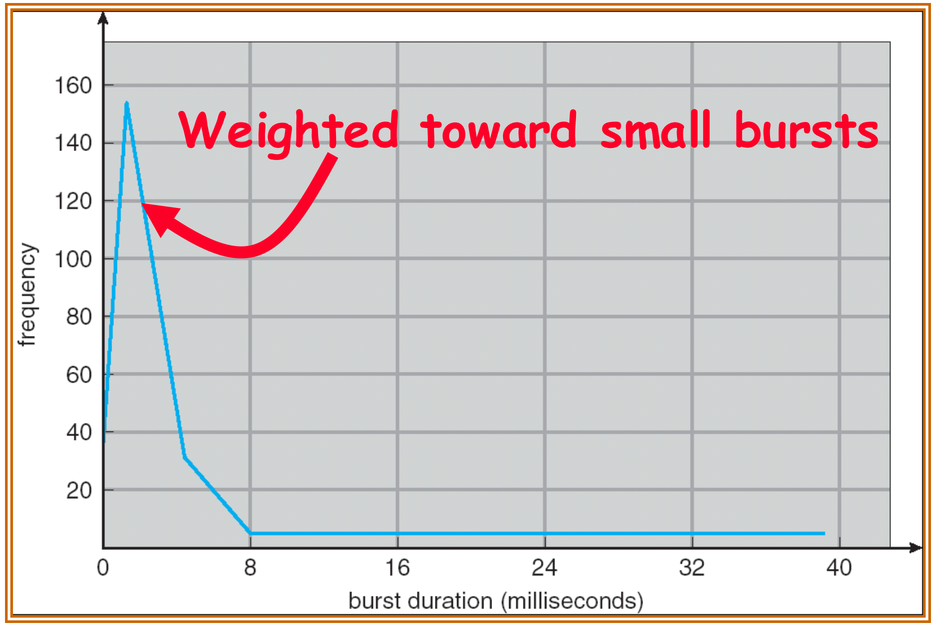
Scheduling: All About Queues

Scheduling Assumptions

- CPU scheduling big area of research in early 70's
- Many implicit assumptions for CPU scheduling:
  - One program per user
  - One thread per program
  - Programs are independent
- Clearly, these are unrealistic but they simplify the problem so it can be solved
  - For instance: is "fair" about fairness among users or programs?
    - » If I run one compilation job and you run five, you get five times as much CPU on many operating systems
- The high-level goal: Dole out CPU time to optimize some desired parameters of system

Assumption: CPU Bursts





- Execution model: programs alternate between bursts of CPU and I/O
  - Program typically uses the CPU for some period of time, then does I/O, then uses CPU again
  - Each scheduling decision is about which job to give to the CPU for use by its next CPU burst
  - With timeslicing, thread may be forced to give up CPU before finishing current CPU burst

Scheduling Policy Goals/Criteria

- Minimize Response Time
  - Minimize elapsed time to do an operation (or job)
  - Response time is what the user sees:
    - » Time to echo a keystroke in editor
    - » Time to compile a program
    - » Real-time Tasks: Must meet deadlines imposed by World
- Maximize Throughput
  - Maximize operations (or jobs) per second
  - Throughput related to response time, but not identical:
    - » Minimizing response time will lead to more context switching than if you only maximized throughput
  - Two parts to maximizing throughput
    - » Minimize overhead (for example, context-switching)
    - » Efficient use of resources (CPU, disk, memory, etc)
- Fairness
  - Share CPU among users in some equitable way
  - Fairness is not minimizing average response time:
    - » Better *average* response time by making system *less* fair

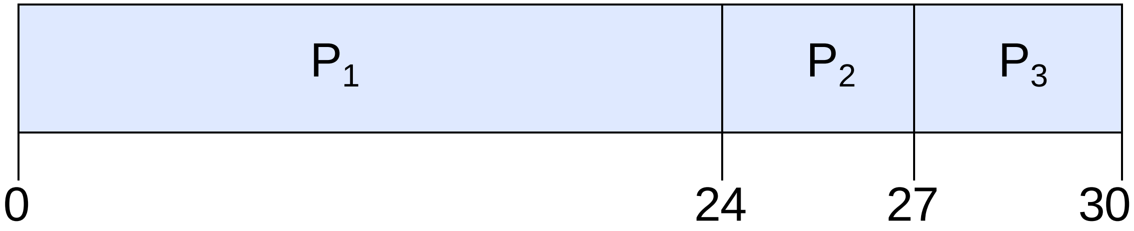
First-Come, First-Served (FCFS) Scheduling

- First-Come, First-Served (FCFS)
  - Also “First In, First Out” (FIFO) or “Run until done”
    - » In early systems, FCFS meant one program scheduled until done (including I/O)
    - » Now, means keep CPU until thread blocks

- Example:

Process	Burst Time
P_1	24
P_2	3
P_3	3

  - Suppose processes arrive in the order: P_1 , P_2 , P_3
    The Gantt Chart for the schedule is:



  - Waiting time for $P_1 = 0$; $P_2 = 24$; $P_3 = 27$
  - Average waiting time: $(0 + 24 + 27)/3 = 17$
  - Average Completion time: $(24 + 27 + 30)/3 = 27$
- *Convoy effect:* short process stuck behind long process

Convoy effect

- With FCFS non-preemptive scheduling, convoys of small tasks tend to build up when a large one is running.

FCFS Scheduling (Cont.)

- Example continued:
  – Suppose that processes arrive in order: P2 , P3 , P1
    Now, the Gantt chart for the schedule is:

  – Waiting time for P1 = 6; P2 = 0; P3 = 3
  – Average waiting time: (6 + 0 + 3)/3 = 3
  – Average Completion time: (3 + 6 + 30)/3 = 13
- In second case:
  – Average waiting time is much better (before it was 17)
  – Average completion time is better (before it was 27)
- FIFO Pros and Cons:
  – Simple (+)
  – Short jobs get stuck behind long ones (-)
    » Safeway: Getting milk, always stuck behind cart full of items!
      Upside: get to read about Space Aliens!

Conclusion

- Monitors: A lock plus one or more condition variables
  - Always acquire lock before accessing shared data
  - Use condition variables to wait inside critical section
    - » Three Operations: `Wait()`, `Signal()`, and `Broadcast()`
- Monitors represent the logic of the program
  - Wait if necessary
  - Signal when change something so any waiting threads can proceed
- Readers/Writers Monitor example
  - Shows how monitors allow sophisticated controlled entry to protected code
  - Mesa scheduling allows a more relaxed checking of wait conditions
- Monitors supported natively in a number of languages
- Scheduling Goals:
  - Minimize Response Time (e.g. for human interaction)
  - Maximize Throughput (e.g. for large computations)
  - Fairness (e.g. Proper Sharing of Resources)
  - Predictability (e.g. Hard/Soft Realtime)
- Round-Robin Scheduling:
  - Give each thread a small amount of CPU time when it executes; cycle between all ready threads
  - Pros: Better for short jobs