Part III Synchronization

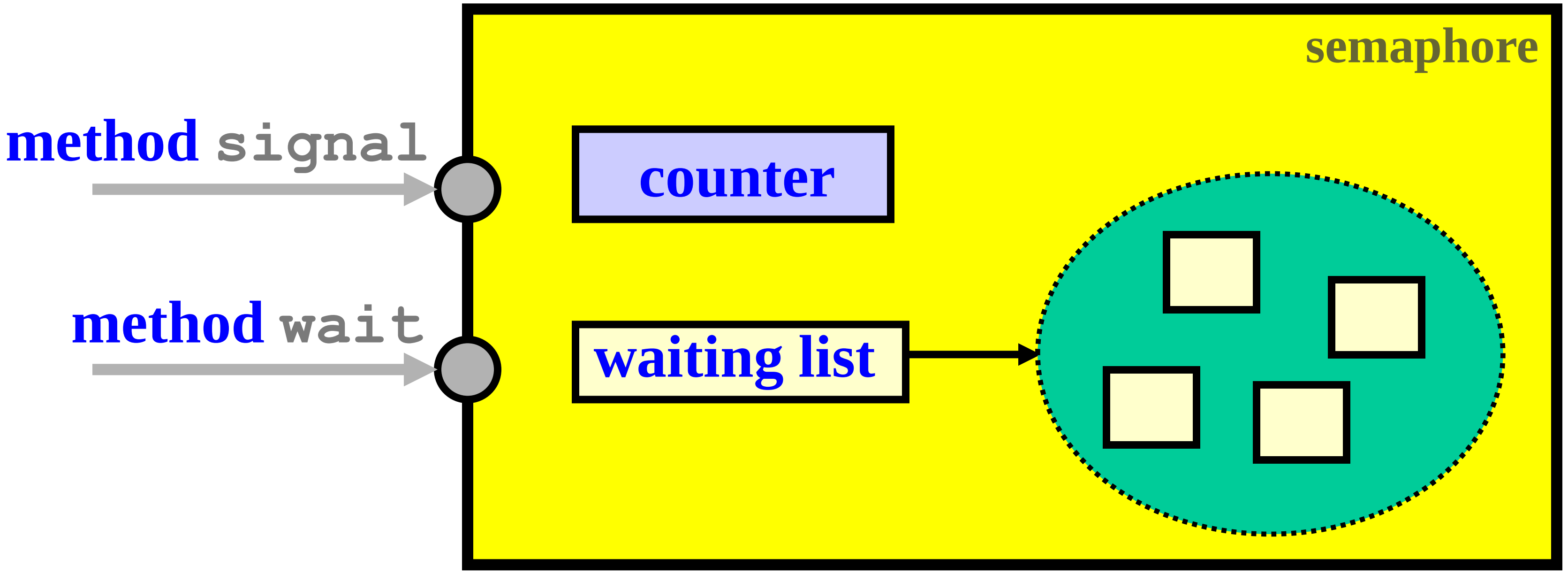
Semaphores

The bearing of a child takes nine months,
no matter how many women are assigned.

Frederick P. Brooks Jr.

Semaphores

- A ***semaphore*** **is an object that consists of a private counter, a private waiting list of processes, and two public methods (e.g., member functions):** `signal` **and** `wait`**.**



Semaphore Method: wait

```
void wait(sem S)
{
    S.count--;
    if (S.count < 0) {
        add the caller to the waiting list;
        block();
    }
}
```

- **After decreasing the counter by 1, if the new value becomes negative, then**
  - **add the caller to the waiting list, and**
  - **block the caller.**

Semaphore Method: *signal*

```
void signal(sem S)
{
    S.count++;
    if (S.count <= 0) {
        remove a process P from the waiting list;
        resume(P);
    }
}
```

- **After increasing the counter by 1, if the new value is not positive (e.g., non-negative), then**
  - **remove a process P from the waiting list,**
  - **resume the execution of process P, and return**

Important Note: 1/4

```
S.count--;                    S.count++;
if (S.count<0) {              if (S.count<=0) {
    add to list;                  remove P;
    block();                      resume(P);
}                             }
```

- If `S.count < 0`, `abs(S.count)` is the number of waiting processes.
- This is because processes are added to (*resp*., removed from) the waiting list only if the counter value is `< 0` (*resp*., `<= 0`).

Important Note: 2/4

```
S.count--;                    S.count++;
if (S.count<0) {              if (S.count<=0) {
    add to list;                  remove P;
    block();                      resume(P);
}                             }
```

- The waiting list can be implemented with a queue if FIFO order is desired.
- However, ***the correctness of a program should not depend on a particular implementation (e.g., ordering) of the waiting list.***

Important Note: 3/4

```
S.count--;                 S.count++;
if (S.count<0) {           if (S.count<=0) {
   add to list;               remove P;
   block();                   resume(P);
}                          }
```

- **The caller may be blocked in the call to `wait()`.**
- **The caller is never blocked in the call to `signal()`. If `S.count > 0`, `signal()` returns and the caller continues. Otherwise, a waiting process is released and the caller continues. In this case, *two* processes continue.**

The Most Important Note: 4/4

```
S.count--;                  S.count++;
if (S.count<0) {            if (S.count<=0) {
    add to list;                remove P;
    block();                    resume(P);
}                           }
```

- wait() and signal() must be executed ***atomically*** (*i.e.*, as one uninterruptible unit).
- Otherwise, ***race conditions*** may occur.
- ***Homework***: use execution sequences to show race conditions if wait() and/or signal() is not executed atomically.

Typical Uses of Semaphores

- **There are three typical uses of semaphores:**
  - ❖**mutual exclusion:**

    Mutex (*i.e.*, *Mut*ual *Ex*clusion) locks
  - ❖**count-down lock:**

    Keep in mind that a semaphore has a private counter that can count.
  - ❖**notification:**

    Wait for an event to occur and indicate an event has occurred.

Use 1: Mutual Exclusion (Lock)

```
                                   initialization is important
semaphore S = 1;
int       count = 0;    // shared variable

       Process 1                          Process 2
while (1) {                          while (1) {
    // do something       entry          // do something
    S.wait();                            S.wait();
      count++;    critical sections        count--;
    S.signal();                          S.signal();
    // do something       exit           // do something
}                                    }
```

- What if the initial value of `S` is zero?
- `S` is a *binary semaphore* (`count` being 0 or 1).

Use 2: Count-Down Counter

```
semaphore  S = 3;
```

Process 1

```
while (1) {
   // do something
   S.wait();
```

at most 3 processes can be here!!!

```
   S.signal();
   // do something
}
```

Process 2

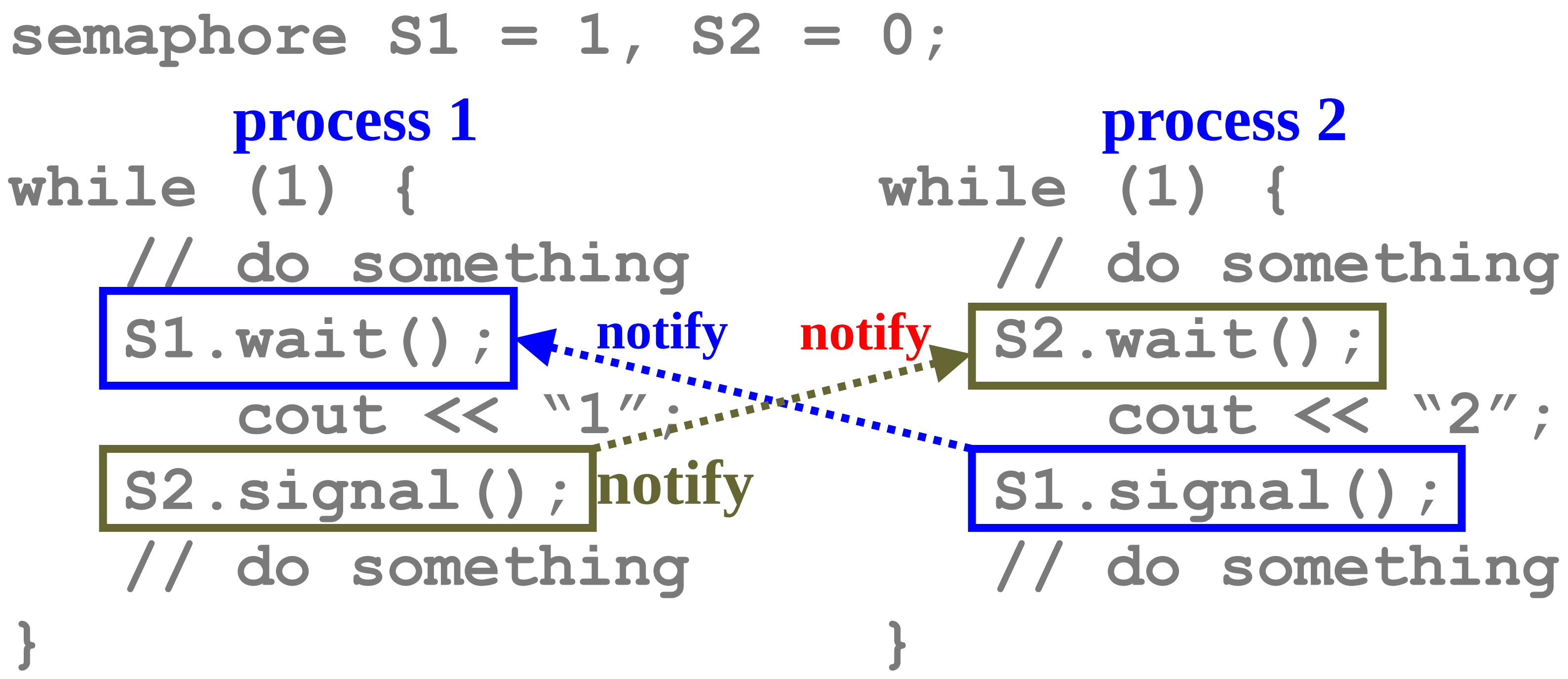
```
while (1) {
   // do something
   S.wait();
```

at most 3 processes can be here!!!

```
   S.signal();
   // do something
}
```

- **After three processes pass through `wait()`, this section is locked until a process calls `signal()`.**

Use 3: Notification

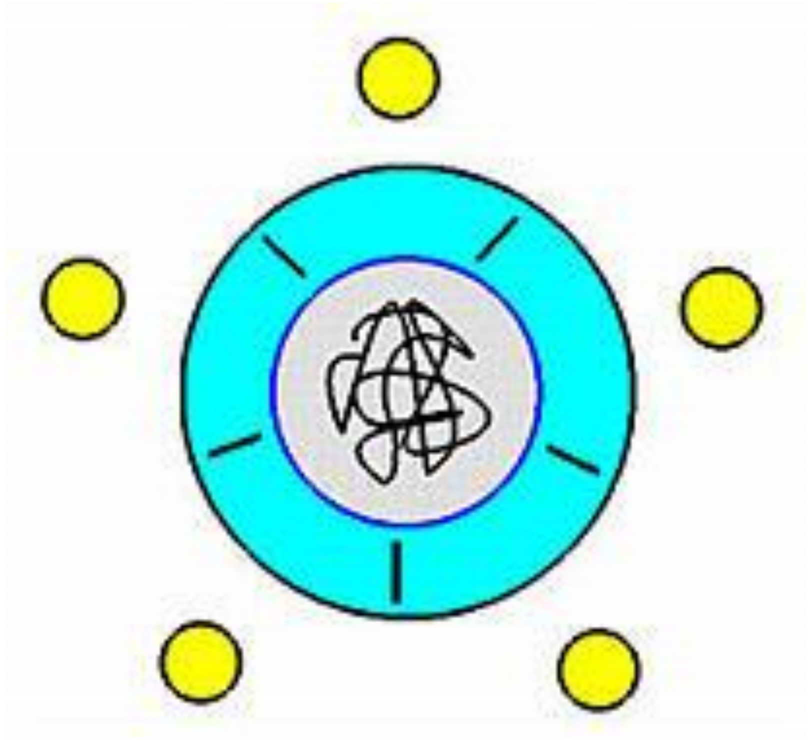


```
semaphore S1 = 1, S2 = 0;
        process 1                        process 2
while (1) {                      while (1) {
   // do something                  // do something
  S1.wait();                       S2.wait();
     cout << "1";                     cout << "2";
  S2.signal();                     S1.signal();
   // do something                  // do something
}                                }
```

- **Process 1 uses `S2.signal()` to notify process 2, indicating "I am done. Please go ahead."**
- **The output is `1 2 1 2 1 2` ......**
- **What if `S1` and `S2` are both 0's or both 1's?**
- **What if `S1` = 0 and `S2` = 1?**

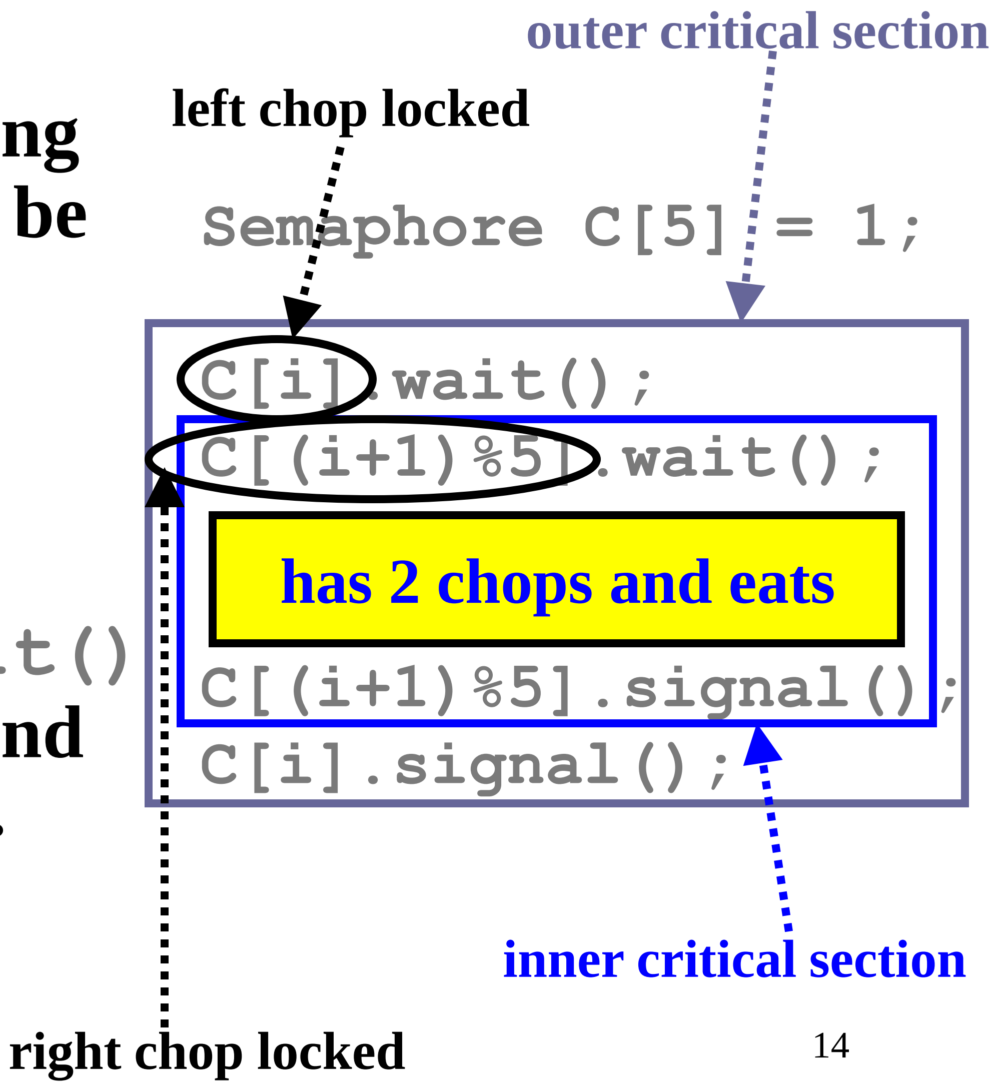
Dining Philosophers

- Five philosophers are in a thinking - eating cycle.
- When a philosopher gets hungry, he sits down, picks up *his left* and then *his right* chopsticks, and eats.
- A philosopher can eat only if he has *both* chopsticks.
- After eating, he puts down both chopsticks and thinks.
- This cycle continues.



Dining Philosopher: Ideas

- Chopsticks are shared items (by two neighboring philosophers) and must be protected.
- Each chopstick has a semaphore with initial value 1 (i.e., available).
- A philosopher calls `wait()` to pick up a chopstick and `signal()` to release it.



```
Semaphore C[5] = 1;

C[i].wait();
C[(i+1)%5].wait();
    has 2 chops and eats
C[(i+1)%5].signal();
C[i].signal();
```

Dining Philosophers: Code

```
semaphore  C[5] = 1;
```

philosopher *i*

```
while (1) {
   // thinking
   C[i].wait();
   C[(i+1)%5].wait();
   // eating
   C[(i+1)%5].signal();
   C[i].signal();
   // finishes eating
}
```

wait for my left chop

wait for my right chop

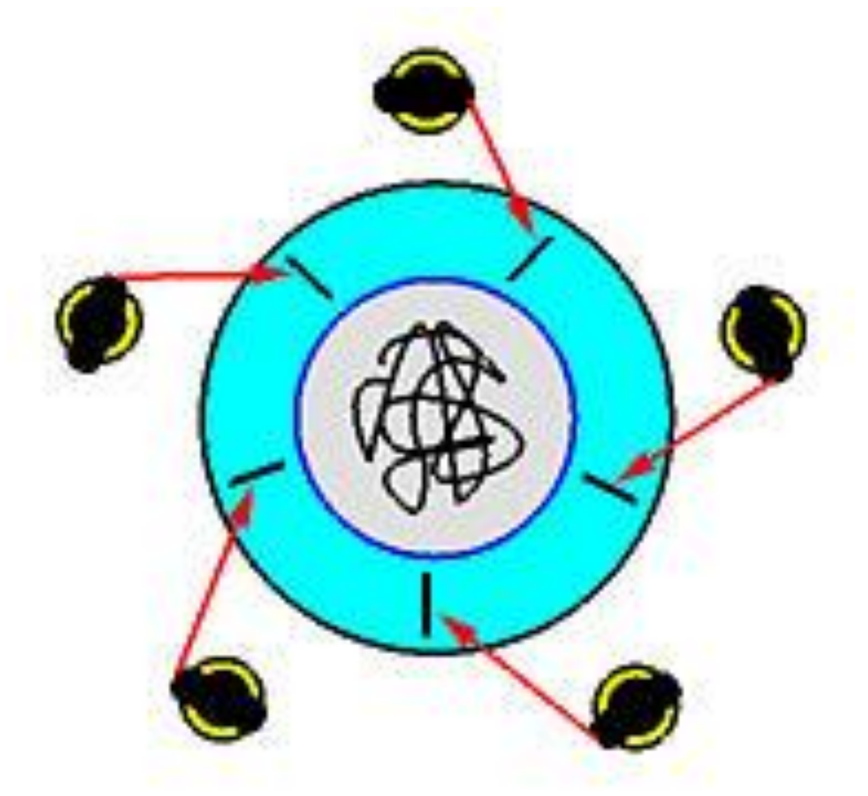
release my right chop

release my left chop

Does this solution work?

Dining Philosophers: Deadlock!

- If all five philosophers sit down and pick up their left chopsticks at the same time, this causes a ***circular waiting*** and the program deadlocks.
- An easy way to remove this deadlock is to introduce a weirdo who picks up his right chopstick first!



Dining Philosophers: A Better Idea

```
semaphore C[5] = 1;
```

philosopher *i* (0, 1, 2, 3)

```
while (1) {
   // thinking
   C[i].wait();
   C[(i+1)%5].wait();
   // eating
   C[(i+1)%5].signal();
   C[i].signal();
   // finishes eating;
}
```

Philosopher 4: the weirdo

```
while (1) {
   // thinking
   C[(i+1)%5].wait();
   C[i].wait();
   // eating
   C[i].signal();
   C[(i+1)%5].signal();
   // finishes eating
}
```

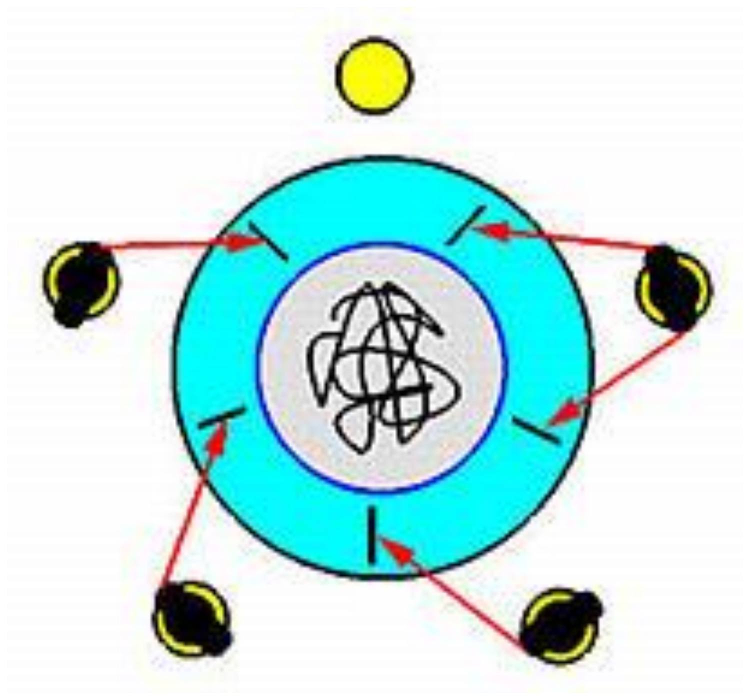
lock left chop

lock right chop

Dining Philosophers: Questions

- The following are some important questions for you to think about.
  - We choose philosopher 4 to be the weirdo. Does this choice matter?
  - Show that this solution does not cause ***circular waiting***.
  - Show that this solution does not cause ***circular waiting*** even if we have more than 1 and less than 5 weirdoes.
- This solution is not ***symmetric*** because not all threads run the same code.

Count-Down Lock Example



- The naïve solution to the dining philosophers problem causes circular waiting.
- If only four philosophers are allowed to sit down, deadlock cannot occur.
- Why? If all four sit down at the same time, the right-most one may have both chopsticks!
- What if the right-most one could not eat? ***Exercise!***

Count-Down Lock Example

```
semaphore C[5]= 1;
semaphore Chair = 4;

while (1) {
   // thinking
   Chair.wait();
      C[i].wait();
      C[(i+1)%5].wait();
      // eating
      C[(i+1)%5].signal();
      C[i].signal();
   Chair.signal();
}
```

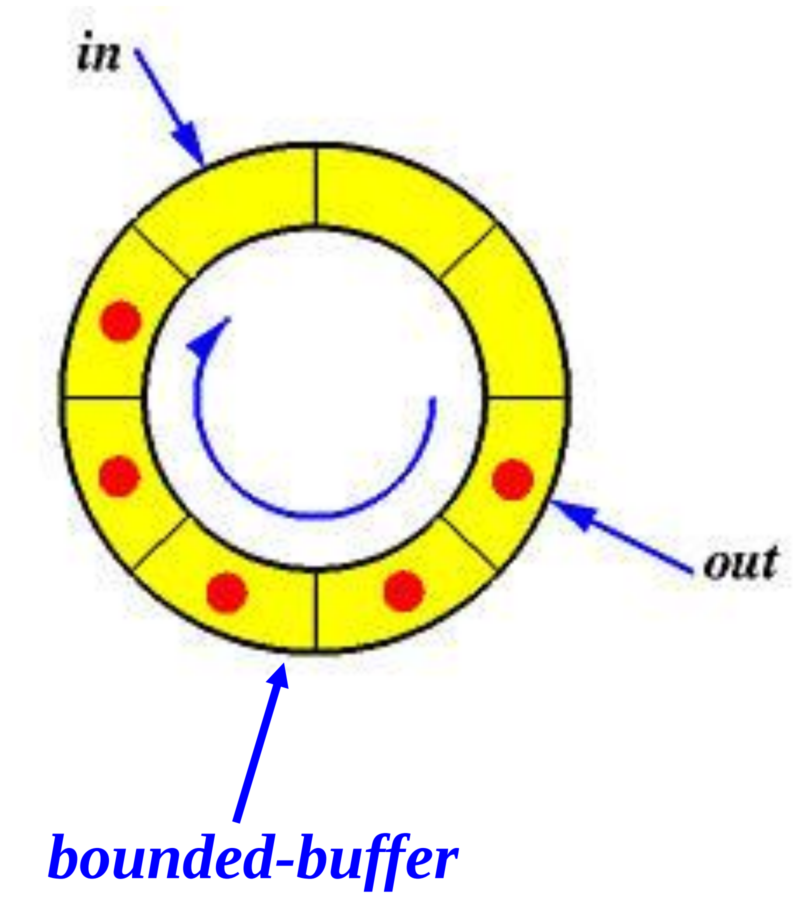
get a chair

this is a count-down lock that only allows 4 to go!

this is our old friend

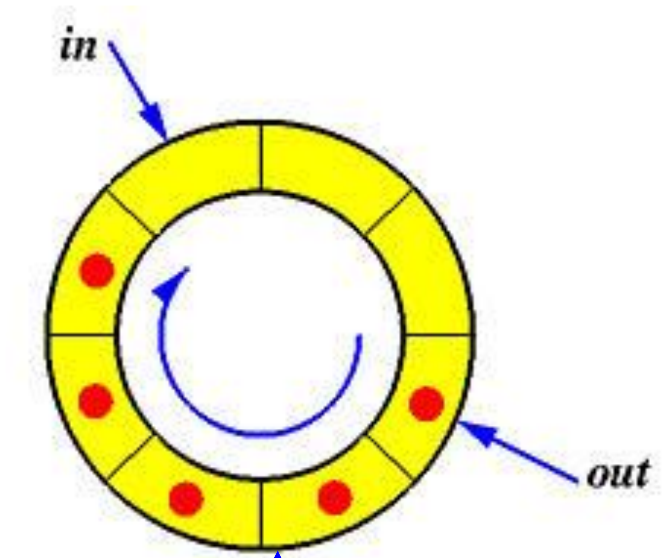
release my chair

The Producer/Consumer Problem



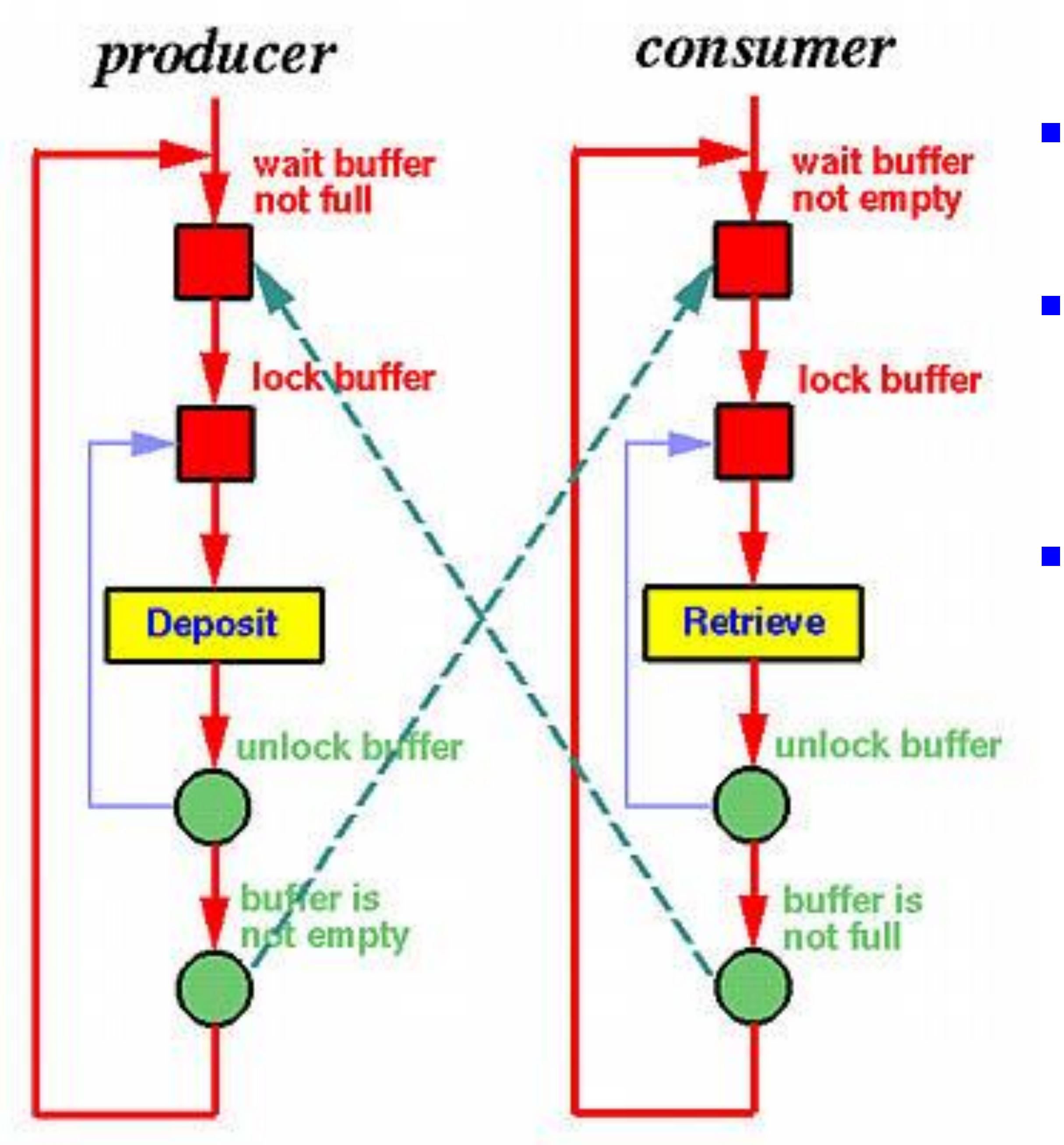
- Suppose we have a circular buffer of *n* slots.
- Pointer *in* (*resp*., *out*) points to the first empty (*resp*., filled) slot.
- Producer processes keep adding data into the buffer.
- Consumer processes keep retrieving data from the buffer.

Problem Analysis



buffer is implemented with an array `Buf[ ]`

- **A producer deposits data into `Buf[in]` and a consumer retrieves info from `Buf[out]`.**
- **`in` and `out` must be advanced.**
- **`in` is shared among producers.**
- **`out` is shared among consumers.**
- **If `Buf` is full, producers should be blocked.**
- **If `Buf` is empty, consumers should be blocked.**



- **A semaphore to protect the buffer.**
- **Another semaphore to block producers if the buffer is full.**
- **One more semaphore to block consumers if the buffer is empty.**

Solution

number of slots

```
semaphore NotFull=n, NotEmpty=0, Mutex=1;
```

producer

```
while (1) {
  NotFull.wait();
    Mutex.wait();
      Buf[in] = x;
      in = (in+1)%n;
    Mutex.signal();
  NotEmpty.signal();
}
```

consumer

```
while (1) {
  NotEmpty.wait();
    Mutex.wait();
      x = Buf[out];
      out = (out+1)%n;
    Mutex.signal();
  NotFull.signal();
}
```

notifications

critical section

Question

- What if the producer code is modified as follows?
- **Answer:** a deadlock may occur. Why?

order changed

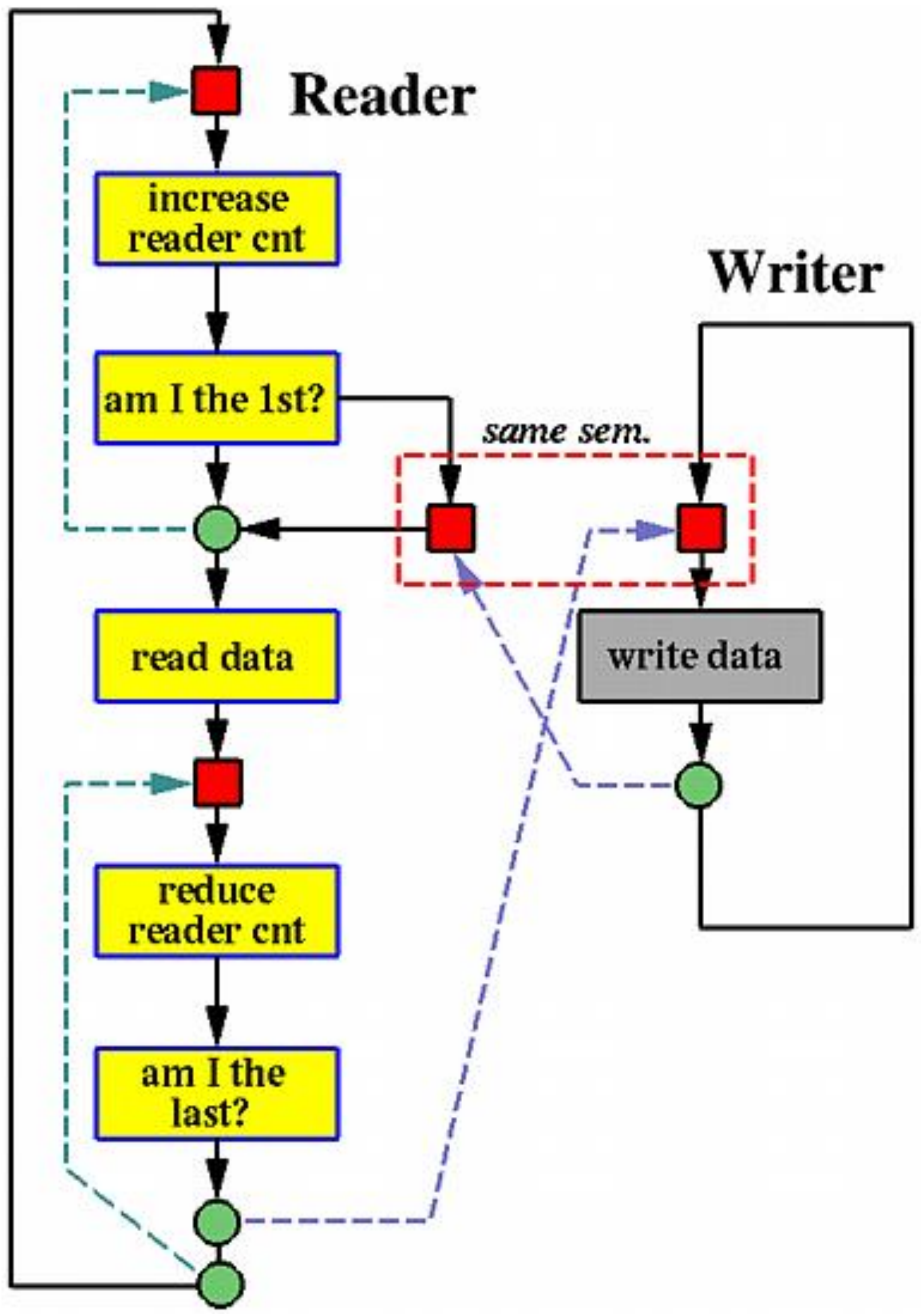
```
while (1) {
   Mutex.wait();
     NotFull.wait();
       Buf[in] = x;
       in = (in+1)%n;
     NotEmpty.signal();
   Mutex.signal();
}
```

The Readers/Writers Problem

- Two groups of processes, readers and writers, access a shared resource by the following rules:
  - Readers can read simultaneously.
  - Only one writer can write at any time.
  - When a writer is writing, no reader can read.
  - If there is any reader reading, all incoming writers must wait. Thus, readers have a higher priority.

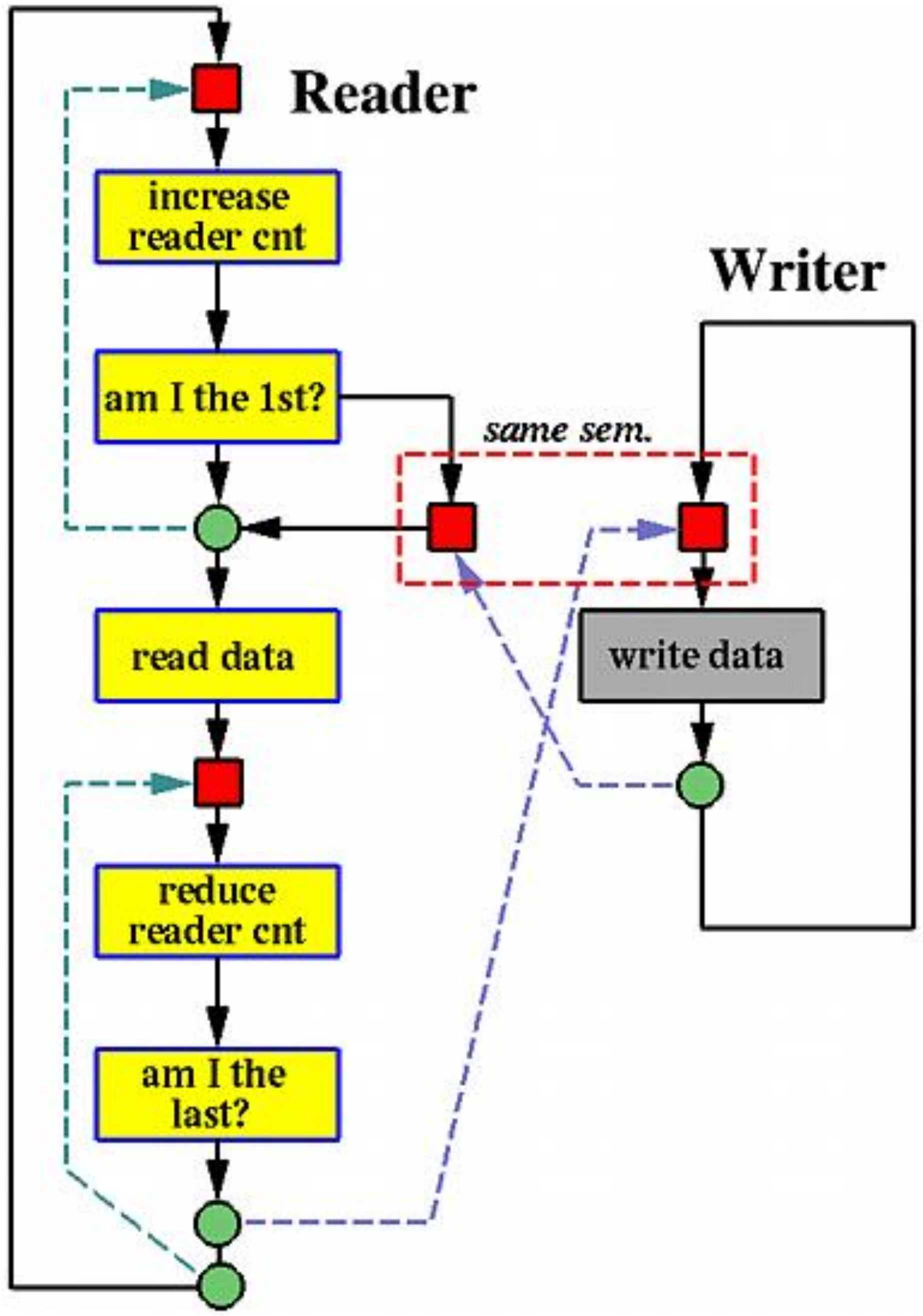
Problem Analysis

- We need a semaphore to block readers if a writer is writing.
- When a writer arrives, it must know if there are readers reading. A reader count is required and must be protected by a lock.
- This reader-priority version has a problem: if readers keep coming in an overlapping way, waiting writers have no chance to write.



Readers

- When a reader arrives, it adds 1 to the counter.
- If it is the first reader, waits until no writer is writing.
- Reads data.
- Decreases the counter.
- If it is the last reader, notifies the waiting readers and writers that no reader is reading.



Writers

- When a writer comes in, it waits until no reader is reading and no writer is writing.
- Then, it writes data.
- Finally, notifies waiting readers and writers that no writer is writing.

Solution

```
semaphore Mutex = 1, WrtMutex = 1;
int       RdrCount;
```

reader

```
while (1) {
  Mutex.wait();
    RdrCount++;
    if (RdrCount == 1)
      WrtMutex.wait();
  Mutex.signal();
  // read data
  Mutex.wait();
    RdrCount--;
    if (RdrCount == 0)
      WrtMutex.signal();
  Mutex.signal();
}
```

blocks both readers and writers

writer

```
while (1) {
  WrtMutex.wait();
  // write data
  WrtMutex.signal();
}
```

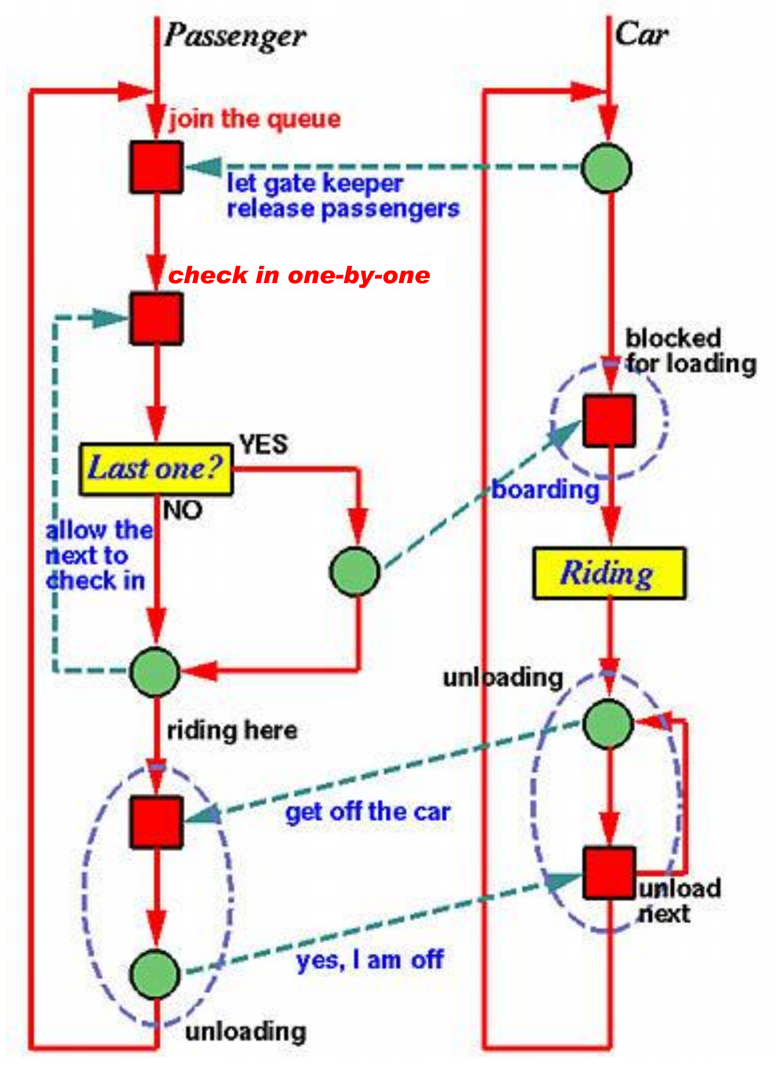
The Roller-Coaster Problem: 1/5

- Suppose there are n passengers and one roller coaster car. The passengers repeatedly wait to ride in the car, which can hold maximum C passengers, where $C < n$.
- The car can go around the track only when it is full. After finishes a ride, each passenger wanders around the amusement park before returning to the roller coaster for another ride.
- Due to safety concerns, the car only rides T times and then shut-down.

The Roller-Coaster Problem: 2/5

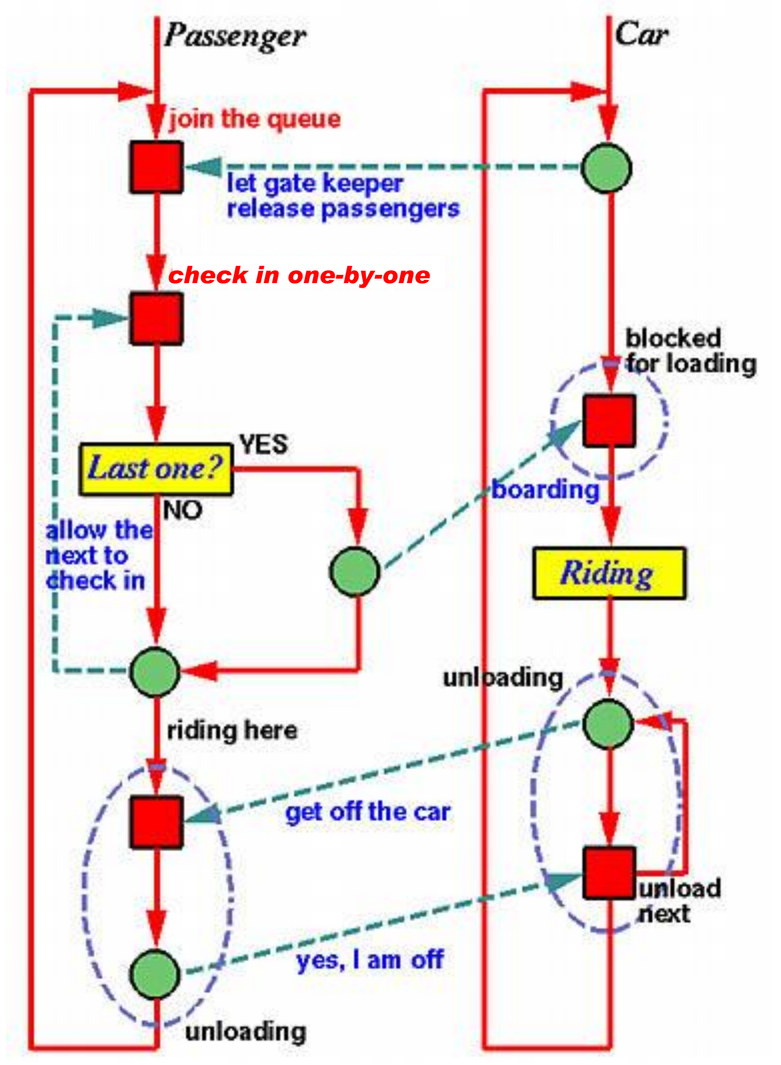
- The car always rides with exactly *C* passengers
- No passengers will jump off the car while the car is running
- No passengers will jump on the car while the car is running
- No passengers will request another ride before they get off the car.

The Roller-Coaster Problem: 3/5



- A passenger makes a decision to have a ride, and joins the queue.
- The queue is managed by a gate keeper.
- Passengers check in one-by-one.
- The last passenger tells the car that all passengers are on board.
- Then, they have a ride.
- After riding passengers get off the car one-by-one.
- They go back to play for a while and come back for a ride.

The Roller-Coaster Problem: 4/5



- The car comes and lets the gate keeper know it is available so that the gate keeper could release passengers to check in.
- The car is blocked for loading.
- When the last passenger in the car, s/he informs the car that all passengers are on board, the car starts a ride.
- After this, the car waits until all passengers are off. Then, go for another round.

The Roller-Coaster Problem: 5/5

```
int count = 0;
Semaphore Queue = Boarding = Riding = Unloading = 0;
Semaphore Check-In = 1;
```

Passenger

```
Wait(Queue);
Wait(Check-In);
if (++count==Maximum)
   Signal(Boarding);
Signal(Check-In);
Wait(Riding);
Signal(Unloading);
```

Car

```
for (i = 0; i < #rides; i++) {
   count = 0; // reset counter before boarding
   for (j = 1; j <= Maximum; j++)
      Signal(Queue); // car available
   Wait(Boarding);
   // all passengers in car
   // and riding
   for (j = 1; j <= Maximum; j++) {
      Signal(Riding);
      Wait(Unloading);
   }
   // all passengers are off
}
```

one ride

Unload passengers one-by-one
Is this absolutely necessary?
Can `Unloading` be removed? *Ex.*

A Quick Summary: 1/2

- We have learned a few tricks in this component: lock, count-down lock and notification.
- Very often a counter is needed to determine if certain condition is met (e.g., number of readers in the readers-writers problem, check-in and boarding in the roller-coaster problem).
- Sometimes threads may have to be “paired-up” like the get-off process we saw in the roller-coaster problem.
- Use these basic and frequently seen patterns to solve other problems.

A Quick Summary: 2/2

- Using many semaphores could mean more locking and unlocking activities, and could be ***inefficient***.
- Using only a few semaphores could produce very large critical sections, and a thread could stay in a critical section for a long time. Thus, other threads may have to wait very long to get in.
- Therefore, try your best to minimize the number of semaphores and reduce the length of locking time.

What Is a Pattern?

- **A *pattern* is simply a description/template for solving a problem that can be used in several situations.**
- **However, a pattern is *NOT* a complete solution to a problem. It is just a template and requires extra work to make it a solution to a specific problem.**
- **We will discuss a few patterns related to the use of semaphores.**

Mutual Exclusion – Of Course!

- This is the easiest one for enforcing mutual exclusion so that race conditions will not occur.
- A semaphore is initialized to 1. Then, use the `Wait()` and `Signal()` methods to lock and unlock the semaphore, respectively.

```
Semaphore Lock(1);

Wait(Lock);
   // critical section
Signal(Lock);
```

```
Semaphore   S(1);
int         c = 0;

Wait(S);                Wait(S);
  c++;                    c--;
Signal(S);              Signal(S);
if (c >= 3) {           if (c == 0) {
    ...                     ...
```

while `c` is being tested, it could be updated!

Enter-and-Test: 1/2

- In many applications, a thread may enter a critical section and test for a condition. If that condition is met, the thread does ***something$_1$***. Otherwise, its does ***something$_2$***.
- Frequently, one of the two ***something***s may involve a wait.

Reader: Enter

```
Mutex.wait();
    RdrCount++;
    if (RdrCount == 1)
      WrtMutex.wait();
Mutex.signal();
  // read data
```

critical section

if the condition is met (i.e., `RdrCount` being 1), then wait until it is notified by another thread. In this case, the first reader does something.

Enter-and-Test: 2/2

- Usually, a wait may be used in the entry part to wait for a particular condition to occur, and a signal is used upon exit to notify other threads.

Reader: Exit

```
// read data
  Mutex.wait();
    RdrCount--;
    if (RdrCount == 0)
      WrtMutex.signal();
  Mutex.signal();
}
```

critical section

if the condition is met (i.e., `RdrCount` being 0), then tell someone, a reader or a writer, to continue.

In this case, the last reader does something.

Exit-Before-Wait: 1/2

- In many applications, a thread exits a critical section and then blocks itself.
- Usually, a thread updates some variables in a critical section, and then waits for a resource from another thread.

Roller-Coaster: Passenger

```
Wait(Queue);
Wait(Check-In);
if (++count==Maximum)
    Signal(Boarding);
Signal(Check-In);
Wait(Riding);
Signal(Unloading);
```

if the condition is met (i.e., `count` being the maximum), then notify some thread.

after exiting the critical section, wait for some event to happen.

critical section for `count`

Exit-Before-Wait: 2/2

- This `signal`ing an event followed by `wait`ing on another has to be used with care.
- A context switch can happen between the `signal` and the `wait`.
- For example, a thread enters the critical section, signals `s1` upon exit, and gets swapped out before reaches the wait. This could cause a deadlock. ***Why?*** So, be careful!

```
Wait(s1);
  // critical section
Signal(s1);
Wait(s2);
```

a context switch could occur here!

Conditional Waiting/Signaling

- A thread waits or notifies another thread if a condition is satisfied.
- Make sure that no race condition will occur while the condition is being tested.

```
if (count > 0)                  if (count == 0)
   Signal(OK_to_GO);               Wait(Block_Myself);
```

are there other threads updating `count` at the same time?

Passing the Baton: 1/5

- If a thread is in its critical section, it holds the ***baton*** (i.e., the critical section).
- That thread passes the ***baton*** (i.e., the critical section) to another thread.
- If there are waiting threads for a condition that is now true, the ***baton*** (i.e., the critical section) is passed to one of them.
- If no thread is waiting, the ***baton*** is passed to the next thread that tries to enter the CS.
- This is a technique that can make the use of semaphores more efficient.

Passing the Baton: 2/5

- The ***Waiting*** thread waits on `Condition` if `Event` is not there. The ***Signaling*** thread sets `Event` and releases the ***Waiting*** thread.

```
Semaphore Mutex(1);
Semaphore Condition(0);
Bool      Event = FALSE;
```

Waiting Thread

```
Wait(Mutex);
while (!Event) {
   Signal(Mutex);
   Wait(Condition);
   Wait(Mutex);
}
```

try again!

Signaling Thread

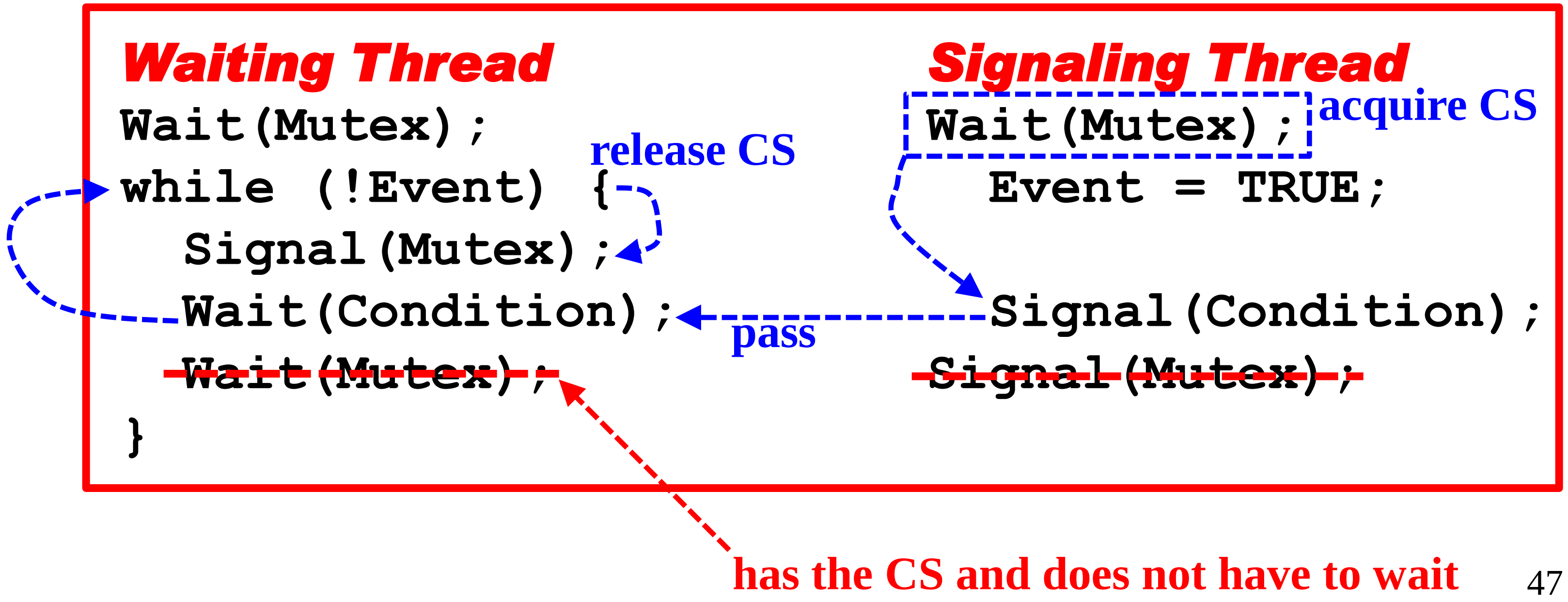
```
Wait(Mutex);
   Event = TRUE;

   Signal(Condition);
Signal(Mutex);
```

critical section for protecting `Event`

Passing the Baton: 3/5

- ***Waiting*** **does not acquire the CS. Instead, *Signaling* has the CS, does not release it, and gives the CS to *Waiting* (i.e., baton passed)**
- ***Signaling*** **must be sure that *Waiting* will not do any harm to the CS.**



Waiting Thread

```
Wait(Mutex);
while (!Event) {
   Signal(Mutex);
   Wait(Condition);
   ~~Wait(Mutex);~~
}
```

Signaling Thread

```
Wait(Mutex);
   Event = TRUE;

Signal(Condition);
~~Signal(Mutex);~~
```

Passing the Baton: 4/5

```
Semaphore Mutex(1), Condition(0);
int       Event = FALSE, Waiting = 0;
```

Waiting Thread

```
Wait(Mutex);
if (!Event) {
  Waiting++;
  Signal(Mutex);
  Wait(Condition);
}
...
if (Waiting > 0) {
  Waiting--;
  Signal(Condition);
}
else
  Signal(Mutex);
...
```

Signaling Thread

```
Wait(Mutex);
Event = TRUE;
if (Waiting > 0) {
  Waiting--;
  Signal(Condition);
else
  Signal(Mutex);
...
```

baton acquired

a `Mutex` needed to protect `Waiting`

baton passed

baton released

Passing the Baton: 5/5

- ***Passing the baton*** technically transfers the ownership of a critical section from a thread to another thread.
- The thread that has the baton does not need a signal to release it. Instead, the CS is directly given to another that needs it. The receiving thread does not need a wait for the CS.
- In this way, mutual exclusion may be destroyed; but, we reduce the number of entering and exiting a mutex.

Passing the Baton: Example

- We shall use the reader-priority version of the readers/writers problem as a more complex example.
- Note the following conditions:
  - If there is no writer writing, a reader can read.
  - If there is no readers reading and there are waiting writers, allow a writer to write (i.e., better!).
  - If there are readers reading OR a writer writing, no writer can write.
  - If there are waiting readers, a finishing writer should allow a reader to read (i.e. reader priority).
  - If there are waiting writers and no waiting reader, a finishing writer should allow a writer to write.

Passing the Baton: Example

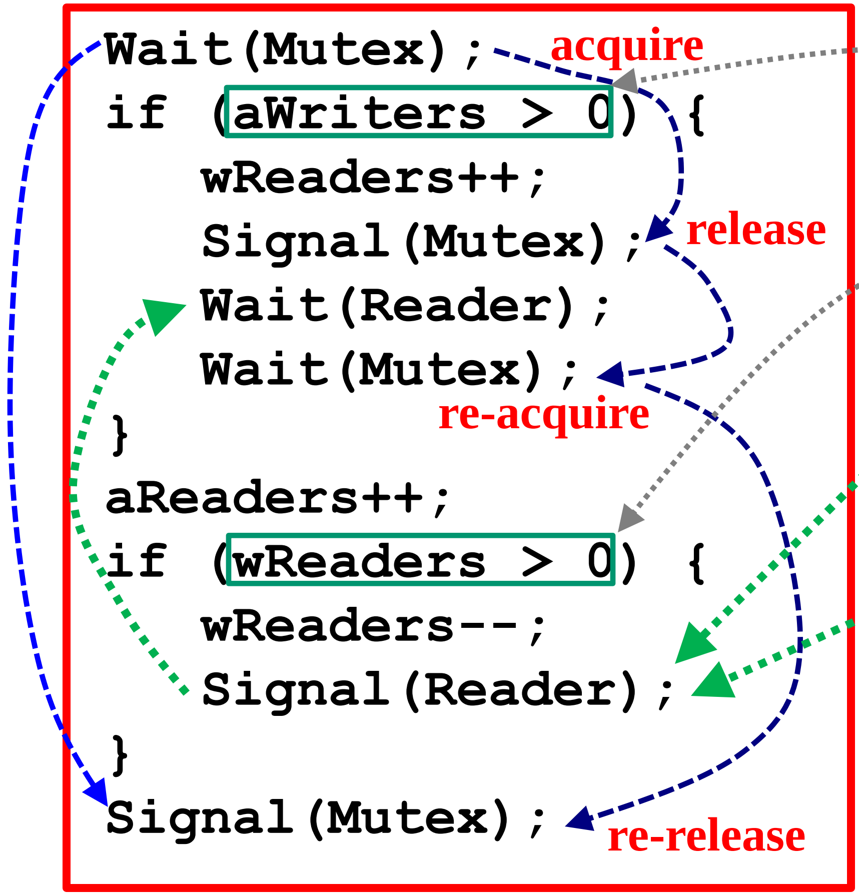
- We will need counters for counting waiting readers and writers and active readers and writer.
- A semaphore for protecting all counters.
- A semaphore for blocking readers.
- A semaphore for blocking writers.

```
int aReaders = 0;        // number of active readers (>= 0)
int aWriters = 0;        // number of active writer (0 or 1)
int wReaders = 0;        // number of waiting readers
int wWriters = 0;        // number of waiting writers

Semaphore Mutex(1);      // semaphore for protecting counters
Semaphore Reader(0);     // semaphore for blocking readers
Semaphore Writer(0);     // semaphore for blocking writers
```

Passing the Baton: Example

Developing the Entry Section for ***Readers***



```
Wait(Mutex);
if (aWriters > 0) {
    wReaders++;
    Signal(Mutex);
    Wait(Reader);
    Wait(Mutex);
}
aReaders++;
if (wReaders > 0) {
    wReaders--;
    Signal(Reader);
}
Signal(Mutex);
```

The first reader, who sees no writer writing and some readers waiting, releases the waiting readers.

The release of readers is in a cascading way (i.e., one after the other).

The first thread acquires the baton, and may pass it to each of the released thread. Then, the last thread releases the baton!

Passing the Baton: Example

Developing the Entry Section for ***Readers***: Passing the Baton

```
Wait(Mutex);
if (aWriters > 0) {
    wReaders++;
    Signal(Mutex);
    Wait(Reader);
    ~~Wait(Mutex);~~
}
aReaders++;
if (wReaders > 0) {
    wReaders--;
    Signal(Reader);
}
else
    Signal(Mutex);
```

- The first reader, who gets the baton and sees no writer writing and some readers waiting, will release the waiting readers and pass its baton to the released reader.
- Each released reader, after releasing the next reader, passes the baton to it.
- The last released returns the baton.
- Note that the critical section (i.e., the baton) is locked throughout this cascading releasing, and no other thread can pass through the first `Wait(Mutex)`.

Passing the Baton: Example

Developing the Exit Section for ***Readers***

```
Wait(Mutex);                      acquire
aReaders--;
if (aReaders=0 & wWriters>0) {
    wWriters--;
    Signal(Mutex);                release
    Signal(Writer);
}
else
    Signal(Mutex);
```

If this is the last reader and there are waiting writers, let one writer go.

Otherwise, simply go away.

This signal is not needed, because the last reader can pass the baton to the released writer!

Passing the Baton: Example

Developing the Exit Section for ***Readers***: Passing the Baton

```
Wait(Mutex);
aReaders--;
if (aReaders=0 & wWriters>0) {
   wWriters++;
   ~~Signal(Mutex);~~
   Signal(Writer);
}
else
   Signal(Mutex);
```

If this is the last reader and there are waiting writers, let one writer go.

Otherwise, simply go away.

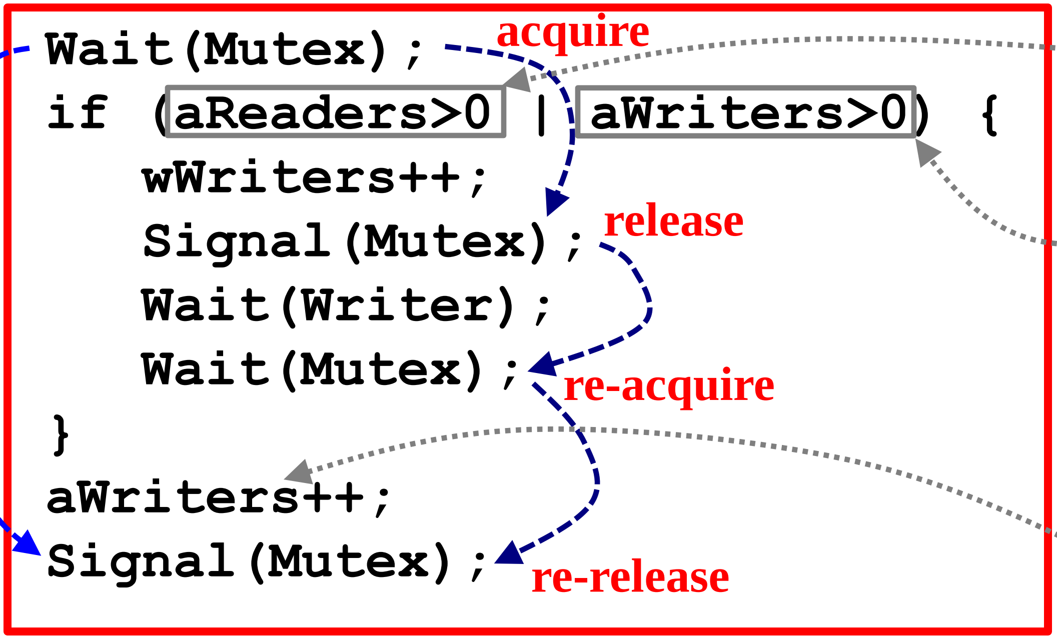
The baton is passed to the released writer.

```
Wait(Mutex);
aReaders--;
if (aReaders=0 & wWriters>0) {
   wWriters--;
   Signal(Writer);
}
Signal(Mutex);
```

Would this work properly in terms of passing the baton? Why? Exercise!

Passing the Baton: Example

Developing the Entry Section for ***Writers***



```
Wait(Mutex);
if (aReaders>0 | aWriters>0) {
    wWriters++;
    Signal(Mutex);
    Wait(Writer);
    Wait(Mutex);
}
aWriters++;
Signal(Mutex);
```

A writer, who gets the baton and sees <u>some readers reading</u> ***OR*** a <u>writer writing</u>, will release the baton and wait.

Later, this writer reacquires the baton to update `aWriters`.

Otherwise (i.e., no readers reading ***AND*** no writer writing), it increases the number of active writers, releases the baton, and starts writing.

Passing the Baton: Example

Developing the Entry Section for *Writers*: Passing the Baton

```
Wait(Mutex);   acquire
if (aReaders>0 | aWriters>0) {
    wWriters++;
    Signal(Mutex); release
    Wait(Writer); receives the baton
    ~~Wait(Mutex);~~      from a Reader
}
aWriters++;      release the received baton
Signal(Mutex);
```

A writer, who gets the baton and sees some readers reading *OR* a writer writing, will release the baton and wait.

Otherwise (i.e., no readers reading *AND* no writer writing), it increases the number of active writers, releases the baton, and stars writing.

Exit Section of Readers: Passing the Baton

```
Wait(Mutex);
aReaders--;
if (aReaders=0 & wWriters>0) {
   wWriters--;
   Signal(Writer);
}
Signal(Mutex);
```

The exiting reader acquires the baton, releases a writer w/o releasing the baton.
Hence, the released writer has the baton, increases the active writers count, releases the baton, and writes.

Passing the Baton: Example

Developing the Exit Section for *Writers*

```
Wait(Mutex);   acquire
aWriters--;
if (wReaders > 0) {
    wReaders--;
    Signal(Mutex);   release
    Signal(Readers);
}
else if (wWriters > 0) {
    wWriters--;
    Signal(Mutex);   release
    Signal(Writer);
}
else
    Signal(Mutex);   release
```

Lock the `Mutex` first.

If there are waiting readers, let one of them go.

If there is no waiting readers but there are waiting writers, let one of them go.

If there is no waiting readers and no waiting writers, then do nothing.

Don't forget to release the `Mutex`.

Passing the Baton: Example

Developing the Exit Section for *Writers*: Passing the Baton

```
Wait(Mutex);
aWriters--;
if (wReaders > 0) {
    wReaders--;
    ~~Signal(Mutex);~~
    Signal(Readers);
}
else if (wWriters > 0) {
    wWriters--;
    ~~Signal(Mutex);~~
    Signal(Writer);
}
else
    Signal(Mutex);
```

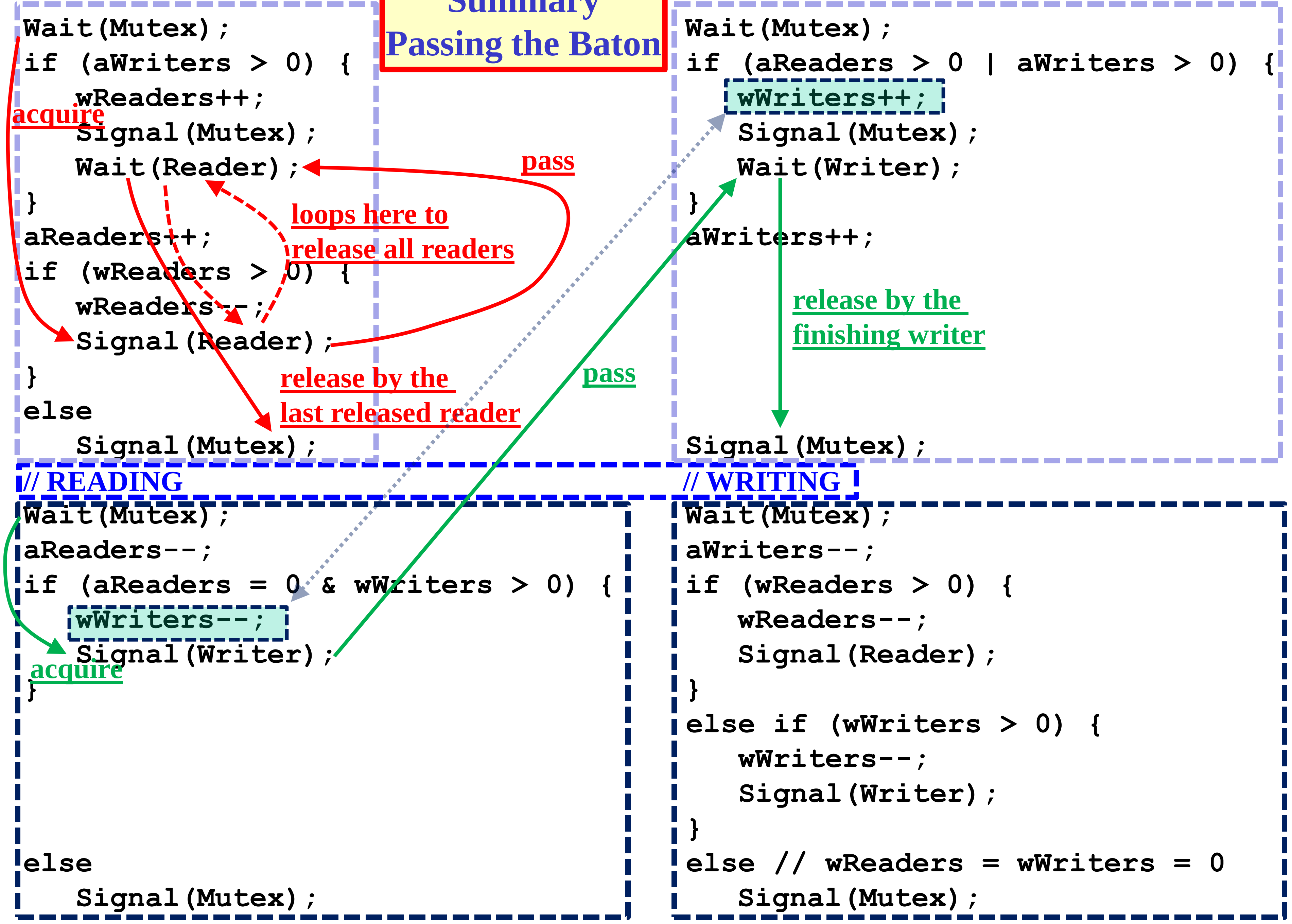
This Writer has acquired the baton.

It can pass the baton to a released Reader or a released Writer.

The baton is not passed if there is no waiting readers and there is no waiting writers.

In this case, this writer has to release the baton explicitly.

Summary Passing the Baton



```
Wait(Mutex);
if (aWriters > 0) {
    wReaders++;
    Signal(Mutex);
    Wait(Reader);
}
aReaders++;
if (wReaders > 0) {
    wReaders--;
    Signal(Reader);
}
else
    Signal(Mutex);
```

```
Wait(Mutex);
if (aReaders > 0 | aWriters > 0) {
    wWriters++;
    Signal(Mutex);
    Wait(Writer);
}
aWriters++;
```

```
Signal(Mutex);
```

```
// READING
```

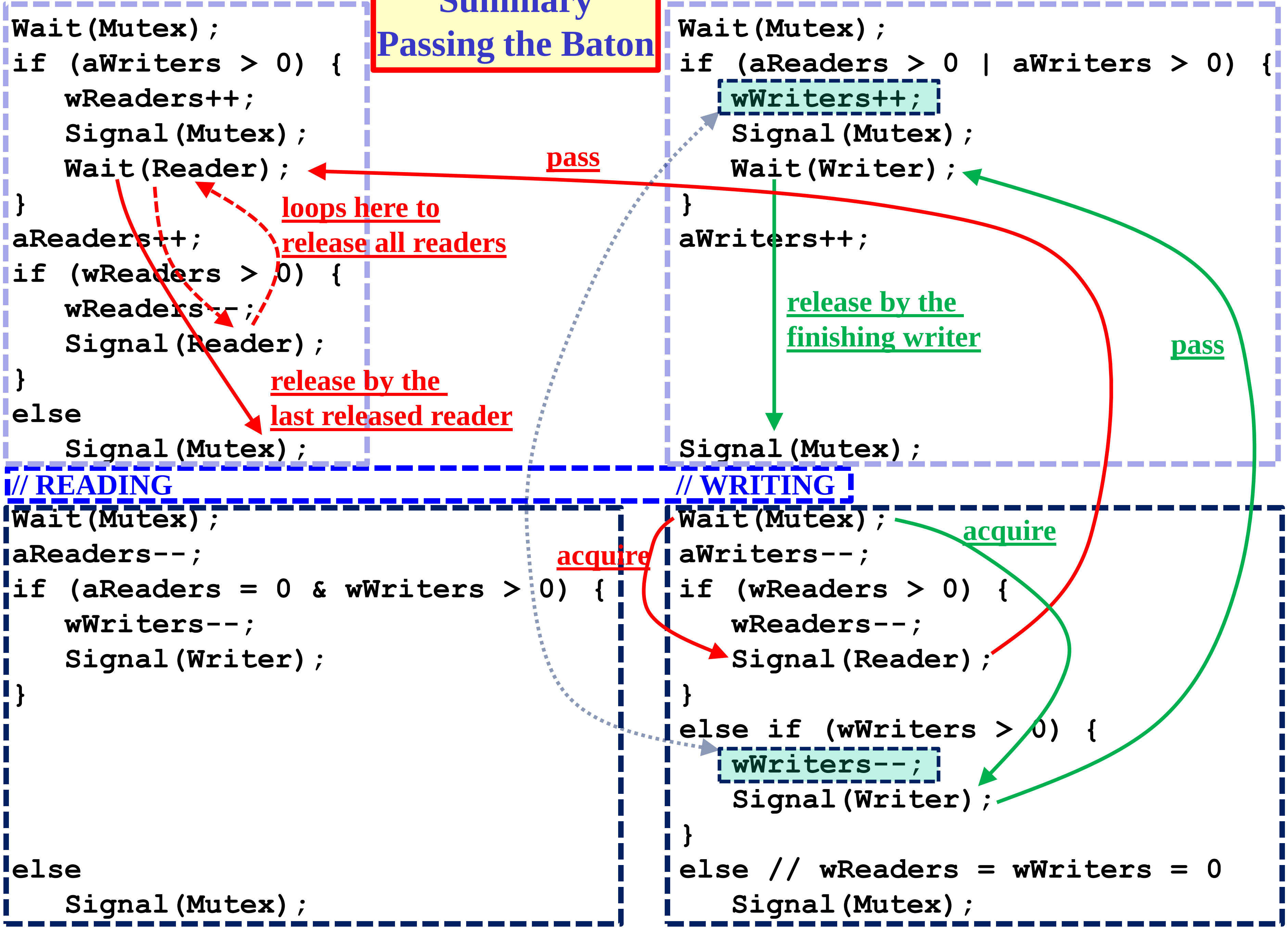
```
// WRITING
```

```
Wait(Mutex);
aReaders--;
if (aReaders = 0 & wWriters > 0) {
    wWriters--;
    Signal(Writer);
}
else
    Signal(Mutex);
```

```
Wait(Mutex);
aWriters--;
if (wReaders > 0) {
    wReaders--;
    Signal(Reader);
}
else if (wWriters > 0) {
    wWriters--;
    Signal(Writer);
}
else // wReaders = wWriters = 0
    Signal(Mutex);
```

acquire
pass
loops here to release all readers
release by the last released reader
pass
release by the finishing writer
acquire

Summary
Passing the Baton



```
Wait(Mutex);
if (aWriters > 0) {
    wReaders++;
    Signal(Mutex);
    Wait(Reader);
}
aReaders++;
if (wReaders > 0) {
    wReaders--;
    Signal(Reader);
}
else
    Signal(Mutex);
```

```
Wait(Mutex);
if (aReaders > 0 | aWriters > 0) {
    wWriters++;
    Signal(Mutex);
    Wait(Writer);
}
aWriters++;
Signal(Mutex);
```

```
// READING
Wait(Mutex);
aReaders--;
if (aReaders = 0 & wWriters > 0) {
    wWriters--;
    Signal(Writer);
}
else
    Signal(Mutex);
```

```
// WRITING
Wait(Mutex);
aWriters--;
if (wReaders > 0) {
    wReaders--;
    Signal(Reader);
}
else if (wWriters > 0) {
    wWriters--;
    Signal(Writer);
}
else // wReaders = wWriters = 0
    Signal(Mutex);
```

pass
loops here to release all readers
release by the last released reader
release by the finishing writer
pass
acquire
acquire

Passing the Baton: Example

- One of the several advantages of this solution is that it can easily be modified to achieve other goals. Here is a writer-priority version.
- A ***writer-priority*** version should satisfy the following conditions:
  1. New readers are blocked if a writer is waiting, and
  2. A waiting reader is released if no writer is writing.

Study the conditions for releasing readers and writers.

Passing the Baton: Example

- To meet ***Condition (1)***, we have to change the first (enter) `if` statement of the reader thread:

added component

```
                                                   // as long as there
                                                   //  is a writer waiting
if (aWriters > 0 || wWriters > 0) {                // yield to writers
   wReaders++;                                     // joint the line,
   Signal(Mutex);                                  // release the baton,
   Wait(Reader);                                   // and wait
}
```

When a reader arrives, if there are writers waiting or writing, this reader blocks, and, hence yields to writers.

Passing the Baton: Example

- To meet **Condition (2)**, we have to strengthen the last (exit) `if` statement of the writer thread:

```
if (wReaders > 0 && wWriters == 0) { // release readers
   wReaders--;                        //   only if there
   Signal(Reader);                    //   is no writers
}
else if (wWriters > 0) {              // if no readers
   wWriters--;                        //   but some writers
   Signal(Writer);                    //   release one
}
else
   Signal(Mutex);                     // no readers/writers
```

added component

Release a reader if there is no writer waiting.

Otherwise (i.e., no waiting readers or some waiting writers), release a writer.

Finally (i.e., no waiting readers and no waiting writers), do nothing.

Passing the Baton: Example

- A *fair* version should allow readers and writers take turns (i.e., no starvation).
- We assume the semaphores being used is implemented so that every blocked thread will be eventually released (i.e., no starvation).
- A fair version must satisfy the following:
  1. When a writer finishes, all waiting readers get a turn
  2. When all current readers finish reading, one waiting writer can write.

Study the conditions for releasing readers and writers.

Passing the Baton: Example

- We need to change the last (exit) `if` of the writer.
- A new `Bool` variable `Writing` is need to indicate whether a writer is writing. `Writing` is set to `TRUE` when a writer starts writing, and is set to `FALSE` when a reader starts reading.

```
if (wReaders > 0 & (wWriters = 0 | Writing)) {
   wReaders--;
   Signal(Reader); a reader can read
}
else if (wWriters > 0) & (wReaders = 0 | ¬Writing)) {
   wWriters--;
   Signal(Writer); a writer can writer
}
else // wReaders = wWriters = 0
   Signal(Mutex);
```

NEW: no waiting ***or*** writing writer

This is set by the current exiting writer. Because it exits, no writer is writing.

NEW: no waiting readers ***or*** no writing writer

Passing the Baton: Example

- This example, including its extensions and the passing the baton pattern, is due to Gregory R. Andrews. Refer to the following for more detailed discussions.
  1. Gregory R. Andrews, *Concurrent Programming: Principles and Practice*, Benjamin/Cummings, 1991.
  2. Gregory R. Andrews, A Method for Solving Synchronization Problems, *Science of Computer Programming*, Vol. 13 (1989/1991), pp. 1-21.

Semaphores with ***ThreadMentor***

Semaphores with ThreadMentor

- ***ThreadMentor*** has a class `Semaphore` with two methods `Wait()` and `Signal()`.
- Class `Semaphore` requires a non-negative integer as an initial value.
- A name is optional.

```
Semaphore Sem(“S”,1);
Sem.Wait();
// critical section
Sem.Signal();

Semaphore *Sem;
Sem = new
   Semaphore(“S”,1);
Sem->Wait();
// critical section
Sem->Signal();
```

Dining Philosophers: 4 Chairs

```
Semaphore Chairs(4);
Mutex     Chops[5];

class phil::public Thread
{
  public:
    phil(int n, int it);
  private:
    int  Number;
    int  iter;
    void ThreadFunc();
};
```

Count-Down and Lock!

```
Void phil::ThreadFunc()
{
 int i, Left=Number,
     Right=(Number+1)%5;
 Thread::ThreadFunc();
 for (i=0; i<iter; i++) {
   Chairs.Wait();
     Chops[Left].Lock();
     Chops[Right].Lock();
     // Eat
     Chops[Left].Unlock();
     Chops[Right].Unlock();
   Chairs.Signal();
}
```

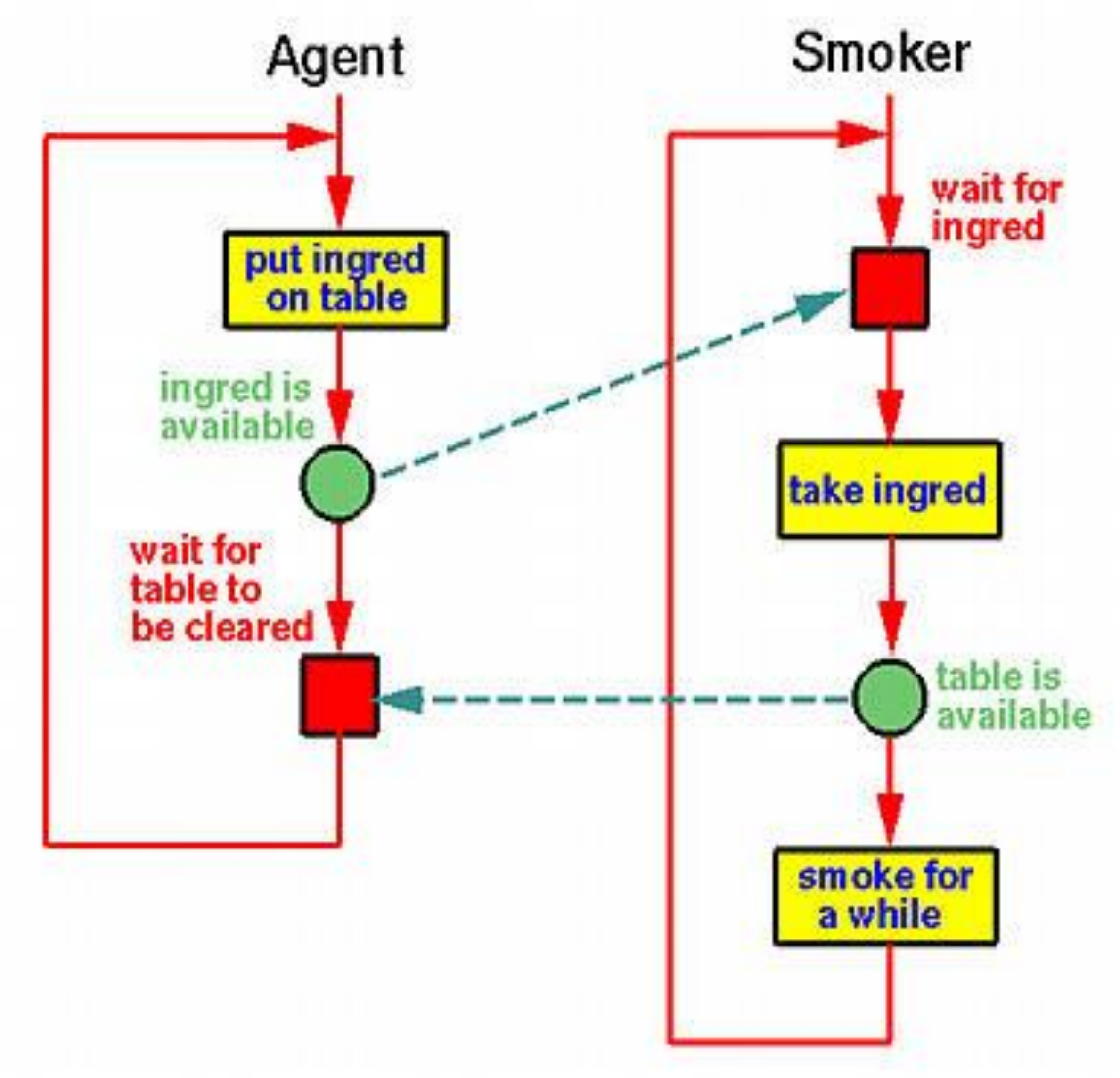
The Smokers Problem: 1/6

- Three ingredients are needed to make a cigarette: tobacco, paper and matches.
- An agent has an infinite supply of all three.
- Each of the three smokers has an infinite supply of one ingredient only. That is, one of them has tobacco, the second has paper, and the third has matches.
- They share a table.

The Smokers Problem: 2/6

- The agent adds two randomly selected different ingredients on the table, and notifies the needed smoker.
- A smoker waits until agent's notification. Then, takes the two needed ingredients, makes a cigarette, and smokes for a while.
- This process continues forever.
- ***How can we use semaphores to solve this problem?***

The Smokers Problem: 3/6



The Smokers Problem: 4/6

- Semaphore `Table` protects the table.
- Three semaphores `Sem[3]` are used, one for each smoker:

Smoker #	*Has*	*Needs*	*Sem*
0	0	1 & 2	`Sem[0]`
1	1	2 & 0	`Sem[1]`
2	2	0 & 1	`Sem[2]`

The Smokers Problem: 5/6

agent thread

```
class A::public Thread
{
  private:
    void ThreadFunc();
};
```

smoker thread

```
class Smk::public Thread
{
  public:
    Smk(int n);
  private:
    void ThreadFunc();
    int  No;
};
```

clear the table

```
Smk::Smk(int n)
{
  No = n;
}

Void Smk::ThreadFunc()
{
  Thread::ThreadFunc();
  while (1) {
    Sem[No]->Wait();
    Table.Signal();
    // smoker a while
  }
}
```

waiting for ingredients

The Smokers Problem: 6/6

```
void A::ThreadFunc()
{
  Thread::ThreadFunc();
  int  Ran;
  while (1) {
    Ran = // random #
          // in [0,2]
    Sem[Ran]->Signal();
    Table.Wait();
  }
}
```

ingredients are ready

waiting for the table to be cleared

```
void main()
{
  Smk *Smoker[3];
  A    Agent;

  Agent.Begin();
  for (i=0;i<3;i++) {
   Smoker = new Smk(i);
   Smoker->Begin();
  }
  Agent.Join();
}
```

The End