Concurrent and Parallel Programming, Part I

Programming Languages

CS 214

Hey, did you hear the joke about mutex?

No, I was locked out

Introduction

Suppose you and that "special someone" are shopping for champagne and oysters for a romantic dinner...

You might do your shopping either of two ways:

- The "we can't bear to be apart" approach: together, you
  - find the oysters,
  - find the champagne,
  - pay for what you've selected at the checkout
- The "unromantic but efficient" divide-and-conquer approach:
  - one of you finds the oysters,
  - the other finds the champagne,
  - rendezvous at the checkout to pay for what you've selected

If the average time to find champagne+oysters sequentially is τ, then finding them *concurrently* takes about $\tau/2$.

Concurrent Programming

Most modern programming languages provide built-in support for concurrent processing.

- Ada provides a *Task* construct, and each distinct task is automatically executed concurrently.
- Java provides a *Thread* class, and each distinct thread can be executed concurrently.
- C++ added a standard *thread* class in C++11.
- Erlang, Go, Scala, ... provide multithreading/processing capabilities

Older languages:

- C relies on external libraries for concurrency (e.g., Unix *fork()*, POSIX *pthreads*, OpenMP, MPI, ...).
- E-lisp provides a *start-process* function, but it is *not standard Lisp*.

Example: Ada

We might represent our sequential approach as follows:

```
procedure RomanticApproach is
begin
  FindOysters;
  FindChampagne;
  PayAtCheckout;
end RomanticApproach;
```

do this
then this
then this

By contrast, our concurrent approach is:

```
procedure EfficientApproach is
  task OysterFinder;
  task body OysterFinder is begin
    FindOysters; RendezvousAtCheckout;
  end OysterFinder;
begin
  FindChampagne; RendezvousAtCheckout;
end EfficientApproach;
```

do this

and this simultaneously

Example: Java

In Java, our sequential approach is expressed as:

```
class RomanticApproach {
 public static void main(String [] args) {
  findOysters();
  findChampagne();
  payAtCheckout();
 }
}
```

By contrast, our concurrent approach is expressed as:

```
class EfficientApproach {
 class OysterFinder extends Thread {
   public void run() {
    findOysters(); rendezvousAtCheckout();
   }
 }
 public static void main(String [] args) {
  OysterFinder of = new OysterFinder();
  of.start();
  findChampagne(); rendezvousAtCheckout();
 }
}
```


Terminology

- A *uniprocessor* is a computer with one processing core...
  - With a time-sharing OS, concurrent processing results in *pseudo-parallel execution* (aka *logical concurrency*), because the OS time-shares the single core among the processes/threads.
- A *multiprocessor* is a computer with multiple cores...
  - Concurrent processing results in *parallel execution* (aka *true concurrency*), as the OS can simultaneously run different processes/threads on different cores.
    - In a *tightly-coupled multiprocessor*, the cores
      - *share a common main memory*, and
      - are usually in *close physical proximity*.
    - In a *loosely-coupled multiprocessor*, the cores
      - have *no shared memory* (each has its own *local memory*),
      - are often *not in close physical proximity*.

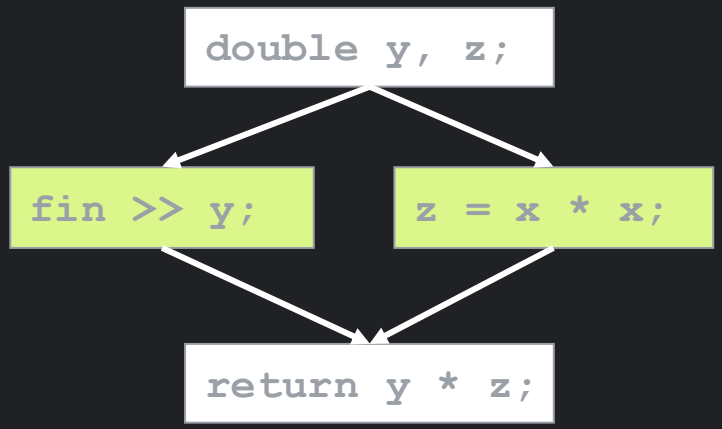
Parallelizing Compilers

What *dependencies* exist in the following function?

```
void f(double x) {
  double y, z;        // 1
  fin >> y;           // 2 … depends on 1
  z = x * x;          // 3 … depends on 1
  return y * z;       // 4 … depends on 2, 3
}
```

Parallelizing compilers build *dependency graphs*, and use them to identify pieces of code that can be executed concurrently:

- branches in the graph (e.g., 2 & 3) can be safely executed in parallel
- CPU must have the extra hardware to perform *statement-level parallelism*



Processes and Threads

A computation is sometimes called a *process*:

```
int main() {
  s1;
  s2;
  …
  sn;
}
```

The sequence of *events* that occur as control flows through a process is called a *thread of execution*:

If, for the same inputs, the sequence of events always occurs in the same order, the sequence is called *deterministic*; otherwise, the sequence is called *non-deterministic*.

Goal: Speedup

One goal of concurrent processing is to achieve **speedup**:

If a task requires τ time-units to solve sequentially,
but can be split into **p** subtasks that can be solved in parallel,
then parallel processing can perform it in $\sim\tau/p$ time-units.

Formally, speedup can be define as:

$$\text{Speedup} = T_1 / T_N$$

where: T_1 is the time **1** task takes to solve the problem, and
T_N is the time **N** tasks take to solve the problem.

If it takes one person 10 minutes to find champaign+oysters, but it takes two people 6 minutes, the speedup is 10/6 = 1.67.

Goal: Responsiveness

... is another goal of concurrent processing.

Example 1: GUI Interfaces

- If an application has a single thread and it has to perform a time-consuming task, then the GUI will "freeze" while the thread is performing that task.
- If the application uses one thread to handle user-interface events and forks a separate thread to perform each task, then the GUI will remain responsive.

Example 2: Network servers (e.g., a web server)

- If a server has a single thread and has to perform a time-consuming task, then the server will be unable to accept incoming requests while it is performing the task.
- If the server uses one thread to accept incoming requests and forks a new thread to handle each request, the server will accept and handle all requests it receives.

Event Interleaving

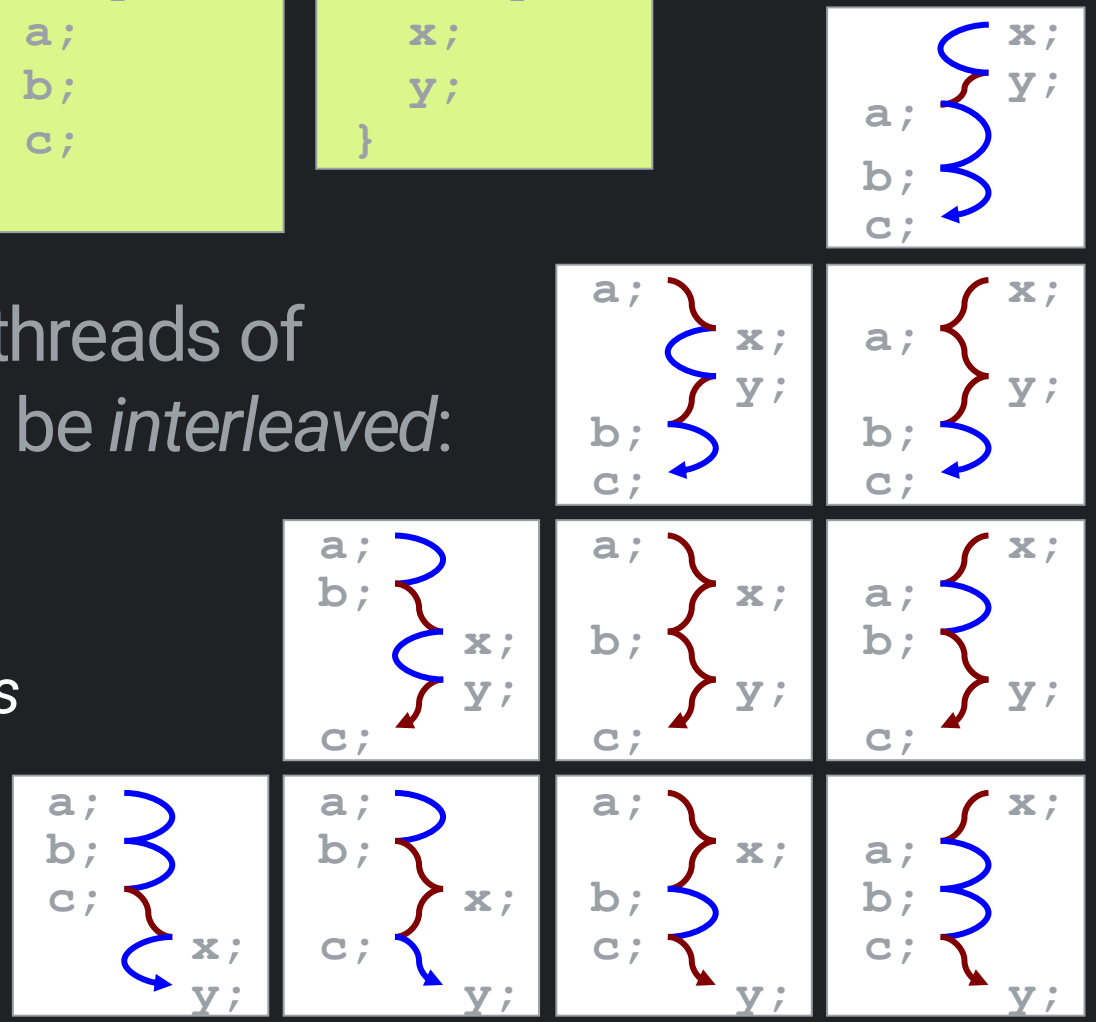
When a computation consists of two or more processes:

```
void p() {
  a;
  b;
  c;
}
```

```
void q() {
  x;
  y;
}
```

then the events in the threads of those processes may be *interleaved*:

– Each sequence is deterministic *within itself*, but the *sequencing across both processes* is non-deterministic.



Interleaving in Ada

We can see non-deterministic behavior in Ada as follows:

```
procedure Interleave is
 task A;
 task body A is begin
   put("a");
 end A;
 task B;
 task body B is begin
   put("b");
 end B;
 task C;
 task body C is begin
   put("c");
 end C;
begin
  null;
end Interleave;
```

Sample Run:

```
% ./interleave
abc
% ./interleave
bca
% ./interleave
cba
% ./interleave
cba
...
```

How many distinct executions are there?

→ The number of permutations of {a, b, c}

→ Discrete Math: a set of *n* elements has *n!* permutations, so *3! == 6* distinct possibilities.

You have a problem so you decide to use:

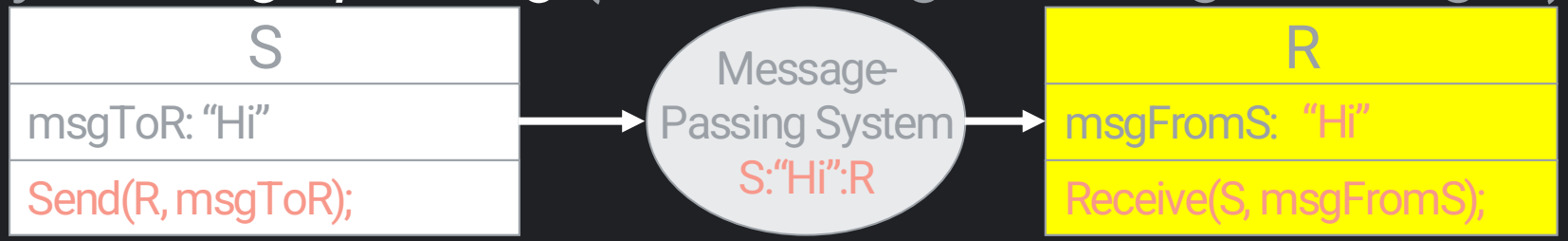
- floating point numbers.
  - Now you have 2.00000000000182372 problems
- strings.
  - Now you have "2" problems
- Unicode
  - Now you have \u0032 problems.
- Threads
  - you problems.2 have Now
- Java
  - Now you have a ProblemFactory().
- Locks
  - Now you h

Communication

If a language allows us to divide a task into subtasks, it should also provide a way for those tasks to *communicate*.

- On a tightly-coupled multiprocessor, two tasks can communicate through the *shared memory*:

- On a loosely-coupled multiprocessor, they communicate by *message-passing* (i.e., sending-receiving messages):



Shared Memory Synchronization

If two tightly-coupled processes try to access shared memory simultaneously, the result may be incorrect... What can go wrong?

TravelAgent1

```
if (emptySeats > 0)
  emptySeats–;
else
  display("no more seats!");
```

emptySeats: 1

TravelAgent2

```
if (emptySeats > 0)
  emptySeats–;
else
  display("no more seats!");
```

Accesses to shared memory must be *synchronized* to avoid this:

```
synchronize { // Java
  if (emptySeats > 0)
    emptySeats–;
  else
    display("no more seats!");
}
```

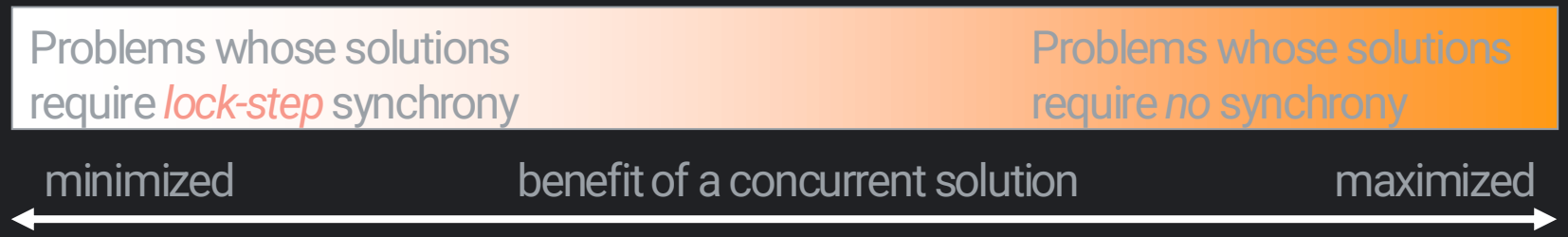
emptySeats: 1

```
synchronize { // Java
  if (emptySeats > 0)
    emptySeats–;
  else
    display("no more seats!");
}
```

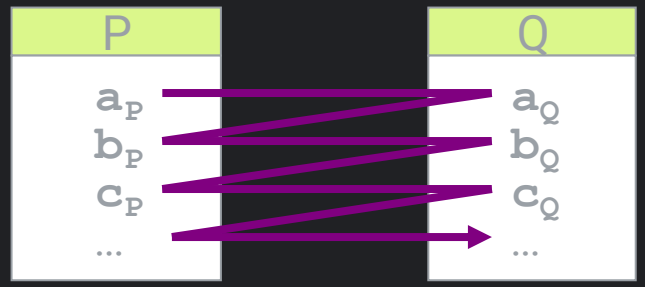
Synchronization forces one process to wait until the other is finished.

Synchrony

Concurrent computations lie on a continuum, depending on how much communication/synchronization they entail:



– *Lock-step synchronous* computations must communicate or be re-synchronized after every step of the computation:

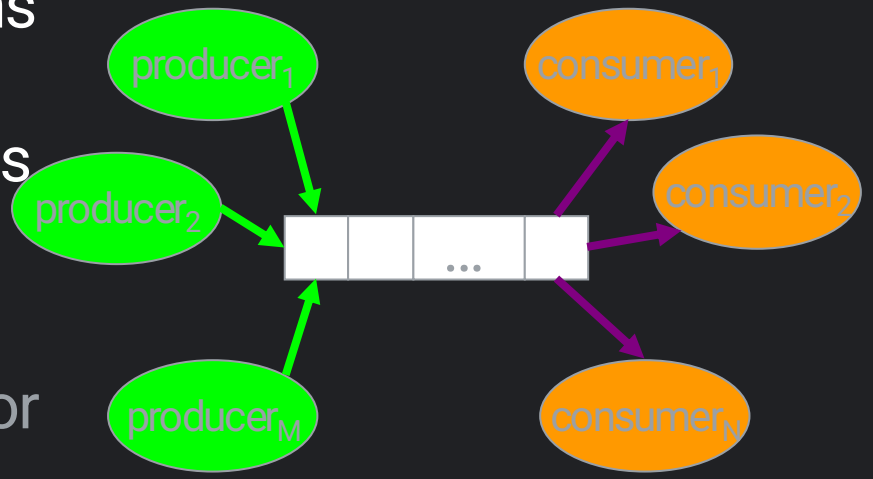


– *Asynchronous* (aka *embarrassingly parallel*) computations require no communication/synchronization of their processes

The Producer-Consumer Problem

There are a number of "classic" synchronization problems, one of which is the producer-consumer problem...

- There are M *producers* that put items into a buffer. The buffer is shared with N *consumers* that remove items from the buffer.
  - The problem is to devise a solution that ensures no items are ever lost or duplicated.

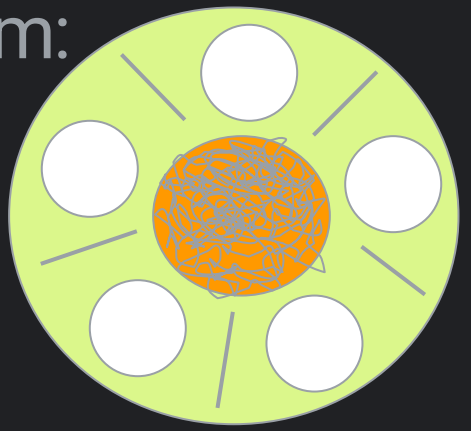


Accesses to the buffer must be synchronized: if multiple producers / consumers access it simultaneously, producers may overwrite each other's values, consumers may retrieve the same value, etc.

In the *bounded-buffer version*, the buffer has a fixed-capacity *N*.

The Dining Philosophers Problem

... is another "classic" synchronization problem:



Five philosophers sit at a table, alternating between eating noodles and thinking. In order to eat, a philosopher must have two chopsticks. However, there is a single chopstick between each pair of plates, so if one is eating, neither neighbor can eat. A philosopher puts down both chopsticks when thinking.

- Devise a solution that ensures:
  - no philosopher starves; and
  - a hungry philosopher is only prevented from eating by his immediate neighbor(s).

```
task philosopher is
  while True begin
     think(randomTime);
     get(left);
     get(right);
     eat();
     release(left);
     release(right);
  end while;
End philosopher;
```

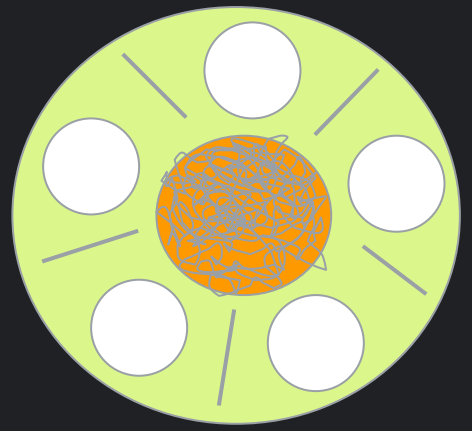
Deadlock!

The Dining Philosophers (ii)

How about this instead?

```
task philosopher is begin
  while True begin
    think(randomTime);
    while not (have(left) and have(right))
     begin
       get(left);
       if notInUse(right) then
         get(right);
       else
         release(left);
       end if;
     end while;
     eat;
     release(left);
     release(right);
 end while;
end philosopher;
```

Livelock!



A software tester
walks into a bar.
Runs into a bar.
Crawls into a bar.
Dances into a bar.
Flies into a bar.
Jumps into a bar.

And orders:
a beer.
2 beers.
0 beers.
99999999 beers.
a lizard in a beer glass.
-1 beer.
“qwertyuiop” beers.
–Testing complete.–

A real customer walks into the bar and asks where the bathroom is.
The bar goes up in flames.

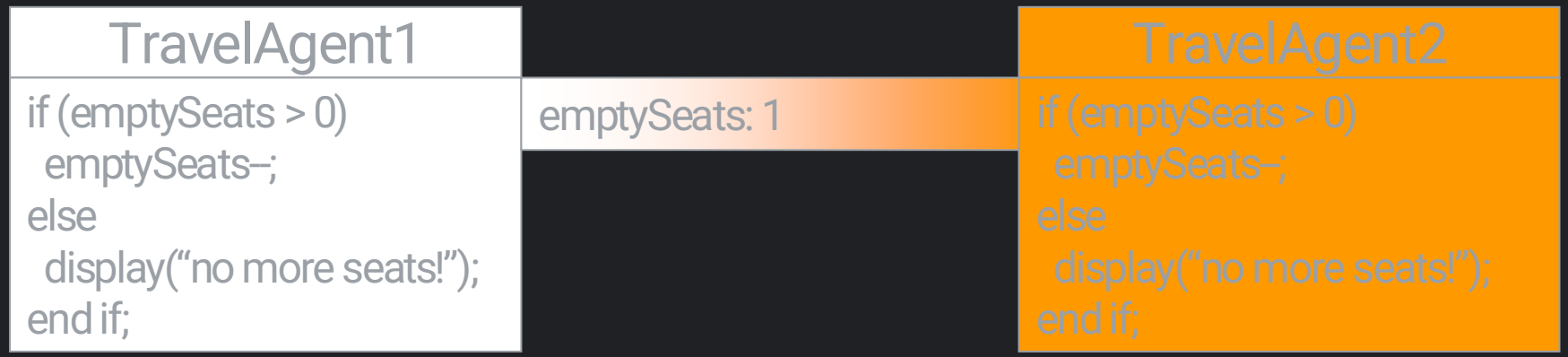
Did you hear the joke about the party where the hosts didn’t serve any drinks?

There’s no punch line.

Mutual Exclusion

An object that can only be accessed by "one-thing-at-a-time" (e.g., shared memory) is called a *mutually-exclusive* object:

- An access by one process *excludes* other processes from access
- A task may have to 'wait its turn'to access the object
- Many real-world objects (e.g., chopsticks) are mutually exclusive
- Shared-memory writes are mutually exclusive: *write-write conflicts*!



- Shared-memory *reads* are not mutually exclusive, unless any task tries to write to the shared memory: *read-write conflicts!*

Synchronization Primitives

In 1965, Dijkstra proposed the *semaphore*: a shared-memory programming mechanism that can be used to synchronize accesses to a mutually-exclusive resource, with two values: {*locked, unlocked*}, and three simple operations:

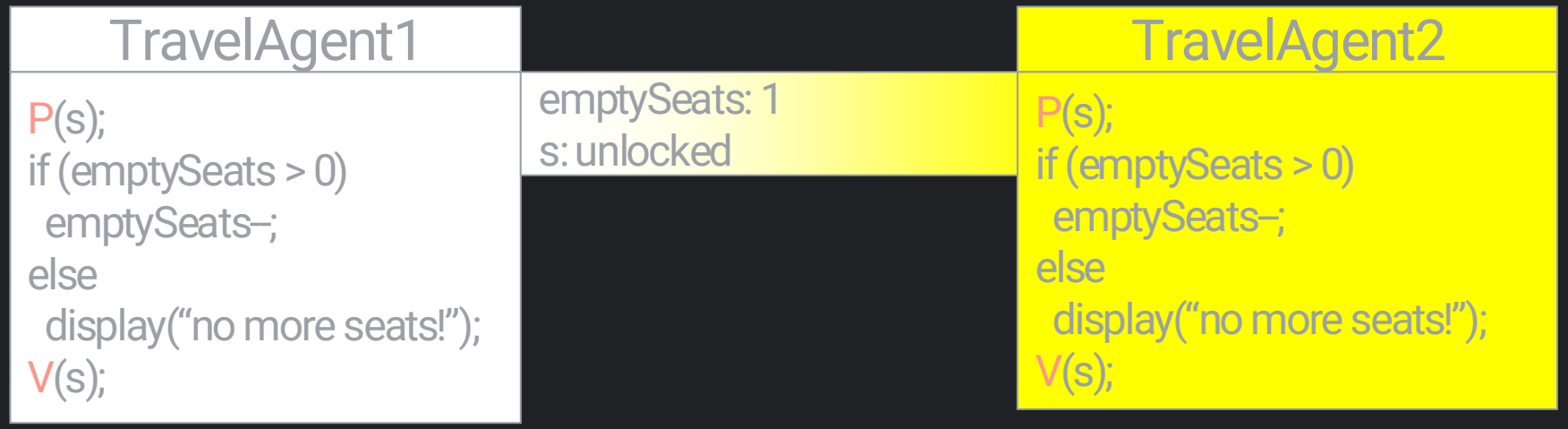
- *Initialize* the semaphore to *unlocked*
- P: *Lock* the semaphore (wait if it is already *locked*)
- V: *Unlock* the semaphore (awaken the first process waiting for it).

Java 1.7 added a *Semaphore* class:

Operation	Dijkstra	Java Syntax
Initialization (unlocked)	s: Semaphore;	s = new Semaphore(1);
Lock the semaphore	P(s);	s.acquire();
Unlock the semaphore	V(s);	s.release();

Semaphores and Mutual Exclusion

A semaphore is a shared-memory variable that can be used to enforce mutually exclusive access to other shared-memory variables:



Whichever travel agent executes P(s) *first* (even by a nanosecond) will lock s, decrement emptySeats, and then unlock s.

Whichever travel agent executes P(s) *second* will find s locked and have to wait until the other agent unlocks s, discover that emptySeats == 0, and then get the "no more seats" message.

Semaphores and Lockstep Synchrony

A semaphore also permits two processes to execute in lock-step:

S		R
msgToR:	sharedSpace: okToWrite: unlocked okToRead: locked	msgFromS:

loop {
P(okToWrite);
sharedSpace = msgToR;
V(okToRead);
}
		loop {
		P(okToRead);
		msgFromS = sharedSpace;
		V(okToWrite);
		}

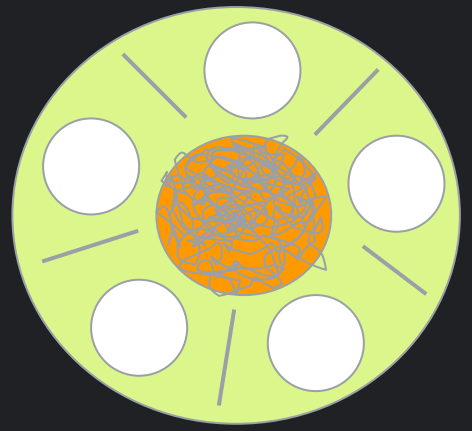
- If *R* executes first, it will wait on the (*locked*) *okToRead* semaphore, until *S* signals (after it writes a value to the shared memory)...
- If *S* executes first, it will lock the (*unlocked*) *okToWrite* semaphore, write its message to shared memory, signal *okToRead*, and then wait on the (locked) *okToWrite* until *R* signals (after it finishes reading).

A *critical section* is a group of statements that access shared space.

Dining Philosophers (iii)

What if we use a Semaphore?

```
Semaphore: wantBothSticks;
task philosopher is begin
  while True begin
    think(randomTime);
    while not haveBothSticks begin
       P(wantBothSticks);
       if available(leftStick) and
           available(rightStick) then begin
           get(left);
           get(right);
       end if;
       V(wantBothSticks);
     end while;
    eat();
    release(leftStick);
    release(rightStick);
  end while;
end philosopher;
```



This seems to do it, but synchrony is so tricky, it's hard to be 100% certain it's correct …

Locks and Condition Variables

A semaphore may be used for either of two purposes:

- *Mutual exclusion*: guarding access to a critical section
- *Synchronization*: making threads/processes suspend/resume

This dual use can lead to confusion: it may be unclear which role a semaphore is playing in a given computation...

For this reason, newer languages provide *distinct constructs for each*:

- *Locks*: guarding access to a critical section
- *Condition Variables*: making threads wait until a condition is true

Locks support mutually-exclusive access to shared memory; condition variables support thread/process synchronization.

Locks

Like a Semaphore, a lock has two associated operations:

- *acquire()* - try to lock the lock; if it is locked, go to sleep
- *release()* - unlock the lock; awaken a waiting thread (if any)

The *acquire()* is analogous to the Semaphore *P()* operation;
the *release()* is analogous to the Semaphore *V()* operation.

These can be used to 'guard' a critical section:

```
sharedLock.acquire();
// access sharedObj
sharedLock.release();
```

```
Lock sharedLock;
Object sharedObj;
```

```
sharedLock.acquire();
// access sharedObj
sharedLock.release();
```

Every Java class inherits a *hidden lock* from class *Object*;
the *synchronized* keyword uses it:

```
synchronized {
  // critical section
}
```


Condition Variables

A *Condition* is a predefined type available in some languages that can be used to declare variables for synchronization.

When a thread needs to suspend execution inside a critical section until some condition is met, a *Condition* can be used.

There are three operations for a *Condition*:

- *wait()*
  - suspend immediately; enter a queue of waiting threads
- *signal()*, aka *notify()* in Java
  - awaken a waiting thread (usually the first in the queue), if any
- *broadcast()*, aka *notifyAll()* in Java
  - awaken all waiting threads, if any

Every Java class inherits from class *Object* a hidden condition-variable, and the *wait()*, *notify()* & *notifyAll()* methods that use it.

A woman was in the hospital, screaming from the pain of giving birth.

“What’s wrong?” her husband asked after an especially loud scream.

“What’s wrong?” the woman shouted, “These contractions are going to be the death of me!”

Her husband replied, “Sorry, honey …

… What *is* wrong?”

Monitors

Semaphores, Locks, and Conditions are simple but powerful synchronization tools; but many believe that they are *too powerful for the average programmer* (like the *goto*)...

– Deadlocks/livelocks/non-mutual-exclusion are easy mistakes to make

Just as control structures were "higher level" than the *goto*, language designers began looking for higher level ways to synchronize processes.

In 1973, Brinch-Hansen and Hoare proposed the *monitor*, a class whose methods are automatically accessed in a mutually-exclusive manner.

– A monitor *prevents simultaneous access by multiple threads*

Mesa-Style Monitors

Concurrent Pascal was first to provide a *Monitor* construct:

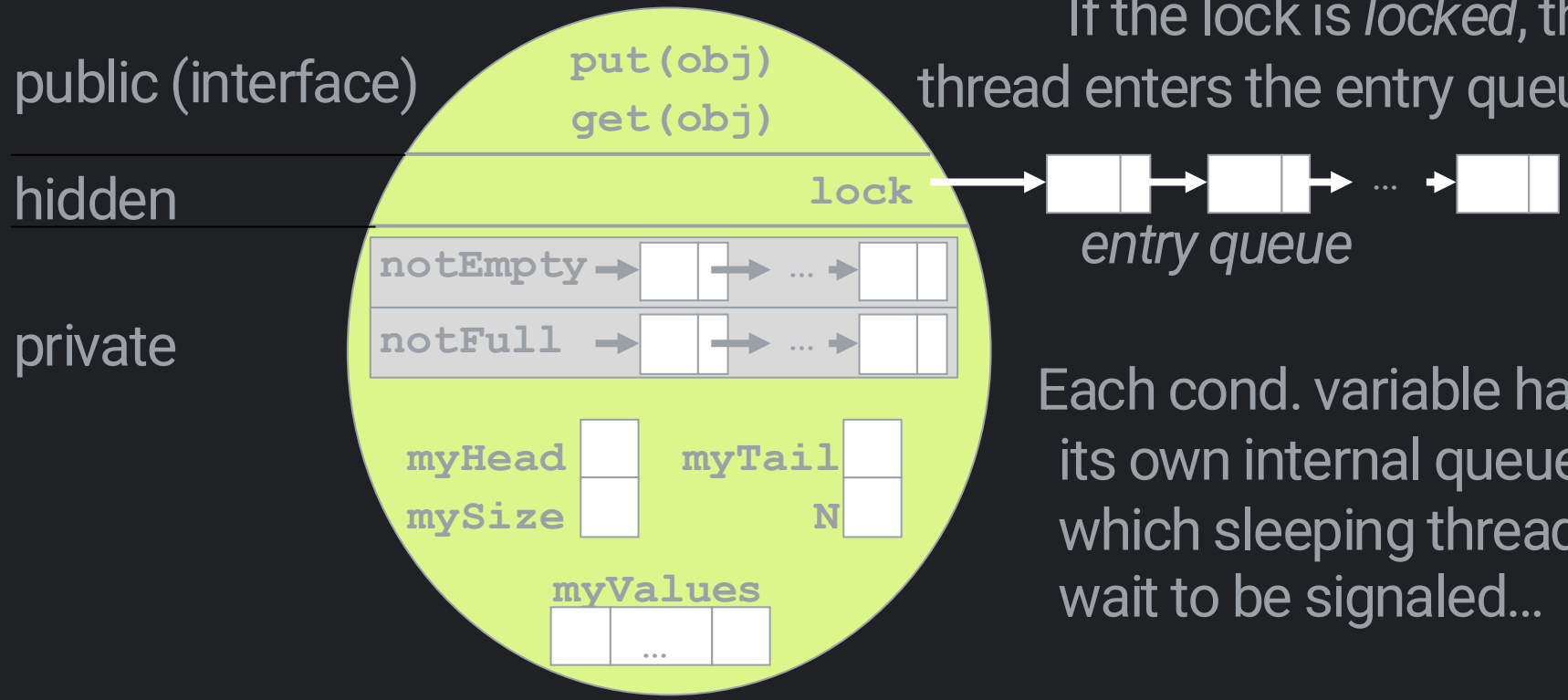
```
type BoundedBuffer = Monitor
 constant N := 1024;
 myHead, myTail, mySize: integer := 0;
 myValues : array(0..N-1) of Object;
 notEmpty, notFull: Condition;
 procedure put(obj: Object) begin
    while mySize = N do notFull.wait; end;
    myValues(myHead) := obj;
    myHead := (myHead + 1) mod N; mySize := mySize + 1;
    notEmpty.signal;
 end;
 procedure get(var obj: Object) begin
   while mySize = 0 do notEmpty.wait; end;
   obj = myValues(myTail);
   myTail = (myTail + 1) mod N; mySize := mySize - 1;
   notFull.signal;
 end;
end;
```


Monitor Visualisation

The compiler 'wraps' calls to *put()* and *get()* as follows:

```
buf.lock.acquire();
… call to put or get
buf.lock.release();
```

If the lock is *locked*, the thread enters the entry queue



Each cond. variable has its own internal queue, in which sleeping threads wait to be signaled...

Java Monitors

Java classes with *synchronized methods* are monitors...

Example: Let's build a self-synchronizing *BoundedBuffer* class:

```
public class BoundedBuffer extends Object {
 private int mySize, myMax,
             myHead, myTail;
 private Object [] myValues;
 public BoundedBuffer(int n) {
   myMax = n;
   mySize = myHead = myTail = 0;
   myValues = new Object[n];
 }
 public synchronized int size() { return mySize; }
 public int capacity() { return myMax; }
 public synchronized int isFull() { return mySize == myMax; }
 public synchronized int isEmpty() { return mySize == 0; }
 // … continued on next page …
```

A *synchronized* method acquires the class's lock to guarantee "one-thread-at-a-time" execution...

Buffer Synchrony

```
// … continued from previous page …
 public synchronized void put(Object obj) {
    while ( this.isFull() )
       try{ wait(); } catch(Exception e) {}
    myValues[myHead] = obj;
    myHead = (myHead + 1) % myMax;
    mySize++;
    notifyAll();
 }
 public synchronized Object get() {
   Object result;
   while ( this.isEmpty() )
      try{ wait(); } catch(Exception e) {}
   result = myValues[myTail];
   myTail = (myTail + 1) % myMax;
   mySize--;
   notifyAll();
   return result;
 }
}
```

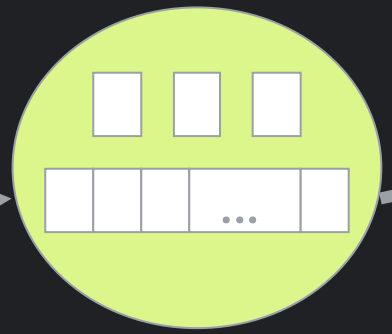
The wait() operation causes the executing thread to *suspend*.

The notifyAll() operation *awakens* all waiting threads.

Bounded Buffer Producer-Consumer

We can then use our *BoundedBuffer* as follows:

```
// producer thread
for (;;) {
  // produce Item it;
  buf.put(it);
}
```




```
// consumer thread
for (;;) {
  buf.get(it);
  // consume Item it;
}
```

Self-synchrony: No synchronization needed in producer or consumer...

Recall: Every Java class inherits a hidden *lock* from *Object*...

– When a *synchronized* method is called, it tries to *acquire* the lock (waiting if it is already locked), and *releases* the lock on termination.

Every Java class inherits a hidden *condition variable* from *Object*...

– wait() suspends a thread on the condition; notify() awakens a thread waiting on the condition; notifyAll() awakens all waiting threads.

More Recent Java

In 2005, Java 1.5 added the package java.util.concurrent:

- A ThreadPool class and an Executor framework to make the management of groups of threads easier and more convenient
- Classes for thread-safe data structures (list, queue, map, ...)
- Classes for synchronization (semaphore, barrier, mutex, latch, ...)
- Classes for creating lock and condition variables;
- Classes for atomic operations (arithmetic, test-and-set, ...)

Subsequent Java releases have continued to add features:

- Futures, for asynchronous computations
- ForkJoinTasks and ForkJoinPools for recursive parallelism
- Lambda expressions, CompletableFutures, parallel streams, WorkStealingThreadPools for load-balancing, ...

At a park, a man walked by an attractive woman sitting alone on a bench. Suddenly, she sneezed and a glass eye flew out of her eye socket. Acting on reflex, the man caught and handed it back to her.

“This is so embarrassing,” the woman said, putting her eye back in place. ”But I’m grateful to you for catching it – it probably would have shattered on the sidewalk. Can I buy you a coffee as thanks?”

“Certainly,” the man said and they went to a café. They had a lovely conversation and the man found her even more attractive. He said, “I find you very charming. Are you this nice to everyone?”

“No,” she said, ...

... “You just happened to catch my eye.”