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

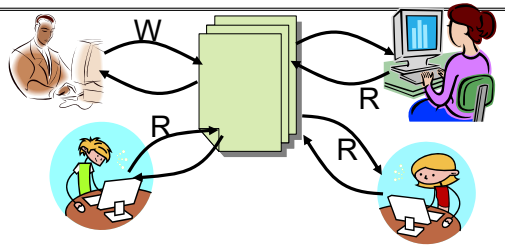
- Monitor: a lock and zero or more condition variables for managing concurrent access to shared data
  - Use of Monitors is a programming paradigm
  - Some languages like Java provide monitors in the language
- Condition Variable: a queue of threads waiting for something *inside* a critical section
  - 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

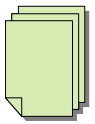
- Monitors represent the synchronization logic of the program
  - Wait if necessary
  - Signal when change something so any waiting threads can proceed
- Basic structure of mesa monitor-based program:

```
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);
  }
```


Administrivia

- Still grading Midterm 1 (Sorry)
  - Finishing soon!
  - Solutions also will be up soon.
- Homework #2 due Thursday, 2/22
- Homework #3: Released on Friday 2/23
  - Option to do this in Rust!
  - Rust crash course on Monday 2/26
- Professor Kubi's office hours changed:
  - Monday (1:00-2:00PM), Thursday (3:00-4:00PM)
  - 673 Soda Hall
- FYI: Next Midterm on 3/14
  - PI Day!

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!

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?

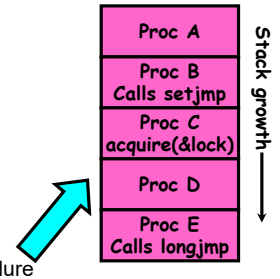
```
Wait(Lock *thelock, Semaphore *thesema) {
   release(thelock);
   semaP(thesema);
   acquire(thelock);
}
Signal(Semaphore *thesema) {
   if semaphore queue is not empty
      semaV(thesema);
}
```

  - 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

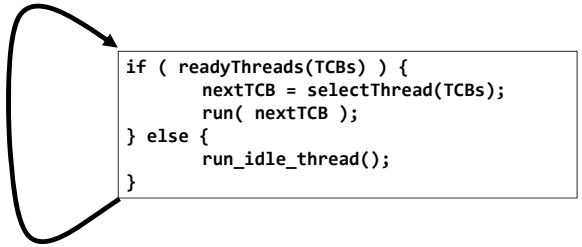
- Every Java object has an associated lock:
  - Lock is acquired on entry and released on exit from a synchronized method
  - Lock is properly released if exception occurs inside a synchronized method
  - Mutex execution of synchronized methods (beware deadlock)

```
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();
}
```

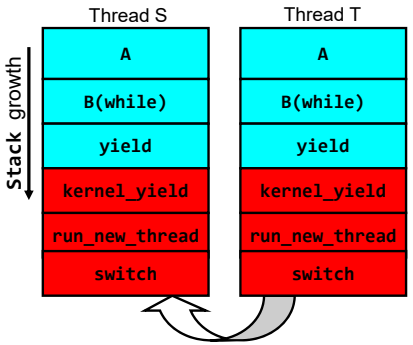
- Discussion of Scheduling:
  - Which thread should run on the CPU next?
- Scheduling goals, policies
- Look at a number of different schedulers

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

Hardware context switch support in x86

- Syscall/Intr (U → K)
  - PL 3 → 0;
  - TSS ← EFLAGS, CS:EIP;
  - SS:ESP ← k-thread stack (TSS PL 0);
  - push (old) SS:ESP onto (new) k-stack
  - push (old) EFLAGS, CS:EIP, <err>
  - CS:EIP ← <k target handler>
- Then
  - *Handler saves other regs, etc*
  - *Does all its works, possibly choosing other threads, changing PTBR (CR3)*
  - kernel thread has set up user GPRs
- iret (K → U)
  - PL 0 → 3;
  - EFLAGS, CS:EIP ← popped off k-stack
  - SS:ESP ← popped off k-stack

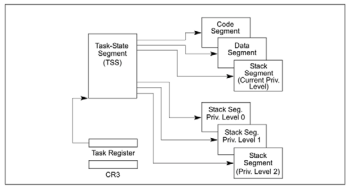
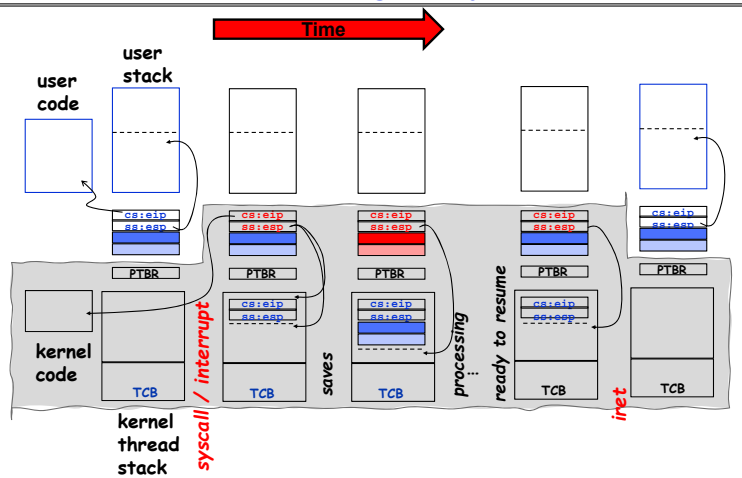


Figure 7-1. Structure of a Task

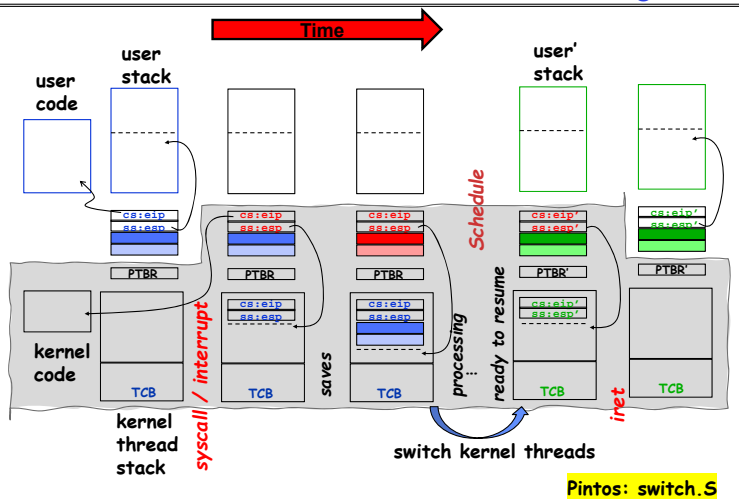
pg 2,942 of 4,922 of x86 reference manual

Pintos: tss.c, intr-stubs.S

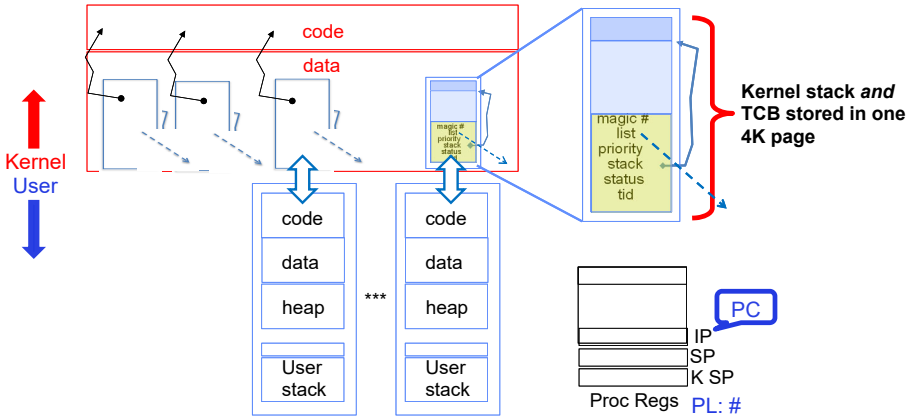
Pintos: Kernel Crossing on Syscall or Interrupt



Pintos: Context Switch – Scheduling

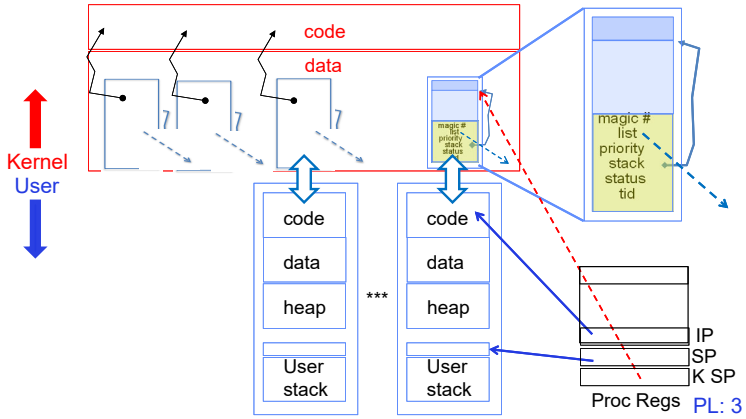


MT Kernel single Thread Process ala Pintos/x86



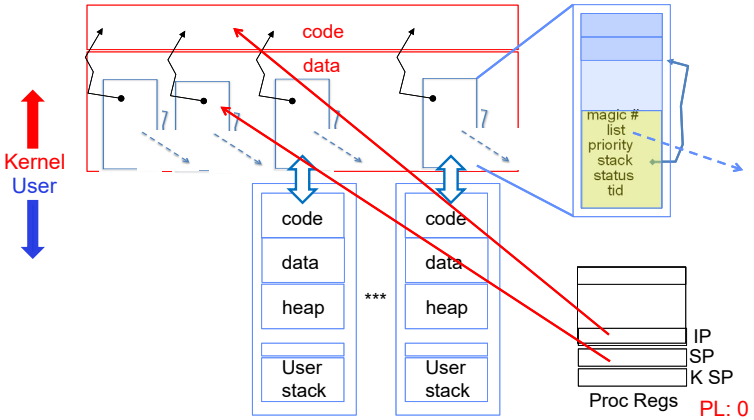
- Each user process/thread associated with a kernel thread, described by a 4KB page object containing TCB and kernel stack for the kernel thread

Running User Code with Kernel stack waiting



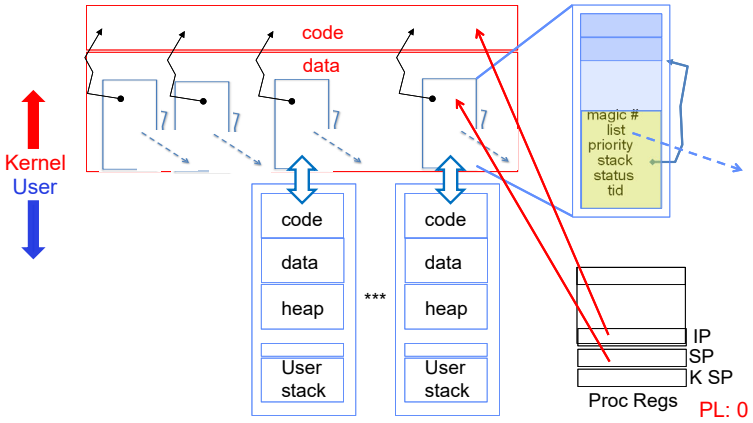
- x86 CPU holds interrupt SP in register
- During user thread execution, associated kernel thread is "standing by"

In Kernel Thread: No User Component



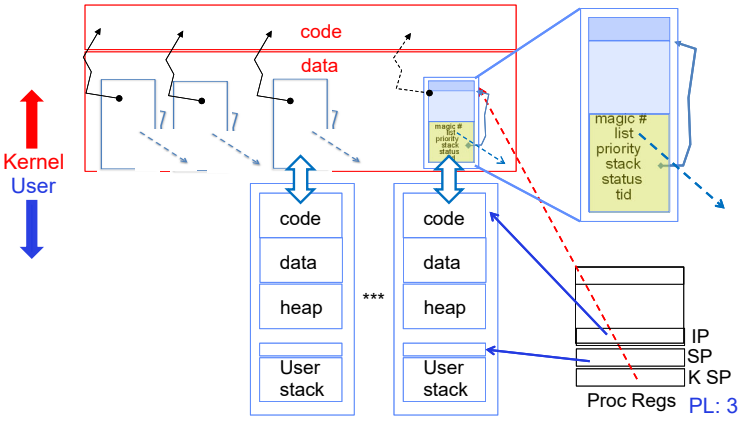
- Kernel threads execute with small stack in thread structure
- Pure kernel threads have no corresponding user-mode thread

User → Kernel (interrupts, syscalls)



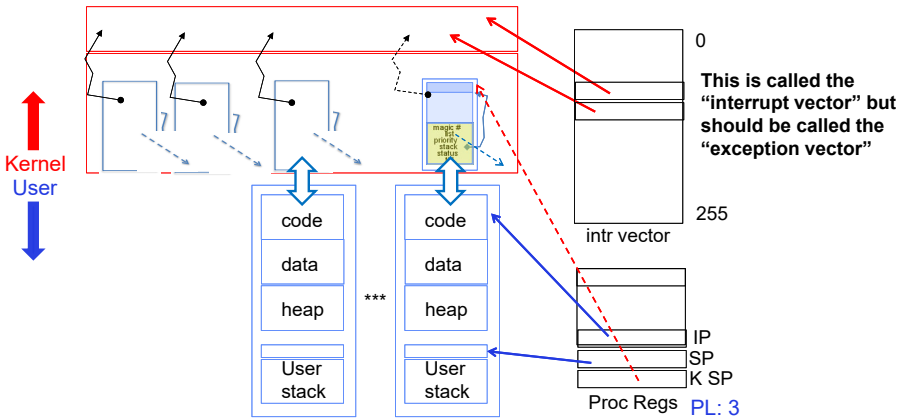
- Mechanism vectors through "interrupt vector"

Kernel → User



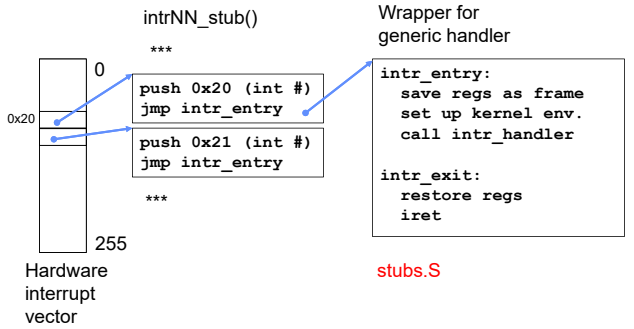
- Interrupt return (iret) restores user stack, IP, and PL

User → Kernel via "interrupt vector" (interrupts & traps)

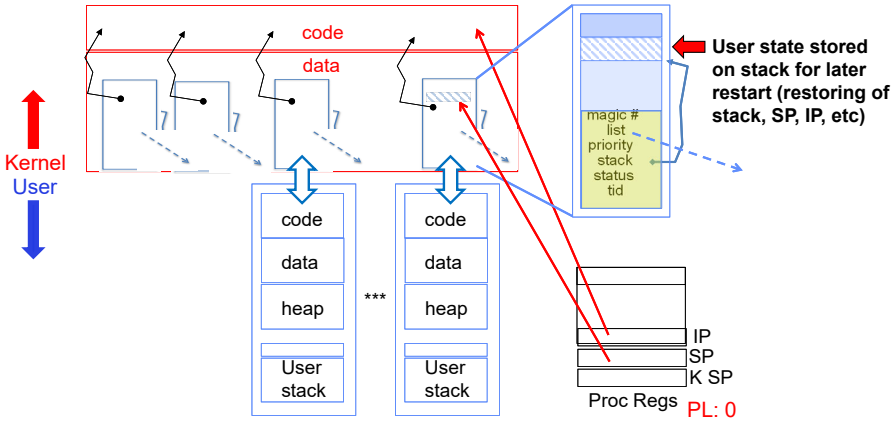


- Interrupts (timer) or trap (syscall, page fault) transfers through interrupt vector (IDT)
  - Each slot for different exception type

Pintos Interrupt Processing for Timer (0x20)

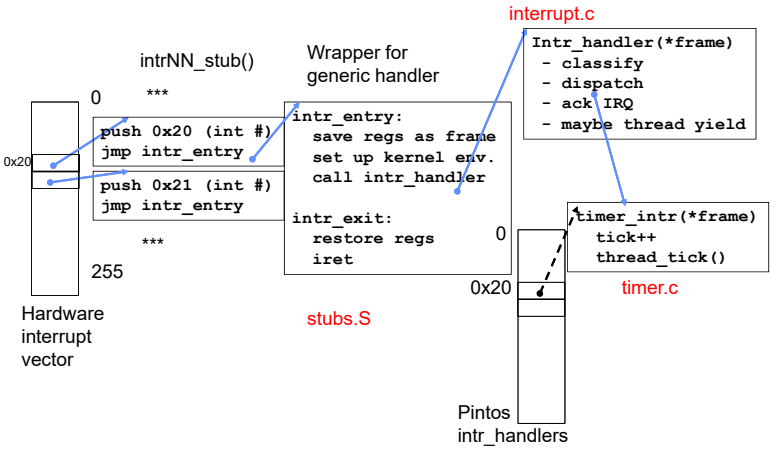


Switch to Kernel Stack for Thread

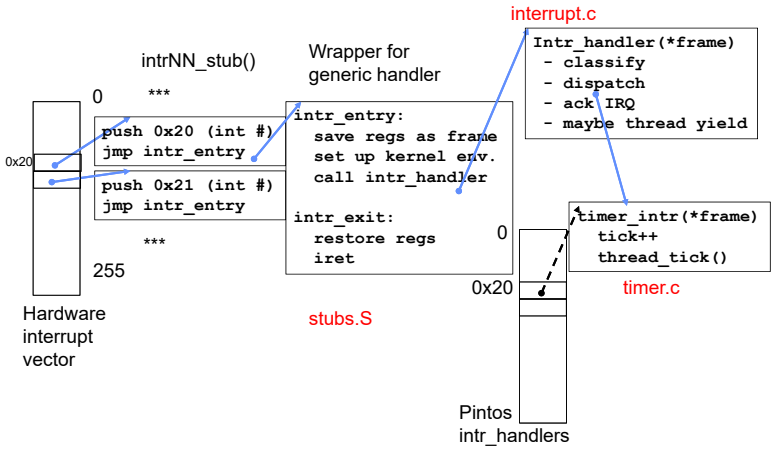


- Information required to restart thread stored on kernel stack
  - Switching becomes simple to different kernel stack and restoring

Pintos Interrupt Processing for Timer (0x20)



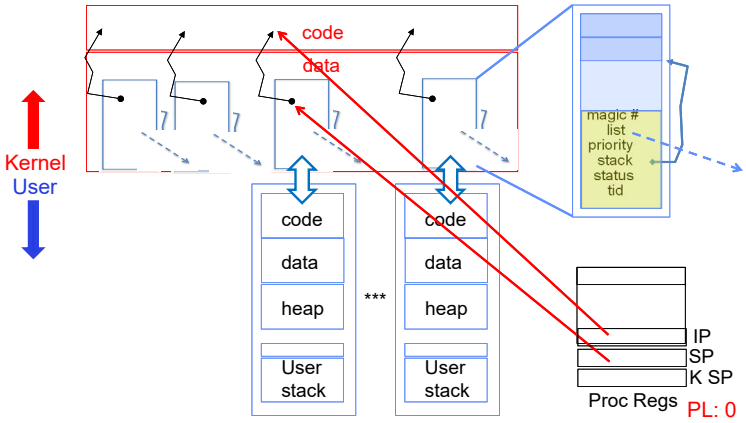
Pintos Interrupt Processing for Timer (0x20)



Timer may trigger thread switch

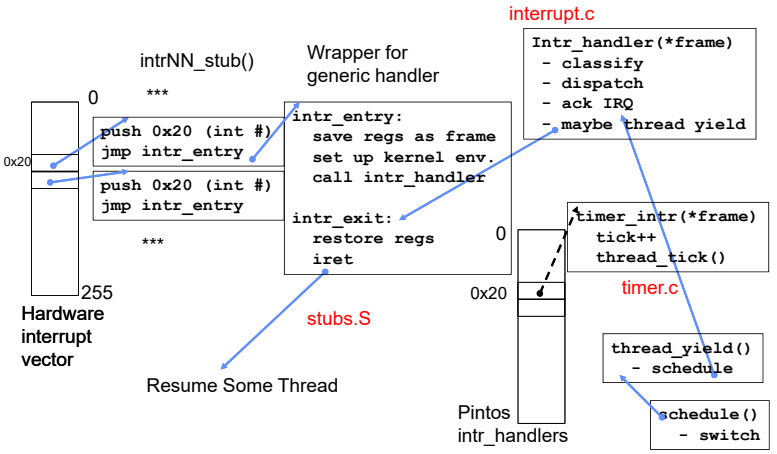
- thread_tick
  - Updates thread counters
  - If quanta exhausted, sets yield flag
- thread_yield
  - On path to rtn from interrupt
  - Sets current thread back to READY
  - Pushes it back on ready_list
  - Calls schedule to select next thread to run upon iret
- Schedule
  - Selects next thread to run
  - Calls switch_threads to change regs to point to stack for thread to resume
  - Sets its status to RUNNING
  - If user thread, activates the process
  - Returns back to intr_handler

Thread Switch (switch.S)

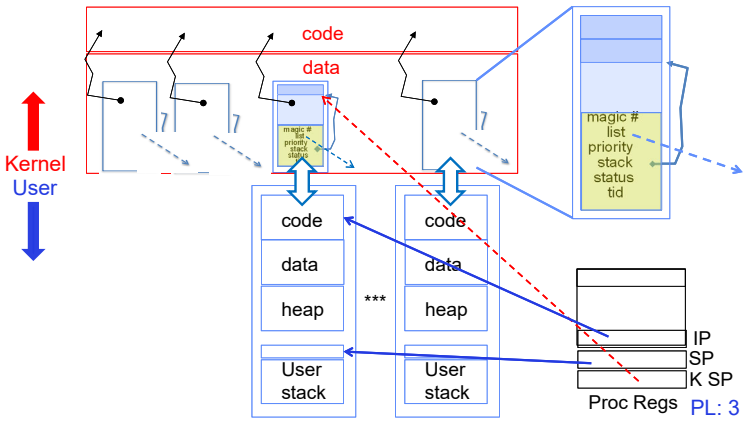


- switch_threads: save regs on current small stack, change SP, return from destination threads call to switch_threads

Pintos Return from Processing for Timer (0x20)



Kernel → Different User Thread



- iret restores user stack and priority level (PL)

Famous Quote WRT Scheduling: Dennis Richie

Dennis Richie,
Unix V6, slp.c:

```
2230    /*
2231     * If the new process paused because it was
2232     * swapped out, set the stack level to the last call
2233     * to savu(u_ssav).  This means that the return
2234     * which is executed immediately after the call to aretu
2235     * actually returns from the last routine which did
2236     * the savu.
2237     *
2238     * You are not expected to understand this.
2239     */
```

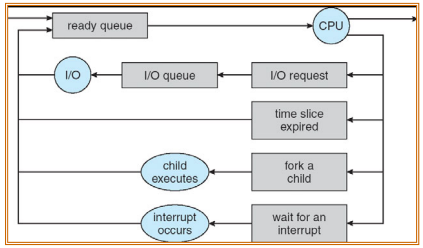
"If the new process paused because it was swapped out, set the stack level to the last call to savu(u_ssav). This means that the return which is executed immediately after the call to aretu actually returns from the last routine which did the savu."

"You are not expected to understand this."

Source: Dennis Ritchie, Unix V6 slp.c (context-switching code) as per The Unix Heritage Society(tuhs.org); gif by Eddie Koehler.

Included by Ali R. Butt in CS3204 from Virginia Tech

Recall: Scheduling



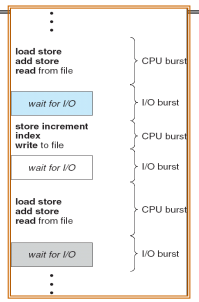
- Question: How is the OS to decide which of several tasks to take off a queue?
- Scheduling: deciding which threads are given access to resources from moment to moment
  - Often, we think in terms of CPU time, but could also think about access to resources like network BW or disk access

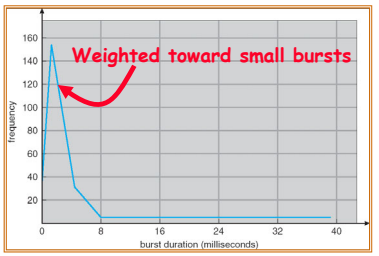
Scheduling: All About Queues

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

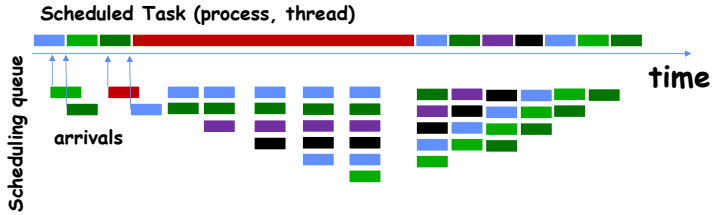
- First-Come, First-Served (FCFS)
  - Also "First In, First Out" (FIFO) or "Run until done"
    - » In early systems, FCFS meant one program scheduled until done (including I/O)
    - » Now, means keep CPU until thread blocks
- Example:

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