CS162
Operating Systems and Systems Programming
Lecture 9

Synchronization Continued, Readers/Writers example, Scheduling

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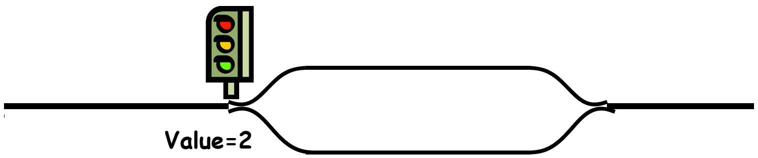
Review: Semaphores

- Definition: a Semaphore has a non-negative integer value and supports the following two operations:
  - P(): an atomic operation that waits for semaphore to become positive, then decrements it by 1
    - » Think of this as the wait() operation
  - V(): an atomic operation that increments the semaphore by 1, waking up a waiting P, if any
    - » This of this as the signal() operation
  - Only time can set integer directly is at initialization time
- Semaphore from railway analogy
  - Here is a semaphore initialized to 2 for resource control:



Review: Full Solution to Bounded Buffer

```
Semaphore fullBuffer = 0; // Initially, no coke
Semaphore emptyBuffers = numBuffers;
                          // Initially, num empty slots
Semaphore mutex = 1;      // No one using machine

Producer(item) {
    emptyBuffers.P();     // Wait until space
    mutex.P();            // Wait until buffer free
    Enqueue(item);
    mutex.V();
    fullBuffers.V();      // Tell consumers there is
                          // more coke
}
Consumer() {
    fullBuffers.P();      // Check if there's a coke
    mutex.P();            // Wait until machine free
    item = Dequeue();
    mutex.V();
    emptyBuffers.V();     // tell producer need more
    return item;
}
```

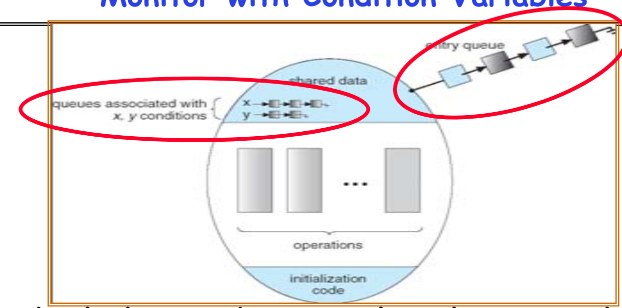

Discussion about Solution

- Why asymmetry?
  - Producer does: `emptyBuffer.P()`, `fullBuffer.V()`
  - Consumer does: `fullBuffer.P()`, `emptyBuffer.V()`
- Is order of P's important?
- Is order of V's important?
- What if we have 2 producers or 2 consumers?
  - Do we need to change anything?

Motivation for Monitors and Condition Variables

- Semaphores are a huge step up; just think of trying to do the bounded buffer with only loads and stores
  - Problem is that semaphores are dual purpose:
    - » They are used for both mutex and scheduling constraints
    - » Example: the fact that flipping of P's in bounded buffer gives deadlock is not immediately obvious. How do you prove correctness to someone?
- Cleaner idea: Use *locks* for mutual exclusion and *condition variables* for scheduling constraints
- Definition: **Monitor**: a **lock** and zero or more **condition variables** for managing concurrent access to shared data
  - Some languages like Java provide this natively
  - Most others use actual locks and condition variables

Monitor with Condition Variables



- **Lock**: the lock provides mutual exclusion to shared data
  - Always acquire before accessing shared data structure
  - Always release after finishing with shared data
  - Lock initially free
- **Condition Variable**: a queue of threads waiting for something *inside* a critical section
  - Key idea: make it possible to go to sleep inside critical section by atomically releasing lock at time we go to sleep
  - Contrast to semaphores: Can't wait inside critical section

Simple Monitor Example (version 1)

- Here is an (infinite) synchronized queue

```
Lock lock;
Queue queue;

AddToQueue(item) {
   lock.Acquire();         // Lock shared data
   queue.enqueue(item);    // Add item
   lock.Release();         // Release Lock
}

RemoveFromQueue() {
   lock.Acquire();         // Lock shared data
   item = queue.dequeue();// Get next item or null
   lock.Release();         // Release Lock
   return(item);           // Might return null
}
```

- Not very interesting use of "Monitor"
  - It only uses a lock with no condition variables
  - Cannot put consumer to sleep if no work!

Condition Variables

- How do we change the RemoveFromQueue() routine to wait until something is on the queue?
  - Could do this by keeping a count of the number of things on the queue (with semaphores), but error prone
- **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!
  - In Birrell paper, he says can perform signal() outside of lock – IGNORE HIM (this is only an optimization)

Complete Monitor Example (with condition variable)

- Here is an (infinite) synchronized queue

```
Lock lock;
Condition dataready;
Queue queue;

AddToQueue(item) {
   lock.Acquire();          // Get Lock
   queue.enqueue(item);     // Add item
   dataready.signal();      // Signal any waiters
   lock.Release();          // Release Lock
}

RemoveFromQueue() {
   lock.Acquire();          // Get Lock
   while (queue.isEmpty()) {
      dataready.wait(&lock); // If nothing, sleep
   }
   item = queue.dequeue();  // Get next item
   lock.Release();          // Release Lock
   return(item);
}
```


Mesa vs. Hoare monitors

- Need to be careful about precise definition of signal and wait. Consider a piece of our dequeue code:

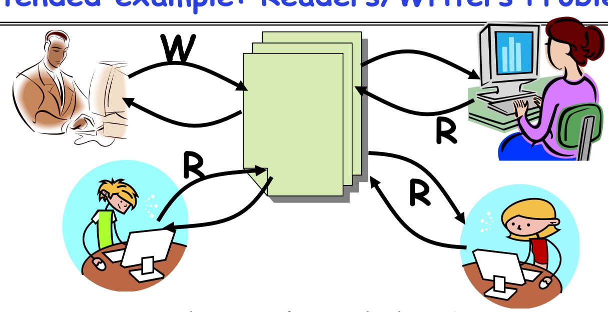
```
while (queue.isEmpty()) {
   dataready.wait(&lock); // If nothing, sleep
}
item = queue.dequeue();// Get next item
```

  – Why didn't we do this?

```
if (queue.isEmpty()) {
   dataready.wait(&lock); // If nothing, sleep
}
item = queue.dequeue();// Get next item
```

- Answer: depends on the type of scheduling
  – Hoare-style (most textbooks):
    » Signaler gives lock, CPU to waiter; waiter runs immediately
    » Waiter gives up lock, processor back to signaler when it exits critical section or if it waits again
  – Mesa-style (most real operating systems):
    » Signaler keeps lock and processor
    » Waiter placed on ready queue with no special priority
    » Practically, need to check condition again after wait

Extended example: 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

Administrivia

- Midterm coming up soon!
  – Wednesday 10/14, 6:30-9:30 pm
  – In 145/155 Dwinelle, 6:30-9:30pm
  – No class that day
- Details
  – Intend this to be 2-hour exam in 3 hour slot
  – 1 page of hand-written note, both sides
  – Closed book
- Topics will include the material from that Monday

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
    » Conditioin okToWrite = NIL

Code for a Reader

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


Code for a Writer

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


Simulation of Readers/Writers solution

- Consider the following sequence of operators:
  - R1, R2, W1, R3
- On entry, each reader checks the following:
  ```
  while ((AW + WW) > 0) { // Is it safe to read?
    WR++;                 // No. Writers exist
    okToRead.wait(&lock); // Sleep on cond var
    WR--;                 // No longer waiting
  }
  AR++;                   // Now we are active!
  ```
- First, R1 comes along:
  AR = 1, WR = 0, AW = 0, WW = 0
- Next, R2 comes along:
  AR = 2, WR = 0, AW = 0, WW = 0
- Now, readers make take a while to access database
  - Situation: Locks released
  - Only AR is non-zero

Simulation(2)

- Next, W1 comes along:

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

- Can't start because of readers, so go to sleep:
  AR = 2, WR = 0, AW = 0, WW = 1
- Finally, R3 comes along:
  AR = 2, WR = 1, AW = 0, WW = 1
- Now, say that R2 finishes before R1:
  AR = 1, WR = 1, AW = 0, WW = 1
- Finally, last of first two readers (R1) finishes and wakes up writer:

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


Simulation(3)

- When writer wakes up, get:
  AR = 0, WR = 1, AW = 1, WW = 0
- Then, when writer finishes:

```
if (WW > 0){             // Give priority to writers
  okToWrite.signal();    // Wake up one writer
} else if (WR > 0) {     // Otherwise, wake reader
  okToRead.broadcast();  // Wake all readers
}
```

  - Writer wakes up reader, so get:
    AR = 1, WR = 0, AW = 0, WW = 0
- When reader completes, we are finished

Questions

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

```
while ((AW + WW) > 0) { // Is it safe to read?
  WR++;                 // No. Writers exist
  okToRead.wait(&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
  okToWrite.signal();   // Wake up one writer
```

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

```
AR--;                   // No longer active
okToWrite.broadcast();  // Wake up one writer
```

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

Can we construct Monitors from Semaphores?

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

```
Wait()   { semaphore.P(); }
Signal() { semaphore.V(); }
```

- Does this work better?

```
Wait(Lock lock) {
   lock.Release();
   semaphore.P();
   lock.Acquire();
}
Signal() { semaphore.V(); }
```

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 lock) {
    lock.Release();
    semaphore.P();
    lock.Acquire();
}
Signal() {
    if semaphore queue is not empty
        semaphore.V();
}
```

  - 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?

Monitor Conclusion

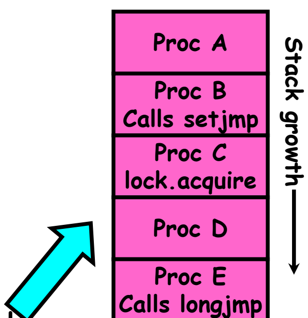
- Monitors represent the logic of the program
  - Wait if necessary
  - Signal when change something so any waiting threads can proceed
- Basic structure of monitor-based program:

```
lock
while (need to wait) {       Check and/or update
    condvar.wait();            state variables
}                              Wait if necessary
unlock

do something so no need to wait

lock

condvar.signal();            Check and/or update
                               state variables
unlock
```


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() {
    lock.acquire();
    …
    if (exception) {
        lock.release();
        return errReturnCode;
    }
    …
    lock.release();
    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!

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;
  …
}
```

  - Even Better: auto_ptr<T> facility. See C++ Spec.
    - » Can deallocate/free lock regardless of exit method

Java Language Support for Synchronization

- Java has explicit support for threads and thread synchronization
- Bank Account example:

```
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;
  }
}
```

  - Every object has an associated lock which gets automatically acquired and released on entry and exit from a *synchronized* method.

Java Language Support for Synchronization (con't)

- Java also has *synchronized* statements:

```
synchronized (object) {
    …
}
```

  - Since every Java object has an associated lock, this type of statement acquires and releases the object's lock on entry and exit of the body
  - Works properly even with exceptions:

```
synchronized (object) {
  …
  DoFoo();
  …
}
void DoFoo() {
  throw errException;
}
```


Java Language Support for Synchronization (con't 2)

- In addition to a lock, every object has a single condition variable associated with it
  - How to wait inside a synchronization method of block:
    - » `void wait(long timeout); // Wait for timeout`
    - » `void wait(long timeout, int nanoseconds); //variant`
    - » `void wait();`
  - How to signal in a synchronized method or block:
    - » `void notify();    // wakes up oldest waiter`
    - » `void notifyAll(); // like broadcast, wakes everyone`
  - Condition variables can wait for a bounded length of time. This is useful for handling exception cases:

```
t1 = time.now();
while (!ATMRequest()) {
  wait (CHECKPERIOD);
  t2 = time.new();
  if (t2 – t1 > LONG_TIME) checkMachine();
}
```

  - Not all Java VMs equivalent!
    - » Different scheduling policies, not necessarily preemptive!

Recall: Better Implementation of Locks by Disabling Interrupts

- Key idea: maintain a lock variable and impose mutual exclusion only during operations on that variable

```
int mylock = FREE;
Acquire(&mylock) – wait until lock is free, then grab
Release(&mylock) – Unlock, waking up anyone waiting
```

```
Acquire(int *lock) {
   disable interrupts;
   if (*lock == BUSY) {
      put thread on wait queue;
      Go to sleep();
      // Enable interrupts?
   } else {
      *lock = BUSY;
   }
   enable interrupts;
}
```

```
Release(int *lock) {
   disable interrupts;
   if (anyone on wait queue) {
      take thread off wait queue
      Place on ready queue;
   } else {
      *lock = FREE;
   }
   enable interrupts;
}
```

- Really only works in kernel – why?

In-Kernel Lock: Simulation

Value: 0 | waiters | owner | READY

Running

Thread A | *Thread B*

```
INIT
  int value = 0;

Acquire() {
  disable interrupts;
  if (value == 1) {
    put thread on wait-queue;
    go to sleep() //??
  } else {
    value = 1;
  }
  enable interrupts;
}

Release() {
 disable interrupts;
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  } else {
    value = 0;
  }
  enable interrupts;
}
```

Thread A:
```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

Thread B:
```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```


In-Kernel Lock: Simulation

Value: 1 | waiters | owner | READY

Running

Thread A | *Thread B*

```
INIT
  int value = 0;

Acquire() {
  disable interrupts;
  if (value == 1) {
    put thread on wait-queue;
    go to sleep() //??
  } else {
    value = 1;
  }
  enable interrupts;
}

Release() {
 disable interrupts;
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  } else {
    value = 0;
  }
  enable interrupts;
}
```

Thread A:
```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

Thread B:
```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```


In-Kernel Lock: Simulation

Value: 1 | waiters | owner | READY

Running | Running

Thread A | *Thread B*

```
INIT
  int value = 0;

Acquire() {
  disable interrupts;
  if (value == 1) {
    put thread on wait-queue;
    go to sleep() //??
  } else {
    value = 1;
  }
  enable interrupts;
}

Release() {
 disable interrupts;
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  } else {
    value = 0;
  }
  enable interrupts;
}
```

Thread A:
```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

Thread B:
```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

In-Kernel Lock: Simulation

Value: 1 | waiters | owner | READY

Running — *Thread A*

Running — *Thread B*

```
INIT
  int value = 0;
```

Thread A:

```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

```
Acquire() {
  disable interrupts;
  if (value == 1) {
    put thread on wait-queue;
    go to sleep() //??
  } else {
    value = 1;
  }
  enable interrupts;
}

Release() {
 disable interrupts;
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  } else {
    value = 0;
  }
  enable interrupts;
}
```

Thread B:

```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```


In-Kernel Lock: Simulation

Value: 1 | waiters | owner | READY

Running — *Thread A*

Thread B

```
INIT
  int value = 0;
```

Thread A:

```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

```
Acquire() {
  disable interrupts;
  if (value == 1) {
    put thread on wait-queue;
    go to sleep() //??
  } else {
    value = 1;
  }
  enable interrupts;
}

Release() {
 disable interrupts;
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  } else {
    value = 0;
  }
  enable interrupts;
}
```

Thread B:

```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```


In-Kernel Lock: Simulation

Value: 1 | waiters | owner | READY

Running — *Thread A*

Running — *Thread B*

```
INIT
  int value = 0;
```

Thread A:

```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

```
Acquire() {
  disable interrupts;
  if (value == 1) {
    put thread on wait-queue;
    go to sleep() //??
  } else {
    value = 1;
  }
  enable interrupts;
}

Release() {
 disable interrupts;
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  } else {
    value = 0;
  }
  enable interrupts;
}
```

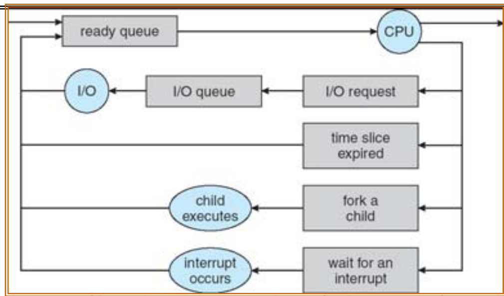
Thread B:

```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```


Discussion

- Notice that Scheduling here involves deciding who to take off the wait queue
  - Could do by priority, etc.
- Same type of code works for condition variables
  - The Wait queue becomes unique for each condition variable
  - Once again, transition two and from queues occurs with interrupts disabled

Recall: CPU Scheduling

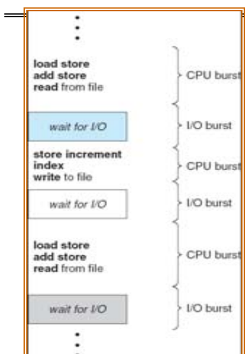


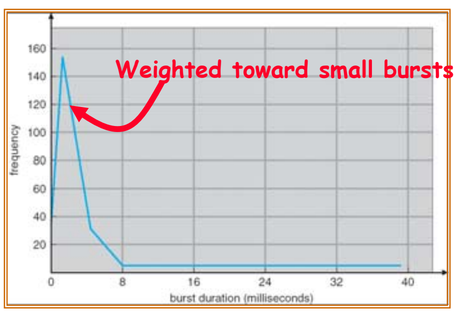
- Earlier, we talked about the life-cycle of a thread
  - Active threads work their way from Ready queue to Running to various waiting queues.
- Question: How is the OS to decide which of several tasks to take off a queue?
  - Obvious queue to worry about is ready queue
  - Others can be scheduled as well, however
- **Scheduling**: deciding which threads are given access to resources from moment to moment

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





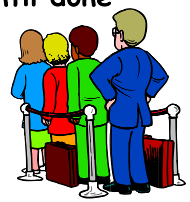
- Execution model: programs alternate between bursts of CPU and I/O
  - Program typically uses the CPU for some period of time, then does I/O, then uses CPU again
  - Each scheduling decision is about which job to give to the CPU for use by its next CPU burst
  - With timeslicing, thread may be forced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

P_1	P_2	P_3
0–24	24–27	27–30

  - 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 behind long process

FCFS Scheduling (Cont.)

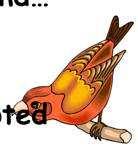
- Example continued:
  - Suppose that processes arrive in order: P_2 , P_3 , P_1 Now, the Gantt chart for the schedule is:

P_2	P_3	P_1
0–3	3–6	6–30

  - Waiting time for P_1 = 6; P_2 = 0; P_3 = 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 small items. Upside: get to read about space aliens!

Round Robin (RR)

- FCFS Scheme: Potentially bad for short jobs!
  - Depends on submit order
  - If you are first in line at supermarket with milk, you don't care who is behind you, on the other hand…
- Round Robin Scheme
  - Each process gets a small unit of CPU time (*time quantum*), usually 10-100 milliseconds
  - After quantum expires, the process is preempted and added to the end of the ready queue.



  - n processes in ready queue and time quantum is $q \Rightarrow$
    - » Each process gets $1/n$ of the CPU time
    - » In chunks of at most q time units
    - » No process waits more than $(n-1)q$ time units
- Performance
  - q large $\Rightarrow$ FCFS
  - q small $\Rightarrow$ Interleaved (really small $\Rightarrow$ hyperthreading?)
  - q must be large with respect to context switch, otherwise overhead is too high (all overhead)

Example of RR with Time Quantum = 20

- Example:

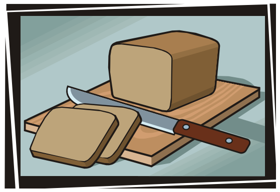
Process	Burst Time
P_1	53
P_2	8
P_3	68
P_4	24

  - The Gantt chart is:

P_1	P_2	P_3	P_4	P_1	P_3	P_4	P_1	P_3	P_3
0–20	20–28	28–48	48–68	68–88	88–108	108–112	112–125	125–145	145–153

  - Waiting time for
    P_1=(68-20)+(112-88)=72
    P_2=(20-0)=20
    P_3=(28-0)+(88-48)+(125-108)=85
    P_4=(48-0)+(108-68)=88
  - Average waiting time = (72+20+85+88)/4=66¼
  - Average completion time = (125+28+153+112)/4 = 104½
- Thus, Round-Robin Pros and Cons:
  - Better for short jobs, Fair (+)
  - Context-switching time adds up for long jobs (-)

Round-Robin Discussion



- How do you choose time slice?
  - What if too big?
    - » Response time suffers
  - What if infinite (∞)?
    - » Get back FIFO
  - What if time slice too small?
    - » Throughput suffers!
- Actual choices of timeslice:
  - Initially, UNIX timeslice one second:
    - » Worked ok when UNIX was used by one or two people.
    - » What if three compilations going on? 3 seconds to echo each keystroke!
  - In practice, need to balance short-job performance and long-job throughput:
    - » Typical time slice today is between 10ms – 100ms
    - » Typical context-switching overhead is 0.1ms – 1ms
    - » Roughly 1% overhead due to context-switching

Comparisons between FCFS and Round Robin

- Assuming zero-cost context-switching time, is RR always better than FCFS?
- Simple example: 10 jobs, each take 100s of CPU time
  RR scheduler quantum of 1s
  All jobs start at the same time
- Completion Times:

Job #	FIFO	RR
1	100	991
2	200	992
…	…	…
9	900	999
10	1000	1000

  - Both RR and FCFS finish at the same time
  - Average response time is much worse under RR!
    - » Bad when all jobs same length
- Also: Cache state must be shared between all jobs with RR but can be devoted to each job with FIFO
  - Total time for RR longer even for zero-cost switch!

Earlier Example with Different Time Quantum

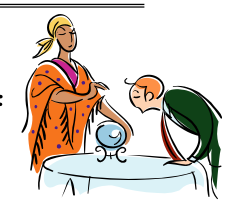
Best FCFS:

P_2 [8]	P_4 [24]	P_1 [53]	P_3 [68]

0 8 32 85 153

	Quantum	P_1	P_2	P_3	P_4	Average
Wait Time	Best FCFS	32	0	85	8	$31\frac{1}{4}$
	Q = 1	84	22	85	57	62
	Q = 5	82	20	85	58	$61\frac{1}{4}$
	Q = 8	80	8	85	56	$57\frac{1}{4}$
	Q = 10	82	10	85	68	$61\frac{1}{4}$
	Q = 20	72	20	85	88	$66\frac{1}{4}$
	Worst FCFS	68	145	0	121	$83\frac{1}{2}$
Completion Time	Best FCFS	85	8	153	32	$69\frac{1}{2}$
	Q = 1	137	30	153	81	$100\frac{1}{2}$
	Q = 5	135	28	153	82	$99\frac{1}{2}$
	Q = 8	133	16	153	80	$95\frac{1}{2}$
	Q = 10	135	18	153	92	$99\frac{1}{2}$
	Q = 20	125	28	153	112	$104\frac{1}{2}$
	Worst FCFS	121	153	68	145	$121\frac{3}{4}$

What if we Knew the Future?

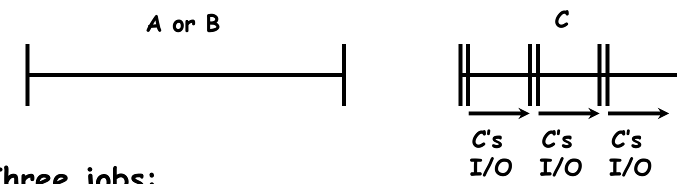


- Could we always mirror best FCFS?
- Shortest Job First (SJF):
  - Run whatever job has the least amount of computation to do
  - Sometimes called "Shortest Time to Completion First" (STCF)
- Shortest Remaining Time First (SRTF):
  - Preemptive version of SJF: if job arrives and has a shorter time to completion than the remaining time on the current job, immediately preempt CPU
  - Sometimes called "Shortest Remaining Time to Completion First" (SRTCF)
- These can be applied either to a whole program or the current CPU burst of each program
  - Idea is to get short jobs out of the system
  - Big effect on short jobs, only small effect on long ones
  - Result is better average response time

Discussion

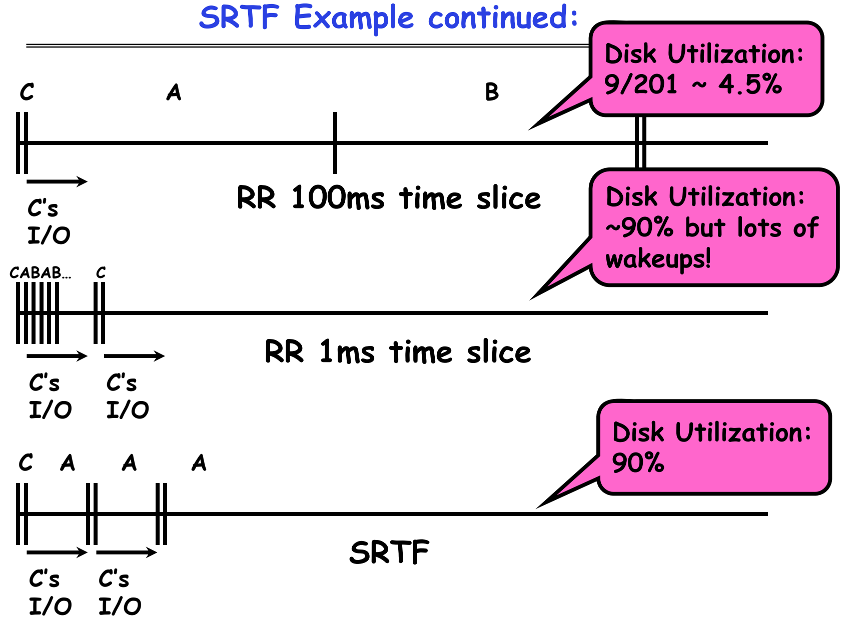
- SJF/SRTF are the best you can do at minimizing average response time
  - Provably optimal (SJF among non-preemptive, SRTF among preemptive)
  - Since SRTF is always at least as good as SJF, focus on SRTF
- Comparison of SRTF with FCFS and RR
  - What if all jobs the same length?
    - » SRTF becomes the same as FCFS (i.e. FCFS is best can do if all jobs the same length)
  - What if jobs have varying length?
    - » SRTF (and RR): short jobs not stuck behind long ones

Example to illustrate benefits of SRTF



- Three jobs:
  - A,B: both CPU bound, run for week
    C: I/O bound, loop 1ms CPU, 9ms disk I/O
  - If only one at a time, C uses 90% of the disk, A or B could use 100% of the CPU
- With FIFO:
  - Once A or B get in, keep CPU for two weeks
- What about RR or SRTF?
  - Easier to see with a timeline

SRTF Example continued:

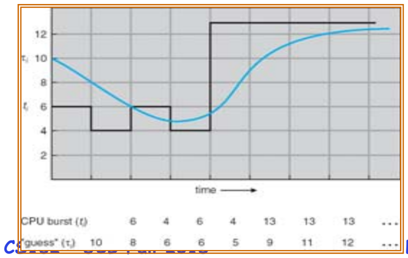


SRTF Further discussion

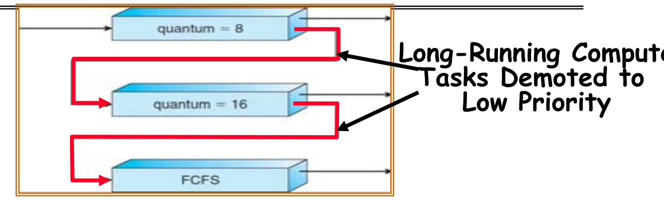
- Starvation
  - SRTF can lead to starvation if many small jobs!
  - Large jobs never get to run
- Somehow need to predict future
  - How can we do this?
  - Some systems ask the user
    - » When you submit a job, have to say how long it will take
    - » To stop cheating, system kills job if takes too long
  - But: Even non-malicious users have trouble predicting runtime of their jobs
- Bottom line, can't really know how long job will take
  - However, can use SRTF as a yardstick for measuring other policies
  - Optimal, so can't do any better
- SRTF Pros & Cons
  - Optimal (average response time) (+)
  - Hard to predict future (-)
  - Unfair (-)

Predicting the Length of the Next CPU Burst

- **Adaptive**: Changing policy based on past behavior
  - CPU scheduling, in virtual memory, in file systems, etc
  - Works because programs have predictable behavior
    - » If program was I/O bound in past, likely in future
    - » If computer behavior were random, wouldn't help
- Example: SRTF with estimated burst length
  - Use an estimator function on previous bursts: Let t_{n-1}, t_{n-2}, t_{n-3}, etc. be previous CPU burst lengths. Estimate next burst $\tau_n = f(t_{n-1}, t_{n-2}, t_{n-3}, \ldots)$
  - Function f could be one of many different time series estimation schemes (Kalman filters, etc)
  - For instance, exponential averaging $\tau_n = \alpha t_{n-1} + (1-\alpha)\tau_{n-1}$ with $(0 < \alpha \leq 1)$



Multi-Level Feedback Scheduling



- Another method for exploiting past behavior
  - First used in CTSS
  - Multiple queues, each with different priority
    - » Higher priority queues often considered "foreground" tasks
  - Each queue has its own scheduling algorithm
    - » e.g. foreground – RR, background – FCFS
    - » Sometimes multiple RR priorities with quantum increasing exponentially (highest:1ms, next:2ms, next: 4ms, etc)
- Adjust each job's priority as follows (details vary)
  - Job starts in highest priority queue
  - If timeout expires, drop one level
  - If timeout doesn't expire, push up one level (or to top)

Scheduling Details

- Result approximates SRTF:
  - CPU bound jobs drop like a rock
  - Short-running I/O bound jobs stay near top
- Scheduling must be done between the queues
  - Fixed priority scheduling:
    - » serve all from highest priority, then next priority, etc.
  - Time slice:
    - » each queue gets a certain amount of CPU time
    - » e.g., 70% to highest, 20% next, 10% lowest
- **Countermeasure**: user action that can foil intent of the OS designer
  - For multilevel feedback, put in a bunch of meaningless I/O to keep job's priority high
  - Of course, if everyone did this, wouldn't work!
- Example of Othello program:
  - Playing against competitor, so key was to do computing at higher priority the competitors.
    - » Put in printf's, ran much faster!

Scheduling Fairness

- What about fairness?
  - Strict fixed-priority scheduling between queues is unfair (run highest, then next, etc):
    - » long running jobs may never get CPU
    - » In Multics, shut down machine, found 10-year-old job
  - Must give long-running jobs a fraction of the CPU even when there are shorter jobs to run
  - Tradeoff: fairness gained by hurting avg response time!
- How to implement fairness?
  - Could give each queue some fraction of the CPU
    - » What if one long-running job and 100 short-running ones?
    - » Like express lanes in a supermarket—sometimes express lanes get so long, get better service by going into one of the other lines
  - Could increase priority of jobs that don't get service
    - » What is done in UNIX
    - » This is ad hoc—what rate should you increase priorities?
    - » And, as system gets overloaded, no job gets CPU time, so everyone increases in priority⇒Interactive jobs suffer

Lottery Scheduling

- Yet another alternative: Lottery Scheduling
  - Give each job some number of lottery tickets
  - On each time slice, randomly pick a winning ticket
  - On average, CPU time is proportional to number of tickets given to each job
- How to assign tickets?
  - To approximate SRTF, short running jobs get more, long running jobs get fewer
  - To avoid starvation, every job gets at least one ticket (everyone makes progress)
- Advantage over strict priority scheduling: behaves gracefully as load changes
  - Adding or deleting a job affects all jobs proportionally, independent of how many tickets each job possesses

Lottery Scheduling Example

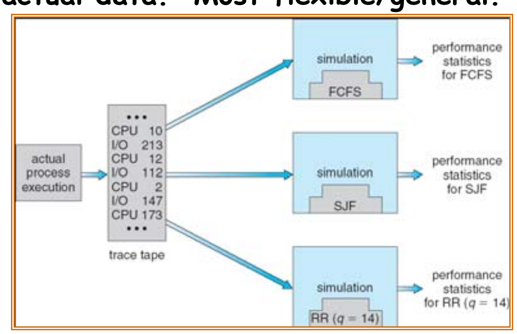
- Lottery Scheduling Example
  - Assume short jobs get 10 tickets, long jobs get 1 ticket

# short jobs/ # long jobs	% of CPU each short jobs gets	% of CPU each long jobs gets
1/1	91%	9%
0/2	N/A	50%
2/0	50%	N/A
10/1	9.9%	0.99%
1/10	50%	5%

  - What if too many short jobs to give reasonable response time?
    - » In UNIX, if load average is 100, hard to make progress
    - » One approach: log some user out

How to Evaluate a Scheduling algorithm?

- Deterministic modeling
  - takes a predetermined workload and compute the performance of each algorithm for that workload
- Queueing models
  - Mathematical approach for handling stochastic workloads
- Implementation/Simulation:
  - Build system which allows actual algorithms to be run against actual data. Most flexible/general.



Summary

- **Semaphores**: Like integers with restricted interface
  - Two operations:
    - » `P()`: Wait if zero; decrement when becomes non-zero
    - » `V()`: Increment and wake a sleeping task (if exists)
    - » Can initialize value to any non-negative value
  - Use separate semaphore for each constraint
- **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()`
- **Scheduling**: selecting a waiting process from the ready queue and allocating the CPU to it
- **FCFS Scheduling**:
  - Run threads to completion in order of submission
  - Pros: Simple
  - Cons: Short jobs get stuck behind long ones
- **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
  - Cons: Poor when jobs are same length

Summary (2)

- **Shortest Job First (SJF)/Shortest Remaining Time First (SRTF):**
  - Run whatever job has the least amount of computation to do/least remaining amount of computation to do
  - Pros: Optimal (average response time)
  - Cons: Hard to predict future, Unfair
- **Multi-Level Feedback Scheduling:**
  - Multiple queues of different priorities
  - Automatic promotion/demotion of process priority in order to approximate SJF/SRTF
- **Lottery Scheduling:**
  - Give each thread a priority-dependent number of tokens (short tasks⇒more tokens)
  - Reserve a minimum number of tokens for every thread to ensure forward progress/fairness
- **Evaluation of mechanisms:**
  - Analytical, Queuing Theory, Simulation