

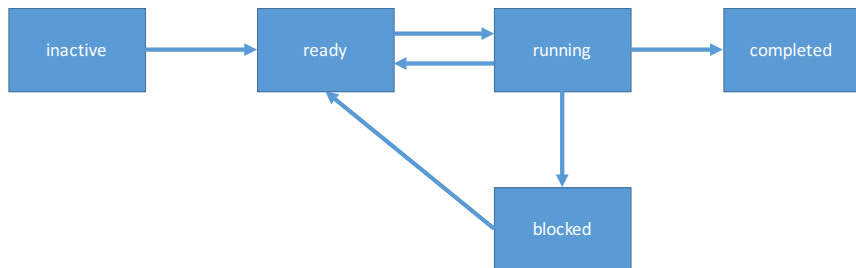
Semaphores

CS511

Motivation

- ▶ Algorithms for mutex seen up until now run on any machine (they only use standard instructions)
- ▶ These are too low-level to be used reliably
- ▶ Semaphores are higher-level constructs
 - ▶ Usually implemented by the OS
 - ▶ Widely used in many PLs

States of a Process



- ▶ A scheduler decides which of the ready processes it should run
 - ▶ Arbitrary interleavings = we assume nothing about the scheduler

Semaphore

A semaphore is an Abstract Data Type with:

- ▶ (Atomic!) Operations:
 - ▶ acquire (or wait)
 - ▶ release (or signal)
- ▶ Data fields:
 - ▶ permissions: non-negative integer
 - ▶ processes: set of processes

Acquire

Acquire consumes a permission, waits if none are available

```
1  atomic acquire() {
2      currentThread = Thread.currentThread();
3      if (permissions > 0) {
4          permissions--;
5      } else {
6          processes.add(thread);
7          currentThread.state = BLOCKED;
8      }
9  }
```

Release

Release frees a permission (wakens a blocked thread, if there are any)

```
1  atomic release() {
2      if (processes.empty()) {
3          permissions++;
4      } else {
5          wakingThread = processes.removeAny();
6          wakingThread.state = READY;
7      }
8  }
```

Mutex or Binary Semaphore

- ▶ A semaphore that only admits 0 or 1 permissions.
 - ▶ Semaphores that allow arbitrary values of permission are called **counting** semaphores
- ▶ Initialized to $(0, \emptyset)$ or $(1, \emptyset)$
- ▶ The acquire operation is unchanged
- ▶ The release operation is now defined as:

```
1  atomic release() {
2      if (permissions == 1) {
3          // do nothing
4      } else if (processes.empty()) {
5          permissions = 1;
6      } else {
7          wakingThread = processes.removeAny();
8          wakingThread.state = READY;
9      }
10 }
```

Note: if permissions is 1, successive calls to `release` are lost

Mutual Exclusion using mutex

- ▶ We now revisit the critical section problem for two processes
- ▶ Using a semaphore `mutex` the solution is trivial
 - ▶ P wishes to enter: preprotocol `mutex.acquire()`
 - ▶ When P exits: postprotocol `mutex.release()`

Mutual Exclusion using mutex

```
1 global Semaphore mutex = new Semaphore(1);

1 thread P: {
2     // non-critical section
3     mutex.acquire();
4     // critical section
5     mutex.release();
6     // non-critical section
7 }

1 thread Q: {
2     // non-critical section
3     mutex.acquire();
4     // critical section
5     mutex.release();
6     // non-critical section
7 }
```

Mutual Exclusion using mutex

```
1 global Semaphore mutex = new Semaphore(1);

1 thread P: {                                1 thread Q: {
2     // non-critical section                2     // non-critical section
3     mutex.acquire();                       3     mutex.acquire();
4     // critical section                    4     // critical section
5     mutex.release();                       5     mutex.release();
6     // non-critical section                6     // non-critical section
7 }                                           7 }
```

This solution does not use busy waiting since a process that blocks in the acquire goes into the BLOCKED state and only returns to the READY state once it is given permission to do so.

Semaphores in Java

Class Semaphore in `java.util.concurrent`

► `java.util.concurrent.Semaphore`

```
1  /** Creates a semaphore with the given number of permits */
2  Semaphore(int permits)

1  /** Acquires a permit from this Semaphore,
2      blocking until one is available */
3  void acquire()

1  /** Releases a permit, returning it to the semaphore */
2  void release()
```

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2  void release()
```

Example:

```
1  Semaphore mutex = new Semaphore(1);
2  mutex.acquire()
3  // critical section
4  mutex.release()
```

Semaphore Invariants

Let k be the initial value of the `permissions` field of a semaphore s

where

- ▶ `#releases` is the number of `s.release()` statements executed
- ▶ `#acquire` is the number of `s.acquire()` statements executed
- ▶ A blocked process is considered not to have executed an `acquire` operation.

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Let k be the initial value of the `permissions` field of a semaphore s

1. $\text{permissions} \geq 0$
2. $\text{permissions} = k + \# \text{releases} - \# \text{acquires}$

where

- ▶ $\# \text{releases}$ is the number of `s.release()` statements executed
- ▶ $\# \text{acquire}$ is the number of `s.acquire()` statements executed
- ▶ A blocked process is considered not to have executed an `acquire` operation.

The Semaphore Solution for the MEP ($k = 1$)

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Item 1 guarantees:

- ▶ **Mutual Exclusion** (`#criticalSection` ≤ 1 since $0 \leq \text{permissions}$)
- ▶ **Absence of deadlock** (it never happens that `permissions = 0` and `#criticalSection = 0`)
- ▶ **No starvation** between two processes

The Turnstile Problem using Binary Semaphores

```
1 global int counter = 0;
2 global Semaphore mutex = new Semaphore(1);
3
4 turnstile() {
5     repeat (50) {
6         mutex.acquire();
7         counter++;
8         mutex.release();
9     }
10 }
11
12 repeat (2)
13     thread turnstile();
```

The Turnstile Problem using Binary Semaphores (Java)

```
1 public class Turnstile extends Thread {
2     static volatile int counter = 0;
3     static Semaphore mutex = new Semaphore(1);
4     public void run() {
5         for(int i = 0; i < 50; i++){
6             mutex.acquire();
7             counter++;
8             mutex.release();
9             System.out.println(id+"- In comes: "+i );
10        }
11    }
12
13    public static void main(String args[]) {
14        try{
15            Thread m1 = new Turnstile(1);
16            m1.start();
17            Thread m2 = new Turnstile(2);
18            m2.start();
19        } catch(Exception e){}
20    }
21 }
```


Counting Example in Java using Semaphores

```
1 public class Turnstile extends Thread {  
2     static volatile int counter = 0;  
3     ...  
}
```

- ▶ The `volatile` keyword is recommended for variables that are shared
- ▶ It guarantees that
 - ▶ Its value will never be cached thread-locally: all reads and writes will go straight to “main memory”; and
 - ▶ Access to the variable acts as though it is enclosed in a synchronized block, synchronized on itself (more later).

Strong Semaphores

The same solution above for the critical section also works for N processes

```
1 repeat (N) {  
2     thread {  
3         // non-critical section  
4         mutex.acquire();  
5         // critical section  
6         mutex.release();  
7         // non-critical section  
8     }  
9 }
```

- ▶ But there is the possibility of **starvation**.
- ▶ The problem is caused by the fact that blocked processes are placed in a **set** of processes

Strong Semaphores

- ▶ This can be remedied by changing the set to be a queue
- ▶ In Java this is indicated by the second argument of the constructor

```
1  /** Creates a Semaphore with the given number of permits
2      and the given fairness setting. */
3  Semaphore(int permits, boolean fair)
```

- ▶ When fairness is set to `true`, the semaphore gives permits to access mutual resources in the order the threads have asked for it (FIFO)

Semaphores

Synchronization Among Processes

Synchronization Problems

- ▶ The **critical section problem** is an abstraction of the synchronization problems that occur when multiple processes compete for the same resource
- ▶ Another type of synchronization problem is when processes must coordinate the **order of execution**

Revisiting the Turnstile Problem

Suppose we wish to print the counter total for N turnstiles

```
1 repeat (N)
2   thread turnstile();
3   print("Total = " + counter);
```

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```

What happens when we run this code?

Revisiting the Turnstile Problem

```
1 global int counter = 0;
2 global Semaphore mutex = new Semaphore(1);
3 global Semaphore finish = new Semaphore(-N+1);
4
5 turnstile() {
6     repeat (100) {
7         mutex.acquire();
8         counter++;
9         mutex.release();
10    }
11    finish.release();
12 }
13
14 repeat (N)
15     thread turnstile();
16     finish.acquire();
17     print("Total = " + counter);
```


Dining Philosophers



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- Philosophers think and eat, in turns

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- ▶ Philosophers think and eat, in turns
- ▶ They can only eat if they have both forks

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- ▶ Philosophers think and eat, in turns
- ▶ They can only eat if they have both forks
- ▶ They can only grab the forks to their left and right

Dining Philosophers

```
1  Philosopher(id) {  
2      while (true)  
3          // think  
4          // pick forks  
5          // eat  
6          // leave forks  
7  }
```

Dining Philosophers

```
1  Philosopher(id) {  
2      while (true)  
3          // think  
4          // pick forks  
5          // eat  
6          // leave forks  
7  }
```

- ▶ Shared resource: the forks
- ▶ Mutex: at any given moment only one philosopher can have a fork
- ▶ Synchronization: a philosopher can only eat if she/he has both forks
- ▶ Absence of deadlock, livelock and starvation

Dining Philosophers (naive attempt)

```
1 global Semaphore[] forks = [1,...,1]; // N
2
3 Philosopher(id) {
4     left = id;
5     right = (id+1) % N;
6
7     while (true) {
8         // think
9         forks[left].acquire();
10        forks[right].acquire();
11        // eat
12        forks[left].release();
13        forks[right].release();
14    }
15 }
```

Dining Philosophers (naive attempt)

```
1 global Semaphore[] forks = [1,...,1]; // N
2
3 Philosopher(id) {
4     left = id;
5     right = (id+1) % N;
6
7     while (true) {
8         // think
9         forks[left].acquire();
10        forks[right].acquire();
11        // eat
12        forks[left].release();
13        forks[right].release();
14    }
15 }
```

Deadlock: If they all take the left fork, circular waiting

Dining Philosophers (general semaphore)

```
1 global Semaphore[] forks = [1,...,1]; // N
2 global Semaphore chairs = new Semaphore(N-1);
3
4 Philosopher(id) {
5     left = id;
6     right = (id+1) % N;
7
8     while (true) {
9         // think
10        chairs.acquire();
11        forks[left].acquire();
12        forks[right].acquire();
13        // eat
14        forks[left].release();
15        forks[right].release();
16        chairs.release();
17    }
18 }
```

Dining Philosophers (breaking the symmetry)

```
1 global Semaphore[] forks = [1,...,1]; // N
2
3 Philosopher(id) {
4     if (i == 0) {
5         left = 1;
6         right = 0;
7     } else {
8         left = id;
9         right = (id+1) % N;
10    }
11
12    while (true) {
13        // think
14        forks[left].acquire();
15        forks[right].acquire();
16        // eat
17        forks[left].release();
18        forks[right].release();
19    }
20 }
```