UDLAP
UNIVERSIDAD DE LAS AMÉRICAS PUEBLA

Monitors

Dr. José Luis Zechinelli Martini

joseluis.zechinelli@udlap.mx

LDS-1101

Based on the course of Professor Carlo A. Furia, Chalmers University of Technology – University of Gothenburg

Beyond semaphores

- Semaphores provide a powerful, concise mechanism for synchronization and mutual exclusion; unfortunately, they have several shortcomings:
  - They are intrinsically global and unstructured: it is difficult to understand their behavior by looking at a single piece of code
  - They are prone to deadlocks or other incorrect behavior: it is easy to forget to add a single, crucial call to up or down
- In summary semaphores are a low-level synchronization primitive; let's try to raise the level of abstraction

Agenda

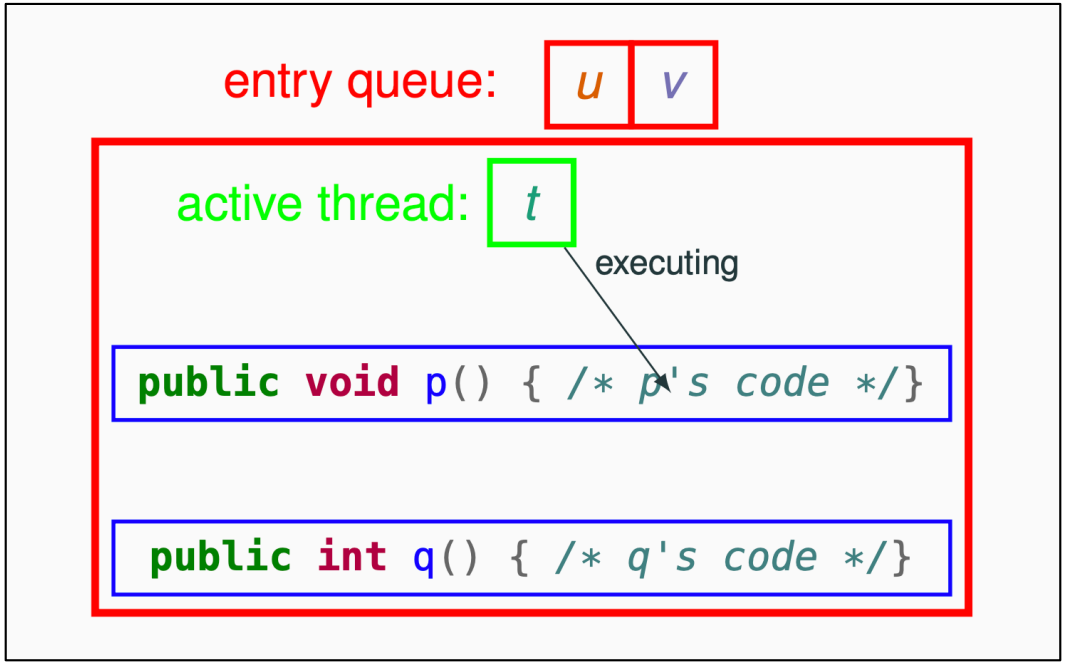
- Monitors
- Signaling disciplines
- Implementing monitors
- Monitors in Java
- Monitors: dos and don’ts

Monitors

- Monitors provide a structured synchronization mechanism built on top of object-oriented constructs — especially the notions of class, object, and encapsulation:
  - In a monitor class:
    - Attributes are private
    - Methods execute in mutual exclusion
- A monitor is an object instantiating a monitor class; how monitors encapsulate synchronization mechanisms:
  - Attributes are shared variables, which all threads running on the monitor can see and modify
  - Methods define critical sections, with the built-in guarantee that at most one thread is active on a monitor at any time

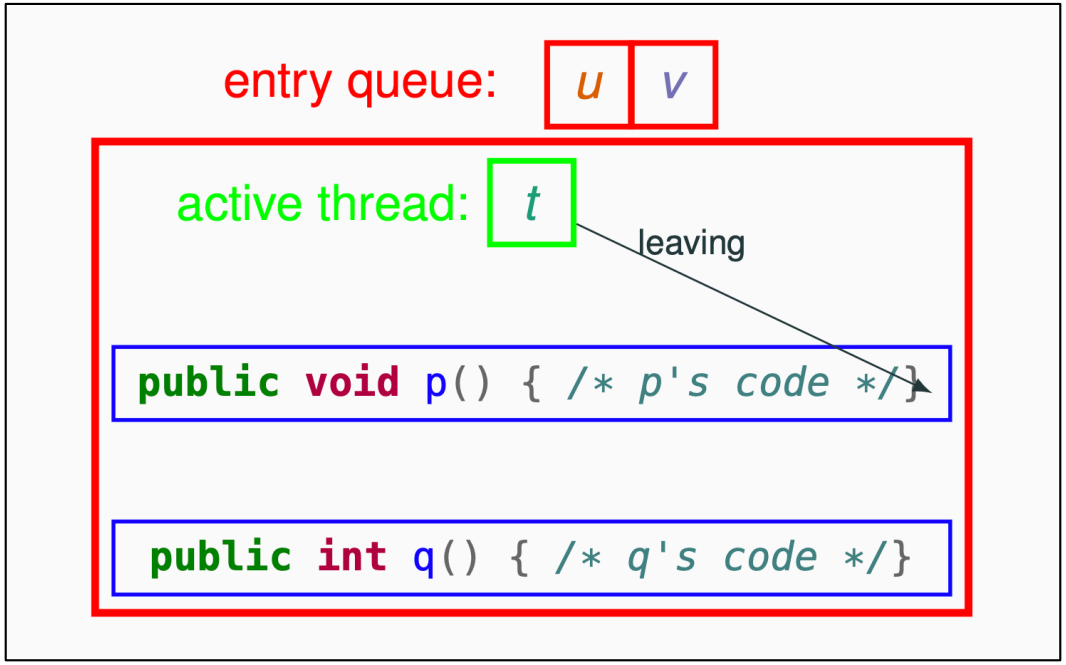
Monitors: Entry queue

- Threads trying to access a monitor queue for entry; as soon as the active thread leaves the monitor the next thread in the entry queue gets exclusive access to the monitor:



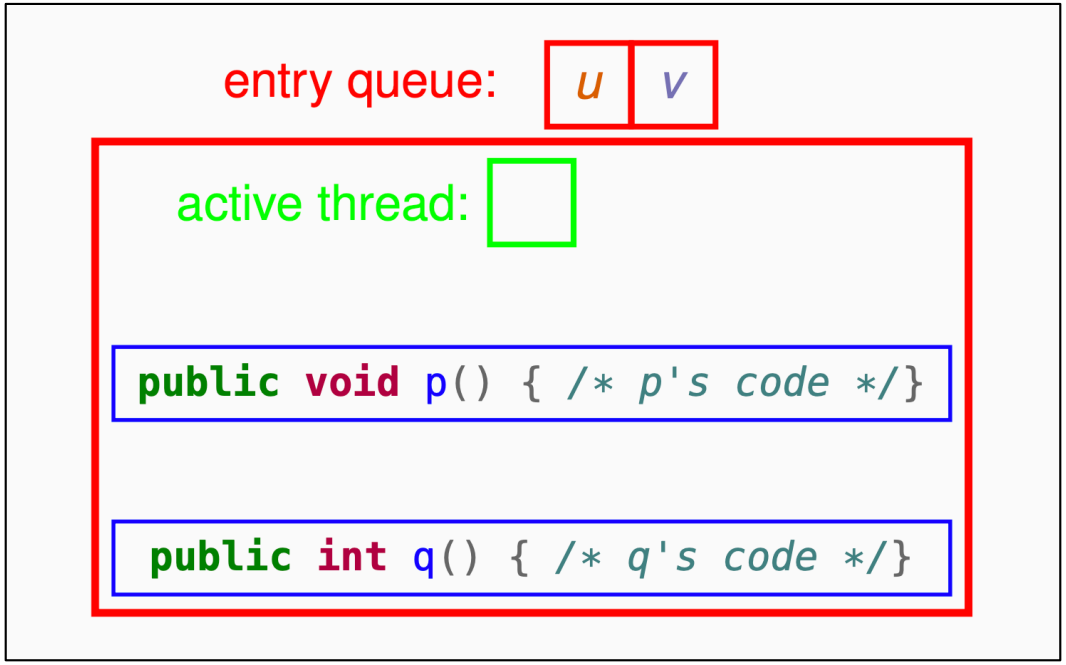
Monitors: Entry queue

- Threads trying to access a monitor queue for entry; as soon as the active thread leaves the monitor the next thread in the entry queue gets exclusive access to the monitor:



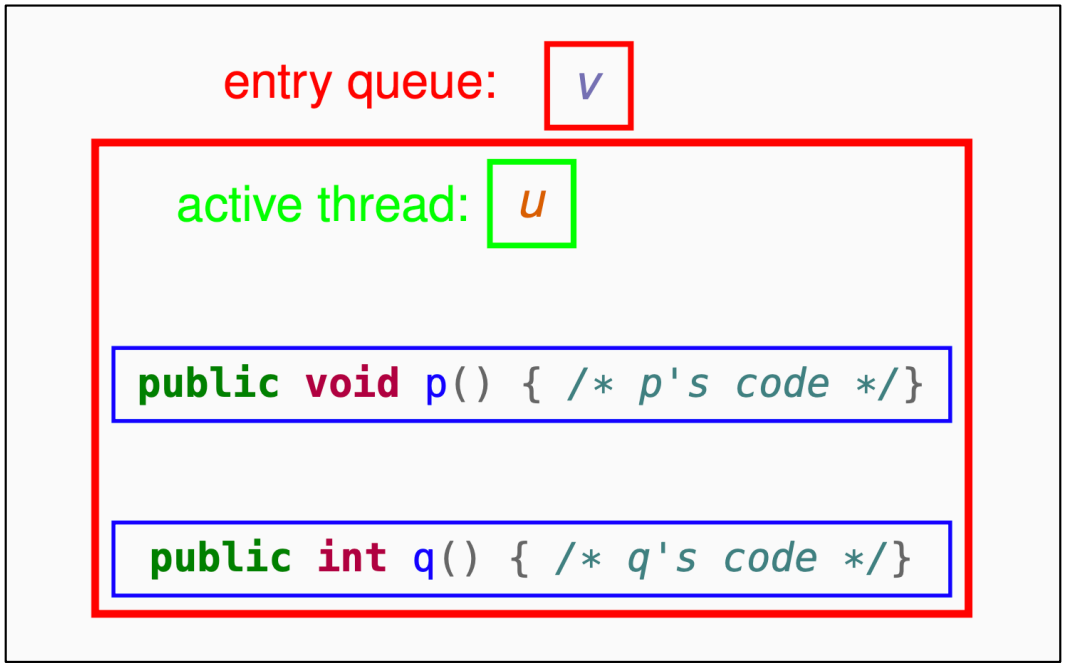
Monitors: Entry queue

- Threads trying to access a monitor queue for entry; as soon as the active thread leaves the monitor the next thread in the entry queue gets exclusive access to the monitor:



Monitors: Entry queue

- Threads trying to access a monitor queue for entry; as soon as the active thread leaves the monitor the next thread in the entry queue gets exclusive access to the monitor:



Monitors in pseudo-code (1)

- We declare monitor classes by adding the pseudo-code keyword **monitor** to regular Java classes:
  - Note that **monitor** is not a valid Java keyword — that is why we highlight it in a different color — but we will use it to simplify the presentation of monitors
- Turning a pseudo-code monitor class into a proper Java class is straightforward:
  - Mark all attributes as private
  - Add locking to all public methods

Monitors in pseudo-code (2)

- Details on how to implement monitors in Java are presented later
- We also occasionally annotate monitor classes with invariants using the pseudo-code keyword **invariant**:
  - **Invariant** is not a valid Java keyword — that is why we highlight it in a different color — but we will use it to help make more explicit the behavior of classes

Counter monitor

- A shared counter that is free from race conditions:

```
monitor class Counter {
        int count = 0;                  // attribute, implicitly private
        public void increment() {       // method, implicitly atomic
                count = count + 1;
        }
        public void decrement() {       // method, implicitly atomic
                count = count - 1;
        }
}
```

- The implementation of monitors guarantees that multiple threads executing increment and decrement run in mutual exclusion

Condition variables (1)

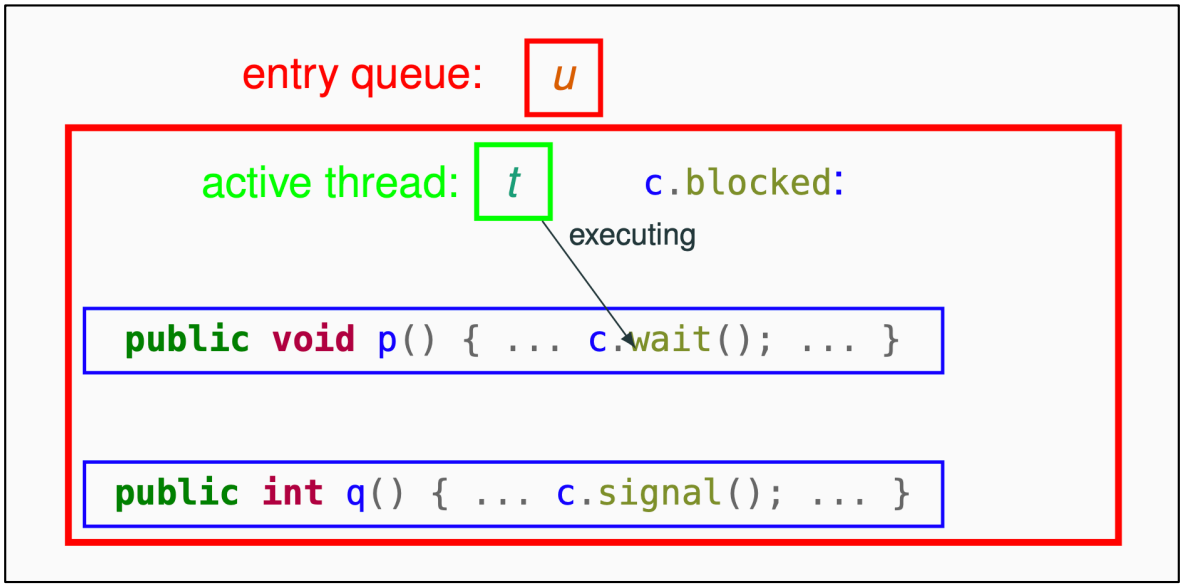
- For synchronization patterns more complex than mutual exclusion, monitors provide condition variables
- A condition variable is an instance of a class with interface:

```
interface Condition {
    void wait();            // block until signal
    void signal();          // signal to unblock
    boolean isEmpty();      // is no thread waiting on this condition?
}
```

- A monitor class can declare condition variables as attributes (private, thus only callable by methods of the monitor)

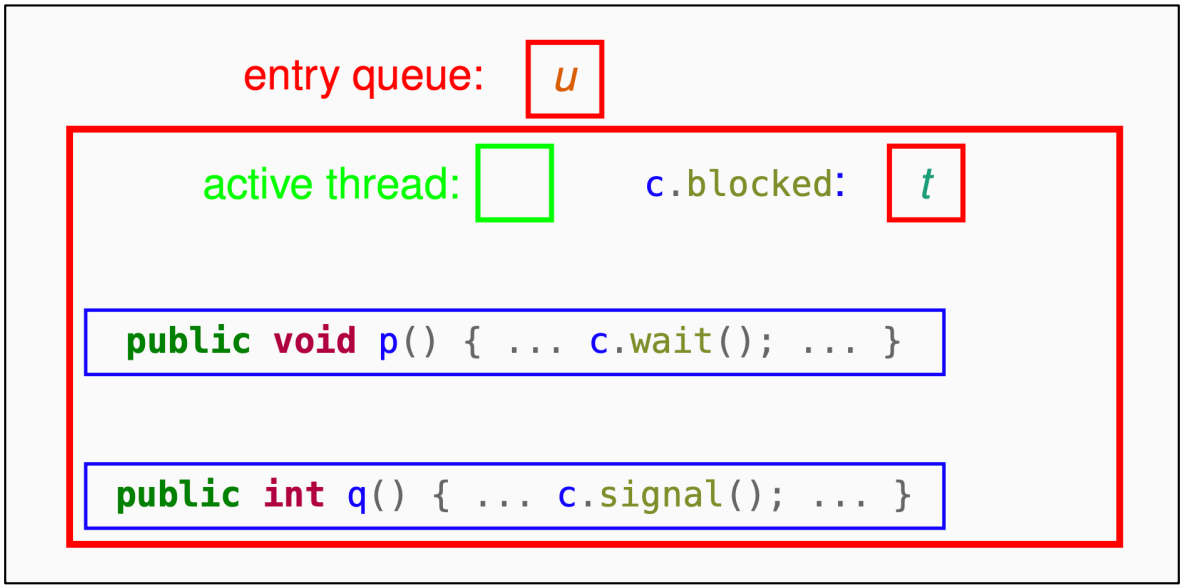
Condition variables (2)

- Every condition variable c includes a **FIFO queue** blocked:
  - c.wait() blocks the running thread, appends it to blocked, and releases the lock on the monitor
  - c.signal() removes one thread from blocked (if it's not empty) and unblocks it



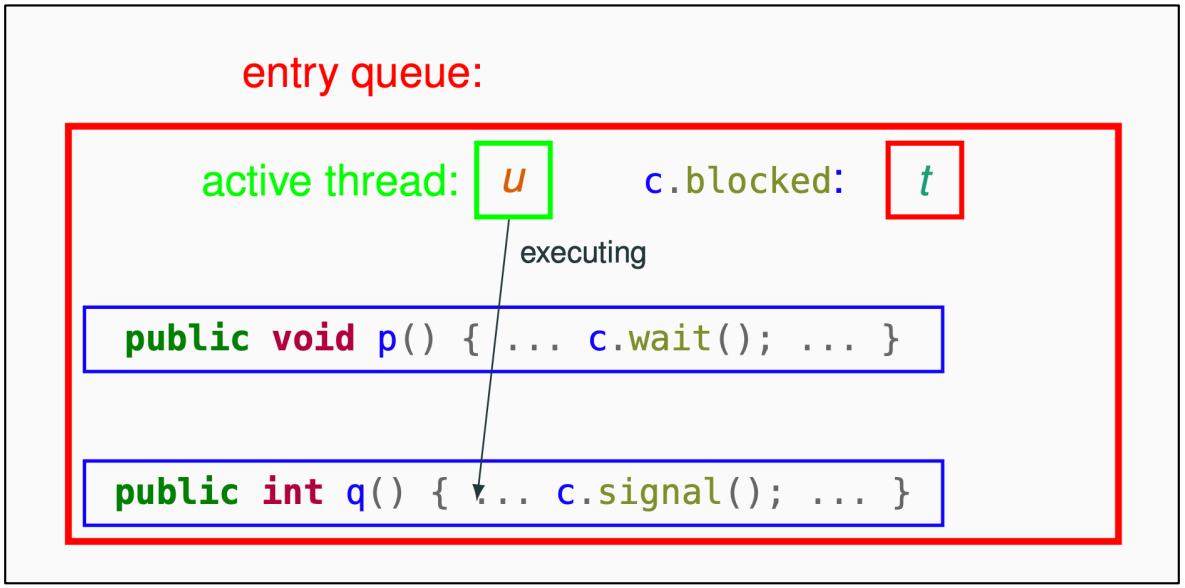
Condition variables (2)

- Every condition variable c includes a **FIFO queue** blocked:
  - c.wait() blocks the running thread, appends it to blocked, and releases the lock on the monitor
  - c.signal() removes one thread from blocked (if it's not empty) and unblocks it



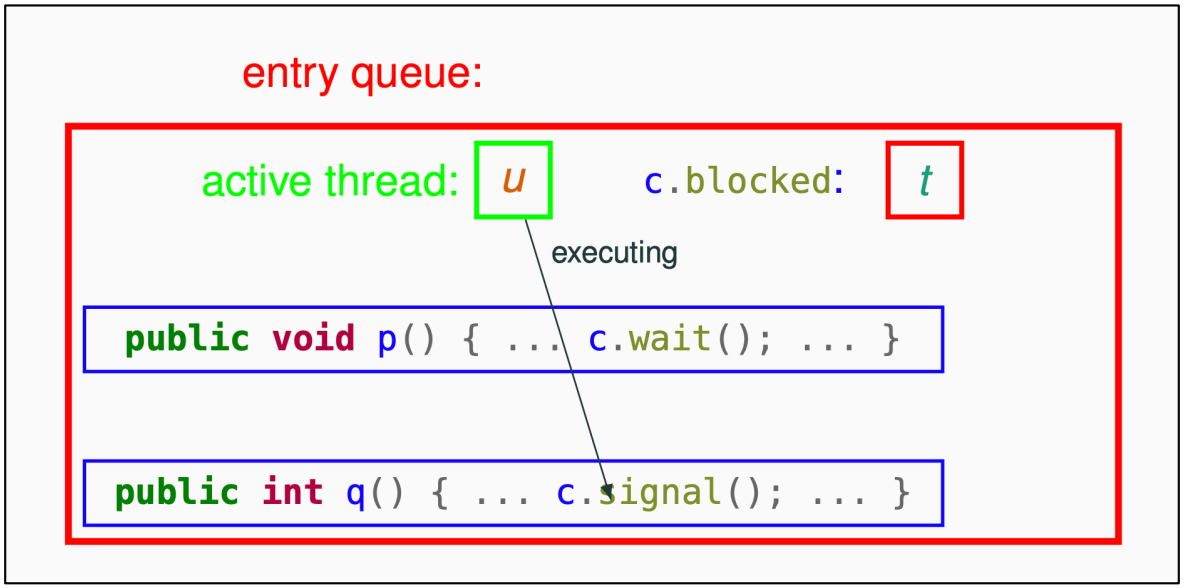
Condition variables (2)

- Every condition variable c includes a **FIFO queue** blocked:
  - c.wait() blocks the running thread, appends it to blocked, and releases the lock on the monitor
  - c.signal() removes one thread from blocked (if it's not empty) and unblocks it



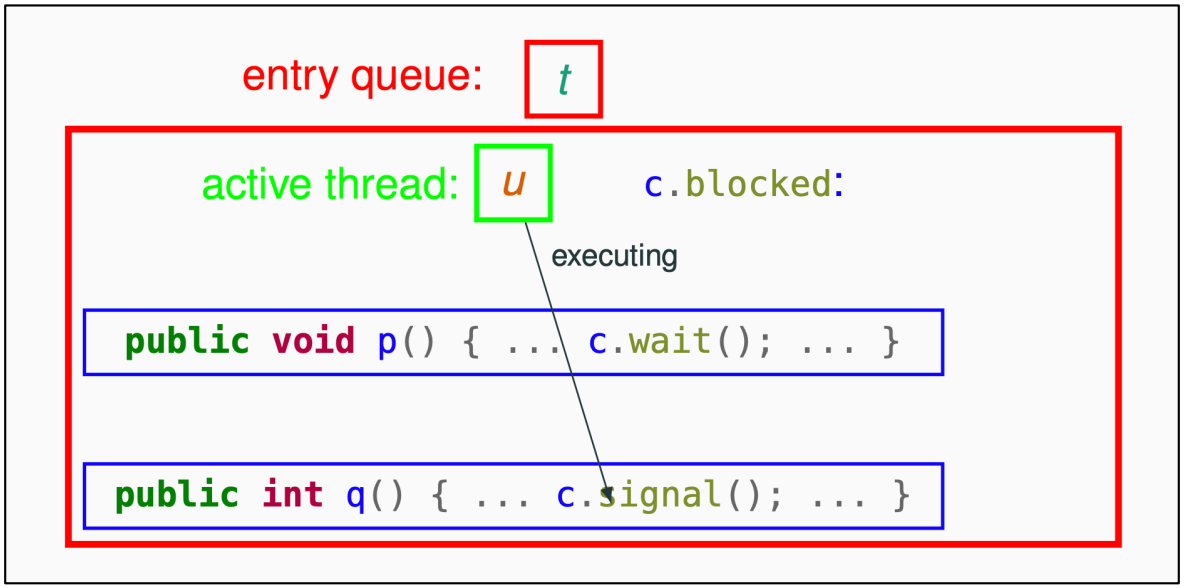
Condition variables (2)

- Every condition variable c includes a **FIFO queue** blocked:
  - c.wait() blocks the running thread, appends it to blocked, and releases the lock on the monitor
  - c.signal() removes one thread from blocked (if it's not empty) and unblocks it



Condition variables (2)

- Every condition variable c includes a **FIFO queue** blocked:
  - c.wait() blocks the running thread, appends it to blocked, and releases the lock on the monitor
  - c.signal() removes one thread from blocked (if it's not empty) and unblocks it



Agenda

- ✓ Monitors
- Signaling disciplines
- Implementing monitors
- Monitors in Java
- Monitors: dos and don’ts

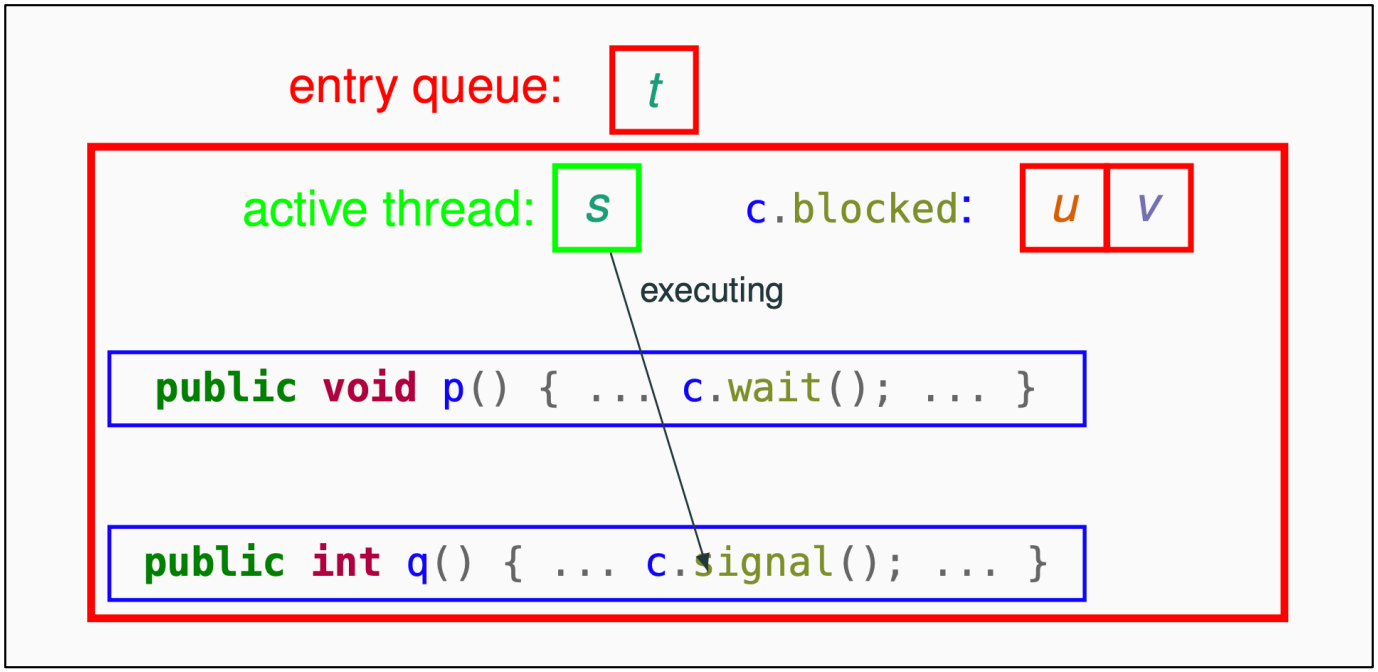
Signaling disciplines

- When a thread s calls signal() on a condition variable, it is executing inside the monitor:
  - Since no more than one thread may be active on a monitor at any time, the thread u unblocked by s cannot enter the monitor immediately

- The signaling discipline determines what happens to a signaling thread s after it unblocks another thread u by signaling:
  - Two main choices of signaling discipline:
    - **Signal and continue**: s continues executing; u is moved to the entry queue of the monitor
    - **Signal and wait**: s is moved to the entry queue of the monitor; u resumes executing (it silently gets the monitor's lock)

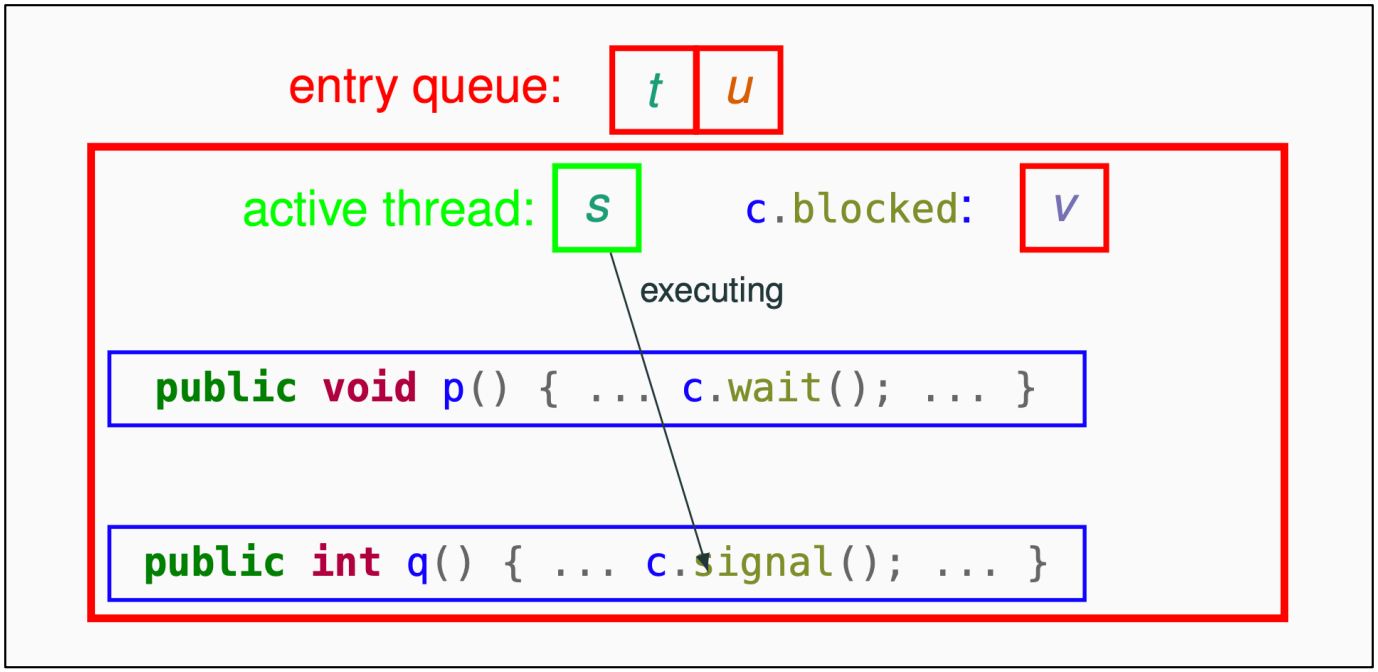
Signal and continue

- Under the signal and continue discipline:
  - The unblocked thread u is moved to the monitor's entry queue
  - The signaling thread s continues executing



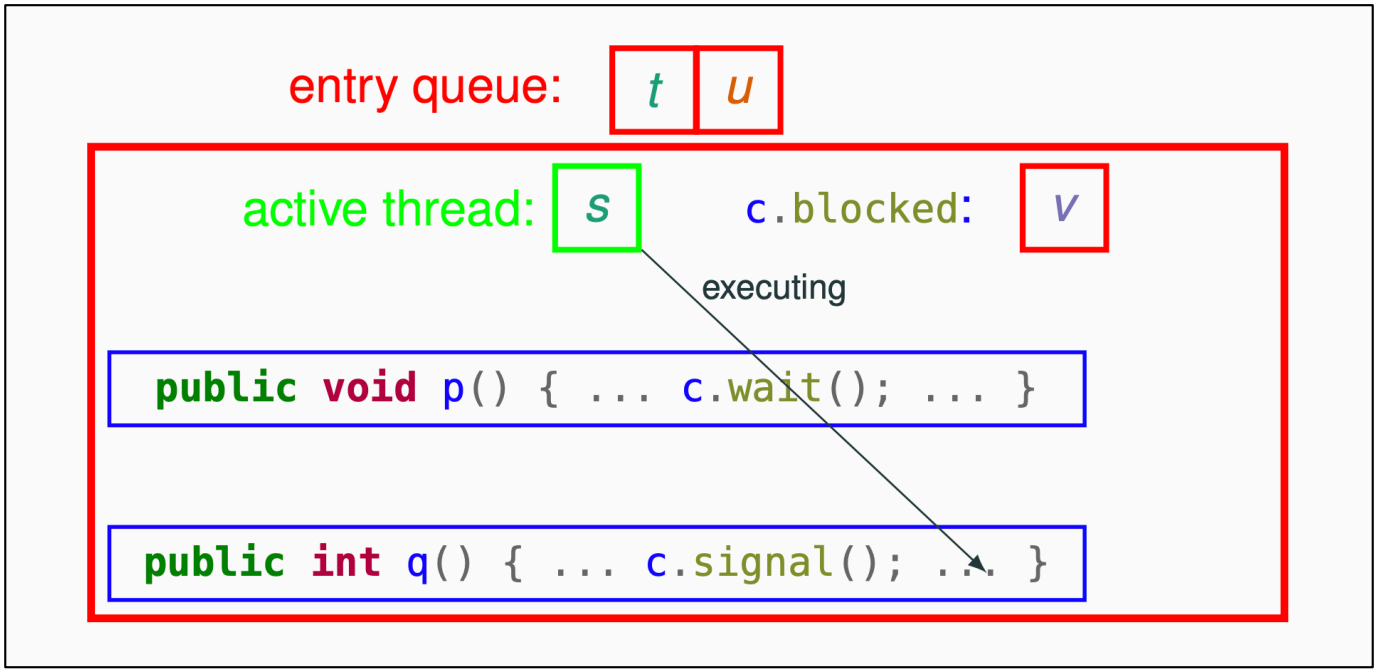
Signal and continue

- Under the signal and continue discipline:
  - The unblocked thread u is moved to the monitor's entry queue
  - The signaling thread s continues executing



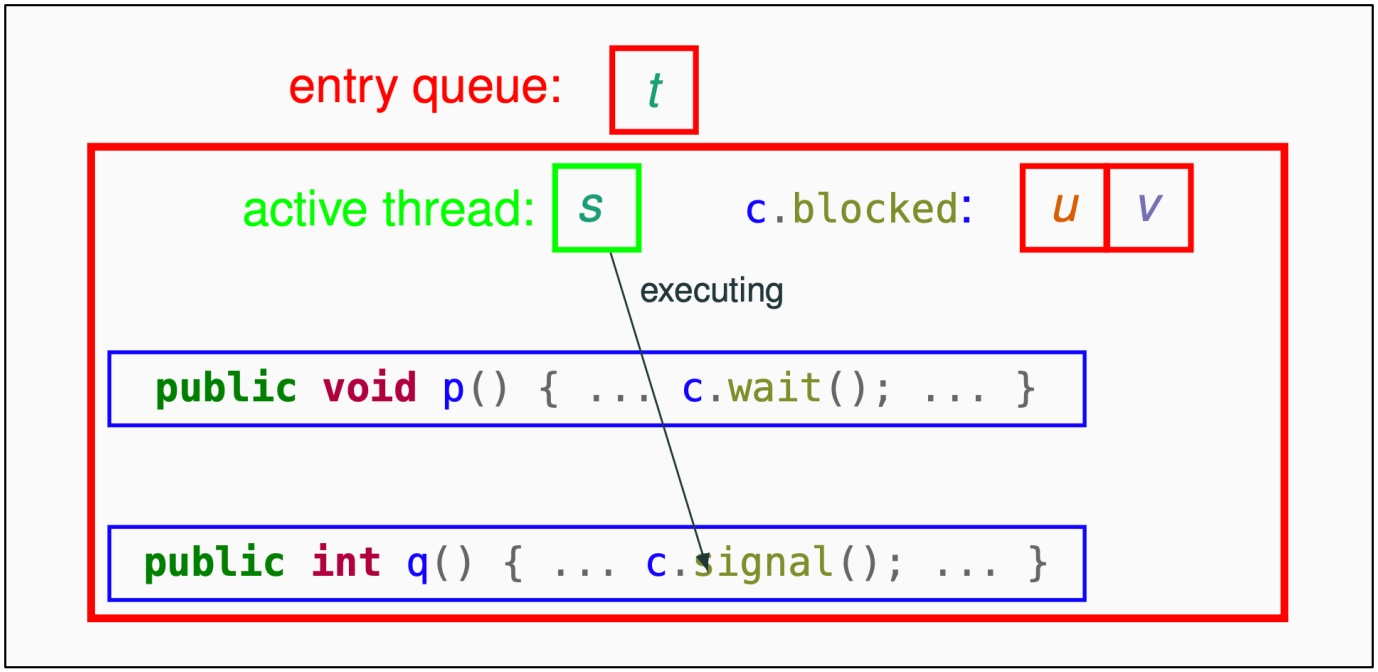
Signal and continue

- Under the signal and continue discipline:
  - The unblocked thread u is moved to the monitor's entry queue
  - The signaling thread s continues executing



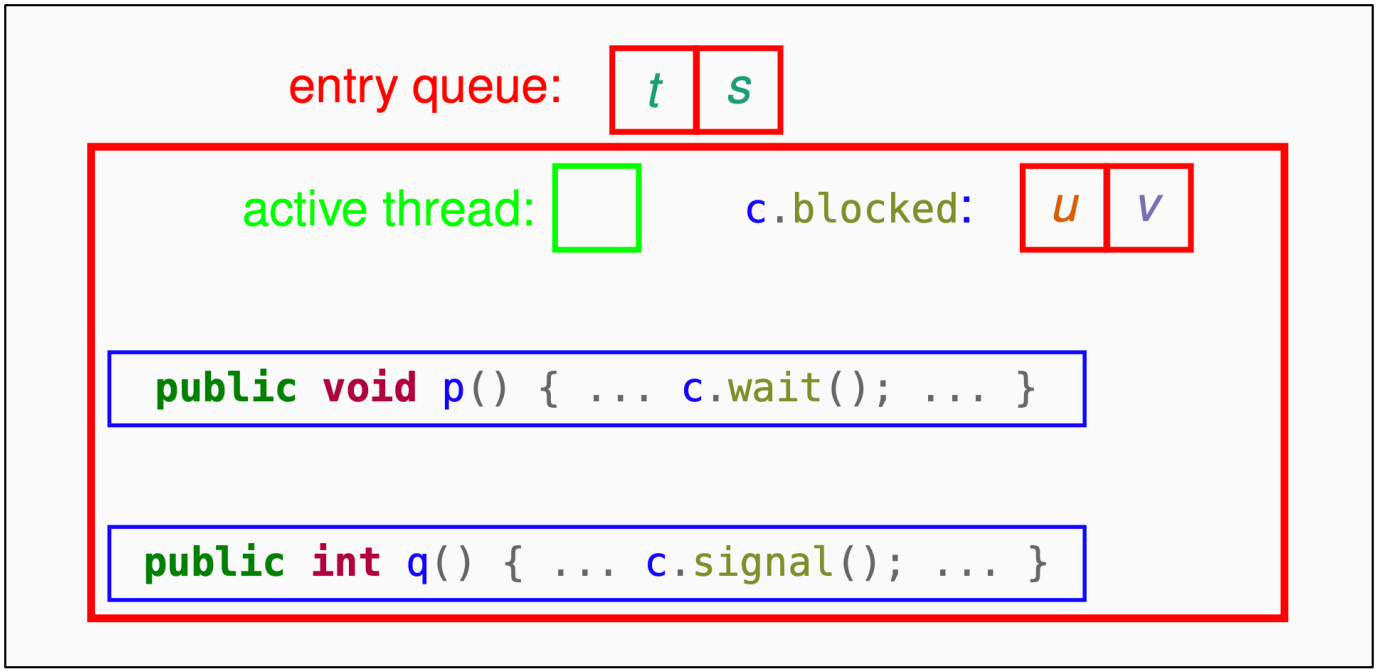
Signal and wait

- Under the signal and wait discipline:
  - The signaling thread s is moved to the monitor's entry queue
  - The unblocked thread u resumes executing



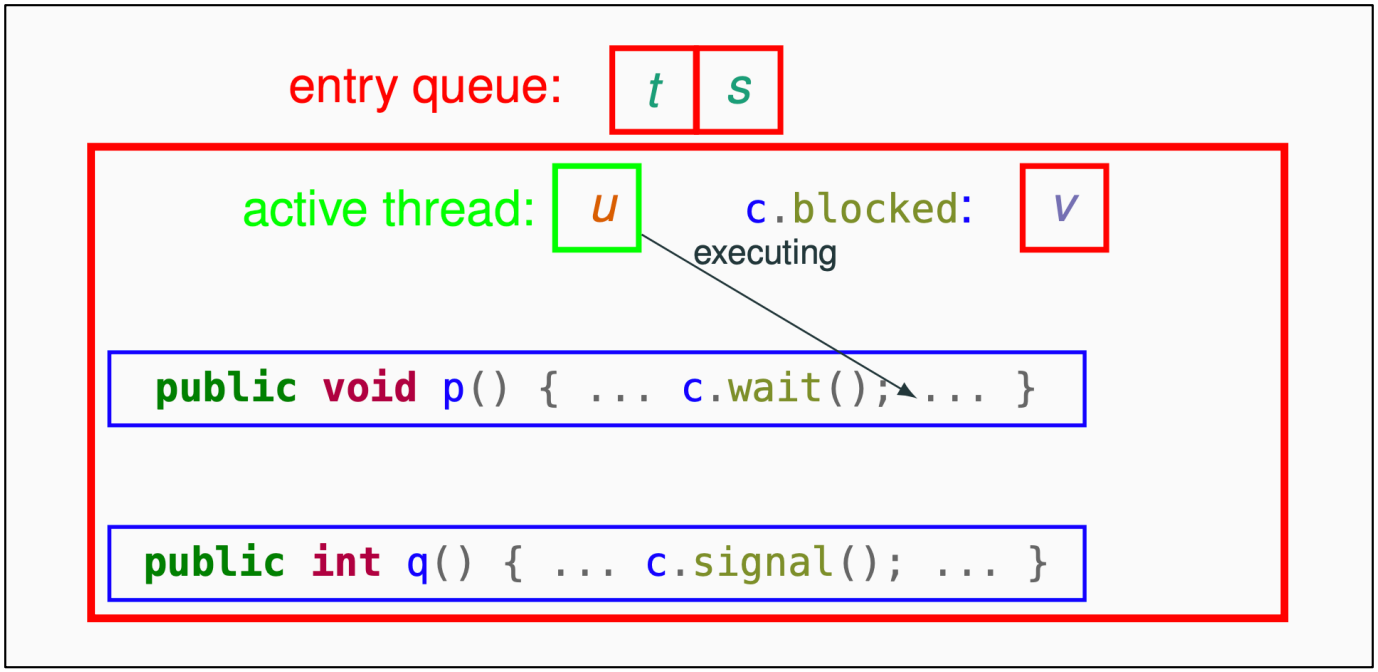
Signal and wait

- Under the signal and wait discipline:
  - The signaling thread s is moved to the monitor's entry queue
  - The unblocked thread u resumes executing



Signal and wait

- Under the signal and wait discipline:
  - The signaling thread s is moved to the monitor's entry queue
  - The unblocked thread u resumes executing



Condition checking under different signaling disciplines (1)

- Under the signal and wait discipline, it is guaranteed that the signaled condition holds when the unblocked thread u resumes execution — because it immediately follows the signal

- In contrast, under the signal and continue discipline, the signaled condition may no longer hold when the unblocked thread u resumes execution — because the signaling thread, or other threads, may change the state while continuing

Condition checking under different signaling disciplines (2)

- Correspondingly, there are different patterns for waiting on a condition variables signaled as if (!buffer.isEmpty()) isNotEmpty.signal():
  - Signal and wait:

```
// check once
if (buffer.isEmpty())
        isNotEmpty.wait();
// here !buffer.isEmpty()
```

  - Signal and continue:

```
// recheck after waiting
while (buffer.isEmpty())
        isNotEmpty.wait();
// here !buffer.isEmpty()
```

Signal all (1)

- The signal and continue discipline does not guarantee that a thread resuming execution after a wait will find that the condition it has been waiting for is true: the signal is only a “hint”
- In spite of this shortcoming, most (if not all) implementations of monitors follow the signal and continue discipline — mainly because it is simpler to implement

Signal all (2)

- Monitors following signal and continue typically also offer a condition-variable method:

```
// unblock all threads blocked on this condition
void signalAll();
```

- This tends to be inefficient, because many threads will wake up only to discover the condition they have been waiting for is still not true, but works correctly with the waiting pattern using a loop (which is still not as inefficient as busy waiting!)

More signaling disciplines

- The signaling discipline determines what happens to a signaling thread s after it unblocks another thread u by signaling:
  - Two variants of signal and continue and signal and wait are also sometimes used:
    - **Urgent signal and continue**: s continues executing; u is moved to the front of the entry queue of the monitor
    - **Signal and urgent wait**: s is moved to the front of the entry queue of the monitor; u resumes executing
  - Precisely, an urgent thread gets ahead of “regular” threads, but may have to queue behind other urgent threads that are waiting for entry
  - This is implemented by adding a urgentEntry queue to the monitor, which has priority over the “regular” entry queue

Signaling disciplines: Summary

- A signaling discipline defines what happens to three sets of threads:
  - S: signaling threads
  - U: unblocked threads
  - E: threads in the entry queue

- Write X > Y to denote that threads in set X have priority over threads in set Y; then, different signaling policies can be expressed as:

Signal and continue	S > U = E
Urgent signal and continue	S > U > E
Signal and wait	U > S = E
Signal and urgent wait	U > S > E

- Other combinations are also possible, but most of them do not make much sense in practice

Agenda

- ✓ Monitors
- ✓ Signaling disciplines
- Implementing monitors
- Monitors in Java
- Monitors: dos and don’ts

Monitors from semaphores

- We give an overview of how to implement monitors using semaphores; this also rigorously defines the semantics of monitors:
  - Every monitor class uses a strong semaphore entry to model the entry queue
  - Every monitor method acquires entry upon entry and releases it upon exit

```
monitor class Counter {

  int x = 0;
  public void inc() {

    x = x + 1;

  }
}
```

```
class Counter {
  // strong semaphore, initially 1
  Semaphore entry = new Semaphore(1);
  int x = 0;
  public void inc() {
    entry.down();
    x = x + 1;
    entry.up();
  }
}
```

Condition variables: Waiting

- Every condition variable uses a queue blocked of threads waiting on the condition:

```
abstract class WaitVariable implements Condition {
        Queue blocked = new Queue<Thread>();        // queue of blocked threads

        // block until signal
        public void wait() {
                entry.up();                         // release monitor lock
                blocked.add(running);               // enqueue running thread
                running.state = BLOCKED             // set state as blocked
        }

        // is no thread waiting?
        public boolean isEmpty() { return blocked.isEmpty(); }
}
```

Condition variables: Signal and continue

```
class SCVariable extends WaitVariable {
        // signal to unblock
        public void signal() {
                if (!blocked.isEmpty()) {
                    Thread u = blocked.remove();     // u is the unblocked thread
                    entry.blocked.add(s);            // u gets moved to entry queue
                    // the running, signaling thread continues executing
                }
        }
}
```

Condition variables: Signal and wait

```
class SWVariable extends WaitVariable {
        // signal to unblock
        public void signal() {
                if (!blocked.isEmpty()) {
                        entry.blocked.add(running);      // the running, signaling thread
                                                         // gets moved to entry queue
                        Thread u = blocked.remove();     // u is the unblocked
                        thread u.state = READY;          // set state as ready to run
                        running.state = BLOCKED;         // set state as blocked
                        // the unblocked, signaled thread resumes executing
                }
        }
}
```

Semaphores from monitors

```
monitor class StrongSemaphore implements Semaphore {
        int count;
        Condition isPositive = new Condition();       // is count > 0?

        public void down() {
                if (count > 0)
                        count = count - 1;
                else isPositive.wait();
        }

        public void up() {
                if (count.isEmpty())
                        count = count + 1;
                else isPositive.signal();
        }
}
```

Semaphores from monitors: A theoretical result

- The result that monitors can implement semaphores (and vice versa) is important theoretically: No expressiveness loss
- However, we implementing a lower-level mechanism (semaphores) using a higher-level one (monitors) is impractical because it's likely to be inefficient
  - As usual, if you need monitors or semaphores use the efficient library implementations available in your programming language of choice
  - Do not reinvent the wheel!

Agenda

- ✓ Monitors
- ✓ Signaling disciplines
- ✓ Implementing monitors
- Monitors in Java
- Monitors: dos and don’ts

Two kinds of Java monitors

- Java does not include full-fledged monitor classes, but it offers support to implement monitor classes following some programming patterns
- There are two sets of monitor-like primitives in Java:
  - One is language based, and has been included since early versions of the Java language
  - One is library based, and has been included since Java 1.5

➢ We have seen bits and pieces of both already, since they feature in simpler synchronization primitives as well

Language-based monitors

- A class JM can implement a monitor class M as follows:
  - Every attribute in JM is private
  - Every method in JM is synchronized — which guarantees it executes atomically

```
monitor class M {
  int x, y;

  public void p()
  { /* ... */ }

  public int q()
  { /* ... */ }
}
```

```
class JM {
  private int x, y;

  public synchronized void p()
  { /* ... */ }

  public synchronized int q()
  { /* ... */ }
}
```

  - ➢ This mechanism does not guarantee fairness of the entry queue associated with the monitor: Entry may behave like a set

Language-based condition variables

- Each language-based monitor implicitly include a single condition variable with signal and continue discipline:
  - Calling wait() blocks the running thread, waiting for a signal
  - Calling notify() unblocks any one thread waiting in the monitor
  - Calling notifyAll() unblocks all the threads waiting in the monitor

```
monitor class M {                    class JM {
  int x; Condition isPos;              private int x;
  public void p()                      public synchronized void p()
  { while (x < 0)                      { while (x < 0)
      isPos.wait(); }                      wait(); }
  public int q()                       public synchronized int q()
  { if (x > 0)                         { if (x > 0)
      isPos.signal(); }                    notify(); }
}                                    }
```

  - This mechanism does not guarantee fairness of the queue of blocked threads: Blocked may behave like a set

How to wait in a language-based monitor

- Calls to wait() always must be inside a loop checking a condition; there are multiple reasons to do this:
  - Under the signal and continue discipline, the signaled condition may be no longer true when an unblocked thread can run
  - Since the blocked queue is not fair, the signaled condition may be "stolen" by a thread that has been waiting for less time
  - Since there is a single implicit condition variable, the signal may represent a condition other than the one the unblocked thread is waiting for
  - In Java (and other languages), spurious wakeups are possible: A waiting thread may be unblocked even if no thread signaled

Library-based monitors

- A class LM can implement a monitor class M using explicit locks:
  - Add a private monitor attribute — a fair lock
  - Every method in LM start by locking monitor and ends by unlocking monitor — which guarantees it executes atomically

```
monitor class M {

  int x, y;

  public void p()
  { /* ... */ }
}
```

```
class LM {
  private final Lock monitor
    = new ReentrantLock(true); // fair lock
  private int x, y;

  public void p()
  { monitor.lock();
    /* ... */
    monitor.unlock(); }
}
```

  - This mechanism guarantees fairness of the entry queue associated with the monitor: Entry behaves like a queue

Library-based condition variables (1)

- Condition variables with signal and continue discipline can be generated by a monitor's lock:

```
monitor class M {

  Condition isXPos
    = new Condition();
  Condition isYPos
    = new Condition();

  int x, y;
  // ...
}
```

```
class JM {
  private final Lock monitor
    = new ReentrantLock(true);
  private final Condition isXPos
    = monitor.newCondition();
  private final Condition isYPos
    = monitor.newCondition();

  private int x, y;
  // ...
}
```

Library-based condition variables (2)

- Each library-based condition variable c has signal and continue discipline:
  - Calling c.await() blocks the running thread, waiting for a signal
  - Calling c.signal() unblocks any one thread waiting on c
  - Calling c.signalAll() unblocks all the threads waiting on c
  - This mechanism guarantees fairness of the queue of blocked threads associated with the condition variable: Blocked behaves like a queue
    - When signalAll() is called, the ordering of lock reacquisition is also fair (same order as in blocked) — provided the lock itself is fair
  - These methods must be called while holding the lock used to generate the condition variable; otherwise, an IllegalMonitorStateException is thrown

How to wait in a library-based monitor

- Calls to await() always must be inside a loop checking a condition
- There are multiple reasons to do this (compare to the case of language-based monitors):
  - Under the signal and continue discipline, the signaled condition may be no longer true when an unblocked thread can run
  - In Java (and other languages), spurious wakeups are possible: A waiting thread may be unblocked even if no thread signaled

Threads, interrupted (1)

- Waiting operations (in monitors as well as in semaphores) may be interrupted by some low-level code that calls a thread's interrupt() method:
  - This is apparent in the signature of the waiting methods, which typically may throw an object of type InterruptedException: Interrupting a waiting thread wakes up the thread, which has to handle the exception
- We normally ignore the case of interrupted threads, since it belongs to lower-level programming:
  - When calling waiting primitives, you typically propagate the exception to the main method (or simply catch and ignore it)

Threads, interrupted (2)

- It is important that programs ensure that an interrupted thread still leaves the system in a consistent state by releasing all locks it holds:
  - In language-based monitors, an interrupted thread in a synchronized method automatically releases the monitor's lock
  - In library-based monitors, use a final block to release the monitor's lock in case of exception:

```
class LM {
  private final Lock monitor = new ReentrantLock(true);

  public void p() {
    monitor.lock();
    try { /* ... */ }
    finally { monitor.unlock(); }
  }
}
```

Agenda

- ✓ Monitors
- ✓ Signaling disciplines
- ✓ Implementing monitors
- ✓ Monitors in Java
- ■ Monitors: dos and don’ts

Nested monitor calls (1)

- What happens if a method in monitor M calls a method n in monitor N (with condition variable cN)?

- Different rules are possible:

  1) Prohibit nested calls
  2) Release lock on M before acquiring lock on N
  3) Hold lock on M while also locking N
     a) When waiting on cN release both locks on N and on M
     b) When waiting on cN release only lock on N

Nested monitor calls (2)

- Rules 3 are prone to deadlock — especially rule 3.b — because deadlocks often occur when trying to acquire multiple locks
- Java monitors (both language- and library-based) follow the deadlock-prone rule 3.b
- Rule of thumb: Avoid nested monitor calls as much as possible.
- Note that if N is the same object as M, nested calls are not a problem (the implicit locks are reentrant)

Monitors: pros

- Monitors provide a structured approach to concurrent programming, which builds atop the familiar notions of objects and encapsulation
  - This raises the level of abstraction of concurrent programming compared to semaphores
- Monitors introduce separation of concerns when programming concurrently:
  - Mutual exclusion is implicit in the use of monitors
  - Condition variables provide a clear means of synchronization

Monitors: cons

- Monitors generally have a larger performance overhead than semaphores; as usual, performance must be traded against error proneness
- The different signaling disciplines are a source of confusion, which tarnishes the clarity of the monitor abstraction:
  - In particular, signal and continue is both less intuitive (because a condition can change before a waiting thread has a chance to run on the monitor) and the most commonly implemented discipline
- For complex synchronization patterns, nested monitor calls are another source of complications