Races, locks, and semaphores

Lecture 2 of TDA384/DIT391
Principles of Concurrent Programming

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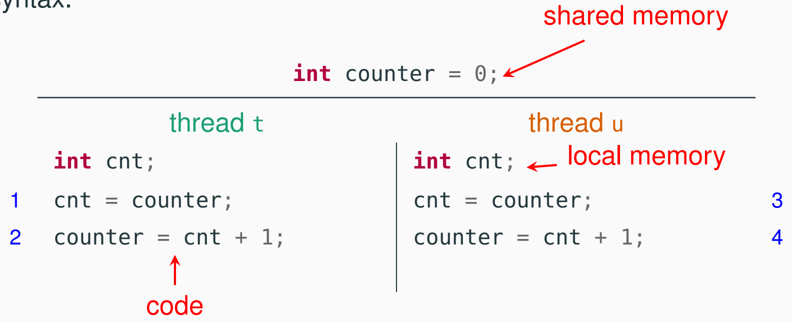
Based on course slides by Carlo A. Furia

Today's menu

Concurrent programs

Abstraction of concurrent programs

We use an abstract notation for multi-threaded applications, which is similar to the pseudo-code used in Ben-Ari's book but uses Java syntax.



```
int counter = 0;
```

thread t	thread u
`int cnt;`	`int cnt;`
1 `cnt = counter;`	`cnt = counter;` 3
2 `counter = cnt + 1;`	`counter = cnt + 1;` 4

Each line of code includes exactly one instruction that can be executed atomically.

Traces

A sequence of states gives an execution trace of the concurrent program. (The program counter pc points to the atomic instruction that will be executed next.)

#	t'S LOCAL	u'S LOCAL	SHARED
1	pc_t : 1 cnt_t : ⊥	pc_u : 1 cnt_u : ⊥	counter: 0
2	pc_t : 2 cnt_t : 0	pc_u : 1 cnt_u : ⊥	counter: 0
3	pc_t : 2 cnt_t : 0	pc_u : 2 cnt_u : 0	counter: 0
4	pc_t : 2 cnt_t : 0	done	counter: 1
5	done	done	counter: 1

```
int counter = 0;
```

thread t		thread u	
	`int cnt;`	`int cnt;`	
1	`cnt = counter;`	`cnt = counter;`	3
2	`counter = cnt + 1;`	`counter = cnt + 1;`	4

Races

Race conditions

Concurrent programs are nondeterministic:

- executing multiple times the same concurrent program with the same inputs may lead to different execution traces
- this is a result of the nondeterministic interleaving of each thread's trace to determine the overall program trace
- in turn, the interleaving is a result of the scheduler's decisions

A race condition is a situation where the correctness of a concurrent program depends on the specific execution

The concurrent counter example has a race condition:

- in some executions the final value of `counter` is 2 (correct),
- in some executions the final value of `counter` is 1 (wrong).

Race conditions can greatly complicate debugging!

Concurrency humor

Knock knock.

– “Race condition.”

– “Who’s there?”

Data races

Race conditions are typically caused by a lack of synchronization between threads that access shared memory.

A data race occurs when two concurrent threads

- access a shared memory location,
- at least one access is a write,
- the threads use no explicit synchronization mechanism to protect the shared data.

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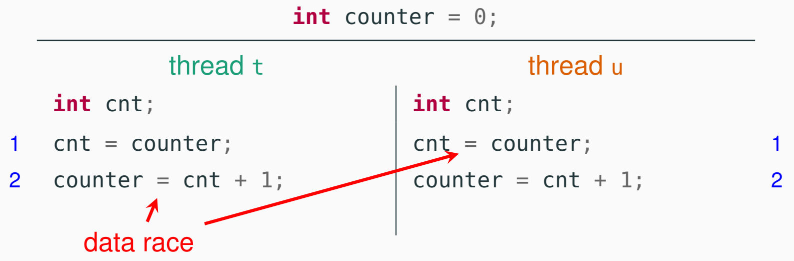

```
int counter = 0;
```

thread t

```
  int cnt;
1 cnt = counter;
2 counter = cnt + 1;
```

thread u

```
int cnt;
cnt = counter;          1
counter = cnt + 1;      2
```

Data races

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- access a shared memory location,
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```
                     int counter = 0;
-------------------------------------------------------------
          thread t              |           thread u
    int cnt;                    | int cnt;
1   cnt = counter;              | cnt = counter;           1
2   counter = cnt + 1;          | counter = cnt + 1;       2
```

data race

Data races vs. race conditions

A data race occurs when two concurrent threads

- access a shared memory location,
- at least one access is a write,
- the threads use no explicit synchronization mechanism to protect the shared data.

Not every race condition is a data race

- race conditions can occur even when there is no shared memory access
- for example in filesystems or network access

Not every data race is a race condition

- the data race may not affect the result
- for example if two threads write the same value to shared memory

Synchronization problems

Push out the races, bring in the speed

Concurrent programming introduces:

+ the potential for parallel execution (faster, better resource usage)
− the risk of race conditions (incorrect, unpredictable computations)

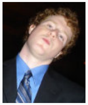
The main challenge of concurrent programming is thus introducing parallelism without introducing race conditions.

This requires to restrict the amount of nondeterminism by synchronizing processes/threads that access shared resources.

Synchronization

We will present several synchronization problems that often appear in concurrent programming, together with solutions.

My concurrent program will be so fast, there will be no time to check the answer!



– Scott West, circa 2010

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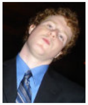


– Scott West, circa 2010

- Correctness (that is, avoiding race conditions) is more important than performance: an incorrect result that is computed very quickly is no good!
- However, we also want to retain as much concurrency as possible, otherwise we might as well stick with sequential programming

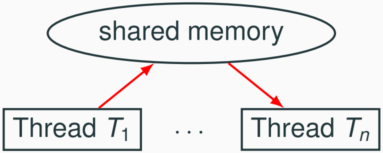
Shared memory vs. message passing synchronization

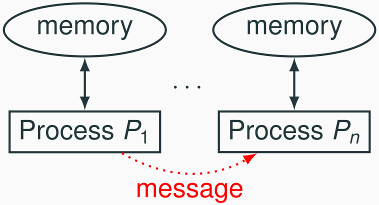
Shared memory synchronization:

- synchronize by writing to and reading from shared memory
- natural choice in shared memory systems such as threads

Message passing synchronization:

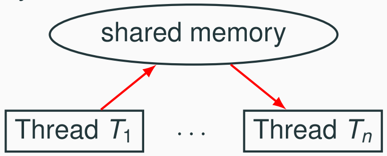
- synchronize by exchanging messages
- natural choice in distributed memory systems such as processes



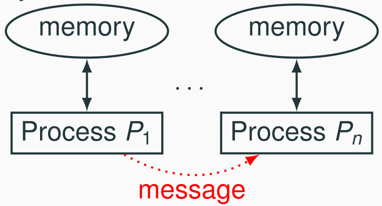


Shared memory vs. message passing synchronization

Shared memory synchronization:



Message passing synchronization:



The two synchronization models overlap:

- send a message by writing to and reading from shared memory (example: message board)
- share information by sending a message (example: order a billboard)

However, in the first part of the course we will focus on synchronization problems that arise in shared memory concurrency; in the second part we will switch to message passing.

The mutual exclusion problem

The mutual exclusion problem is a fundamental synchronization problem, which arises whenever multiple threads have access to a shared resource.

critical section: the part of a program that accesses the shared resource (for example, a shared variable)

mutual exclusion property: no more than one thread is in its critical section at any given time

The mutual exclusion problem: devise a protocol for accessing a shared resource that satisfies the mutual exclusion property

Simplifications to present solutions in a uniform way:

- the critical section is an arbitrary block of code
- threads continuously try to enter the critical section
- threads spend a finite amount of time in the critical section
- we ignore what the threads do outside their their critical sections

The mutual exclusion problem

The mutual exclusion problem: devise a protocol for accessing a shared resource that satisfies the mutual exclusion property

```
T shared;
```

thread t_j

```
// continuously
while (true) {
  entry protocol
  critical section {
    // access shared data
  }
  exit protocol
} /* ignore behavior
outside critical section */
```

thread t_k

```
// continuously
while (true) {
  entry protocol
  critical section {
    // access shared data
  }
  exit protocol
} /* ignore behavior
outside critical section */
```

may depend on thread

depends on computation

Mutual exclusion problem example: concurrent counter

Updating a shared variable consistently is an instance of the mutual exclusion problem.

```
int counter = 0;
```

thread t

```
int cnt;
while (true) {
  entry protocol
  critical section {
    cnt = counter;
    counter = cnt + 1;
  }
  exit protocol
  return;
}
```

thread u

```
int cnt;
while (true) {
  entry protocol
  critical section {
    cnt = counter;
    counter = cnt + 1;
  }
  exit protocol
  return;
}
```

take turn incrementing `counter`

What’s a good solution to the mutual exclusion problem?

A fully satisfactory solution is one that achieves three properties:

1. Mutual exclusion: at most one thread is in its critical section at any given time
2. Freedom from deadlock: if one or more threads try to enter the critical section, some thread will eventually succeed
3. Freedom from starvation: every thread that tries to enter the critical section will eventually succeed

A good solution should also work for an arbitrary number of threads sharing the same memory.

(Note that freedom from starvation implies freedom from deadlock.)

Deadlocks

A mutual exclusion protocol provides exclusive access to shared resources to one thread at a time.

Threads that try to access the resource when it is not available will have to block and wait.

Mutually dependent waiting conditions may introduce a deadlock

A deadlock is the situation where a group of threads wait forever because each of them is waiting for resources that are held by another thread in the group (circular waiting)

Deadlock: example

A deadlock is the situation where a group of threads wait forever because each of them is waiting for resources that are held by another thread in the group (circular waiting)

A protocol that achieves mutual exclusion but introduces a deadlock:

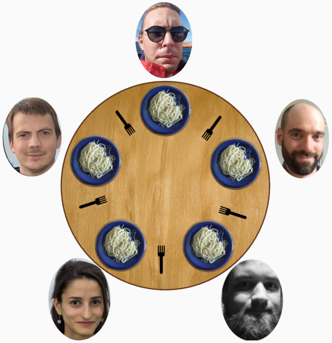
entry protocol: wait until all other threads have executed their critical section

Via, resti servita Madama brillante
– E. Tommasi Ferroni, 2012

The dining philosophers

The dining philosophers is a classic synchronization problem introduced by Dijkstra. It illustrates the problem of deadlocks using a colorful metaphor (by Hoare).

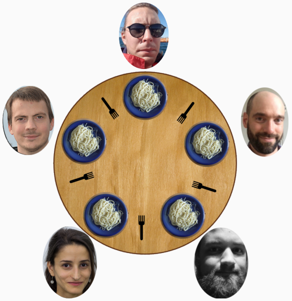
- Five philosophers are sitting around a dinner table, with a fork in between each pair of adjacent philosophers.
- Each philosopher alternates between thinking (non-critical section) and eating (critical section).
- In order to eat, a philosopher needs to pick up the two forks that lie to the philopher's left and right.
- Since the forks are shared, there is a synchronization problem between philosophers (threads).



Deadlocking philosophers

An unsuccessful attempt at solving the dining philosophers problem:

```
entry protocol ($P_k$) {
  left_fork.acquire();  // pick up left fork
  right_fork.acquire(); // pick up right fork
}
critical section { eat(); }
exit protocol  ($P_k$) {
  left_fork.release();   // release left fork
  right_fork.release();  // release right fork
}
```



This protocol deadlocks if all philosophers get their left forks, and wait forever for their right forks to become available.

The Coffman conditions

Necessary conditions for a deadlock to occur:

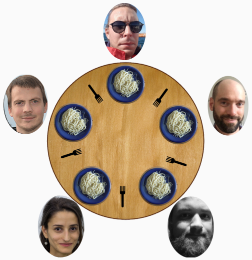
1. Mutual exclusion: threads may have exclusive access to the shared resources.
2. Hold and wait: a thread that may request one resource while holding another resource.
3. No preemption: resources cannot forcibly be released from threads that hold them.
4. Circular wait: two or more threads form a circular chain where each thread waits for a resource that the next thread in the chain is holding.

Avoiding deadlocks requires to break one or more of these conditions.

Breaking a circular wait

A solution to the dining philosophers problem that avoids deadlock by avoiding a circular wait: pick up first the fork with the lowest id number. This avoids the circular wait because not every philosopher will pick up their left fork first.

```
entry protocol ($P_k$) {
  if (left_fork.id()
      < right_fork.id()) {
    left_fork.acquire();
    right_fork.acquire();
  } else {
    right_fork.acquire();
    left_fork.acquire();
  }
}
critical section { eat(); }
exit protocol  ($P_k$) { /* ... */ }
```

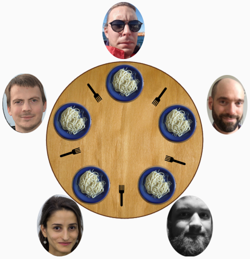


Ordering shared resources and forcing all threads to acquire the resources in order is a common measure to avoid deadlocks.

Starving philosophers

A solution to the dining philosophers problem that avoids deadlock by breaking hold and wait (and thus circular wait): pick up both forks at once (atomic operation).

```
entry protocol ($P_k$) {
  forks.acquire(); // pick up left and right fork,
                   // atomically
}
critical section { eat(); }
exit protocol  ($P_k$) {
  forks.release(); // release left and right fork,
                   // atomically
}
```



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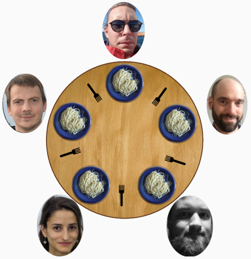

This protocol avoids deadlocks, but it may introduce starvation: a philosopher may never get a chance to pick up the forks.

Starvation

No deadlocks means that the system makes progress as a whole.

However, some individual thread may still make no progress because it is treated unfairly in terms of access to shared resources.

Starvation is the situation where a thread is perpetually denied access to a resource it requests.

Avoiding starvation requires an additional assumption about the scheduler.

Fairness

Starvation is the situation where a thread is perpetually denied access to a resource it requests.

Avoiding starvation requires the scheduler to

"give every thread a chance to execute".

Weak fairness: if a thread continuously requests (that is, requests without interruptions) access to a resource, then access is granted eventually (or infinitely often).

Strong fairness: if a thread requests access to a resource infinitely often, then access is granted eventually (or infinitely often).

Applied to a scheduler:

- request = a thread is ready (enabled)
- fairness = every thread has a chance to execute

Sequential philosophers

Another solution to the dining philosophers problem that avoids deadlock as well as starvation: a (fair) waiter decides which philosopher eats; the waiter gives permission to eat to one philosopher at a time.

```
entry protocol ($P_k$) {
  while (!waiter.can_eat(k)) {
    // wait for permission to eat
  }
  left_fork.acquire();
  right_fork.acquire();
}
critical section { eat(); }
exit protocol  ($P_k$) { /* ... */ }
```

Having a centralized arbiter avoids deadlocks and starvation, but a waiter who only gives permission to one philosopher a time basically reduces the philosophers to following a sequential order without active concurrency.

Locks

Lock objects

A lock is a data structure with interface:

```
interface Lock {
  void lock();     // acquire lock
  void unlock();   // release lock
}
```

- several threads share the same object `lock` of type `Lock`
- multiple threads calling `lock.lock()` results in exactly one thread *t* acquiring the lock:
  - *t*'s call `lock.lock()` returns: *t* is holding the lock
  - other threads block on the call `lock.lock()`, waiting for the lock to become available
- a thread *t* that is holding the lock calls `lock.unlock()` to release the lock:
  - *t*'s call `lock.unlock()` returns; the lock becomes available
  - another thread waiting for the lock may succeed in acquiring it

Locks are also called mutexes (they guarantee mutual exclusion).

Using locks

With lock objects the entry/exit protocols are trivial:

- entry protocol: call `lock.lock()`
- exit protocol: call `lock.unlock()`

```
int counter = 0;    Lock lock = new Lock();
```

thread `t`

```
  int cnt;
1 lock.lock();
2   cnt = counter;
3   counter = cnt + 1;
4 lock.unlock();
```

thread `u`

```
int cnt;
lock.lock();             5
  cnt = counter;         6
  counter = cnt + 1;     7
lock.unlock();           8
```

The implementation of the `Lock` interface should guarantee mutual exclusion, deadlock freedom, and starvation freedom.

Using locks in Java

```java
// package with lock-related classes
import java.util.concurrent.locks.*;

// shared with other synchronizing threads
Lock lock;

while (true) {
  lock.lock();       // entry protocol
  try {
    // critical section
    // mutual exclusion is guaranteed
    // by the lock protocol
  } finally { // lock released even if an exception
              // is thrown in the critical section
    lock.unlock();   // exit protocol
  }
}
```

Counter with mutual exclusion

```
public class LockedCounter extends CCounter
{
    @Override
    public void run() {
        lock.lock(); ← entry protocol
        try  {
critical    // int cnt = counter;
section     // counter = counter + 1;
            super.run();
        } finally {
            lock.unlock(); ← exit protocol
        }
    }
    // shared by all threads working on this object
    private Lock lock = new ReentrantLock();
}
```

The `main` is as before, but instantiates an object of class `LockedCounter`.

- What is printed by running: `java ConcurrentCount`?
- May the printed value change in different reruns?

Built-in locks in Java

Every object in Java has an implicit lock, which can be accessed using the keyword **`synchronized`**.

Whole method locking
(synchronized methods):

```java
synchronized T m() {
  // the critical section
  // is the whole method
  // body
}
```

Every call to `m` implicitly:

1. acquires the lock
2. executes `m`
3. releases the lock

Block locking
(synchronized block):

```java
synchronized(this) {
  // the critical section
  // is the block's content
}
```

Every execution of the block implicitly:

1. acquires the lock
2. executes the block
3. releases the lock

Counter with mutual exclusion: with `synchronized`

```java
public class SyncCounter
    extends CCounter
{
    @Override
    public synchronized
    void run() {
        // int cnt = counter;
        // counter = counter + 1;
        super.run();
    }
}
```

```java
public class SyncBlockCounter
  extends CCounter
{
  @Override
  public void run() {
    synchronized(this) {
      // int cnt = counter;
      // counter = counter + 1;
      super.run();
    }
  }
}
```

Lock implementations in Java

The most common implementation of the `Lock` interface in Java is `class ReentrantLock`.

Mutual exclusion:

- `ReentrantLock` guarantees mutual exclusion

Starvation:

- `ReentrantLock` does not guarantee freedom from starvation by default
- however, calling the constructor with `new ReentrantLock(true)` “favors granting access to the longest-waiting thread”
- this still does not guarantee that thread scheduling is fair

Deadlocks:

- one thread will succeed in acquiring the lock
- however, deadlocks may occur in systems that use multiple locks (remember the dining philosophers)

Built-in lock implementations in Java

The built-in locks – used by `synchronized` methods and blocks – have the same behavior as the explicit locks of `java.util.concurrent.locks` (with no guarantee about starvation).

Built-in locks, as well as all lock implementations in `java.util.concurrent.locks`, are re-entrant: a thread holding a lock can lock it again without causing a deadlock.

Semaphores

Semaphores

Photo: British railway semaphores,
David Ingham, 2008

Semaphores

A (general/counting) semaphore is a data structure with interface:

```
interface Semaphore {
  int count();   // current value of counter
  void up();     // increment counter
  void down();   // decrement counter
}
```

Several threads share the same object `sem` of type `Semaphore`:

- initially `count` is set to a nonnegative value `C` (the capacity)
- a call to `sem.up()` atomically increments `count` by one
- a call to `sem.down()`: waits until `count` is positive, and then atomically decrements `count` by one

Semaphores for permissions

A semaphore is often used to regulate access permits to a finite number of resources:

- the capacity `C` is the number of initially available resources
- `up` (also called `signal`) releases a resource, which becomes available
- `down` (also called `wait`) acquires a resource if it is available

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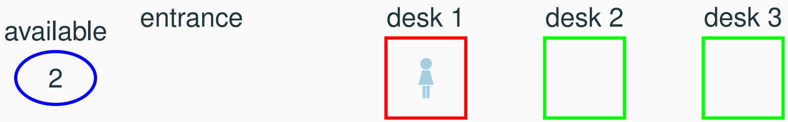
Example: hot desks.



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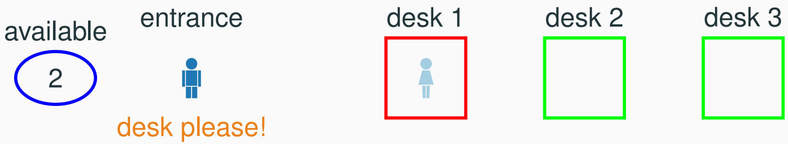

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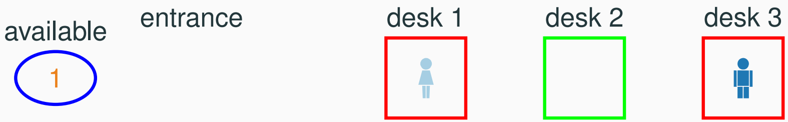

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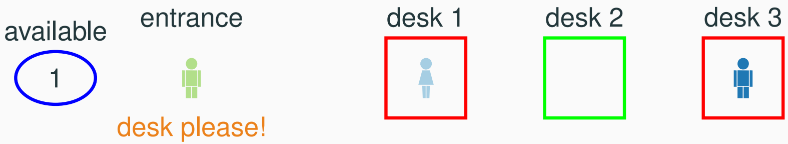

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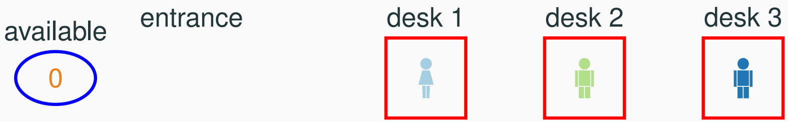

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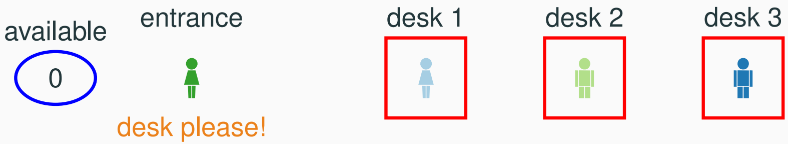

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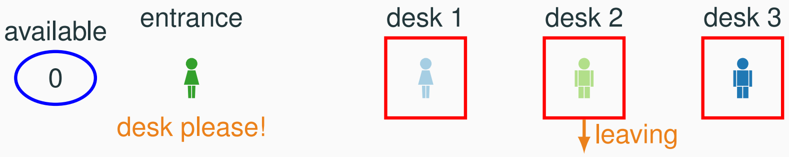

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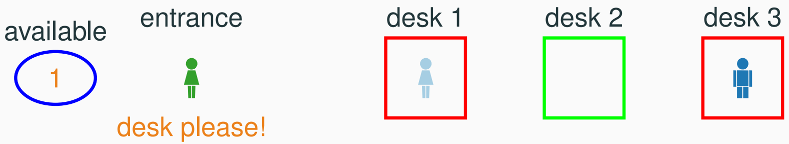
Example: hot desks.

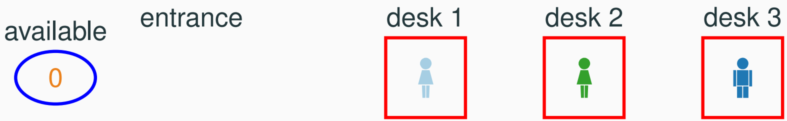


Semaphores for permissions

A semaphore is often used to regulate access permits to a finite number of resources:

- the capacity `C` is the number of initially available resources
- `up` (also called `signal`) releases a resource, which becomes available
- `down` (also called `wait`) acquires a resource if it is available

Example: hot desks.



Mutual exclusion for two processes with semaphores

With semaphores the entry/exit protocols are trivial:

- initialize semaphore to 1
- entry protocol: call `sem.down()`
- exit protocol: call `sem.up()`

```
             Semaphore sem = new Semaphore(1);
---------------------------------------------------------------
           thread t            |          thread u
   int cnt;                    | int cnt;
1  sem.down();                 | sem.down();                 5
2    cnt = counter;            |   cnt = counter;            6
3    counter = cnt + 1;        |   counter = cnt + 1;        7
4  sem.up();                   | sem.up();                   8
```

The implementation of the `Semaphore` interface guarantees mutual exclusion, deadlock freedom, and starvation freedom.

Weak vs. strong semaphores

Every implementation of semaphores should guarantee the atomicity of the `up` and `down` operations, as well as deadlock freedom (for threads only sharing one semaphore: deadlocks may still occur if there are other synchronization constraints).

Fairness is optional:

weak semaphore: threads waiting to perform `down` are scheduled nondeterministically

strong semaphore: threads waiting to perform `down` are scheduled fairly in FIFO (First In First Out) order

Invariants

An object's invariant is a property that always holds between calls to the object's methods:

- the invariant holds initially (when the object is created)
- every method call starts in a state that satisfies the invariant
- every method call ends in a state that satisfies the invariant

For example: a bank account that cannot be overdrawn has an invariant `balance >= 0`

```
class BankAccount {
  private int balance = 0;
  void deposit(int amount)
    { if (amount > 0) balance += amount; }
  void withdraw(int amount)
    { if (amount > 0 && balance > amount) balance -= amount; }
}
```

Invariants in pseudo-code

We occasionally annotate classes with invariants using the pseudo-code keyword `invariant`. Note that `invariant` is not a valid Java keyword – that is why we highlight it in a different color – but we will use it whenever it helps make more explicit the behavior of classes.

```
class BankAccount {
  private int balance = 0;
  void deposit(int amount)
    { if (amount > 0) balance += amount; }
  void withdraw(int amount)
    { if (amount > 0 && balance > amount) balance -= amount; }
  invariant { balance >= 0; } // not valid Java code
}
```

Invariants of semaphores

A semaphore object with initial capacity C satisfies the invariant:

```
interface Semaphore {
  int count();
  void up();
  void down();

  invariant {
    count() >= 0;
    count() == C + #up - #down;
  }
}
```

number of calls to up

number of calls to down

Invariants characterize the behavior of an object, and are very useful for proofs.

Binary semaphores

A semaphore with capacity 1 and operated such that `count()` is always at most 1 is called a binary semaphore.

```
interface BinarySemaphore extends Semaphore {
  invariant
  {  0 <= count() <= 1;
     count() == C + #up - #down; }
}
```

Binary semaphores

A semaphore with capacity 1 and operated such that `count()` is always at most 1 is called a binary semaphore.

```
interface BinarySemaphore extends Semaphore {
  invariant
  {  0 <= count() <= 1;
     count() == C + #up - #down; }
}
```

Mutual exclusion uses a binary semaphore:

```
Semaphore sem = new Semaphore(1); // shared by all threads
```

thread `t`

```
sem.down();
  // critical section
sem.up();
```

If the semaphore is strong this guarantees starvation freedom.

Binary semaphores vs. locks

Binary semaphore are very similar to locks with one difference:

- in a lock, only the thread that decrements the counter to 0 can increment it back to 1
- in a semaphore, a thread may decrement the counter to 0 and then let another thread increment it to 1

Thus (binary) semaphores support transferring of permissions.

Using semaphores in Java

```java
package java.util.concurrent;

public class Semaphore {

  Semaphore(int permits); // initialize with capacity ‘permits’
  Semaphore(int permits, boolean fair);
          // fair == true  ⇔ create a strong semaphore
          // fair == false ⇔ create a weak semaphore (default)

  void acquire();          // corresponds to down
  void release();          // corresponds to up
  int availablePermits();  // corresponds to count
}
```

Method `acquire` may throw an `InterruptedException`: catch or propagate.

Synchronization with semaphores

The *k*-exclusion problem

The *k*-exclusion problem: devise a protocol that allows up to *k* threads to be in their critical sections at the same time

- Mutual exclusion problem = 1-exclusion problem
- The “hot desks” are an instance of the *k*-exclusion problem

The *k*-exclusion problem

The *k*-exclusion problem: devise a protocol that allows up to *k* threads to be in their critical sections at the same time

- Mutual exclusion problem = 1-exclusion problem
- The “hot desks” are an instance of the *k*-exclusion problem

A solution to the *k*-exclusion problem using a semaphore of capacity *k*: a straightforward generalization of mutual exclusion.

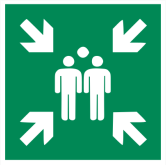
```
Semaphore sem = new Semaphore(k); // shared by all threads
```

thread `t`

```
sem.down();
  // critical section
sem.up();
```

Barriers

A barrier is a form of synchronization where there is a point (the barrier) in a program's execution that all threads in a group have to reach before any of them is allowed to continue



Barriers

A barrier is a form of synchronization where there is a point (the barrier) in a program's execution that all threads in a group have to reach before any of them is allowed to continue

A solution to the barrier synchronization problem for 2 threads using binary semaphores.

```
Semaphore[] done = {new Semaphore(0), new Semaphore(0)};
```

t_0

```
// code before barrier
done[t0].up();   // t done
done[t1].down(); // wait u
// code after barrier
```

t_1

```
// code before barrier
done[t1].up();   // u done
done[t0].down(); // wait t
// code after barrier
```

Barriers

A barrier is a form of synchronization where there is a point (the barrier) in a program's execution that all threads in a group have to reach before any of them is allowed to continue

A solution to the barrier synchronization problem for 2 threads using binary semaphores.

capacity 0 forces `up` before first `down`

```
Semaphore[] done = {new Semaphore(0), new Semaphore(0)};
```

t_0	t_1
`// code before barrier`	`// code before barrier`
`done[`t_0`].up();   // t done`	`done[`t_1`].up();   // u done`
`done[`t_1`].down(); // wait u`	`done[`t_0`].down(); // wait t`
`// code after barrier`	`// code after barrier`

`up` done unconditionally

`down` waits until the other thread has reached the barrier

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