Design and Analysis of Operating Systems
CSCI 3753

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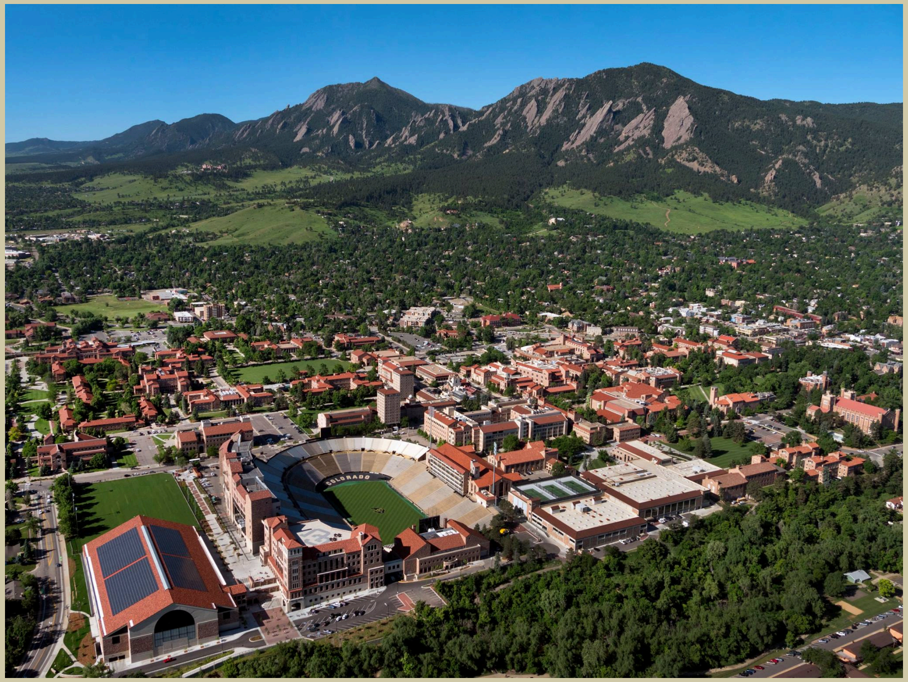
Mutexes and Semaphores



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Mutual exclusion using TS

```
shared boolean lock = FALSE;
shared int count;
Shared data_type buffer[MAX];
```

Code for p_1

```
while(1) {
    produce (nextdata)
    while(count==MAX);
    Acquire(lock);
    buffer[count] = nextdata;
    count++;
    Release(lock);
}
```

Code for p_2

```
while(1) {
    while(count==0);
    Acquire(lock);
    data = buffer[count-1];
    count--;
    Release(lock);
    consume(data);
}
```

CPU is spinning & waiting

How can we eliminate the busy waiting?

Mutual exclusion using TS

```
shared boolean lock = FALSE;
shared int count;
Shared data_type buffer[MAX];
```

Code for p_1

```
while(1) {
    produce (nextdata)
    while(count==MAX);
    Acquire(lock);
    buffer[count] = nextdata;
    count++;
    Release(lock);
}
```

Code for p_2

```
while(1) {
    while(count==0);
    Acquire(lock);
    data = buffer[count-1];
    count--;
    Release(lock);
    consume(data);
}
```

- Look first at the busy wait when there is no room for data or no data
  - Need a way to pause a process/thread until the space is available or the data is available

sleep( ) and **wakeup( )** primitives

- *sleep()*: causes a running process to block
- *wakeup(pid)*: causes the process whose id is *pid* to move to ready state
  - No effect if process *pid* is not blocked

Using **sleep( )** and **wakeup( )** primitives

```
// producer – place data into buffer
while(1) {
   if (count == MAX) sleep();
   buffer[count] = nextdata;
   count++;
   if (count == 1) wakeup (consumer);
}

// consumer – take data out of buffer
while(1) {
   if (count == 0) sleep();
   getdata = buffer[count-1];
   count--;
   if (count == MAX–1) wakeup (producer);
}
```

Our solution using sleep( ) and wakeup( )

- Still a problem with mutual exclusion of the critical sections containing counter++ and counter-- still exist
  - Could use TS, but that has busy waiting (we will solve this later)
- Possible problem with order of execution:
  - Consumer reads count and count == 0
  - Scheduler schedules the producer to run
  - Producer puts an item in the buffer and signals the consumer to wake up
    - Since consumer has not yet invoked sleep(), the wakeup() invocation by the producer has no effect
  - Scheduler now schedules the Consumer to continue, and the consumer blocks because it missed the wakeup() by the producer
  - Eventually, producer fills up the buffer and blocks
- How can we solve this problem?
  - Could use a mechanism to count the number of sleep() and wakeup() invocations

Semaphores

- Dijkstra proposed more general solution to mutual exclusion

- Semaphore S is an abstract data type that is accessed only through two standard atomic operations
  - wait( ) (also called P(), from Dutch word *proberen* "to test")
    - somewhat equivalent to a test-and-set
    - also involves *decrementing* the value of S
  - signal( ) (V(), from Dutch word *verhogen* "to increment")
    - *increments* the value of S

- OS provides ways to create and manipulate semaphores atomically

Semaphores

```
typedef struct {
    int value;
    PID *list[ ];
} semaphore;
```

Both wait() and signal() operations are atomic

```
wait(semaphore *s) {
    s→value--;
    if (s→value < 0) {
        add this process to s→list;
        sleep ( );
    }
}
```

```
signal(semaphore *s) {
    s→value++;
    if (s→value <= 0) {
        remove a process P from s→list;
        wakeup (P);
    }
}
```

Mutual Exclusion using Semaphores
Binary Semaphore

```
semaphore S = 1;  // initial value of semaphore is 1
int counter;      // assume counter is set correctly somewhere in code
```

Process P1:

```
wait(S);
   // execute critical section
   counter++;
signal(S);
```

Process P2:

```
wait(S);
   // execute critical section
   counter--;
signal(S);
```

- Both processes atomically wait() and signal() the semaphore S, which enables mutual exclusion on critical section code, in this case protecting access to the shared variable ***counter***
- This will solve the mutual exclusion like a mutex lock, but will also eliminate the busy waiting

Problems with Semaphores

shared R1, R2;

semaphore Q = 1;   // binary semaphore as a mutex lock for R1

semaphore S = 1;   // binary semaphore as a mutex lock for R2

Process P1:		*Process P2:*	
wait(S);	(1)	wait(Q);	(2)
wait(Q);	(4)	wait(S);	(3)
modify R1 and R2;		modify R1 and R2;	
signal(S);		signal(Q);	
signal(Q);		signal(S);	

- Potential for Deadlock

Deadlock

- In the previous example,
  - Each process will block on a semaphore
  - The signal() statements will never get executed, so there is no way to wake up the two processes
  - There is no rule about the order in which wait( ) and signal( ) operations may be invoked
  - In general, with N processes sharing N semaphores, the potential for deadlock grows

Other problematic scenarios for Semaphores

- A programmer mistakenly follows a wait() with a second wait() instead of a signal()

- A programmer forgets and omits the wait(mutex) or signal(mutex)

- A programmer reverses the order of wait() and signal()

Another problem with synchronization

shared R1, R2;

semaphore S = 1;   // binary semaphore as a mutex lock for R1 & R2

Process P1:	*Process P2:*	*Process P3:*
wait(S);	wait(S);	wait(S);
modify R1 and R2;	modify R1 and R2;	modify R1 and R2;
signal(S);	signal(S);	signal(S);

Potential for starvation

Starvation

- The possibility that a process would never get to run
- For example, in a multi-tasking system the resources could switch between two individual processes
- Depending on how the processes are scheduled, a third process may never get to run
- The third task is being starved of accessing the resource

Semaphore Solution for Mutual Exclusion

```
semaphore lock = 1;  // initial value of semaphore is 1
shared int count;
shared data_type buffer[MAX];
```

Code for p_1

```
while(1) {
    produce (nextdata)
    while(count==MAX);
    wait(lock);
    buffer[count] = nextdata;
    count++;
    signal(lock);
}
```

Code for p_2

```
while(1) {
    while(count==0);
    wait(lock);
    data = buffer[count-1];
    count--;
    signal(lock);
    consume(data);
}
```

- Busy waiting removed from the mutual exclusion when waiting on lock
- Will show a complete solution in another video

Does the Kernel need Synchronization?

- At any time, many kernel mode processes may be active
  - Share kernel data structures
  - Notice that even though user processes have their own address spaces, race conditions can still arise when they execute in kernel mode, e.g. executing a system call

- Preemptive and non-preemptive kernels
  - Preemptive kernel: allows a process to be preempted while running in kernel mode
    - Race conditions can occur

  - Non-preemptive kernel: does not allow a process to be preempted while running in kernel mode
    - Race conditions cannot occur

Windows Synchronization

- Kernel level
  – Single processor system: temporarily mask interrupts for all interrupt handlers that may also access a shared resource
  – Multiprocessor system: use spin lock (busy waiting)

- User level
  – Dispatcher objects: mutex locks, semaphores, …

Linux Synchronization

- Kernel level
  - Prior to version 2.6, non-preemptive kernel, but later versions are fully preemptive
  - Atomic integers: all math operations on atomic integers are performed without interruptions

```
atomic_t counter;
atomic_set(&counter, 5);
atomic_add(10, &counter);
…
```

  - Mutex locks, spin locks and semaphores, enabling/ disabling interrupts on single processor systems

- User level
  - futex, semop( ): system call

pthread Synchronization

- Mutex locks
  - Used to protect critical sections
- Some implementations provide semaphores through POSIX SEM extension
  - Not part of Pthread standard

```
#include <pthread.h>
pthread_mutex_t m; //declare a mutex object
pthread_mutex_init (&m, NULL); // initialize mutex object
```

```
//thread 1
pthread_mutex_lock (&m);
   //critical section code for th1
pthread_mutex_unlock (&m);
```

```
//thread 2
pthread_mutex_lock (&m);
   //critical section code for th2
pthread_mutex_unlock (&m);
```

pthread mutex

- pthread mutexes can have only one of two states: lock or unlock
- Important restriction
  - Mutex ownership: Only the thread that locks a mutex can unlock that mutex
  - So, mutexes are strictly used for mutual exclusion while binary semaphores can also be used for synchronization between two threads

POSIX semaphores

```
#include <semaphore.h>

int sem_init(sem_t *sem, int pshared, unsigned int value);
//  pshared: 0 (among threads); 1 (among processes)

int sem_wait(sem_t *sem); //same as wait( )

int sem_post(sem_t *sem); //same as signal( )

sem_getvalue( ), sem_close( )
```

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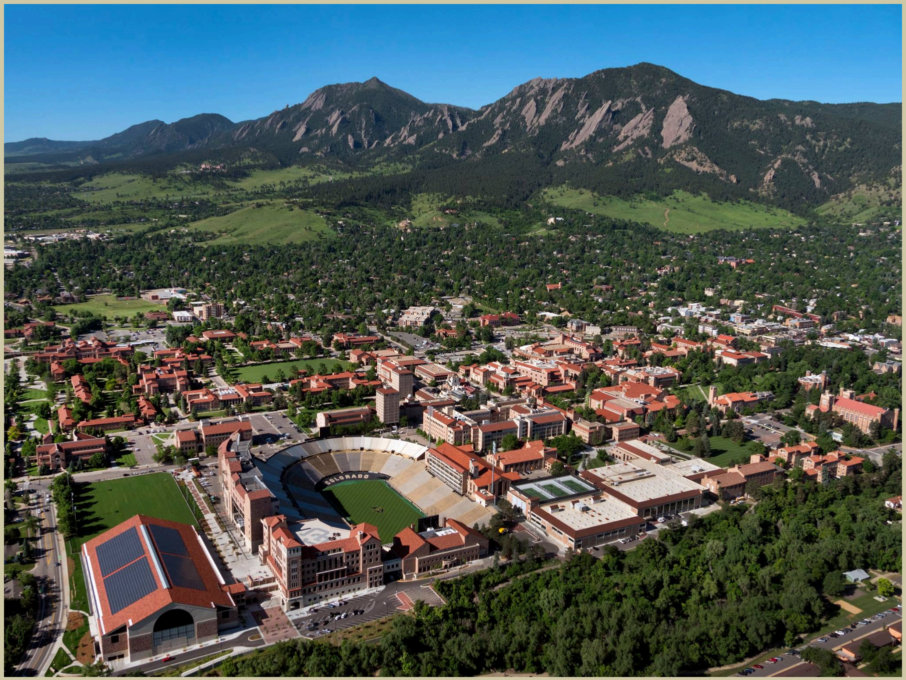

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