Notes for CSC 254; 1, 3, and 8 Apr. 2025

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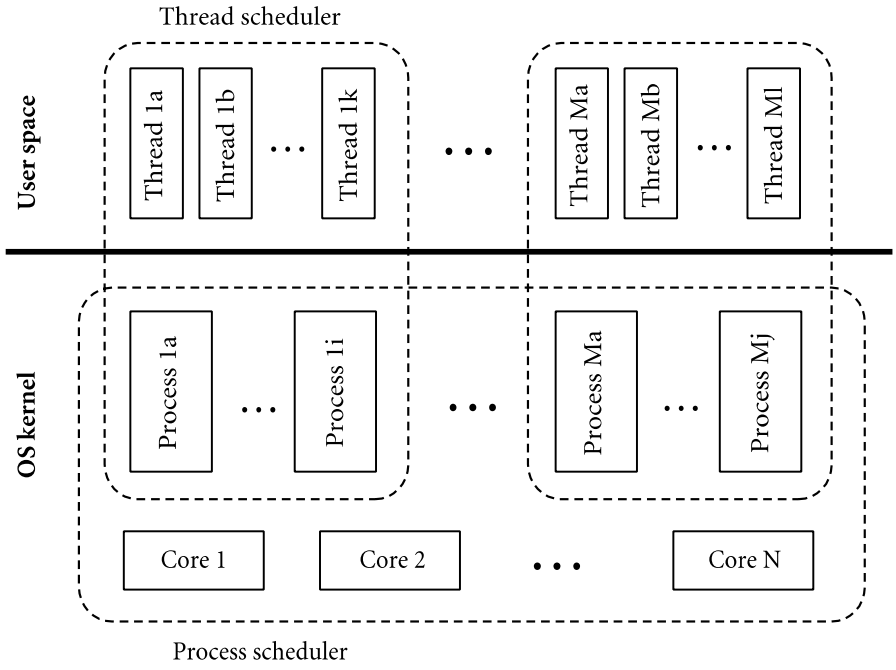
Concurrency (take 258 to learn more)

A ***process*** or ***thread*** is a potentially active execution context. The classic von Neumann (stored program) model of computing has a single thread; parallel programs have more than one. A process/thread can be thought of as an abstraction of a physical ***processor***.

Processes/threads can be implemented via
- multiple CPUs
- kernel-level multiplexing of single physical machine
- language or library level multiplexing of kernel-level abstraction

They can run in true parallel, unpredictably interleaved, or run-until-block; most work focuses on the first two cases, which are equally difficult to deal with.

In common (but by no means universal :-(terminology, each ***processor*** chip has one or more ***cores***, each of which has one or more ***hardware threads***. The operating system multiplexes one or more ***kernel-level threads*** on top of one or hardware threads, and a library package or language run-time system multiplexes one or more ***user-level threads*** on top of the kernel-level threads. Kernel threads in the same address space constitute a ***process***. (But theoreticians say "process" where systems people say "thread.")



Two main classes of programming notation

1) synchronized access to shared memory
2) message passing between processes that don't share memory

Both approaches can be embedded in a programming language.
Both can be implemented on hardware designed for the other, though shared memory on message-passing hardware tends to be slow.

We'll focus here on shared memory. The book covers message passing on the companion site. Shared-memory concurrency is essential to any language that wants programs to run on more than one core (and all but the tiniest embedded processors have had multiple cores for the past 20 years). Code that wants to use the GPU or other accelerators faces additional challenges, not covered here.

Programmers can be provided w/ concurrency via **languages**, **language extensions**, or **libraries**. Some examples:

	Shared memory	Message passing	Distributed computing
Language	Java, C# C/C++11	Go	Erlang
Extension	OpenMP		Remote procedure call
Library	`pthreads`, Windows threads	MPI	Internet libraries

Thread creation syntax

- static set
- co-begin: Algol 68, Occam, SR
- ***parallel loops***
  - iterations are independent: SR, Occam, others
  - or iterations are to run (as if) in lock step: Fortran 95 `forall`
- launch-on-elaboration: Ada, SR
- ***fork/join***: Ada, Modula-3, Java, C#, OpenMP
- implicit receipt: DP, Lynx, RPC systems
- early reply: SR, Lynx
  - Cf. separated `new()` and `start()` in Java

Races

A race condition (or just "a ***race***") occurs when program behavior depends on the order in which events occur in different threads. Races are not all bad; sometimes any of the possible program outcomes are ok (e.g. workers taking things off a task queue). Often, however, we want to avoid them. Suppose processors A and B share memory, and both try to increment variable X at more or less the same time. Very few processors support arithmetic operations on memory (even if the ISA supports provides single instructions for this, they aren't guaranteed to be atomic), so each processor executes

LOAD X
INC
STORE X

Suppose X is initialized to 0. If both processors execute these instruction sequences concurrently, we could see an increase of either one or two.

Data races v. ***synchronization races***

essentially unannotated v. annotated:
synchronization races are the expected ones, which the programmer
tells the implementation (compiler & HW) to implement correctly

Races of one sort or another are what makes concurrent programming hard.
widespread consensus that ***data races are bugs***

Races are particularly pernicious if unintentional or unannotated (so unknown to the compiler), because hardware rarely guarantees visible consistent order of accesses across cores.

initialization example

```
// ready == false

p = new foo(args)
ready = true              while (!ready) {}
                          // use *p
```

butterfly “causality” example

```
// x == y == 0

y = 1     x = 1
a = x     b = y

a == b == 0 ?
```

Races must be considered—and annotated—in the implementation of ***nonblocking algorithms*** (covered in 2/458) and synchronization primitives.

Modern languages are converging on semantics (***memory models***) that say circularity never occurs in “properly synchronized” (data race free) programs.

Synchronization

Synchronization is the art of ensuring that events in different threads happen in a desired order. Synchronization can be used to eliminate races. In our increment example we need to make each thread’s operation ***atomic***. One way to do that (not the only way) is to make the threads take turns. This is called ***mutual exclusion***: only one thread at a time can execute its ***critical section***. Informally, atomicity requires the ***appearance*** that threads take turns; mutual exclusion really makes them take turns. Most synchronization can be regarded as either atomicity or ***condition synchronization***, which means making sure that a given thread does not proceed until some condition holds (e.g., that a variable contains a given value).

[Other ways to get atomicity:
(1) nonblocking algorithms
(2) transactional memory, which may be implemented in hardware or in a library or language, with either nonblocking algorithms or locks.]

Example: bounded buffer.

```
index: 1..SIZE
buf: array [index] of data
nextempty, nextfull : index

procedure insert(d : data)
    // put something into the buffer, waiting if it’s full
```

```
procedure remove : data
    // take something out of the buffer, waiting if it's empty
```

A solution requires

(1) the buffer behaves AS IF only one thread manipulates it at a time.

(2) threads wait for non-full or non-empty conditions as appropriate.

(1) is atomicity; (2) is condition synchronization.

You might be tempted to think of mutual exclusion as a form of condition synchronization (the condition being that nobody else is in the critical section), but it isn't. The distinction is basically existential v. universal quantification—my state v. everybody's state. Mutual exclusion requires multi-thread agreement.

We do ***not*** in general want to over-synchronize. That eliminates parallelism, which we generally want to encourage for performance. Basically, we want to eliminate "bad" race conditions—the ones that cause the program to give incorrect results.

Synchronization can be based either on ***spinning*** (***busy-waiting***) or ***re-scheduling*** (yielding to a different thread). The latter is built on the former. To get started, you have to have something nontrivial that is atomic in hardware—something that happens all at once, as an indivisible action.

On most machines, reads and writes of individual memory locations are atomic (note that this is not trivial; memory and/or busses must be designed to arbitrate and serialize concurrent accesses). In early machines, reads and writes of individual memory locations were ***all*** that was atomic.To simplify the implementation of mutual exclusion, hardware designers began in the late 60's to build so-called ***read-modify-write***, or ***fetch-and-φ***, instructions into their machines.

Spin-based condition synchronization with atomic reads and writes is easy. You just cast each condition in the form of "location X contains value Y" and you keep reading X in a loop until you see what you want. Mutual exclusion is harder. Much early research was devoted to figuring out how to build it from simple atomic reads and writes. Dekker is generally credited with finding the first correct solution for two threads in the early 1960s. Dijkstra published a version that works for N threads in 1965. Peterson published a much simpler two-thread solution in 1981,

while he was on the faculty here at Rochester. It can be extended to N threads with a log-depth tree.

A busy-wait mutual exclusion mechanism is known as a ***spin lock***. The problem with spin locks is that they waste processor cycles. Synchronization mechanisms are needed that interact with a thread/process scheduler to put a thread to sleep and run something else instead of spinning. Note, however, that spin locks are still valuable for certain things, and are widely used. In particular, it is better to spin than to sleep when the expected spin time is less than the rescheduling overhead.

Semaphores were the first proposed ***scheduler-based*** synchronization mechanism, and remain widely used. ***Conditional critical regions*** and ***monitors*** came later. Monitors have the highest-level semantics, but a few sticky semantic problems. They are also widely used. Synchronization in Java 2 provided sort of a hybrid of monitors and CCRs. Java 5 introduced true monitors, but with clunky syntax. Shared-memory synchronization in Ada 95 is yet another hybrid.

Spin Locks

Synchronization with only reads and writes is very subtle. I'm not going to go into the details. Dijkstra and Peterson's N-thread locks require $O(N)$ time to acquire, which is bad. All of the locks based on only reads and writes, including Lamport's $O(1)$ lock, require $O(N)$ space, which is bad. Even Lamport's fast lock is $O(1)$ only in the ***absence*** of contention.

Can do better with atomic read-modify-write (fetch-and-phi) instructions.

```
test_and_set
fetch_and_or
fetch_and_and
fetch_and_add
fetch_and_clear_then_add
fetch_and_store (swap)
```

These typically return the old value, prior to changes, from which you can of course deduce the new value.

universal:

```
compare_and_swap
load-linked + store-conditional
```

The simple ***test_and_set lock***:

```
type lock = Boolean := false
procedure acquire(L : ^lock)
   repeat until test_and_set(L) = false
procedure release(L : ^lock)
   L^ := false
```

Problems:

- not fair (possible starvation)
- LOTS of contention for memory and interconnect bandwidth

Latter problem can be ***partially*** cured, on a cache-coherent machine, by spinning with reads instead of TASes:

```
procedure acquire(L : ^lock)
   // "test-and-test-and-set" lock
   while test_and_set(L) = true
      repeat until L = false
```

This is known as a ***test-and-test_and_set lock***.

There are better solutions to these problems (including my own), but there isn't time to cover them here: take 258!

Busy-wait solution to the bounded buffer problem:

```
index: 0..SIZE-1
buf: array [index] of data
nextempty, nextfull, fullslots : index := 0, 0, 0
mutex : spinlock

procedure insert(d : data)
   loop
      acquire(mutex)
      if fullslots < SIZE
         buf[nextempty] := d
         nextempty++; nextempty %= SIZE
         fullslots++
         release(mutex)
         return
      else
         release(mutex)
```

```
procedure remove : data
   loop
      acquire(mutex)
      if fullslots > 0
         data d := buf[nextfull];
         nextfull++; nextfull %= SIZE;
         fullslots--;
         release(mutex)
         return d
      else
         release(mutex)
```

BTW, Fetch-and-phi operations are useful not only for locking, but for ***nonblocking*** data structures as well—clever algorithms that avoid race conditions without ever locking anything. If a thread is preempted (at any time), other threads can continue to make progress. There exist good nonblocking algorithms for lists, queues, hash tables, search trees, mark-and-sweep garbage collection, and other things. Historically every new nonblocking algorithm has been a publishable result. Transactional memory changes that: some (***not*** all) TM systems are implemented in a nonblocking way under the hood: these provide a universal construction for nonblocking data structures. Operations on traditional nonblocking data structures can then be thought of as optimized hand-written transactions, though it isn't trivial to make these interoperate with general transactions.

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Schedulers

Give us the ability to "put a thread/process to sleep" and run something else on its kernel thread/processor.

Start with coroutines
make uniprocessor run-until-block threads
add preemption
add multiple processors

Coroutines

As in Simula and Modula-2. Covered in section 8.6 in the book.

Multiple execution contexts, only one of which is active.

```
transfer(other):
   save all callee-saves registers on stack    // including ra & fp
   *current := sp
   current := other
   sp := *current
   pop all callee-saves registers     // including ra, but not sp
   return                             // into different coroutine!
```

`other` and `current` are pointers to ***context blocks***.
Each contains `sp`; may contain other stuff as well
(priority, I/O status, accounting info, etc.)

No need to change `pc`; always changes at the same place.
Create new coroutine in a state that looks like it's blocked in `transfer`.
(Or maybe let it execute and then "detach". That's basically early reply.)

Run-until block threads on a single process
Need to get rid of explicit argument to `transfer`.
`ready_list` data structure: threads that are runnable but not running.

```
reschedule:
   t : cb := dequeue(ready_list)
   transfer(t)
```

To do this safely, we need to save `current` somewhere. Two options.

(1) Suppose we're just relinquishing the processor for the sake of fairness (as in MacOS 9 or Windows 3.1):

```
yield:
   enqueue(ready_list, current)
   reschedule
```

(2) Now suppose we're implementing synchronization:

```
sleep_on(q):
   enqueue(q, current)
   reschedule
```

Some other thread/process will move us to the ready list when we can continue.

Preemption

Use timer interrupts (in OS) or signals (in library package) to trigger involuntary yields.

Requires that we protect the scheduler data structures:

```
yield:
   disable_signals()
   enqueue(ready_list, current)
   reschedule
   re-enable_signals()
```

Note that `reschedule` takes us to a different thread, possibly in code other than yield. Invariant: ***every call*** to `reschedule` must be made with signals disabled, and must re-enable them upon its return.

```
disable_signals()
if not <desired condition>
   sleep_on <condition queue>
re-enable_signals()
```

Multiprocessors

Disabling signals doesn't suffice:

```
yield:
   disable_signals()
   acquire(scheduler_lock)          // spin lock
   enqueue(ready_list, current)
   reschedule
   release(scheduler_lock)
   re-enable_signals()

disable_signals()
acquire(scheduler_lock)             // spin lock
if not <desired condition>
   sleep_on <condition queue>
release(scheduler_lock)
re-enable_signals()
```

Scheduler-Based Synchronization

semaphores

So-called ***binary*** semaphores are scheduler-based mutual exclusion locks. The acquire operation is named P; the release operation is named V; these stand for words in Dutch. (Mnemonically, I think of P as standing for "pause", though it doesn't.) Binary semaphores are called "binary" because we can think of them as a counter that is always 0 or 1, and that indicates the number of threads that could perform acquire operations without blocking.

We can extend this to ***general*** semaphores, with non-binary counters. These are useful for certain algorithms, though they don't add any additional power (you can implement them trivially with binary semaphores).

In either case, a semaphore is a special sort of counter. It has an initial value, and it keeps track of the excess (if any) of past V operations over past P operations. A P operation is delayed (the thread is de-scheduled) until #P−#V ≤ C, the initial value of the semaphore.

Here is one possible implementation:

```
type semaphore = record
   N : integer           // initialized to something non-negative
   Q : queue of threads

procedure P(ref S : semaphore) :
   disable_signals()
   acquire(scheduler_lock)
   if S.N > 0
      S.N -:= 1
   else
      sleep_on(S.Q)
   release(scheduler_lock)
   re-enable_signals()
```

```
procedure V(ref S : semaphore) :
   disable_signals()
   acquire(scheduler_lock)
   if S.Q is nonempty
      enqueue(ready_list, dequeue(S.Q))
   else
      S.N +:= 1
   release(scheduler_lock)
   re-enable_signals()
```

What can we do with semaphores? Here is a bounded buffer:

```
shared buf : array [1..SIZE] of data
shared next_full, next_empty : integer := 1
shared mutex : semaphore := 1
shared empty_slots, full_slots : semaphore := SIZE, 0

procedure insert(d : data) :
   P(empty_slots)
   P(mutex)
   buf[next_empty] := d
   next_empty := next_empty mod SIZE + 1
   V(mutex)
   V(full_slots)

function remove returns data :
   P(full_slots)
   P(mutex)
   d : data := buf[next_full]
   next_full := next_full mod SIZE + 1
   V(mutex)
   V(empty_slots)
   return d
```

It is generally assumed that semaphores are fair, in the sense that threads complete P operations in the same order they start them.

Problems with semaphores:

(1) They're pretty low-level. When using them for mutual exclusion, for example (the most common usage), it's easy to forget a P or a V, especially when they don't occur in strictly matched pairs (because you do a V inside an if statement, for example, as in the use of the spin lock in the implementation of P).

(2) Their use is scattered all over the place. If you want to change how threads synchronize access to a data structure, you have to find all the places in the code where they touch that structure, which is difficult and error-prone.

These problems are addressed by ***monitors*** and other language mechanisms.

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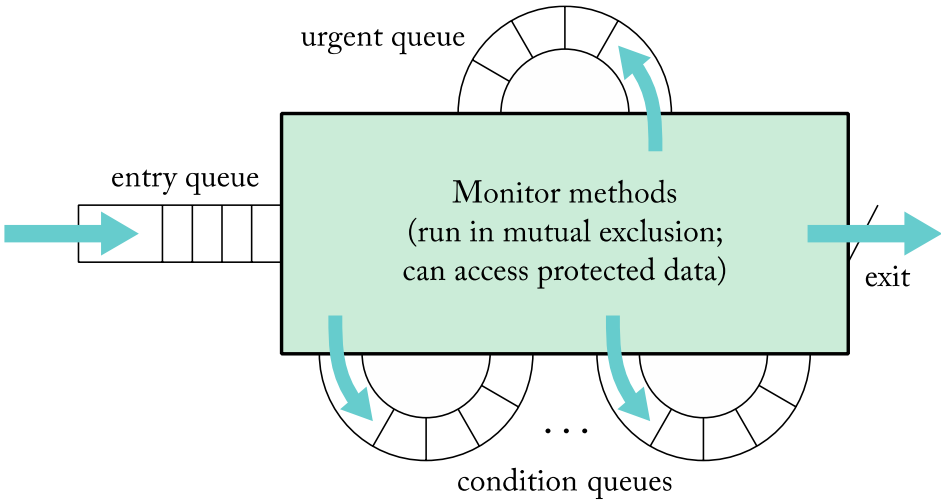
Language-level Synchronization

Scheduler-based locks in many languages (C/C++, Rust, Scala, Ruby, ...)

Monitors

Attempt to address the two weaknesses of semaphores previously discussed. Suggested by Dijkstra, developed more thoroughly by Brinch Hansen, and formalized nicely by Hoare (a real cooperative effort!) in the early 1970s. Several parallel programming languages have incorporated monitors as their fundamental synchronization mechanism. None, to my knowledge, incorporates the precise semantics of Hoare's formalization.

A monitor is a shared object with operations, internal state, and a number of ***condition queues***. Only one operation of a given monitor may be active at a given point in time. A thread that calls a busy monitor is delayed until the monitor is free. On behalf of its calling thread, any operation may suspend itself by ***waiting*** on a condition. An operation may also ***signal*** a condition, in which case one of the waiting threads is resumed, usually the one that waited first.



The precise semantics of mutual exclusion in monitors are the subject of considerable dispute. Hoare's original proposal remains the clearest and most carefully described. It specifies two bookkeeping queues for each monitor: an ***entry queue***, and an ***urgent queue***. When a thread executes a signal operation from within a monitor, it waits in the monitor's urgent queue and the first thread on the appropriate condition queue obtains control of the monitor. When a thread leaves a monitor it unblocks the first thread on the urgent queue or, if the urgent queue is empty, it unblocks the first thread on the entry queue instead.

The two main semantic controversies:

(1) Should a `signal`-er keep going, rather than moving to the urgent queue and letting the `wait`-er in? That reduces context switches but requires that we treat signals as "hints" instead of "absolutes".

The idiom

```
if not condition wait
```

becomes

```
while not condition wait
```

(2) The "nested monitor problem": A calls M1.e1, which calls M2.e2, which waits. Should A release exclusion on M1? If it does, the world may change before it returns, and it may not even be able to resume, if some other thread enters and locks M1. If A doesn't release M1, however, B may not be able to pass through M1 to reach M2 to signal A. The most elegant solution I know of (but which I don't think anybody implements) was suggested by Wettstein: to make signals hints, release all monitors, re-acquire them all ***outermost first*** on wakeup, and require that invariants hold when making nested calls. Java does not release outer monitors.

Building a correct monitor requires that one think about the ***monitor invariant***. (Everybody remember loop invariants?) The monitor invariant is a predicate that captures the notion "the state of the monitor is consistent." It needs to be true initially, and at monitor exit. It also needs to be true at every `wait` statement. In Hoare's formulation, needs to be true at every `signal` operation as well, since some other thread may immediately run.

Hoare's definition of monitors in terms of semaphores makes clear that semaphores can do anything monitors can. The inverse is also true; it is trivial to build semaphores from monitors (if you don't see how, you should figure it out :-)

Concurrency in Java

Explicit threads (in Java from the beginning)

```
class Foo extends Thread {
    public Foo (...) {
        // constructor; does ***not*** start thread running
    }
    public void run() {
        // this is where the thread starts running
    }
}

Foo f = new Foo(...);      // returns when constructor is done
f.start();
    // puts new thread on the ready list,
    //     set up to execute its run routine

...
f.join();
    // optional; waits for f to finish (return from its run method)
```

`start()` is implemented by `Thread`. It calls `run()`. In classes derived from `Thread` you should always override `run`, and you should make threads begin execution by calling `start()`. Never override `start()`. Never call `run()`.

`Executors` (introduced in Java 5). Allow caching of threads to avoid start-up / shut-down costs. Also abstract out the physical parallelism, so you can have N ***tasks*** run by M ≤ N threads under the hood.

```
class Foo implements Runnable {
    ...
    // constructor and run() method same as before
}
...
```

```
ExecutorService pool = Executors.newCachedThreadPool();
...
pool.execute(new Foo( constructor_args ));
...
// indicate that pool will never get any additional tasks
pool.shutdown();
// wait for all workers to complete
try {
   pool.awaitTermination(60, TimeUnit.SECONDS);
} catch(InterruptedException e) {}
```

Runnables are ***object closures***. They're useful for other things besides concurrency—basically anything you want to package up for future execution. There's also a `Callable` that produces a value that can be picked up later.

Can also use `newFixedThreadPool(numThreads)` or `newSingleThreadExecutor()` These are all ***factory*** methods that create and manage `Executor` objects.

NOTE: Because tasks are multiplexed on threads, they should never block, and should rarely busy-wait. When they do, their thread is unable to run anything else.

Java 2 synchronization (really should be generic; leaving that out for simplicity):

```
class BB {
   final private int SIZE = 10;
   private Object[] buf = new Object[SIZE];

   private int nextEmpty = 0;
   private int nextFull = 0;
   private int fullSlots = 0;

   synchronized public void insert(Object d)
         throws InterruptedException {
      while (fullSlots == SIZE) {
         wait();
      }
      buf[nextEmpty] = d;
      nextEmpty = (nextEmpty + 1) % SIZE;
      ++fullSlots;
      notifyAll();       // explain why!
   }
```

```
    synchronized public Object remove()
          throws InterruptedException {
       while (fullSlots == 0) {
          wait();
       }
       Object d = buf[nextFull];
       nextFull = (nextFull + 1) % SIZE;
       --fullSlots;
       notifyAll();       // explain why!
       return d;
    }
}
```

Several operations (e.g. `wait`, `join`, `sleep`) can throw `InterruptedException`. Any time you call one of these you have to be either (a) inside a try block with a handler (`catch` clause) for `InterruptedException`, or (b) inside a method whose header indicates "`throws InterruptedException`". Kind of a nuisance.

What is `InterruptedException` for? It's the way to get a waiting thread to wake up. If `t` is of class `Thread`, `t.interrupt()` will cause `t` to experience an `InterruptedException` the next time it calls a blocking operation.
Note that there is no acceptable way to cause an exception in a non-blocked thread—all such mechanisms have been deprecated.

Notes:

1) You can also use a synchronized ***statement*** (alternative to synchronized method):

```
synchronized(my_obj) {
   // critical section
}
```

2) There is only a single queue associated with each object. If you have threads that may wait for more than one reason, you need to worry about the "wrong kind" of thread waking up:

```
if (!condition) {
   wait();
}
while (!condition) {
   notify();
   wait();
}
```

This can be expensive. In some cases you can get around it by waiting in multiple sub-objects, but this doesn't work in general because a waiting thread relinquishes only the ***inner*** lock, not any outer ones (leading to deadlock if the releasing thread has to get into the same outer objects).

3) A single thread can acquire the lock on a single object multiple times (doesn't exclude itself). Such locks are sometimes said to be *reentrant.* If the thread waits, it releases the lock "the appropriate number of times." When it awakes, it will have re-acquired the lock "the appropriate number of times," and must leave that many synchronized methods or statements (or wait again) before anybody else can get in.

4) `my_obj.notifyAll()` will wake up ***all*** threads waiting on `my_obj`.

5) The lock on an object is associated with the data in the object only by convention. Java guarantees that if one thread releases a lock and a second then acquires it, the second sees all previous writes ***to all data*** by the first.

BB solution in Java 2 without using `notifyAll` is quite a bit harder:

```
class BB {
   final private int SIZE = 10;
   private Object[] buf = new Object[SIZE];

   private Object producerMutex = new Object();
   // waited upon only by producers; protects the following:
      private int nextEmpty = 0;
      private int emptySlots = SIZE;

   private Object consumerMutex = new Object();
   // waited upon only by consumers; protects the following:
      private int nextFull = 0;
      private int fullSlots = 0;

   public void insert(Object d) throws InterruptedException {
      synchronized (producerMutex) {
         while (emptySlots == 0) {
            producerMutex.wait();
         }
```

```
            --emptySlots;
            buf[nextEmpty] = d;
            nextEmpty = (nextEmpty + 1) % SIZE;
         }
         synchronized (consumerMutex) {
            ++fullSlots;
            consumerMutex.notify();
         }
      }

      public Object remove() throws InterruptedException {
         Object d;
         synchronized (consumerMutex) {
            while (fullSlots < 0) {
               consumerMutex.wait();
            }
            --fullSlots;
            d = buf[nextFull];
            nextFull = (nextFull + 1) % SIZE;
         }
         synchronized (producerMutex) {
            ++emptySlots;
            producerMutex.notify();
         }
         return d;
      }
   }
```

Solution using Java 5 locks is efficient and arguably more algorithmically elegant, but syntactically more cluttered due to library-based synchronization:

```
   class BB {
      final private int SIZE = 10;
      private Object[] buf = new Object[SIZE];

      private int nextEmpty = 0;
      private int nextFull = 0;
      private int fullSlots = 0;

      Lock l = new ReentrantLock();
      final Condition emptySlot  = l.newCondition();
      final Condition fullSlot = l.newCondition();

      public void insert(Object d) throws InterruptedException {
         l.lock();
```

```
      try {
         while (fullSlots == SIZE) {
            emptySlot.await();
         }
         buf[nextEmpty] = d;
         nextEmpty = (nextEmpty + 1) % SIZE;
         ++fullSlots;
         fullSlot.signal();
      } finally {
         l.unlock();
      }
   }

   public Object remove() throws InterruptedException {
      l.lock();
      try {
         while (fullSlots == 0) {
            fullSlot.await();
         }
         Object d = buf[nextFull];
         nextFull = (nextFull + 1) % SIZE;
         --fullSlots;
         emptySlot.signal();
         return d;
      } finally {
         l.unlock();
      }
   }
}
```