CSE 451: Operating Systems
Spring 2006

Module 8
Semaphores and Monitors

John Zahorjan
zahorjan@cs.washington.edu
Allen Center 534

Last Time: Locks

- acquire()/release() operations
  - In complicated code, can be hard to get right
    - Some implementations provide "recursive locks"
    - Some implementations complain if one acquires, another releases
      - Some applications rely on one thread acquiring, another releasing
- Come in spinning and blocking varieties
  - Spin if you expect a short wait and there are multiple cores
  - Block if only one CPU/core or you expect long waits
- Blocking involves an update to a queue, i.e., a critical section
  - So, still need spin locks, if just to implement blocking locks

This Time: Other Synchronization Primitivies

- (Synchronization is a way of putting happens-before arcs into the thread graph)

- Semaphores
  - a generalization of blocking locks

- Condition variables
  - A way to wait for an event (while in a critical section)

- Monitors
  - Language (or convention)-based way to never forget to lock or unlock

- Barriers
  - Synchronize n threads in a single statement

- Join
  - Wait for a thread to terminate

Semaphores

- Semaphore = a synchronization primitive
  - higher level of abstraction than locks
  - invented by Dijkstra in 1968, as part of the THE operating system
- A semaphore is:
  - a variable that is manipulated through two operations, P and V (Dutch for "wait" and "signal")
    - **P(sem)** (wait/down)
      - block until sem > 0, then subtract 1 from sem and proceed
    - **V(sem)** (signal/up)
      - add 1 to sem
- Do these operations *atomically*

Blocking in semaphores

- Each semaphore has an associated queue of threads
  - when P (sem) is called by a thread,
    - if sem was “available” (>0), decrement sem and let thread continue
    - if sem was “unavailable” (<=0), place thread on associated queue; run some other thread
  - when V (sem) is called by a thread
    - if thread(s) are waiting on the associated queue, unblock one
      - place it on the ready queue
      - might as well let the “V-ing” thread continue execution
    - otherwise (when no threads are waiting on the sem), increment sem
      - the signal is “remembered” for next time P(sem) is called

Two types of semaphores

- Binary semaphore (aka mutex semaphore)
  - sem is initialized to 1
  - guarantees mutually exclusive access to resource (e.g., a critical section of code)
  - only one thread/process allowed entry at a time
  - Logically equivalent to a blocking lock
- Counting semaphore
  - Let N threads into "critical section," not just one
    - Why? We'll see in a minute...
  - sem is initialized to N
    - N = number of units available
  - represents resources with many (identical) units available
  - allows threads to enter as long as more units are available

Binary Semaphore Usage

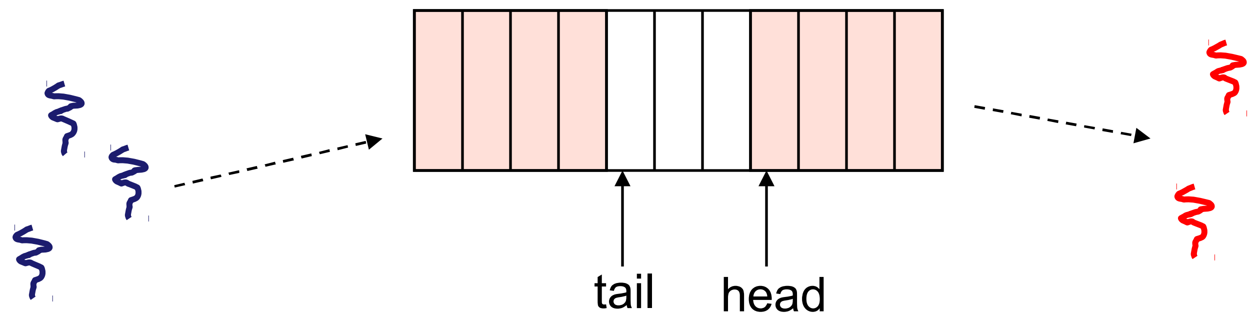
- From the programmer's perspective, P and V on a binary semaphore are just like Acquire and Release on a lock

```
P(sem)
  .
  .
  .
  do whatever stuff requires mutual exclusion; could conceivably
  be a lot of code
  .
  .
  .
V(sem)
```

  - same lack of programming language support for correct usage

Example: Bounded buffer problem

- *AKA* "producer/consumer" problem
  - there is a circular buffer in memory with N entries
  - producer threads insert entries into it (one at a time)
  - consumer threads remove entries from it (one at a time)
- Threads are concurrent
  - so, we must use synchronization constructs to control access to shared variables describing buffer state



Bounded buffer using semaphores (both binary and counting)

```
var mutex: semaphore = 1    ;mutual exclusion to shared data
    empty: semaphore = n    ;count of empty buffers (all empty to start)
    full: semaphore = 0     ;count of full buffers (none full to start)
```

```
producer:
    P(empty)          ; one fewer buffer, block if none available
    P(mutex)          ; get access to pointers
      <add item to buffer>
    V(mutex)          ; done with pointers
    V(full)           ; note one more full buffer
```

```
consumer:
    P(full)           ;wait until there's a full buffer
    P(mutex)          ;get access to pointers
      <remove item from buffer>
    V(mutex)          ; done with pointers
    V(empty)          ; note there's an empty buffer
      <use the item>
```

Note 1:
I have elided all the code concerning which is the first full buffer, which is the last full buffer, etc.

Note 2:
Try to figure out how to do this without using counting semaphores!

Example: Readers/Writers

- Description:
  - A single object is shared among several threads/processes
  - Sometimes a thread just reads the object
  - Sometimes a thread updates (writes) the object

  - **We can allow multiple readers at a time**
    - why?

  - **We can only allow one writer at a time**
    - why?

Readers/Writers using semaphores

```
var mutex: semaphore = 1       ; controls access to readcount
    wrt: semaphore = 1         ; control entry for a writer or first reader
    readcount: integer = 0     ; number of active readers
```

```
writer:
        P(wrt)                 ; any writers or readers?
                <perform write operation>
        V(wrt)                 ; allow others
```

```
reader:
        P(mutex)                            ; ensure exclusion
          readcount++                       ; one more reader
          if readcount == 1 then P(wrt)     ; if we're the first, synch with writers
        V(mutex)
                <perform read operation>
        P(mutex)                            ; ensure exclusion
          readcount--                       ; one fewer reader
          if readcount == 0 then V(wrt)     ; no more readers, allow a writer
        V(mutex)
```

Readers/Writers notes

- Notes:
  - the first reader blocks on P(wrt) if there is a writer
    - any other readers will then block on P(mutex)
  - if a waiting writer exists, the last reader to exit signals the waiting writer
    - can new readers get in while a writer is waiting?
  - when writer exits, if there is both a reader and writer waiting, which one goes next?

Semaphores vs. Locks

- Threads that are blocked at the level of program logic are placed on queues, rather than busy-waiting

- Busy-waiting may be used for the "real" mutual exclusion required to implement P and V
  - but these are very short critical sections – totally independent of application logic

Condition Variables

- Basic operations:
  - Wait()
    - wait until some thread does a signal AND release a lock, as an atomic operation
  - Signal()
    - if any threads are waiting, wake up one
    - (broadcast(): wake them all up)

- signal() is not remembered
  - A signal to a condition variable that has no threads waiting is a no-op

- Qualitative use guideline:
  - You wait() when you can't proceed until some shared state changes
  - You signal() whenever shared state changes from “bad” to “good”

Bounded-buffers with condition variables

```
var mutex: lock              ;mutual exclusion to shared data
     freeslot: condition     ;there's a free slot
     fullslol: condition      ; there's a full slot
```

```
producer:
     lock(mutex)              ; get access to pointers
      If ( buffer is full  ) wait(freeslot);
          <add item to buffer>
      unlock(mutex)           ; done with pointers
```

```
consumer:
      lock(mutex)                          ;wait until there's a full buffer
     If (buffer is empty) wait(fullslot)    ;get access to pointers
          <remove item from buffer>
      unlock(mutex)
          <use the item>
```

Note: This is a subtle bug in this code!

The Bug

- Depending on the implementation...
  - Between the time a thread is woken up by signal() and the time it re-acquires the lock, the condition it is waiting for may be false again
    - Waiting for a thread to put something in the buffer
    - A thread does, and signals
    - Now another thread comes along and consumes
    - The woken thread makes a mistake...
- NOT if (buffer is empty) wait(fullslot)
- INSTEAD while (buffer is empty) wait(fullslot)

Problems with semaphores, locks, and condition variables

- They can be used to solve any of the traditional synchronization problems, but it's easy to make mistkaes
  - They're essentially shared global variables
    - can be accessed from anywhere (bad software engineering)
  - there is no connection between the synchronization variable and the data being controlled by it
  - no control over their use, no guarantee of proper usage
    - Condition variables: will there ever be a signal?
    - Semaphores: will there be a V()?
    - Locks: did you lock when necessary? Unlock at the right time? At all?

- Thus, they are prone to bugs
  - We can reduce the chance of bugs by stylizing the use of synchronization
    - The restrictions of the style may lead to inefficiencies, however
  - Often language help is useful for this

Monitors

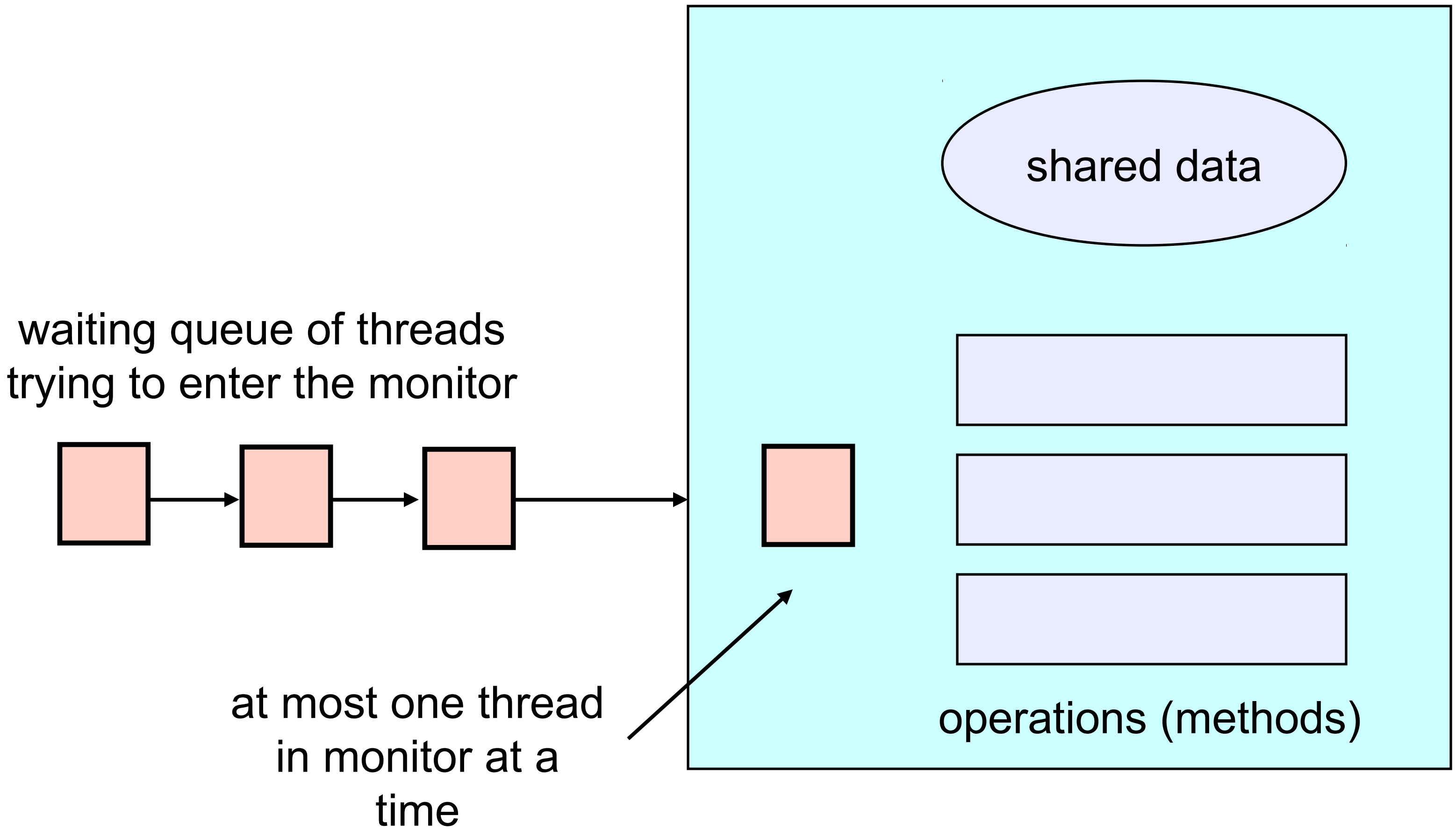
- A *monitor* is a programming language construct that supports controlled access to shared data
  - synchronization code is added by the compiler
    - why does this help?

- A monitor is (essentially) a class in which every method automatically acquires a lock on entry, and releases it on exit:
  - shared data structures (object)
  - procedures that operate on the shared data (object methods)
  - synchronization between concurrent threads that invoke those procedures

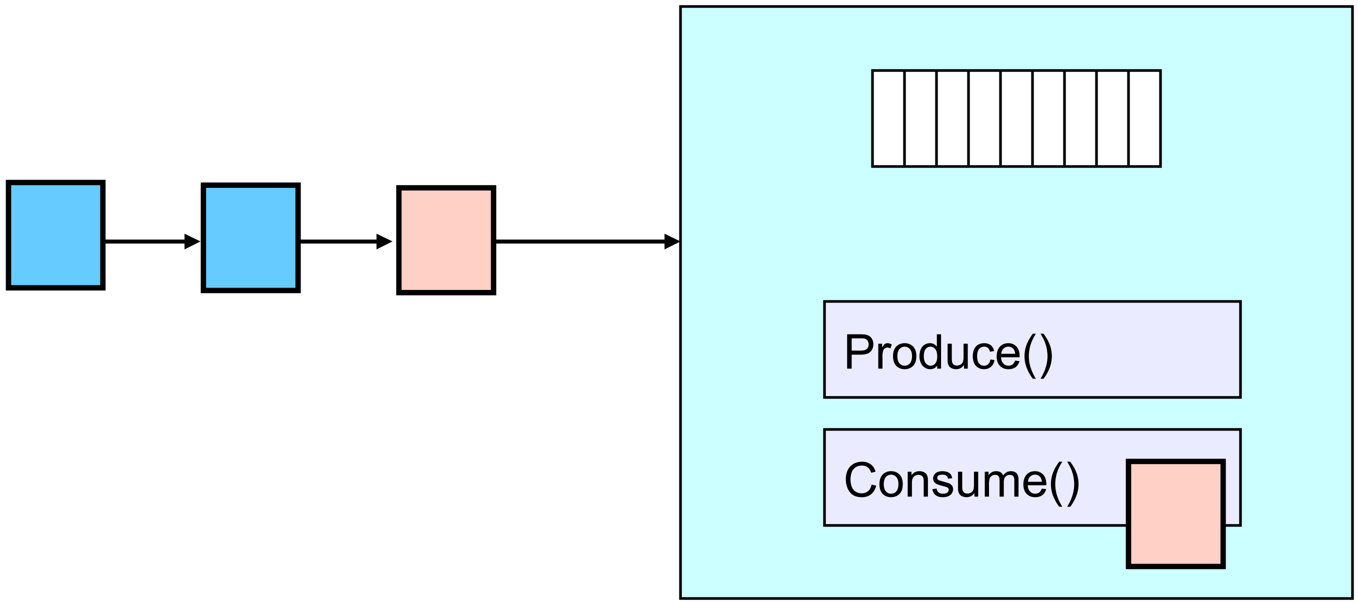
- Data can only be accessed from within the monitor, using the provided procedures
  - protects the data from unstructured access
  - Prevents ambiguity about what the synchronization variable protects

- Addresses the key usability issues that arise with semaphores

A monitor


shared data
waiting queue of threads trying to enter the monitor
at most one thread in monitor at a time
operations (methods)

Monitors Require Condition Variables



- Buffer is empty
- Now what?

Monitors and Java

- Monitors are a somewhat exotic language feature
- Java offers something a tiny bit like monitors
  - It should be clear to you that they're not monitors in the full sense at all!
- Every Java object contains an intrinsic lock
- The *sychronized* keyword locks that lock
- Can be applied to methods, or blocks of statements

Synchronized Methods

- Atomic integer is a commonly provided (or built) package

-
```
public class atomicInt {
    int value;
    public atomicInt(int initVal) {
        value = initVal;
    }
    public synchronized postIncrement() {
        return value++;
    }
    public synchronized postDecrement() {
        return value--;
    }
    …
}
```

Synchronized Statements

- You can lock any Object, and have the lock automatically released when you leave the block of statements

- ```
  void foo(ArrayList list) {
     …
     sychronized(list) {
         <manipulate the list>
     }
  }
  ```
  ```

Barriers

- Sometimes you want (all) N threads to wait until they've all reached a synchronization point
- Example: NxM matrix vector multiply: C = AB

```
for (i=0; i<N; i++) {
        C[i] = 0;
        for ( j=0; j<M; j++) {
          C[i] += A[i][j] * B[j];
        }
}
```

One thread

Wait here until all threads have finished

As threaded code

- *barrier_init(* multBarrier, N+1);
  for (i=0; i<N; i++) {
      thread_start(vectorMultiply, A, B, C, i, M);
  }
  barrier_wait(multBarrier);

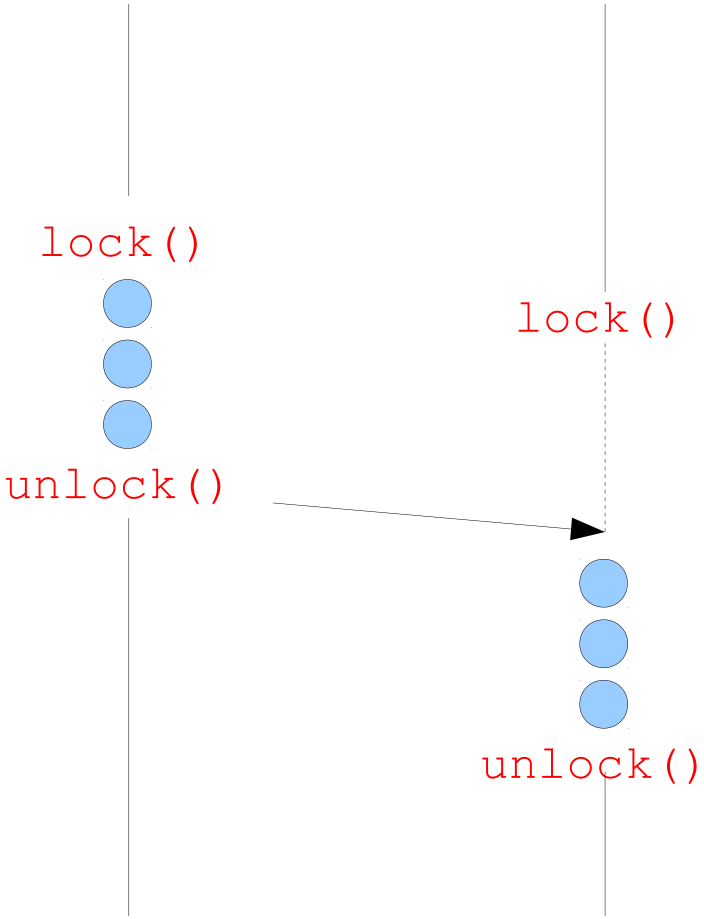
  (The italicized names are not the pthread names...)

- void vectorMultiply(A,B,C,i,M) {
    C[i] = 0;
    for (j=0; j<M; j++) C[i] += A[i][j] * B[j];
    barrier_wait(multBarrier);

Join

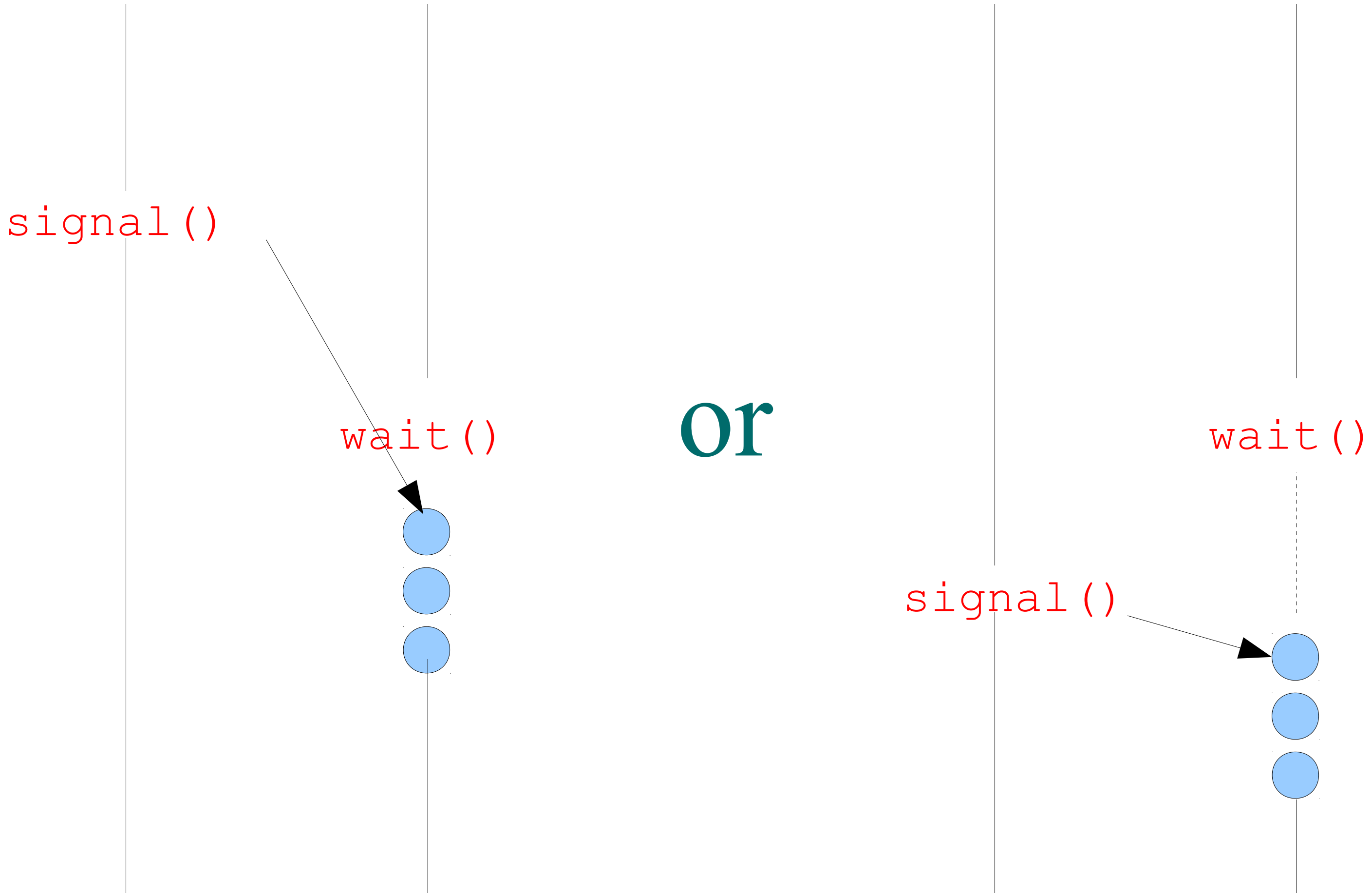
- Sometimes you want to wait until a thread has terminated
  - That's what *join()* is for
- A common use:
  - Start N threads
  - Sit in a loop waiting for thread 1, then thread 2, then …
    - It really doesn't matter much which one finishes first, you just wait in an arbitrary order
- Note: This is not quite the same as using a barrier
  - join() waits until threads have terminated, and so given up all their resources
  - A barrier is achieved before threads have terminated

Summary (in pictures)

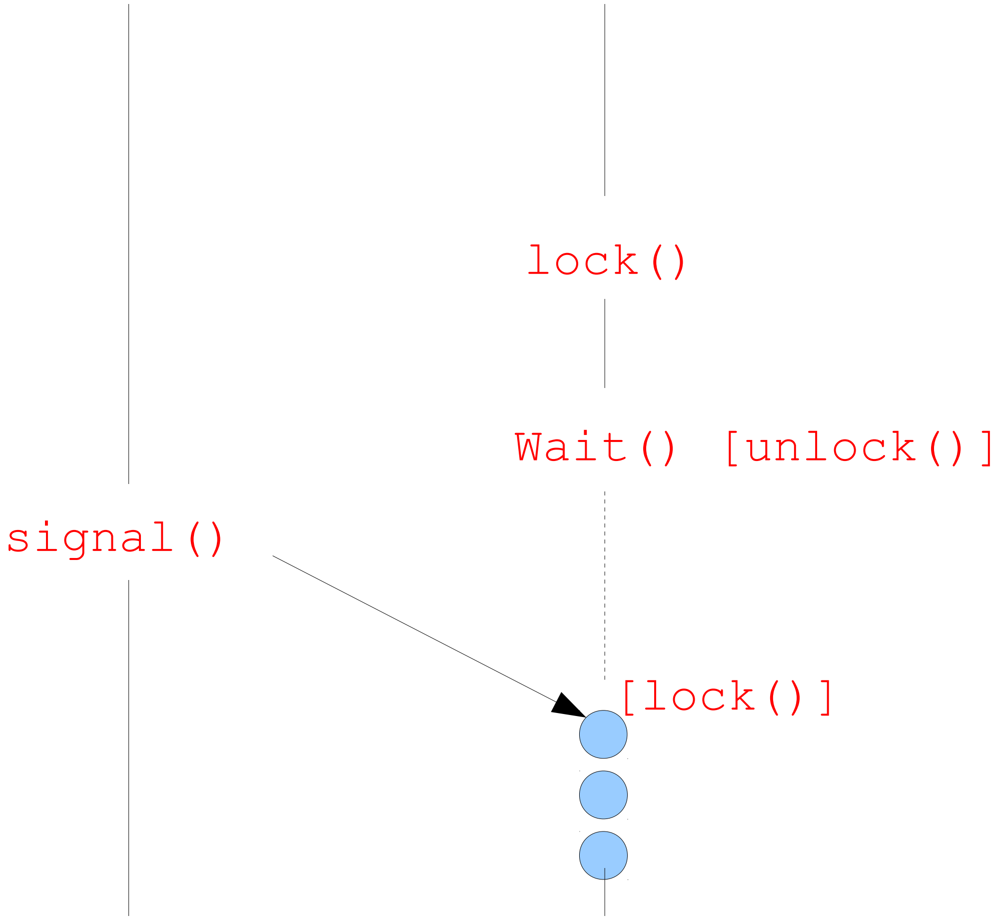


Lock synchronization

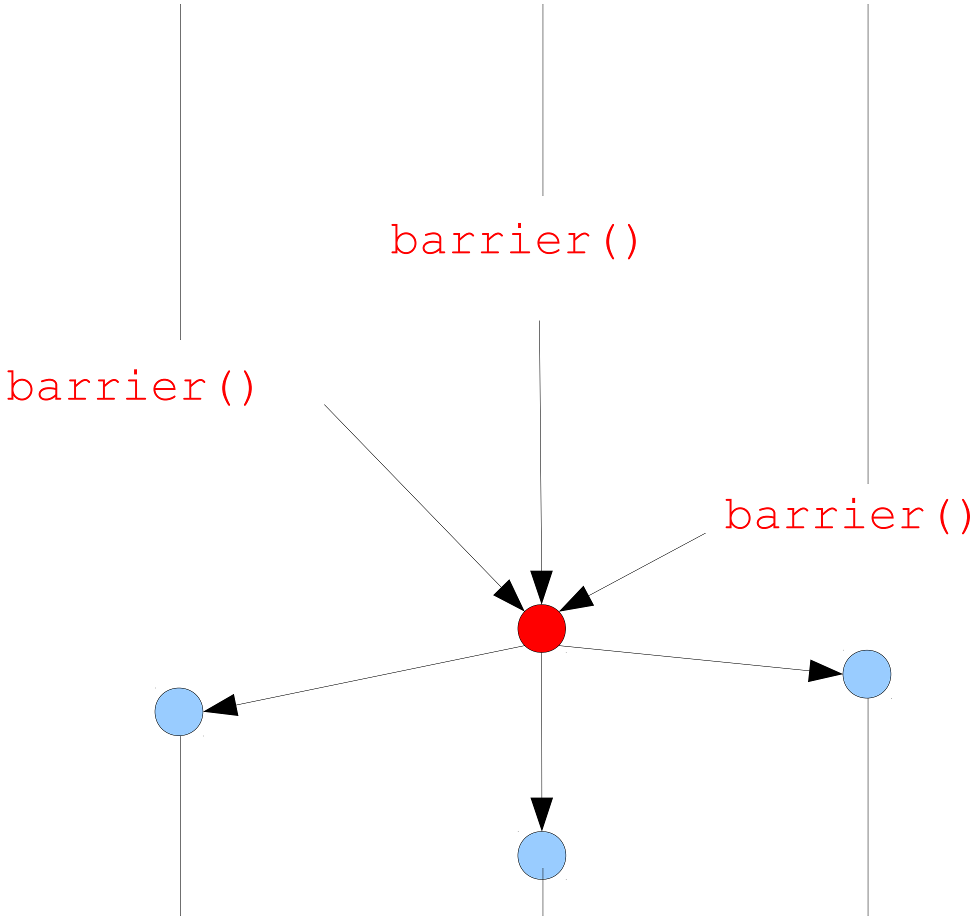
Semaphore Synchronization



Condition variable synchronization



Barrier Synchronization



Join Synchronization