Design and Analysis of Operating Systems
CSCI 3753

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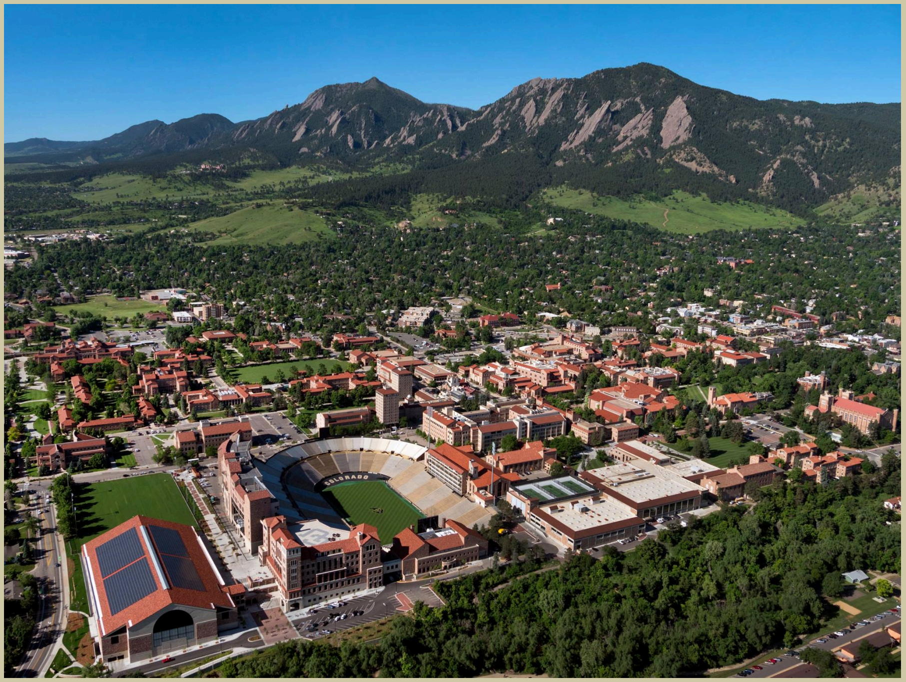
Monitors and Conditional Variables



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Deadlock when using Semaphores

- It can easily occur
  - two tasks, each desires a resource locked by the other process
  - circular dependency
  - programming errors
    - switching order of P() and V()
    - calling wait multiple times
    - forgetting a signal
- Semaphores provide mutual exclusion, but can introduce deadlock

Monitors

- Semaphores can result in deadlock due to programming errors
  - forgot to add a P() or V(), or misordered them, or duplicated them
- To reduce these errors, introduce high-level synchronization primitives, e.g. *monitors with condition variables*
  - essentially automates insertion of P() and V() for you
  - As high-level synchronization constructs, monitors are found in high-level programming languages like Java and C#
  - underneath, the OS may implement monitors using semaphores and mutex locks

Monitors

- Declare a monitor as follows (looks somewhat like a C++ class):

```
monitor monitor_name {
     // shared local variables

     function f1(...) {
     ...
     }
     ...
     function fN(...) {
     ...
     }
     init_code(...) {
     ...
     }
  }
```

- A monitor ensures that only 1 process/thread at a time can be active within a monitor
  – simplifies programming, no need to explicitly synchronize
- Implicitly, the monitor defines a mutex lock

  semaphore mutex = 1;

- Implicitly, the monitor also defines mutual exclusion around each function
  – Each function's critical code is effectively:

```
function fj(...) {
  P(mutex)
  // critical code
  V(mutex)
}
```

Monitors

- Declare a monitor as follows (looks somewhat like a C++ class):

```
monitor monitor_name {
     // shared local variables
       int count;
       data_type data[MAX_COUNT];

     function add_item(...) {
     ...
     }

     ...
     function remove_item(...) {
     ...
     }

     init_code(...) {
     ...
     }
  }
```

- The monitor's private local variables can only be accessed by local monitor functions
- Each function in the monitor can only access variables declared locally within the monitor and its parameters

Monitors and Condition Variables

- Previous definition of a monitor achieves
  - mutual exclusion
  - hiding of wait() and signal() from user
  - loses the ability that semaphores had to enforce order
    - wait() and signal() are used to provide mutual exclusion
    - but have lost the unique ability for one process to signal another blocked process using signal()
    - there is no way to have a process sleep waiting on the signal

- In general, there may be times when one process wishes to signal another process based on a condition, much like semaphores.
  - Thus, augment monitors with *condition variables*.

Condition Variables

- Augment the mutual exclusion of a monitor with an ordering mechanism
  - Recall: Semaphore P() and V() provide both mutual exclusion *and* ordering
  - Monitors alone only provide mutual exclusion
- A condition variable provides ordering
  - Used when one task wishes to wait until a condition is true before proceeding
    - Such as a queue being full enough or data being ready
  - A 2nd task will signal the waiting task, thereby waking up the waiting task to proceed

Monitors and Condition Variables

condition y;

A condition variable *y* in a monitor allows three operations

- y.wait()
  - blocks the calling process
  - can have multiple processes suspended on a condition variable, typically released in FIFO order
  - textbook describes another variation specifying a priority p,   i.e. call y.wait(p)
- y.signal()
  - resumes exactly 1 suspended process.
  - If no process is waiting, then function has *no effect*.
- y.queue()
  - Returns true if there is at least one process blocked on y

A Monitor to Allocate Single Resource

```
monitor ResourceAllocator
{
   boolean busy;
   condition x;
   void acquire(int time) {
            if (busy)
               x.wait(time);
            busy = TRUE;
   }

   void release() {
            busy = FALSE;
            x.signal();
   }

   initialization code() {
    busy = FALSE;
   }
}
```

Condition Variables Example

Block Task 1 until a condition holds true, e.g. queue is empty

```
condition wait_until_empty;
```

Task 1:

```
wait_until_empty.wait();
…  // proceed after queue
         empty
```

Task 2:

```
…
// queue is empty so signal
wait_until_empty.signal();
```

Problem: if Task 2 signals before Task 1 waits, then Task 1 waits *forever* because CV *has no state*!

Condition Variables vs Semaphores

Both have wait() and signal(), but semaphore's signal()/V() *preserves state* in its integer value

```
Semaphore wait_until_empty=0;
```

Task 1:

```
wait(wait_until_empty);
…  // proceed after queue
         empty
```

Task 2:

```
…
// queue is empty so signal
signal(wait_until_empty); //V()
```

if Task 2 signals before Task 1 waits, then Task 1 does *not* wait forever because semaphore has state and remembers earlier signal()

Complex Conditions

- Suppose you want task T1 to wait until a complex set of conditions set by T2 becomes TRUE
  - use a condition variable

```
condition x;
int count=0;
float f=0.0;
```

T1

```
…
while(f!=7.0 && count<=0) {
   x.wait();
}
… // proceed
```

T2

```
…
f=7.0;
count++;
x.signal();
```

Problem: could be a race condition in testing and setting shared variables

Complex Conditions (2)

- Surround the test of the conditions with a mutex to atomically test the set of conditions

```
lock mutex;
condition x;
int count=0;
float f=0.0;
```

T1

```
…
Acquire(mutex);
while(f!=7.0 && count<=0) {
    Release(mutex);
    x.wait();
    Acquire(mutex);
}
Release(mutex);
… // proceed
```

T2

```
…
Acquire(mutex);
f=7.0;
count++;
Release(mutex);
x.signal();
```

Complex Conditions (3)

```
lock mutex;
condition x;
int count=0;
float f=0.0;
```

- pthreads replaces complex sequence of release/wait/acquire() with:

```
pthread_cond_wait(&cond_var,&mutex)
```

T1

```
…
Acquire(mutex);
while(f!=7.0 && count<=0) {
  pthread_cond_wait(&x,&mutex);
}
Release(mutex);
… // proceed
```

T2

```
…
Acquire(mutex);
f=7.0;
count++;
Release(mutex);
x.signal();
```

Broadcast Signals

- In some cases, you may want to wake all tasks blocked on a condition variable x, not just one
  - x.signal() only wakes one task
- *x.broadcast()* is a 3rd operation provided for CVs on some systems
  - Wakes all tasks blocked on a CV
  - In pthreads, `pthread_cond_broadcast()` wakes all waiting threads

Monitors

- Declare a monitor as follows (looks somewhat like a C++ class):

```
monitor monitor_name {
     // shared local variables
        int count;
        data_type data[MAX_COUNT];
        condition y;

     function add_item(...) {
     ...
        y.wait();
     ...
     }

     ...
     function remove_item(...) {
     ...
         y.signal();
     ...
     }

     init_code(...) {
     ...
     }
  }
```

- The monitor's local variables can only be accessed by local monitor functions
- Each function in the monitor can only access variables declared locally within the monitor and its parameters

Monitors and Condition Variables

- Problem: A monitor ensures that only 1 process/thread at a time can be active within a monitor
  - if a process P1 calls y.signal() it would wake another process P2 blocked on y.wait()
  - But we must avoid having two processes at the same time in the monitor
  - Need "wake-up" semantics on a y.signal()
- Two solutions proposed to only have one process active:
  - Hoare semantics, also called signal-and-wait
    - The signaling process P1 waits for P2 to either leave the monitor or wait on another condition, before resuming
  - Mesa semantics, also called signal-and-continue
    - The signaled process P2 continues to wait until the signaling process P1 leaves the monitor or wait on another condition

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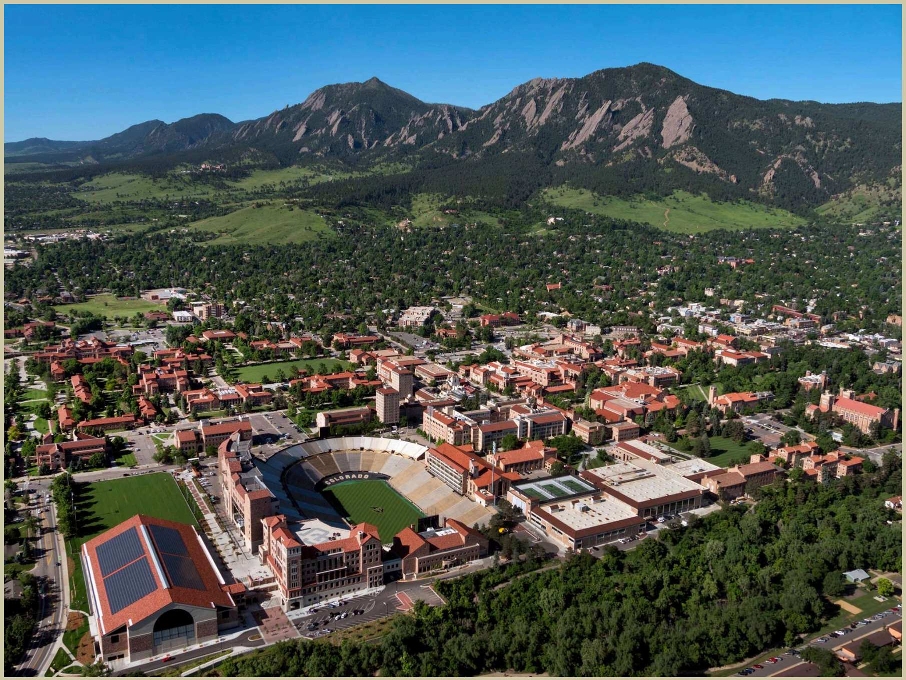

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