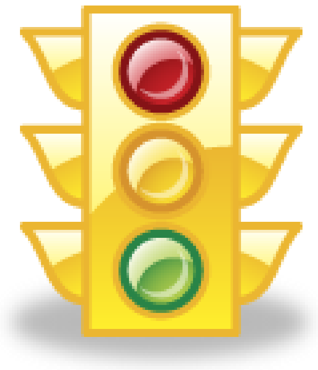
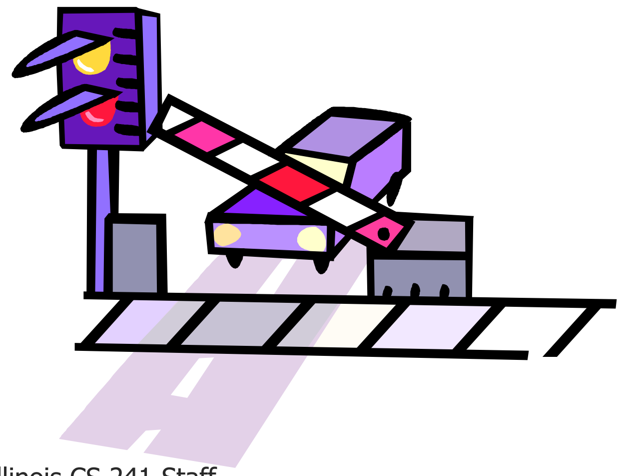
Synchronization and Semaphores





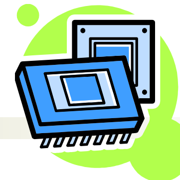
Discussion

- In uni-processors
  - Concurrent processes cannot be overlapped, only interleaved
  - A process runs until it invokes a system call, or is interrupted
  - To guarantee mutual exclusion, hardware support could help by allowing the disabling of interrupts

```
While(true) {
     /* disable interrupts */
     /* critical section */
     /* enable interrupts */
     /* remainder */
}
```

  - What's the problem with this solution?

Discussion



- In multi-processors
  - Several processors share memory
  - Processors behave independently in a peer relationship
  - Interrupt disabling will not work
  - We need hardware support where access to a memory location excludes any other access to that same location
  - The hardware support is based on execution of multiple instructions atomically (test and set)

Test and Set Instruction

```
boolean Test_And_Set(boolean* lock)
   atomic {
   boolean initial;
   initial = *lock;
   *lock = true;
   return initial;
}
```

atomic = *executed in a single shot without any interruption*

Note: this is more accurate than the textbook version

Using Test_And_Set for Mutual Exclusion

```
Pi {
   while(1) {
      while(Test_And_Set(lock)) {
         /* spin */
      }

      /* Critical Section */
      lock =0;
      /* remainder */
   }
}
```

```
void main () {
   lock = 0;
   parbegin(P1,…,Pn);
}
```

What's the problem?

Semaphores

- Fundamental Principle:
  - Two or more processes want to cooperate by means of simple signals
- Special Variable: `semaphore s`
  - A special kind of "int" variable
  - Can't just modify or set or increment or decrement it

Semaphores

- Before entering critical section
  - **`semWait(s)`**
    - Receive signal via semaphore **`s`**
    - “down” on the semaphore
    - Also: **`P`** – proberen
- After finishing critical section
  - **`semSignal(s)`**
    - Transmit signal via semaphore **`s`**
    - “up” on the semaphore
    - Also: **`V`** – verhogen
- Implementation requirements
  - **`semSignal`** and **`semWait`** must be atomic

Semaphores vs. Test_and_Set

Semaphore

```
semaphore s = 1;
Pi {
    while(1)  {
        semWait(s);
        /* Critical Section */
        semSignal(s);
        /* remainder */
    }
}
```

Test_and_Set

```
lock = 0;
Pi {
    while(1) {
        while(Test_And_Set(lock));
        /* Critical Section */
        lock =0;
        /* remainder */
    }
}
```

- Avoid busy waiting by suspending
  - Block if **`s == False`**
  - Wakeup on signal (**`s = True`**)

Inside a Semaphore

- Requirement
  - No two processes can execute `wait()` and `signal()` on the same semaphore at the same time!

- Critical section
  - `wait()` and `signal()` code
  - Now have busy waiting in critical section implementation
    - + Implementation code is short
    - + Little busy waiting if critical section rarely occupied
    - – Bad for applications may spend lots of time in critical sections

Inside a Semaphore

- Add a waiting queue
- Multiple process waiting on **`s`**
  - Wakeup one of the blocked processes upon getting a signal

- Semaphore data structure

```
typedef struct {
    int count;
    queueType queue;
    /* queue for procs.
    waiting on s */
} SEMAPHORE;
```

Binary Semaphores

```
typedef struct bsemaphore {
    enum {0,1} value;
    queueType queue;
 } BSEMAPHORE;
```

```
void semWaitB(bsemaphore s) {
    if (s.value == 1)
        s.value = 0;
    else {
        place P in s.queue;
        block P;
    }
}
```

```
void semSignalB (bsemaphore s)
    {
    if (s.queue is empty())
        s.value = 1;
    else {
        remove P from s.queue;
        place P on ready list;
    }
}
```

General Semaphore

```
typedef struct {
    int count;
     queueType queue;
} SEMAPHORE;
```

```
void semWait(semaphore s) {
    s.count--;
        if (s.count < 0) {
        place P in s.queue;
        block P;
    }
}
```

```
void semSignal(semaphore s) {
    s.count++;
    if (s.count ≤ 0) {
        remove P from s.queue;
        place P on ready list;
    }
}
```

Making the operations atomic

- Isn't this exactly what semaphores were trying to solve? Are we stuck?!
- Solution: resort to **test-and-set**

```
typedef struct {
  boolean lock;
  int count;
  queueType queue;
} SEMAPHORE;
```

```
void semWait(semaphore s) {
  while (test_and_set(lock)) { }
  s.count--;
  if (s.count < 0) {
    place P in s.queue;
    block P;
  }
  lock = 0;
}
```

Making the operations atomic

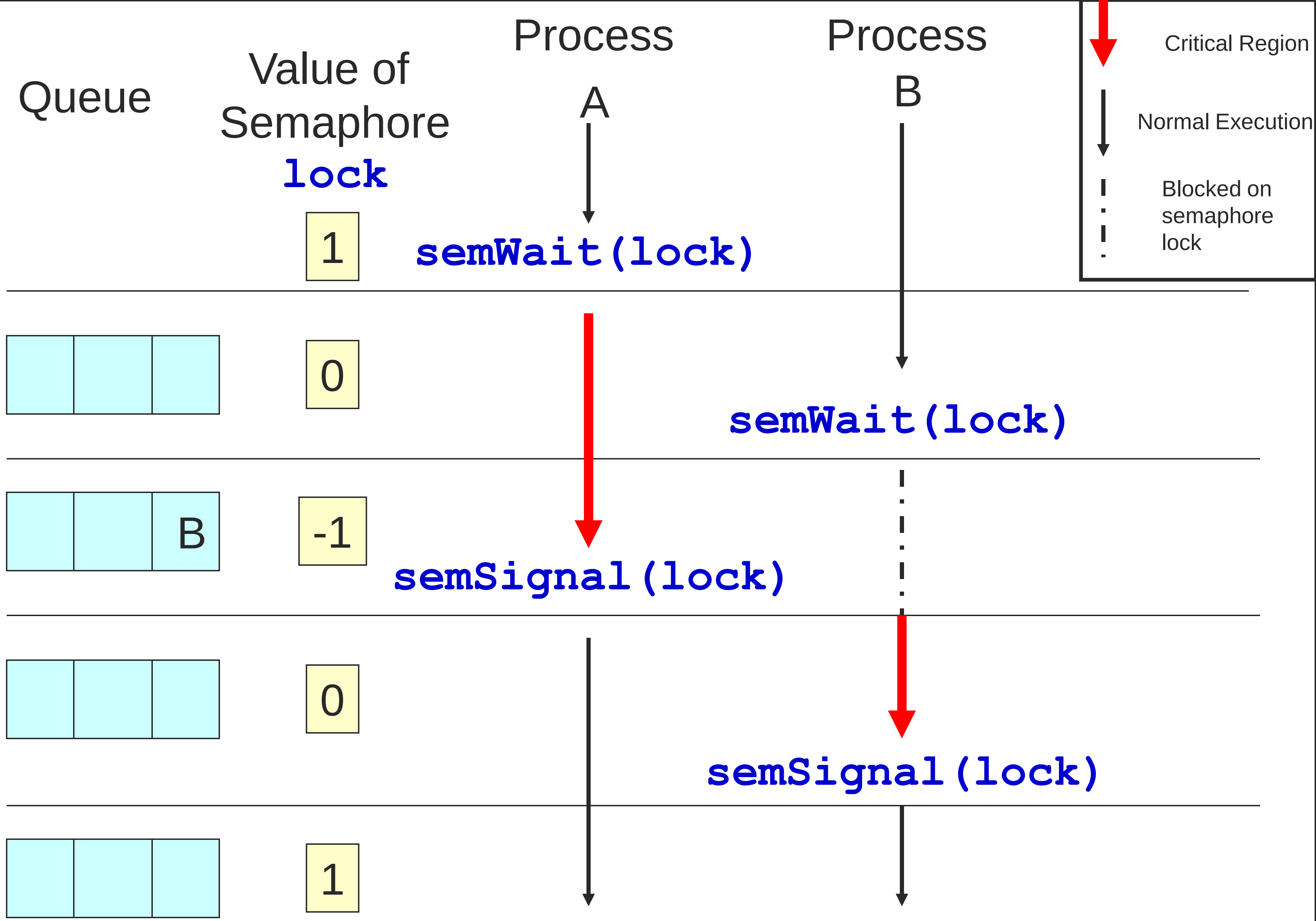
- Busy-waiting again!
- Then how are semaphores better than just using test_and_set?

```
void semWait(semaphore s) {
  while (test_and_set(lock)) { }
  s.count--;
  if (s.count < 0) {
    place P in s.queue;
    block P;
  }
  lock = 0;
}
```

- T&S: busy-wait during critical section
- Sem.: busy-wait just during semWait, semSignal: very short operations!

Mutual Exclusion Using Semaphores

```
semaphore s = 1;
Pi {
   while(1) {
      semWait(s);
      /* Critical Section */
      semSignal(s);
      /* remainder */
   }
}
```



Queue
Value of Semaphore lock
Process A
Process B
Critical Region
Normal Execution
Blocked on semaphore lock
1
semWait(lock)
0
semWait(lock)
B
-1
semSignal(lock)
0
semSignal(lock)
1

Semaphore Example 1

```
semaphore s = 2;
Pi {
    while(1) {
        semWait(s);
        /* CS */
        semSignal(s);
        /* remainder */
    }
}
```

- What happens?
- When might this be desirable?

Semaphore Example 2

```
semaphore s = 0;
Pi {
    while(1) {
        semWait(s);
        /* CS */
        semSignal(s);
        /* remainder */
    }
}
```

- What happens?
- When might this be desirable?

Semaphore Example 3

```
semaphore s = 0;
P1 {
   /* do some stuff */
   semWait(s);
   /* do some more stuff */
}
```

```
semaphore s; /* shared */
P2 {
   /* do some stuff */
   semSignal(s);
   /* do some more stuff */
}
```

- What happens?
- When might this be desirable?

Semaphore Example 4

Process 1 executes:

```
while(1) {
    semWait(S);
    a;
    semSignal(Q);
}
```

Process 2 executes:

```
while(1) {
    semWait(Q);
    b;
    semSignal(S);
}
```

- Two processes
  - Two semaphores: S and Q
  - Protect two critical variables ‘a’ and ‘b’.
- What happens in the pseudocode if Semaphores S and Q are initialized to 1 (or 0)?

Be careful!

Deadlock or Violation of Mutual Exclusion?

1
```
semSignal(s);
critical_section();
semWait(s);
```

2
```
semWait(s);
critical_section();
```

3
```
critical_section();
semSignal(s);
```

4
```
semWait(s);
critical_section();
semWait(s);
```

5
```
semWait(s);
semWait(s);
critical_section();
semSignal(s);
semSignal(s);
```

POSIX Semaphores

- Named Semaphores
  - Provides synchronization between unrelated process and related process as well as between threads
  - Kernel persistence
  - System-wide and limited in number
  - Uses **`sem_open`**
- Unnamed Semaphores
  - Provides synchronization between threads and between related processes
  - Thread-shared or process-shared
  - Uses **`sem_init`**

POSIX Semaphores

- Data type
  - Semaphore is a variable of type **`sem_t`**
- Include **`<semaphore.h>`**
- Atomic Operations

```
int sem_init(sem_t *sem, int pshared,
   unsigned value);
int sem_destroy(sem_t *sem);
int sem_post(sem_t *sem);
int sem_trywait(sem_t *sem);
int sem_wait(sem_t *sem);
```

Unnamed Semaphores

```
#include <semaphore.h>
int sem_init(sem_t *sem, int pshared, unsigned
    value);
```

- Initialize an unnamed semaphore
- Returns
  - 0 on success
  - -1 on failure, sets `errno`
- Parameters
  - `sem`:
    - Target semaphore
  - `pshared`:
    - 0: only threads of the creating process can use the semaphore
    - Non-0: other processes can use the semaphore
  - `value`:
    - Initial value of the semaphore

You cannot make a copy of a semaphore variable!!!

Sharing Semaphores

- Sharing semaphores between threads within a process is easy, use **`pshared==0`**
  - Forking a process creates copies of any semaphore it has… **`sem_t`** semaphores are not shared across processes
- A non-zero **`pshared`** allows any process that can access the semaphore to use it
  - Places the semaphore in the global (OS) environment

`sem_init` can fail

- On failure
  - `sem_init` returns -1 and sets `errno`

`errno`	cause
`EINVAL`	`Value > sem_value_max`
`ENOSPC`	Resources exhausted
`EPERM`	Insufficient privileges

```
sem_t semA;

if (sem_init(&semA, 0, 1) == -1)
  perror("Failed to initialize semaphore semA");
```

Semaphore Operations

```
#include <semaphore.h>
int sem_destroy(sem_t *sem);
```

- Destroy an semaphore
- Returns
  - 0 on success
  - -1 on failure, sets `errno`
- Parameters
  - `sem`:
    - Target semaphore
- Notes
  - Can destroy a `sem_t` only once
  - Destroying a destroyed semaphore gives undefined results
  - Destroying a semaphore on which a thread is blocked gives undefined results

Semaphore Operations

```
#include <semaphore.h>
int sem_post(sem_t *sem);
```

- Unlock a semaphore
- Returns
  - 0 on success
  - -1 on failure, sets **errno** (**== EINVAL** if semaphore doesn't exist)
- Parameters
  - **sem**:
    - Target semaphore
    - sem > 0: no threads were blocked on this semaphore, the semaphore value is incremented
    - sem == 0: one blocked thread will be allowed to run
- Notes
  - **sem_post()** is reentrant with respect to signals and may be invoked from a signal-catching function

Semaphore Operations

```
#include <semaphore.h>
int sem_wait(sem_t *sem);
```

- Lock a semaphore
  - Blocks if semaphore value is zero
- Returns
  - 0 on success
  - -1 on failure, sets **errno** (**== EINTR** if interrupted by a signal)
- Parameters
  - **sem**:
    - Target semaphore
    - sem > 0: thread acquires lock
    - sem == 0: thread blocks

Semaphore Operations

```
#include <semaphore.h>
int sem_trywait(sem_t *sem);
```

- Test a semaphore's current condition
  - Does not block
- Returns
  - 0 on success
  - -1 on failure, sets `errno` (`== AGAIN` if semaphore already locked)
- Parameters
  - `sem`:
    - Target semaphore
    - sem > 0: thread acquires lock
    - sem == 0: thread returns

Example: bank balance

- Want shared variable **balance** to be protected by semaphore when used in:
  - **decshared** – a function that decrements the current value of **balance**
  - **incshared** – a function that increments the **balance** variable.

Example: bank balance

```
int decshared() {
   while (sem_wait(&balance_sem) == -1)
      if (errno != EINTR)
         return -1;
   balance--;
   return sem_post(&balance_sem);
}

int incshared() {
   while (sem_wait(&balance_sem) == -1)
      if (errno != EINTR)
         return -1;
   balance++;
   return sem_post(&balance_sem);
}
```

Summary

- Semaphores
- Semaphore implementation
- POSIX Semaphore
- Programming with semaphores

- Next time: solving real problems with semaphores & more