Announcements

- Assignment 3 online: when should it be due?
  - Monday, March 29.
- Changed earlier today (new clarifications), so re-download.
- Java tips:
  - `catch (Exception ex) {}` is a very bad idea.
  - Close all streams you open.
  - Thread termination and JVM.
  - instanceof.
  - Shifting and bit operations.

Chapter 7: Process Synchronization

- Background.
- The Critical-Section Problem.
- Synchronization Hardware.
- Semaphores.
- Classical Problems of Synchronization.
- Monitors.
- Java Monitors.
- Critical Regions.

Background

- Concurrent access to shared data may result in data inconsistency.
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes.
- Shared-memory solution to bounded-butter problem in book allows at most $n - 1$ items in buffer at the same time.
- Our solution for n items was correct but needed two counters `pcount` and `ccount`. Can we use just one counter?

Bounded Buffer

- Shared data:

```
#define B_SIZE 5
char buffer[B_SIZE];
int count=0;
```

- Producer:

```
int in=0;
while (1) {
    /* produce an item in char nextProduced */
    while (count==B_SIZE)
       /* wait while buffer full */;
    buffer[in]=nextProduced;
    in=(in+1)%B_SIZE; count++; }
```

- Consumer:

```
int out=0;
while (1) {
    while (count==0)
       /* wait while buffer empty */;
    nextConsumed=buffer[out];
    out=(out+1)%B_SIZE; count--;
    /* consume the item in char nextConsumed */ }
```

Bounded Buffer (Cont.)

- The statements

```
count++;
count--;
```

  must be performed *atomically*, meaning that the process cannot be interrupted partway through their execution.
- But they may not be atomic on some CPUs:
  - `count++` may be implemented as:

```
register1=count          LOAD   R1,@count
register1=register1+1    INC    R1
count=register1          STORE  @count,R1
```

  - `count--` may be implemented as:

```
register2=count          LOAD   R2,@count
register2=register2-1    DEC    R2
count=register2          STORE  @count,R2
```

Bounded Buffer (Cont.)

- If both the producer and consumer attempt to update the buffer concurrently, the CPU instructions may get interleaved.
- Interleaving depends upon how the producer and consumer processes are scheduled.
- Assume `count` is initially 5. One interleaving of statements is:

  producer: `register1=count` (`register1` =5)
  producer: `register1=register1+1` (`register1` =6)
  consumer: `register2=count` (`register2` =5)
  consumer: `register2=register2-1` (`register2` =4)
  producer: `count=register1` (`count` =6)
  consumer: `count=register2` (`count` =4)

- The value of `count` may be 4 (or 6 if you swap the last two lines), where the correct result should be 5.

Race Condition

- *Race condition*: The situation where several processes access and manipulate shared data concurrently. The final value of the shared data depends upon which process finishes last.

- To prevent race conditions, concurrent processes must be *synchronized*.

- Extremely hard to write correct multi-threaded code:
  - Must think of all possible combinations in execution paths.
  - Or come up with formal proof of correctness (see textbook).
  - Or run a lot of tests *hoping* a bug will show up (nondeterminism).
  - Only *experience* helps.
  - Hence such a skill is highly valued by employers.

Java `volatile`

- Shared variables *not* always kept in sync:

```
class Test {
    static int i=0, j=0;
    static void incr() { i++; j++; }
    static void print() { System.out.println("i:"+i+" j:"+j); } }
```

  - Thread T0 calls `incr()` repeatedly.
  - Thread T1 calls `print()` repeatedly.
  - Assume T0, T1 scheduled as if `incr()`, `print()` had been mutually exclusive.
  - Output may read `i:1 j:2` because threads can keep local copies of shared variables and sync up the master copies at will (almost...). So `j` can be updated before `i` by T0.

- volatile declaration: update shared variables in the same order the local copies were updated:

```
static volatile int i=0, j=0;
```

- Details: Java Language Specification 8.3.1.4, 17.

The Critical-Section Problem

- Two or more processes all competing to use some shared data.
- Each process has a code segment, called *critical section*, in which the shared data is accessed.
- Problem: ensure that when one process is executing in its critical section, no other process is allowed to execute in its critical section.

Solution Requirements

1. *Mutual Exclusion*: if process P_i is executing in its critical section, then no other processes can be executing in their critical sections.

   Only one dog can eat the bone at a time.

2. *Progress*: if no process is executing in its critical section and there exist some processes that wish to enter their critical section, then the selection of the processes that will enter the critical section next cannot be postponed indefinitely.

   If no dog is eating and many are hungry, a hungry one should get the bone.

3. *Bounded Waiting/No Starvation*: a bound must exist on the number of times that other processes may enter their critical sections after a process has made a request to enter its critical section and before that request is granted:
   - Assume that each process executes at a nonzero speed.
   - No assumption concerning relative speed of the processes.

   If there are many hungry dogs, they all get to eat eventually.

Initial Attempts to Solve Problem

- Only 2 processes, P_0 and P_1.
- Processes may share some common variables to synchronize their actions.
- General structure of every process P_i:

```
while (1) {
    /* entry section */
    /* critical section */
    /* exit section */
    /* remainder section */ }
```

- We'll refer to the other process as P_j (j=1-i).

Algorithm 1

- Shared variables:
  - `int turn=0;`
  - `turn==i` $\Rightarrow$ P_i can enter its critical section.
- Process P_i:

```
while (1) {
    while (turn!=i) /* do nothing */;
    /* critical section */
    turn=1-i;
    /* remainder section */ }
```

- Satisfies mutual exclusion, but not progress: if P_o is fast and wants to go again, it cannot even if P_1 is just spending a long time its is remainder section.

Algorithm 2

- Shared variables:
  - `boolean flag[2]; flag[0]=flag[1]=false;`
  - `flag[i]==true` $\Rightarrow$ P_i wants to enter its critical section.
- Process P_i:

```
while (1) {
    flag[i]=true;
    while (flag[1-i]);
    /* critical section */
    flag[i]=false;
    /* remainder section */ }
```

- Satisfies mutual exclusion, but not progress; if both execute `flag[i]=true` before either starts waiting in their `while` loops, then neither ever moves forward! Processes are too polite: “No, you go first.”

Algorithm 3

- Combined shared variables of algorithms 1 and 2.
- Process P_i:

```
while (1) {
    flag[i]=true;
    turn=1-i;
    while (flag[1-i] && turn==1-i);
    /* critical section */
    flag[i]=false;
    /* remainder section */ }
```

- Meets all three requirements; solves the critical-section problem for two processes.

Bakery Algorithm

- Critical section for n processes.
- Shared variables:
  - `boolean c[n]; /* All false. */`
  - `int t[n]; /* All 0s. */`
- Process P_i:

```
while (1) {
    c[i]=true;
    t[i]=1+max(t[0],...,t[n-1]);
    c[i]=false;
    for (j=0;j<n;j++) {
      while (c[j]);
      while (t[j]!=0 && (t[j],j)<(t[i],i)); }
    /* critical section */
    t[i]=0;
    /* remainder section */ }
```

Choosing a ticket number.

Obtain ticket number; will get no smaller than another process but might get the same.

Done choosing.

Wait for *i* to choose.

j wants to enter (or already is inside) its critical section, and so it has nonzero ticket.

`t[j]<t[i] || (t[j]==t[i] && j<i)`

i waits for *j* to go through if *j* has smaller ticket number; or if same ticket, and *j*<*i*.

Bakery Algorithm (Cont.)

- Why doesn't this work? (Eliminated `c[]`).

```
while (1) {
    t[i]=1+max(t[0],...,t[n-1]);
    for (j=0;j<n;j++) {
       while (t[j]!=0 && (t[j],j)<(t[i],i)); }
    /* critical section */
    t[i]=0;
    /* remainder section */ }
```

- Answer:
  - P_0 reads `t[0],t[1]`.
  - P_1 reads `t[0],t[1]`.
  - P_1 writes `t[1]=1`.
  - P_1 enters critical section because
    - `t[0]!=0` is false (first for-loop iteration), and
    - `(t[1],1)<(t[1],1)` is false (second for-loop iteration).
  - P_0 writes `t[0]=1`.
  - P_0 enters critical section because
    - `(t[0],0)<(t[0],0)` is false (first for-loop iteration), and
    - `(t[1],1)<(t[0],0)` is false (second for-loop iteration).

Bakery Algorithm (Cont.)

- Why doesn't this work? (Replaced `while` with `if` and `while`.)

```
while (1) {
   c[i]=true;
   t[i]=1+max(t[0],...,t[n-1]);
   c[i]=false;
   for (j=0;j<n;j++) {
      while (c[j]);
      if (t[j]!=0 && (t[j],j)<(t[i],i))
         while(t[j]!=0); }
   /* critical section */
   t[i]=0;
   /* remainder section */ }
```

- Intent: P_1 realizes that it has a lower ticket than P_0 (`if`) and waits `while` P_0 remains in its critical section.
- Answer: P_0 can finish, go back, and get a higher ticket number. Now P_0 is stuck and so is P_1 who still thinks that P_0's nonzero ticket number implies P_0 is in its critical section.

Synchronization Hardware

- Test and modify the content of a word *atomically* (i.e. without CPU *ever* preempting process in the middle).
- How? Disable interrupts or use special hardware.

```
boolean testAndSet(boolean *target) {
    boolean result=*target;
    *target=true;
    return result; }
```

- Shared data:

```
boolean lock=false;
```

- Process P_i:

```
while (1) {
    while (testAndSet(&lock));
    /* critical section */
    lock=false;
    /* remainder section */ }
```

If `lock` is `true` then nobody is in the critical section and this process can go ahead. *Atomically* set `lock` to prevent two processes from seeing `false` at the same time.

Bounded wait not satisfied!

Synchronization Hardware (Cont.)

- Atomically swap two variables.

```
void swap(boolean *a, boolean *b) {
    boolean temp=*a; *a=*b; *b=temp; }
```

- Shared data:

```
boolean lock=false;
```

- Process P_i:

`key` acts like return value of `testAndSet()` as well as the `true` constant in its body.

```
while (1) {
   boolean key=true;
   while (key)
       swap(&lock,&key);
   /* critical section */
   lock=false;
   /* remainder section */ }
```

Bounded wait not satisfied!

Synchronization Hardware (Cont.)

- Starvation fix: shared data:

```
boolean waiting[n]; /* All false. */
boolean lock=false;
```

- Process P_i:

```
while (1) {
    waiting[i]=true;
    boolean key=true;
    while (waiting[i] && key) key=testAndSet(&lock);
    waiting[i]=false;
    /* critical section */
    j=(i+1)%n;
    while ((j!=i) && !waiting[j]) j=(j+1)%n;
    if (j=!i) waiting[j]=false;
    else lock=false;
    /* remainder section */ }
```

Wait until either `lock` is available or some other process who held the lock passes it on to P_i by setting its `waiting[i]` to false.

Find first waiting process after P_i in circular order (if any).

If one is found, unblock it and give it the responsibility of unlocking (give it the key).

Otherwise, nobody has been waiting, so release the lock for whoever tries to enter next.

Semaphores

- *Semaphore S*: an integer variable that can only be accessed via two partially indivisible operations. Shown as Java pseudo-class:

```
class Semaphore {
    int mS=1;
    wait() {
        while (mS<=0);
        mS--; }
    signal() {
        mS++; } }
```

Other values useful too.

Once one process is done waiting, it alone can proceed to finish.

Can't modify at the same time.

- Shared data: `Semaphore S;`
- Process P_i:

```
while (1) {
    S.wait();
    /* critical section */
    S.signal();
    /* remainder section */ }
```

Busy-waiting (a.k.a. spin-lock). Useful for short waits in multiple CPU systems (no context-switch). Wasteful in single CPU systems.

Bounded wait not satisfied!

Semaphore Implementation

- Assume two OS system calls:
  - `block()` suspends the thread that invokes it.
  - `wakeup(T)` resumes the execution of a blocked thread `T`.
- Definition *without busy-waiting*:

```
class Semaphore {
   int mS=1;
   LinkedList mL=new LinkedList();
   synchronized wait() {
      mS--;
      if (mS<0) then {
        mL.addLast(Thread.currentThread());
        block(); }
   synchronized signal() {
      mS++;
      if (mS<=0)
         wakeup(mL.removeFirst()); } }
```

Queue of blocked processes. Usually FIFO to prevent starvation. But can be priority queue too.

Calling thread goes off the CPU and into waiting (not ready) queue. No busy-waiting. Assume `block()` releases Java monitor.

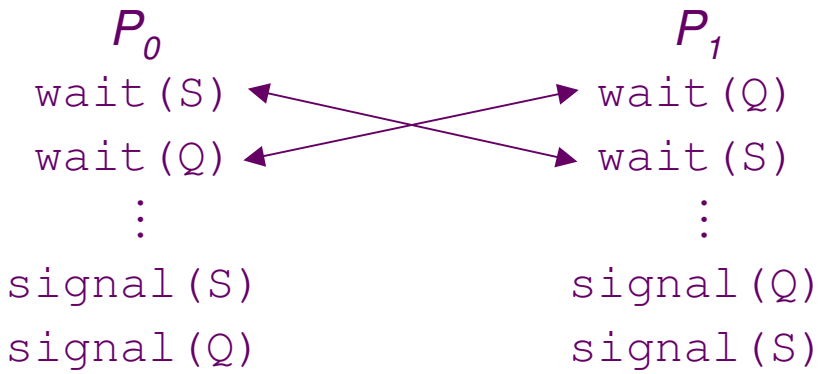
Semaphore as a General Synchronization Tool

- Execute B in P_j only after A executed in P_i.
- Use semaphore `flag` initialized to 0.
- Code:

P_i	P_j
⋮	⋮
A	`wait(flag)`
`signal(flag)`	B

Deadlock and Starvation

- *Deadlock:* two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes.
- Let `S` and `Q` be two semaphores initialized to 1.



- *Starvation:* indefinite blocking. A process may never be removed from the semaphore queue in which it is suspended.

Two Types of Semaphores

- *Counting* semaphore: integer value can range over an unrestricted domain.
- *Binary* semaphore: integer value can be at most 1 (only 0 or 1 in first, busy-waiting definition); can be simpler to implement on some CPUs (hardware constraint).
- Can implement a counting semaphore using binary semaphores.

Implementing a Counting Semaphore

- Data structures:

```
binary-semaphore S1=1, S2=0;
int C= /* Initial value of counting semaphore. */ ;
```

- S1 protects C from concurrent modification.
- S2 blocks process that calls wait() with C<=0.

- *O*perations:

```
wait() {
   wait(S1);
   C--;
   if (C<0) {
      signal(S1);
      wait(S2); }
   signal(S1); }
signal() {
   wait(S1);
   C++;
   if (C<=0) signal(S2);
   else signal(S1); }
```

Must signal S1 before waiting on S2, otherwise nobody can pass through wait(S1) to signal(S2).

If we signal S2 instead of S1, then this is because another process is waiting on S2. That process will take care of signalling S1 here: Intuitively, we pass on the key because we know somebody else is about to unlock.

Classical Problems of Synchronization

- Bounded-Buffer Problem.
- Readers and Writers Problem.
- Dining-Philosophers Problem.

Bounded-Buffer Problem

- Shared data:

```
semaphore full=0, empty=n, mutex=1;
```

Binary semaphore: only needed if buffer access is more complex than array access (e.g. shared linked list).

Counting semaphores

- Producer:

```
int in=0;
while (1) {
      /* produce an item in char nextProduced */
      wait(empty);
      wait(mutex);
      buffer[in]=nextProduced; in=(in+1)%B_SIZE;
      signal(mutex);
      signal(full); }
```

- Consumer:

```
int out=0;
while (1) {
      wait(full);
      wait(mutex);
      nextConsumed=buffer[out]; out=(out+1)%B_SIZE;
      signal(mutex);
      signal(empty);
      /* consume the item in char nextConsumed */ }
```

Readers-Writers Problem

- Shared data:

Protects `readCount`.

Authorizes writer (if any; first reader otherwise) to proceed.

```
semaphore mutex=1, writer=1;
int readCount=0;
```

- Writer: single one accessing shared file for output.

```
while (1) {
        wait(writer);
        /* perform writing */
        signal(writer); }
```

Writer may starve!

- Reader: one or more can have shared read access to file.

```
while (1) {
        wait(mutex);
        readCount++;
        if (readCount==1) wait(writer);
        signal(mutex);
        /* perform reading */
        wait(mutex);
        readCount--;
        if (readCount==0) signal(writer);
        signal(mutex); }
```

First reader locks out the writer by taking over `writer`. Other readers stuck here: since first reader hasn't release `mutex`.

Last reader unlocks writer.

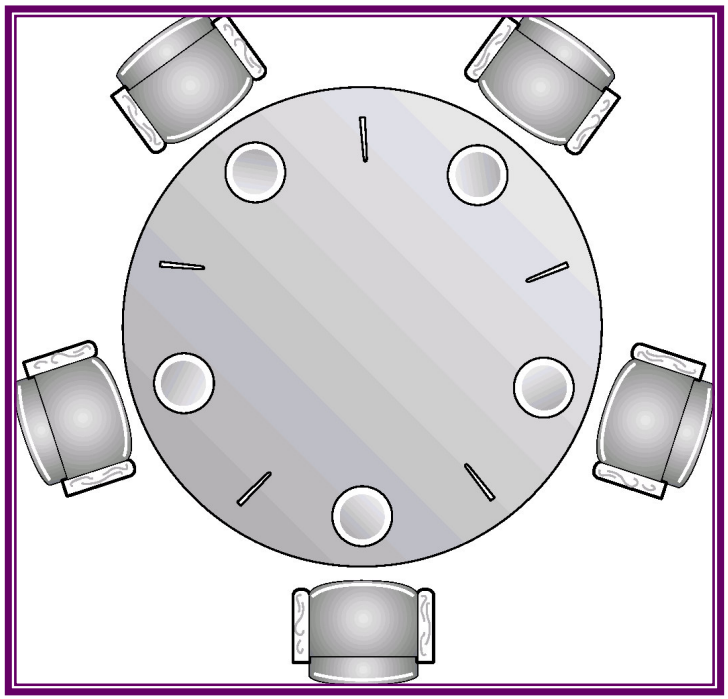
Dining-Philosophers Problem

- Shared data:

```
semaphore chopstick[5]; /* All 1. */
```

- Philosopher *i*:

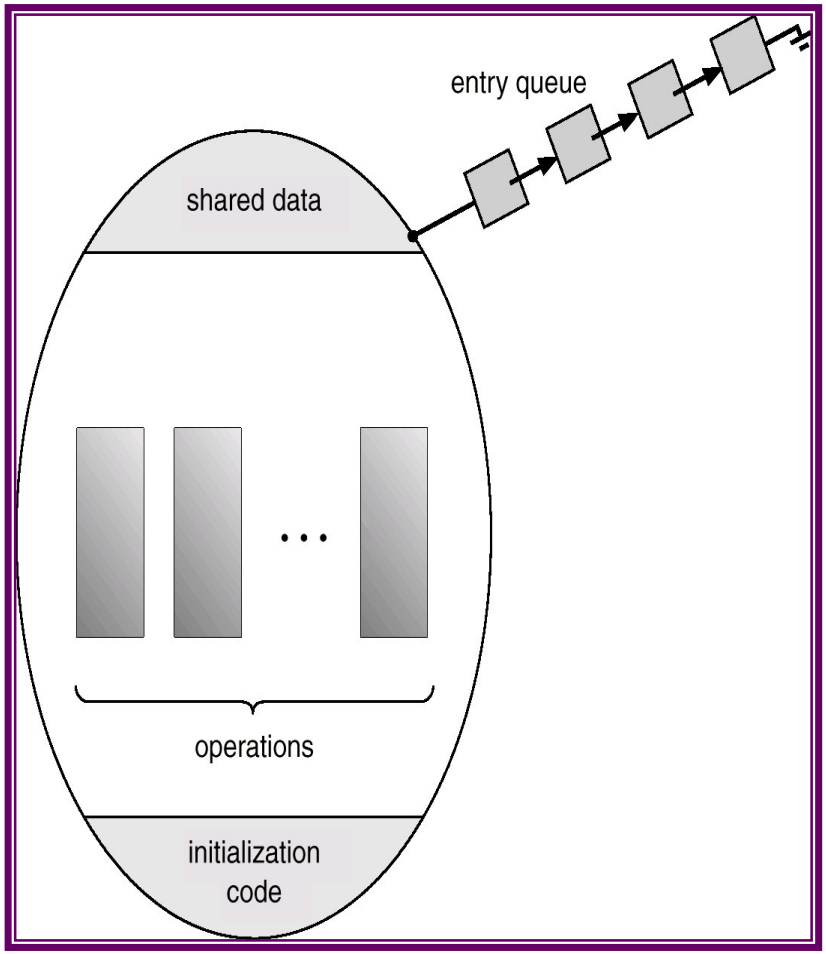
```
while (1) {
    wait(chopstick[i]);
    wait(chopstick[(i+1)%5]);
    /* eat */
    signal(chopstick[i]);
    signal(chopstick[(i+1)%5]);
    /* think */ }
```



Deadlock if each philosopher gets one chopstick!

Monitors

- Related, but not the same as Java monitors. Forget Java for now.
- High-level synchronization construct: at most one thread/process can be actively running any procedure within monitor. Rest are queued up.



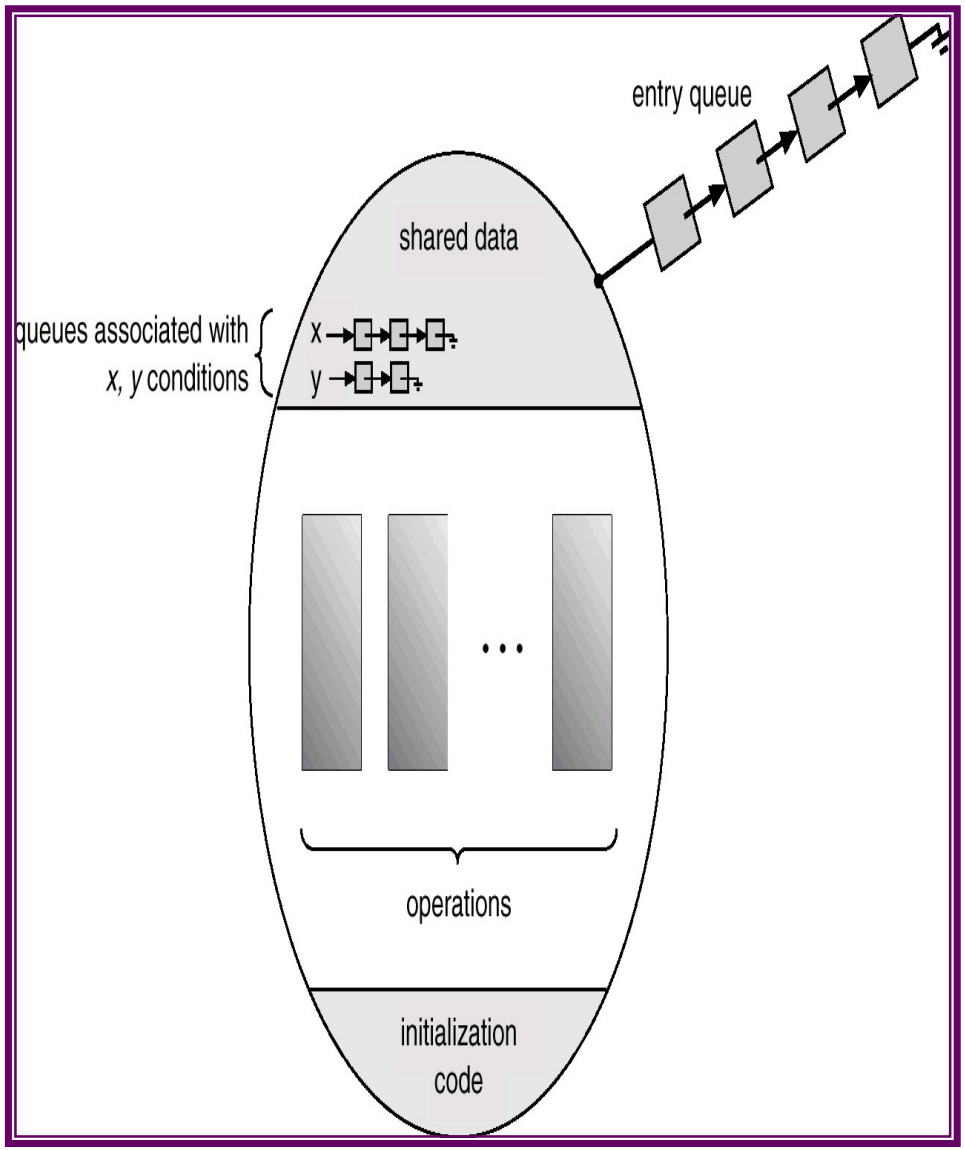

```
monitor monitor-name
{
 /* shared variables */
 procedure body P1 (...) { ... }
 procedure body Pn (...) { ... }
 { /* initialization code */ }
}
```

Monitor `condition`

- To allow a process to suspend itself while executing in the monitor, a `condition` variable must be declared, as

  ```
  condition x;
  ```

  - Condition variable operations:
    - `wait()`: if process P calls `x.wait()`, P is suspended until another process Q...
    - `signal()`: ... runs `x.signal()` which resumes exactly one suspended process, if any; it is a no-op, otherwise.
  - When P is suspended, other procedures can run insides monitor (like Q)...
  - ... but when Q signals P, who goes next (remember: only one process can run inside monitor)? No right/wrong answer.



Dining Philosophers Example

```
monitor dp {
  enum {thinking, hungry, eating} state[5];
  condition self[5];
  // also methods below
  void init() {
    for (int i=0;i<5;i++)
     state[i]=thinking; } }
```

Usage: Philosopher *i*:

```
while (1) {
  pickup(i);
  /* eat */
  putdown(i);
  /* think */ }
```

Deadlock impossible!
Starvation possible!

```
void pickup(int i) {
  state[i]=hungry;
  test(i);
  if (state[i]!=eating)
    self[i].wait(); }
```

Philosopher *i* got hungry but couldn't get both chopsticks at once, so she has to wait until another philospher lets her have her chopsticks.

```
void putdown(int i) {
  state[i]=thinking;
  test((i+4)%5);
  test((i+1)%5); }
```

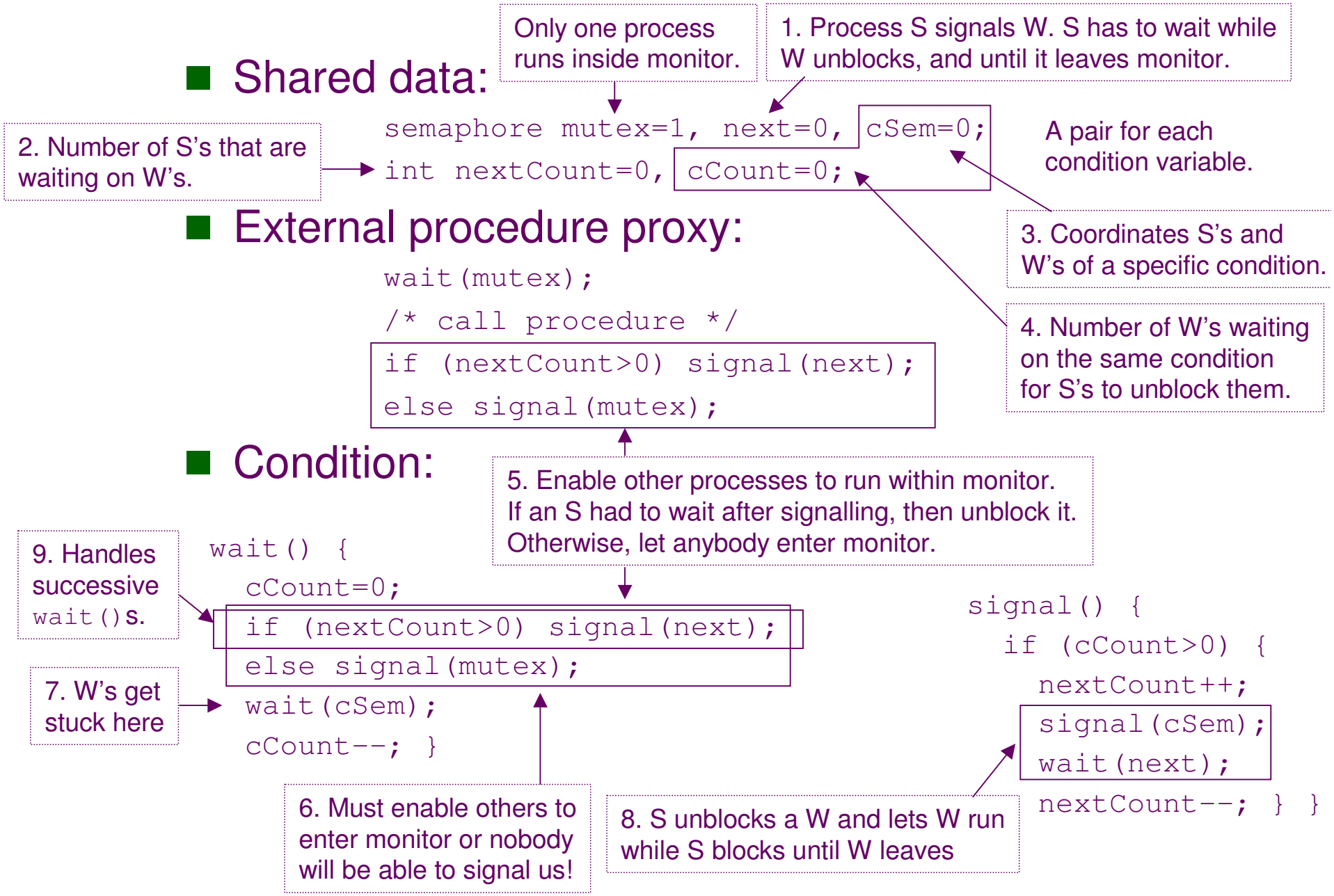
i is done eating. Does either neighbor of *i* want to use the chopsticks she just finished using?

Test whether philosopher *i* can start eating.

```
private void test(int i) {
  if ((state[(i+4)%5]!=eating) &&
   (state[i]==hungry) &&
   (state[(i+1)%5]!=eating)) {
  state[i]=eating;
  self[i].signal(); } }
```

If *i*'s neighbors aren't eating, and *i* wants to eat, then *i* can use their chopsticks.

Monitor Implementation with Semaphores



Correct Monitor Use

- *Conditional-wait* construct:

  `x.wait(c)`

  - Value of `c` is a *priority number*, stored with the name of the process that is suspended.
  - When `x.signal()` is executed, process with smallest priority number is resumed next.

- Resource allocator:

```
monitor ResourceAllocation {
  boolean busy=false;
  condition x;
  void acquire() {
    if (busy) x.wait(System.currentTimeMillis());
    busy=true; }
  void release() {
    busy=false;
    x.signal(); } }
```

- Correctness of allocation technique requires:
  - Users must always call `acquire()` once, then `release()` once.
  - User should not access resource directly.

Java `synchronized`

- Each object instance has a "monitor":
  - It is combination of general monitor + a single condition variable.
  - Classes are objects (`Class` class). So each class has a monitor, too.
  - Ownership of instance monitor:

Same monitor.

```
synchonized void f() { /* owned */ }
void f() { synchronized (this) { /* owned */ } }
```

Different monitors.

  - Ownership of class monitor:

Same monitor.

```
static synchonized void f() { /* owned */ }
void f() { synchronized (this.getClass()) {/* owned */ } }
```

  - General `signal()` is Java's `notify()`. `notifyAll()` is a Java extension.
  - To call general condition variable methods `wait()`, `signal()`, we must be inside general monitor. In Java, to execute `wait()`, `notify()`, `notifyAll()`, one must "own" the monitor.
- Avoids problem of entering critical section and forgetting to tell other threads we left it: syntax enforces this if-enter-must-leave requirement.
- Also solves `volatile` problem : make `incr()`, `print()` synchronized. Java forced to sync up master copies on monitor lock/unlock, *and* mutex is enforced.

Java `synchronized` (Cont.)

- Common mistake:

```
mWaiting=false;
...
synchronized boolean waitIfFirst() throws InterruptedException {
   if (mWaiting) return false; // Somebody else is already waiting.
   mWaiting=true;
   synchronized (mEvent) { mEvent.wait(); }
   mWaiting=false;
   return true; } // Wait took place.
```

  - Intent: the first thread that calls `waitIfFirst()` must wait for an event; all others should just return without waiting. Method `synchronized` protects `mWaiting`.
  - Problem: when one thread starts waiting, it waits on `mEvent`'s monitor, not that of `this` so it still has the monitor of `this`. Hence all other threads block when they call `waitIfFirst()`.

- Even in Java, multi-threading is tough:
  - Semaphore implementation is 60 lines of pure, hard-to-follow code.
  - Wrote 8000-line package to make it easier for average Stanford student. And, yes, first revision had bugs.

Critical Regions

- Another high-level synchronization construct.
- A shared variable `v` of type `T`, is declared as:

  `v: shared T`

- Variable `v` appears only inside statements of the form:

  `region v when` B_i S_i`;`

  where S_i is any other statement and B_i is a boolean expression.
- While expression B_i or statement S_i are being executed, no other process can enter B_i or S_i to access variable `v`; in fact, it may not enter any such B_j or S_j protected by a `region v`. So code blocks referring to the same variable `v` exclude each other in time.
- When a process tries to execute the `region` statement, it first blocks until it gains exclusive access to `v`, and then evalutes B_i:
  - If B_i is true, statement S_i is executed, and then exclusive access is relinquished.
  - If it is false, the process is blocked but it first reliquishes exclusive access; the process is also re-granted exclusive access to retest B_i whenever another process successfully executes any S_j (because its execution may have modified the value of `v` and therefore B_i).

Bounded Buffer Example

- Shared data:

```
#define B_SIZE 5
char buffer[B_SIZE];
count: shared int =0;
```

- Producer:

```
int in=0;
while (1) {
  /* produce an item in char nextProduced */
  region count when (count<B_SIZE) {
    buffer[in]=nextProduced;
    in=(in+1)%B_SIZE;
    count++; }
```

- Consumer:

```
int out=0;
while (1) {
  region count when (count>0) {
    nextConsumed=buffer[out];
    out=(out+1)%B_SIZE;
    count--; }
  /* consume the item in char nextConsumed */ }
```

Implementation Critical Region

```
wait(mutex);
while (!B) {
  firstCount++;
  if (secondCount>0) signal(secondDelay);
  else signal(mutex);
  wait(firstDelay);
  firstCount--;
  secondCount++;
  if (firstCount>0) signal(firstDelay);
  else signal(secondDelay);
  wait(secondDelay);
  secondCount--; }
S;
if (firstCount>0) signal(firstDelay);
else if (secondCount>0) signal(secondDelay);
else signal(mutex);
```

- Lines relevant as long as `B` is true.
- Extra lines relevant as long as a single process finds `B` false.

Remaining lines become relevant when more than one process finds `B` false, and they all have to retest `B` one at a time.

Implementation (Cont.)

- If a single process P evalutes `B` to false, it receives ownership (responsibility to signal) of `mutex` because the first process to finish `S` unblocked P instead of signalling `mutex`. `mutex` blocks other processes from evaluating `B` until P has had a chance to do so.
- In general:
  1. All processes that evaluate `B` to false block at `firstDelay`.
  2. A process that evaluates `B` to true runs `S` and eventually unblocks another process P that was waiting on `firstDelay`.
  3. P starts a cascade, letting all other processes waiting on `firstDelay` to go through. All these processes, P included, then block on `secondDelay`. But the last process through `firstDelay` signals Q, which is one of those blocked processes. Q can now move past `secondDelay`.
  4. Q evaluates `B` again. If `B` is true, Q runs `S` and eventually signals another process to move past `secondDelay`. If `B` is false, Q goes around the loop and blocks at `firstDelay` again; but in doing so, it signals another process to move past `secondDelay`. And so on until either every process is blocked at `firstDelay` again (step 1) or one process evaluates `B` to true, runs `S`, and concludes by unblocking one of the processes waiting on `firstDelay` (step 2).

Implementation (Cont.)

- Mutually exclusive access to the critical section is provided by `mutex`.
- If a process cannot enter the critical section because the `B` is false, it initially waits on the `firstDelay` semaphore; moved to the `secondDelay` semaphore before it is allowed to reevaluate `B`.
- Keep track of the number of processes waiting on `firstDelay` and `secondDelay`, with `firstCount` and `secondCount` respectively.