
Process Management

Synchronization

Lecture 6

Overview

■ Race Condition

- ❑ Problems with concurrent execution

■ Critical Section

- ❑ Properties of correct implementation
- ❑ Symptoms of incorrect implementation

■ Implementations of Critical Section

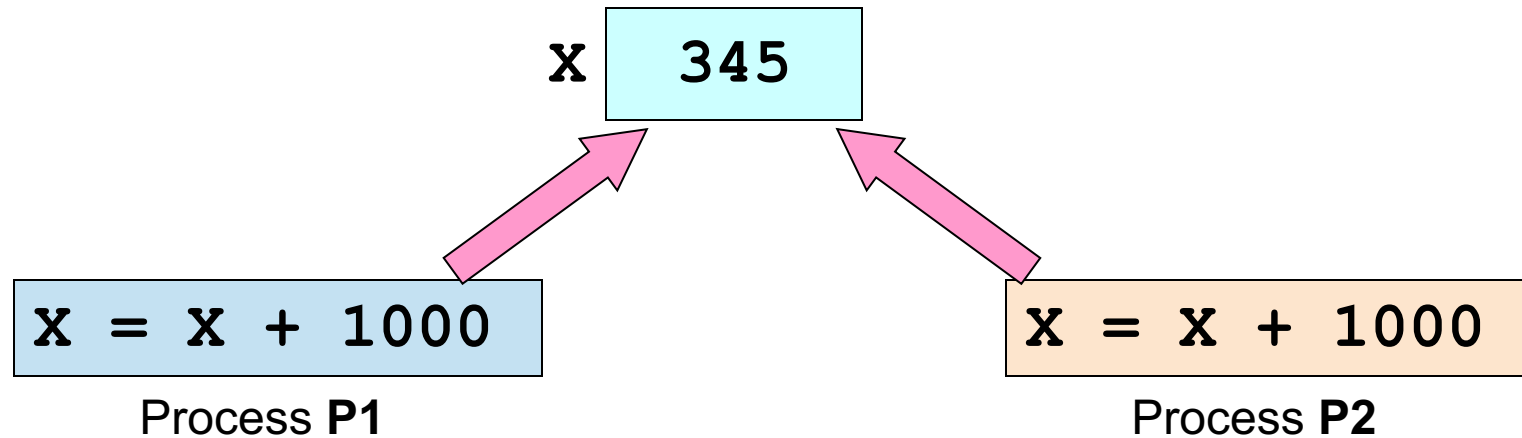
- ❑ Low level
- ❑ High level language
- ❑ High level abstraction

■ Classical synchronization problems

Problems with Concurrent Execution

- When two or more processes:
 - ❑ Execute concurrently in interleaving fashion AND
 - ❑ Share a modifiable resource
 - ➔ **Can cause synchronization problems**
- Execution of a single sequential process is ***deterministic***
 - ❑ Repeated execution gives the same result
- Execution concurrent processes may be non-deterministic
 - ❑ Execution outcome depends on the order in which the shared resource is accessed/modified
 - ❑ known as **race conditions**

Race Condition: Illustration



- Process **P1** and **P2** share a variable **X**
- The statement $X = X + 1000$ can be roughly translated as the following machine instructions:
 1. Load **X** \rightarrow Register1
 2. Add 1000 to Register1
 3. Store Register1 \rightarrow **X**

Race Condition: **Good behavior**

| Time | Value of X | P1 | P2 |
|------|-------------|-------------------|-------------------|
| 1 | 345 | Load X → Reg1 | |
| 2 | 345 | Add 1000 to Reg 1 | |
| 3 | 1345 | Store Reg1 → X | |
| 4 | 1345 | | Load X → Reg1' |
| 5 | 1345 | | Add 1000 to Reg1' |
| 6 | 2345 | | Store Reg1' → X |

- The above execution order exhibits good behavior:
 - Give the desired result **2345**

Race Condition: **Bad behavior**

| Time | Value of X | P1 | P2 |
|------|-------------|------------------|-------------------|
| 1 | 345 | Load X → Reg1 | |
| 2 | 345 | Add 1000 to Reg1 | |
| 3 | 345 | | Load X → Reg1' |
| 4 | 345 | | Add 1000 to Reg1' |
| 5 | 1345 | Store Reg1 → X | |
| 6 | 1345 | | Store Reg1' → X |

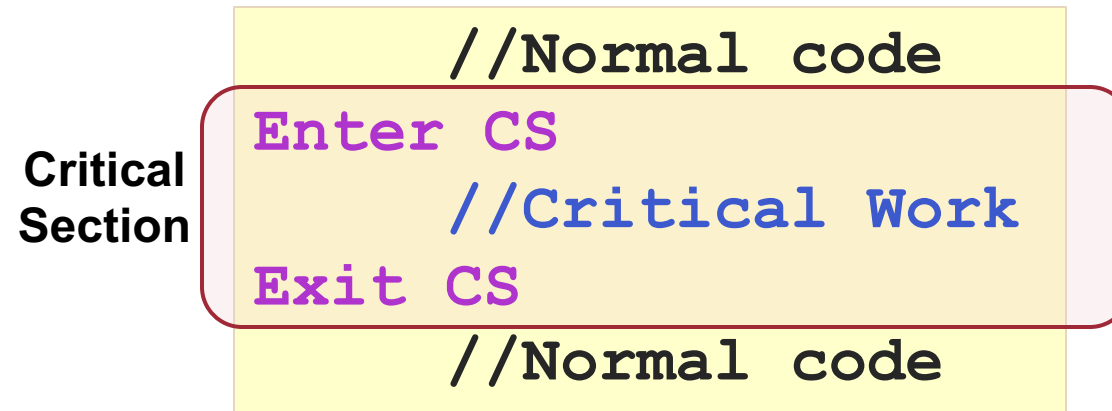
- There are many other execution sequence that exhibit good/bad behaviors!

Race Condition: **Solution**

- Incorrect execution is due to the **unsynchronized access to shared modifiable resources**
- General outline of solution:
 - ❑ Designate code segment with race condition as **critical section**
 - ❑ At any point in time, only **one process** can execute in the critical section
 - ➔ Other processes are prevented from entering the same critical section

Critical Section (CS)

- Generic Skeleton of code with Critical Section(s):



- Example:

```
Enter CS
    X = X + 1000
Exit CS
```

Process P1

```
Enter CS
    X = X + 1000
Exit CS
```

Process P2

Properties of Correct CS Implementation

Mutual Exclusion:

- If process P_i is executing in critical section, all other processes are prevented from entering the critical section.

Progress:

- If no process is in a critical section, one of the waiting processes should be granted access.

Bounded Wait:

- After process P_i request to enter critical section, there exists an upper bound on the number of times other processes can enter the critical section before P_i .

Independence:

- Process **not** executing in critical section should never block other process.

Symptoms of Incorrect Synchronization

■ **Deadlock:**

- ❑ All processes blocked → no progress

■ **Livelock:**

- ❑ Usually related to deadlock avoidance mechanism
- ❑ Processes keep changing state to avoid deadlock and make no other progress
- ❑ Typically processes are not blocked

■ **Starvation:**

- ❑ Some processes never get to make progress in their execution because it is perpetually denied necessary resources

CS Implementations Overview

- Assembly level implementations:
 - Mechanisms provided by the processor
- High level language implementations:
 - Utilizes only normal programming constructs
- High level abstraction:
 - Provide abstracted mechanisms that provide additional useful features
 - Commonly implemented by assembly level mechanisms

Don't worry! The processor has all the answers!

ASSEMBLY LEVEL IMPLEMENTATION

Test and Set: An Atomic Instruction

- A common machine instruction provided by processors to aid synchronization

`TestAndSet Register, MemoryLocation`

- **Behavior:**

1. Load the current content at `MemoryLocation` into `Register`
2. Stores a 1 into `MemoryLocation`

- Important: The above is performed as a **single machine operation**, i.e., **atomic**

Using Test and Set

- For ease of discussion, assume that the *TestAndSet* machine instruction has an equivalent high level language version

TestAndSet() takes a memory address M:

- Returns the current content at M
- Set content of M to 1

```
void EnterCS( int* Lock )  
{  
    while( TestAndSet( Lock ) == 1 );  
}
```

```
void ExitCS( int* Lock )  
{  
    *Lock = 0;  
}
```

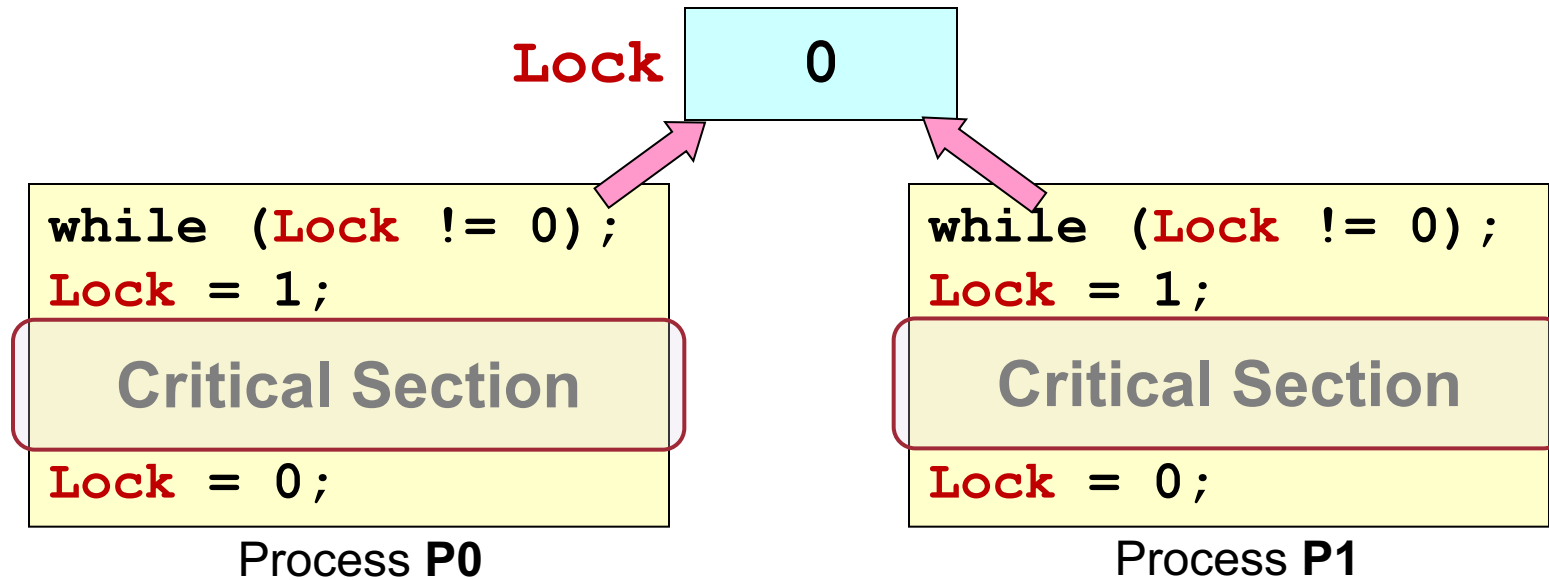
Observations and Comments

- The implementation works!
 - ❑ However, it employs **busy waiting** (keep checking the condition until it is safe to enter critical section)
 - ➔ Wasteful use of processing power
- Variants of this instruction exists on most processors:
 - ❑ Compare and Exchange
 - ❑ Atomic Swap
 - ❑ Load Link / Store Conditional

Using only your brain power.... 😊

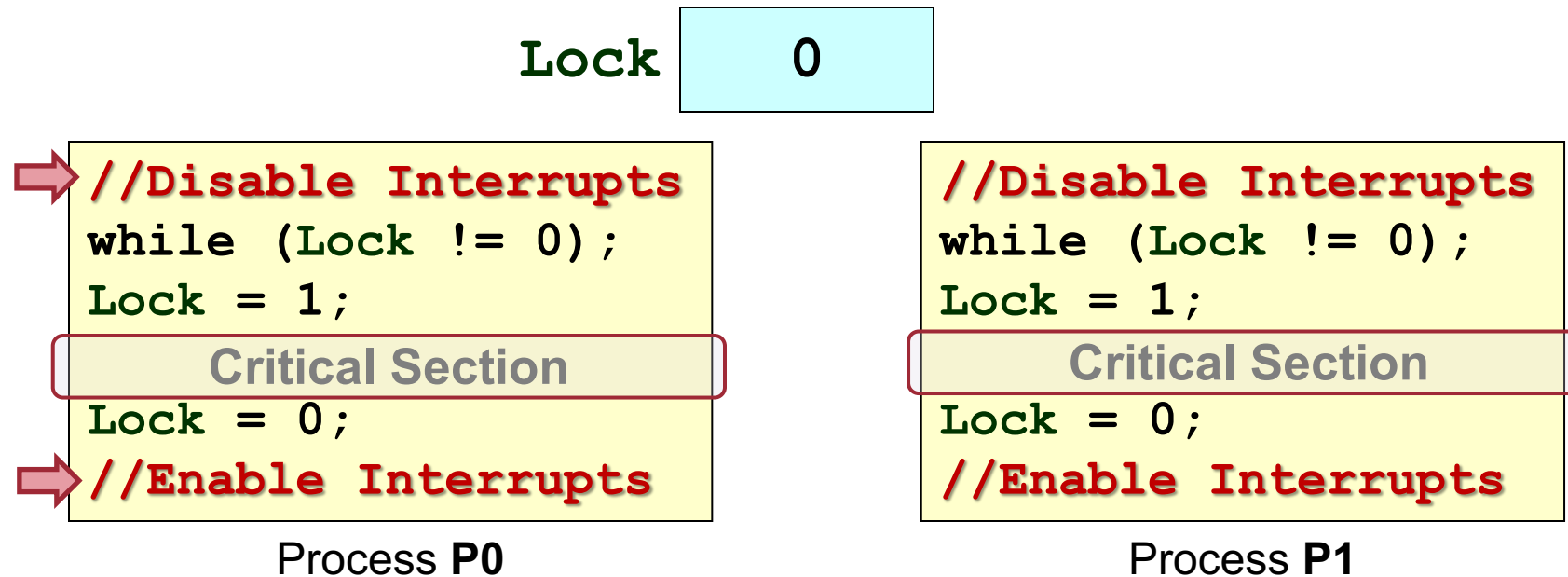
HIGH LEVEL LANGUAGE IMPLEMENTATION

Using HLL: Attempt 1



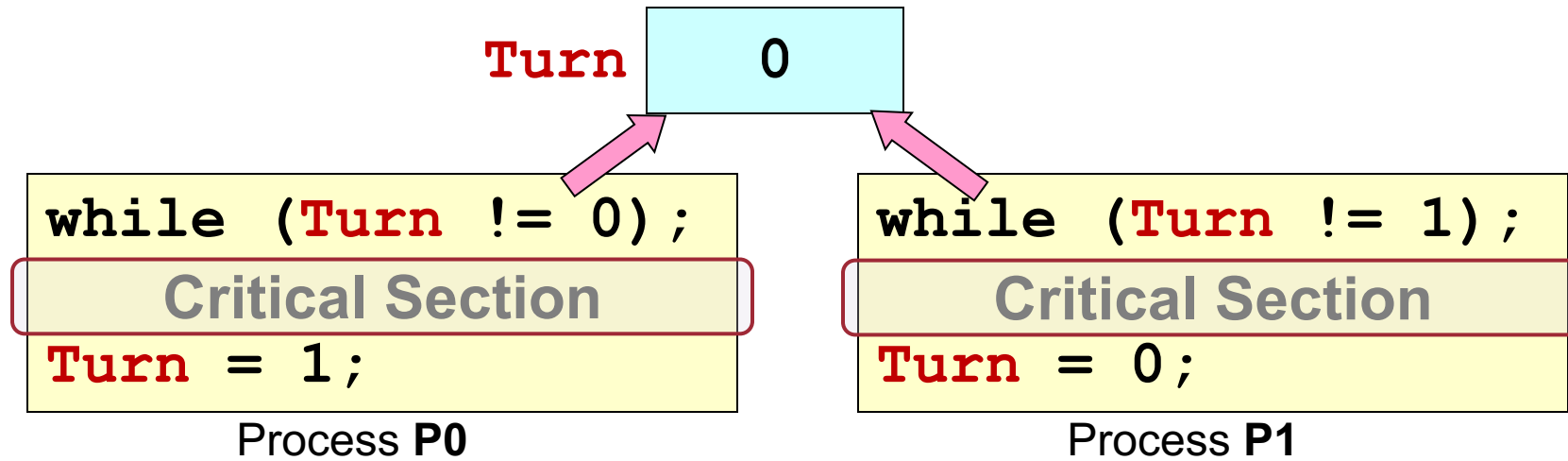
- Makes intuitive sense 😊
 - ❑ But it doesn't work properly 😞
- It violates the “Mutual Exclusion” requirement!
 - ❑ How?

Using HLL : Attempt 1 Fixed*



- Solve the problem by preventing context switch
- However:
 - ❑ Buggy critical section may stall the WHOLE system
 - ❑ Busy waiting
 - ❑ Requires permission to disable/enable interrupts

Using High Level Language: Attempt 2



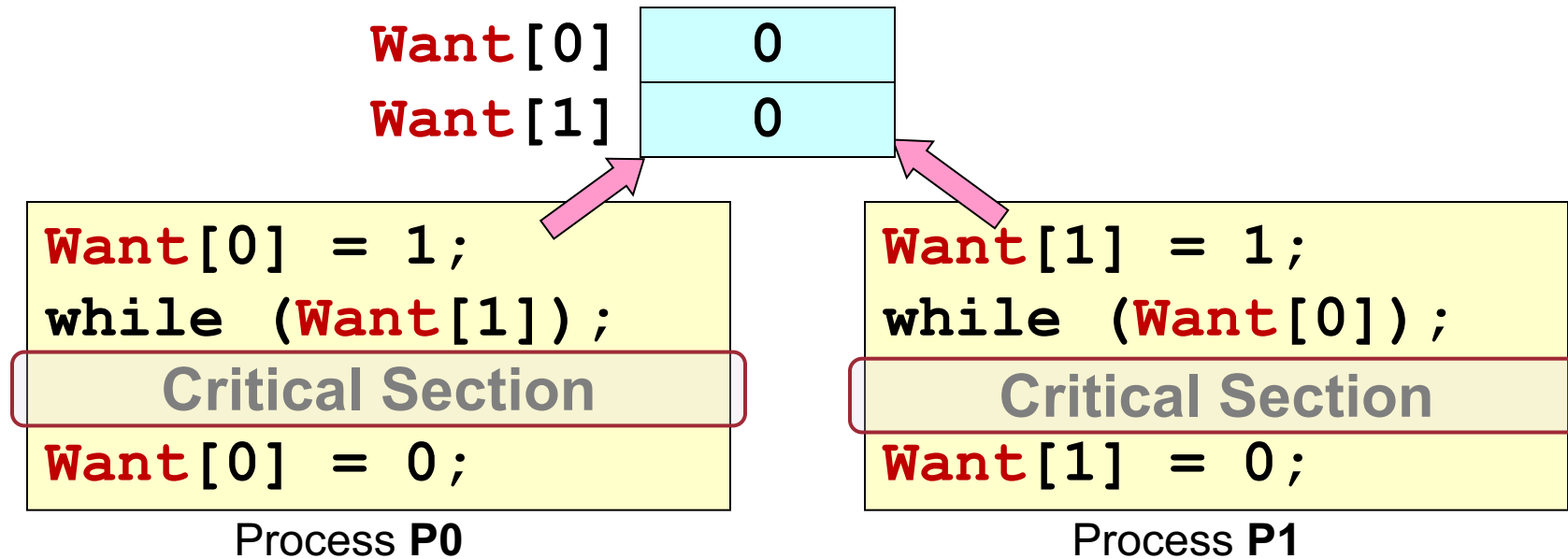
■ Assumption:

- ❑ P0 and P1 executes the above in loop
- ❑ Take turn to enter **critical section**

■ Problems:

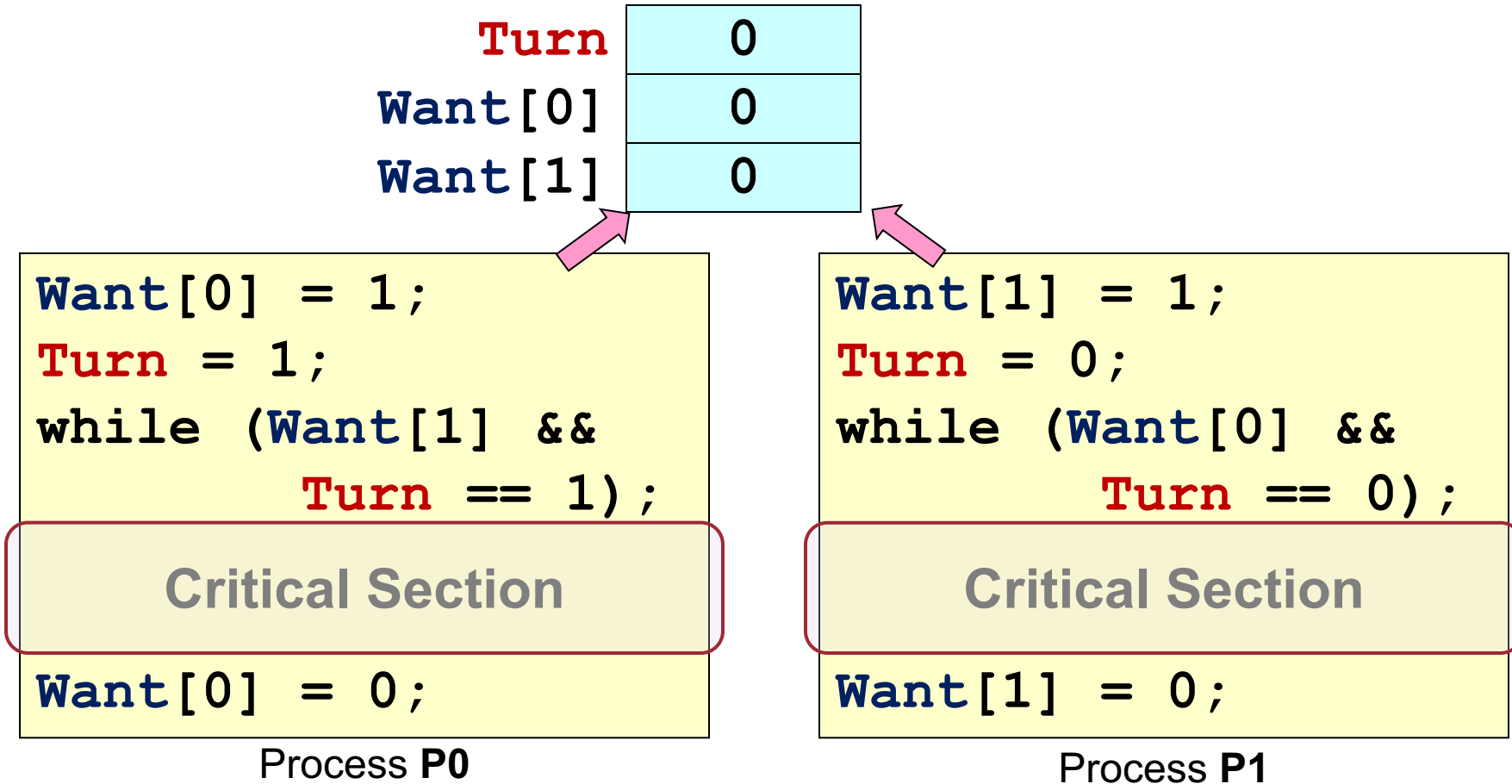
- ❑ Starvation:
 - e.g., If P0 never enters CS, P1 starves
- ❑ Violate the **independence** property!

Using High Level Language: Attempt 3



- Solve the independence problem
 - ❑ If P0 or P1 is not around, another process can still enter CS
- Problem:
 - ❑ Deadlock! Try identify the execution sequence that causes deadlock

Peterson's Algorithm



- Assumption:
 - Writing to **Turn** is an **atomic** operation

Peterson's Algorithm: **Disadvantages**

- **Busy Waiting:**
 - ❑ The waiting process repeatedly test the while-loop condition instead of going into blocked state:
- **Low level:**
 - ❑ Higher-level programming construct is desirable
 - simplify mutual exclusion
 - less error prone
- **Not general:**
 - ❑ General synchronization mechanism is desirable
 - Not just mutual exclusion

Let's go meta.....

HIGH LEVEL ABSTRACTION

High Level Synchronization Mechanism

■ Semaphore:

- ❑ An generalized synchronization mechanism
- ❑ Only behaviors are specified → can have different implementations
- ❑ Provides
 - A way to block a number of processes
 - ❑ Known as **sleeping process**
 - A way to unblock/wake up one or more sleeping process

■ History:

- ❑ Proposed by **Edgar W. Dijkstra** in 1965

Semaphore: **Wait**() and **Signal**()

- A semaphore **S** contains an integer value
 - Can be initialized to any non-negative values initially
- Two **atomic** semaphore operations:

□ **Wait**(**S**)

- If $S \leq 0$, blocks (go to sleep)
- Decrement **S**
- Also known as **P**() or **Down**()

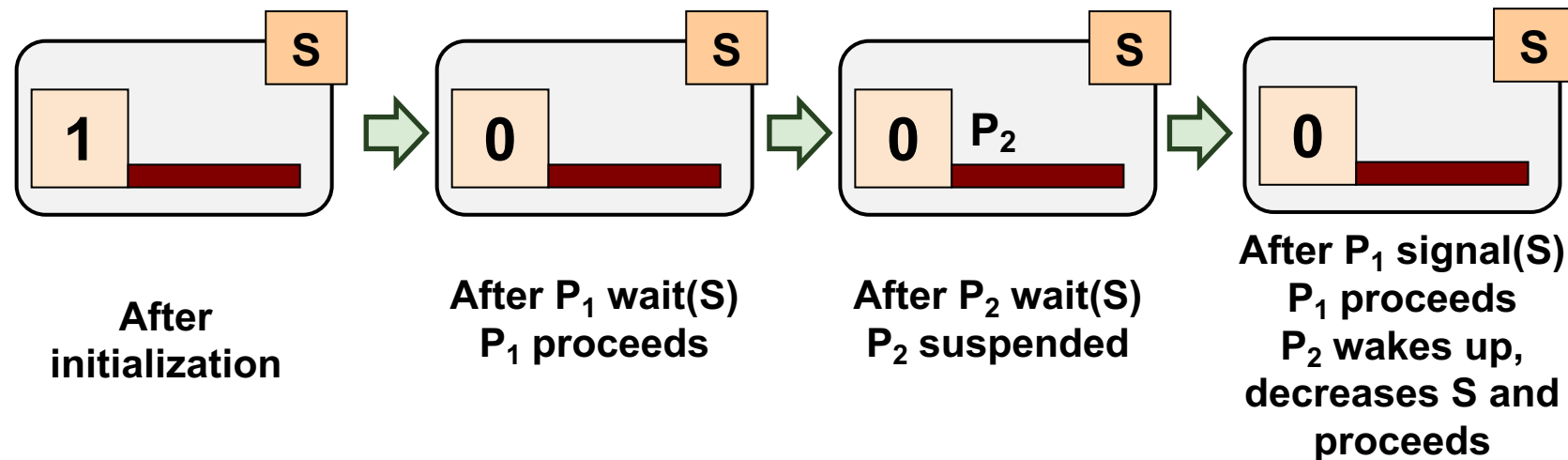
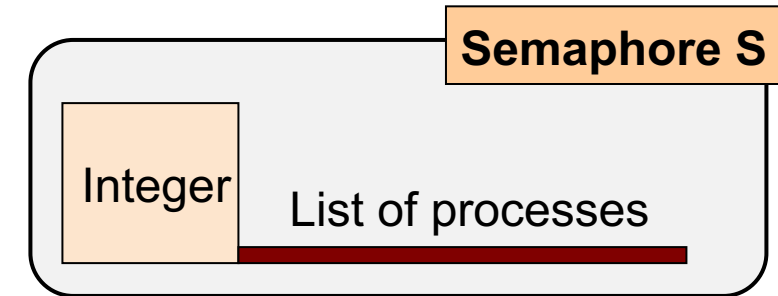
□ **Signal**(**S**)

- Increments **S**
- Wakes up one sleeping process if any
- This operation **never** blocks
- Also known as **V**() or **Up**()

- **Reminder:** The above specifies the **behavior**, not the implementations

Semaphore: **Visualization**

- To aid understanding, you can visualize semaphore as:
 - ❑ A protected integer
 - ❑ A list to keep track of waiting processes
- Example:



Semaphores: **Properties**

- Given:

- $S_{\text{Initial}} \geq 0$

- Then, the following **invariant** must be true:

$$S_{\text{current}} = S_{\text{Initial}} + \# \text{signal}(S) - \# \text{wait}(S)$$

- $\# \text{signal}(S)$:

- number of `signal()` operations executed

- $\# \text{wait}(S)$:

- number of `wait()` operations **completed**

General and Binary Semaphores

- **General semaphore S:**

- $S \geq 0$ ($S = 0, 1, 2, 3, \dots$)
- also called **counting semaphores**

- **Binary semaphore S:**

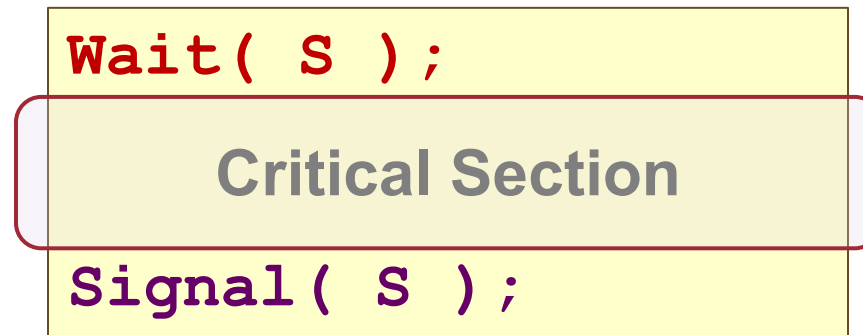
- $S = 0$ or 1

- General semaphore is provided for convenience

- Binary semaphore is sufficient
- i.e., general semaphore can be mimicked by binary semaphores

Semaphore Example: **Critical Section**

- Binary semaphore $s = 1$
- For any process:



- In this case, S can only be 0 or 1
 - Can be deduced by the semaphore invariant
- This usage of semaphore is commonly known as **mutex** (**mut**ual **ex**clusion)

Mutex: Correct CS - Informal Proof

■ Mutual Exclusion:

- N_{CS} = Num of processes in critical section
= Num of processes that completed `wait()` but not `signal()`
= `#Wait(S) - #Signal(S)`
- $S_{Initial} = 1$
- $S_{current} = 1 + \#Signal(S) - \#Wait(S)$
- $S_{current} + N_{CS} = 1$
- Since $S_{current} \geq 0 \Rightarrow N_{CS} \leq 1$

Mutex: Correct CS - Informal Proof (cont)

■ **Deadlock:**

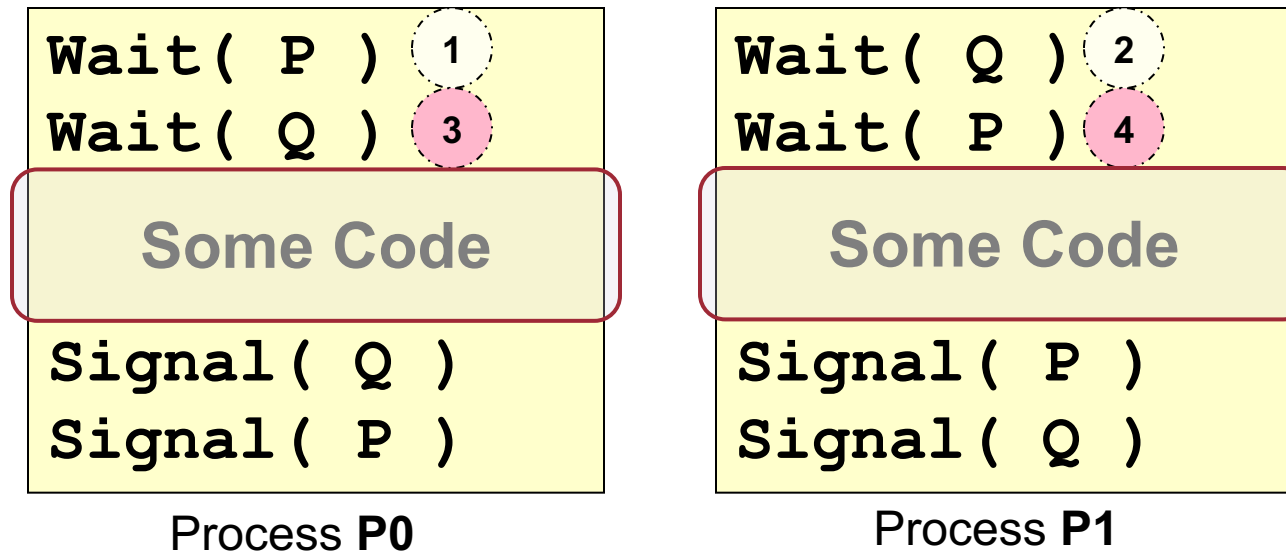
- Deadlock means **all** processes stuck at `wait(S)`
 - $S_{\text{current}} = 0$ and $N_{\text{CS}} = 0$
- But $S_{\text{current}} + N_{\text{CS}} = 1$
- →← (contradiction)

■ **Starvation:**

- Suppose **P1** is blocked at `wait(S)`
- **P2** is in CS, exits CS with `signal(S)`
 - If no other process sleeping, **P1** wakes up
 - If there are other process, **P1** eventually wakes up (assuming fair scheduling)

Incorrect Use of Semaphore: Deadlock

- Deadlock is still possible with incorrect use of semaphore
- Example:
 - ❑ Assume semaphores **P = 1**, **Q = 1** initially



Other High Level Abstractions

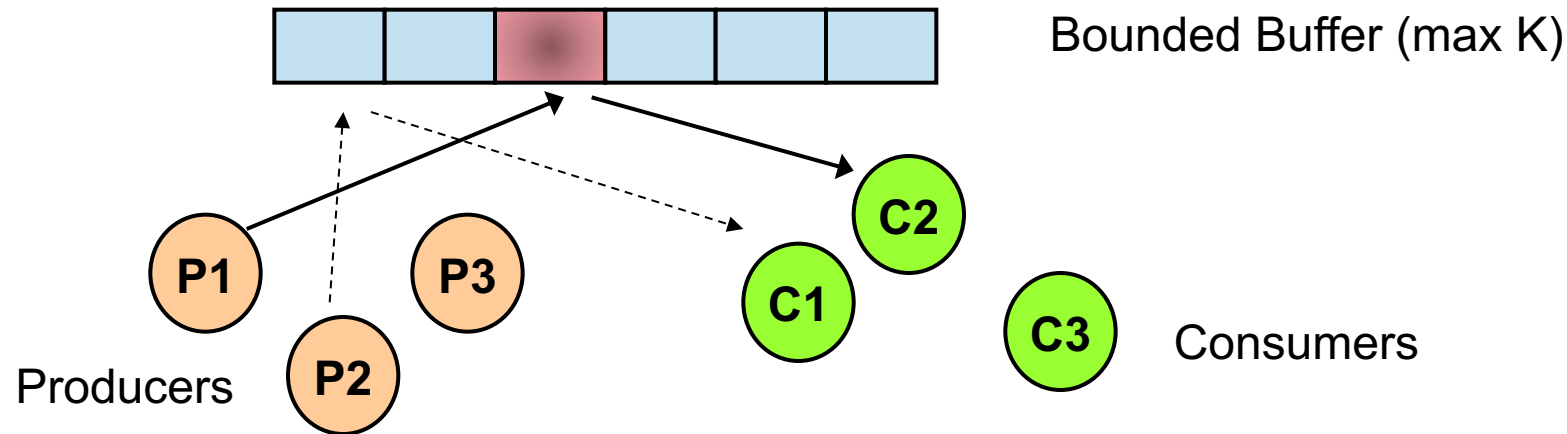
- Semaphore is very powerful:
 - ❑ There are no known unsolvable synchronization problem with semaphore (so far 😊)
 - ❑ Other high level abstractions essentially provide extended features that are inconvenient to express using semaphore alone
- Common alternative: **Conditional Variable**
 - ❑ Allow a task to wait for certain event to happen
 - ❑ Has the ability to ***broadcast***, i.e., wakes up all waiting tasks
 - ❑ related to **monitor**

Killing brain cells of generations of students.....

CLASSICAL SYNCHRONIZATION PROBLEMS

Producer Consumer: Specification

- Processes share a bounded buffer of size K
 - **Producers** produce items to insert in buffer
 - Only when the buffer is **not full** ($< K$ items)
 - **Consumers** remove items from buffer
 - Only when the buffer is **not empty** (> 0 items)



Producer Consumer: **Busy Waiting**

```
while (TRUE) {  
    Produce Item;  
    while (!canProduce);  
    wait( mutex );  
    if (count < K) {  
        buffer[in] = item;  
        in = (in+1) % K;  
        count++;  
        canConsume = TRUE;  
    } else  
        canProduce = FALSE;  
    signal( mutex );  
}
```

Producer Process

```
while (TRUE) {  
    while (!canConsume);  
    wait( mutex );  
    if (count > 0) {  
        item = buffer[out];  
        out = (out+1) % K;  
        count--;  
        canProduce = TRUE;  
    } else  
        canConsume = FALSE;  
    signal( mutex );  
    Consume Item;  
}
```

Consumer Process

■ Initial Values:

- ❑ **count = in = out = 0**
- ❑ **mutex = S(1)** //semaphore with initial value 1
- ❑ **canProduce = TRUE** and **canConsume = FALSE**;

Producer Consumer: **Busy Waiting**

- **canConsume:**
 - ❑ Triggers consumer to *try* to get item
- **canProduce:**
 - ❑ Triggers producer to *try* to produce item
- **wait(mutex) + signal(mutex)** : Creates a CS
- **in = (in+1) % K :**
out = (out+1) % K : Wraps around, circular array
- **Evaluation:**
 - ❑ The code **correctly solves** the problem
 - ❑ However, **busy-waiting** is used

Producer Consumer: **Blocking Version**

```
while (TRUE) {  
    Produce Item;  
  
    wait( notFull );  
    wait( mutex );  
    buffer[in] = item;  
    in = (in+1) % K;  
    count++;  
    signal( mutex );  
    signal( notEmpty );  
}
```

Producer Process

```
while (TRUE) {  
  
    wait( notEmpty );  
    wait( mutex );  
    item = buffer[out];  
    out = (out+1) % K;  
    count--;  
    signal( mutex );  
    signal( notFull );  
  
    Consume Item;  
}
```

Consumer Process

■ Initial Values:

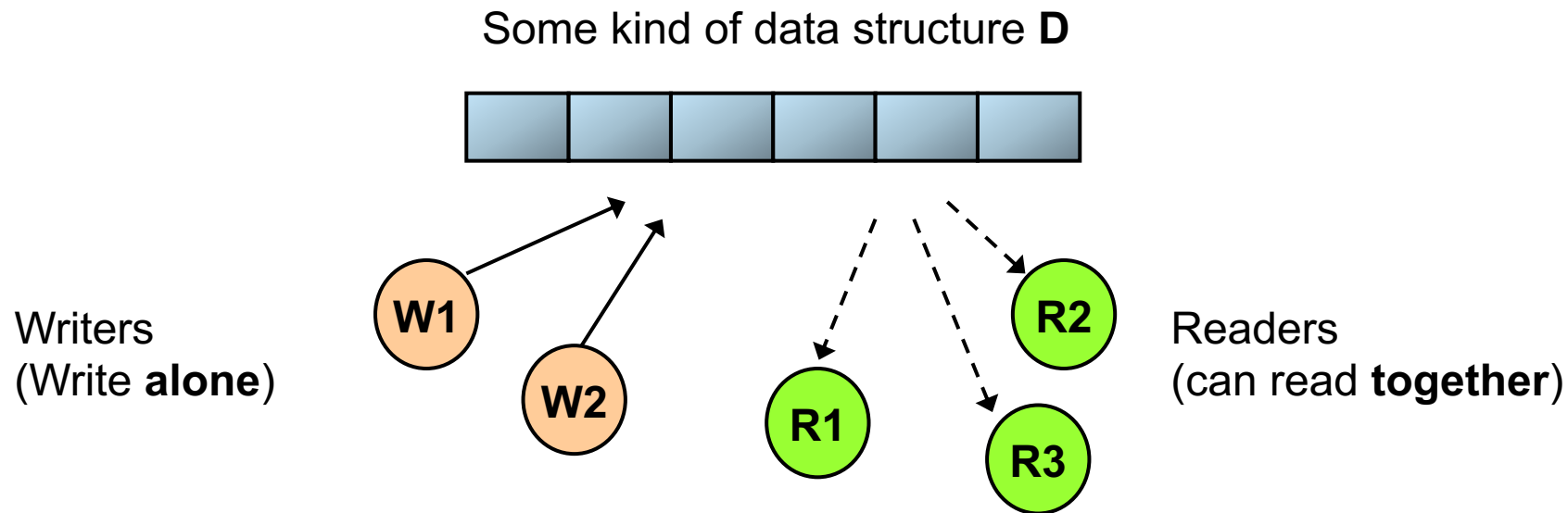
- ❑ `count = in = out = 0`
- ❑ `mutex = S(1), notFull = S(K), notEmpty = S(0)`

Producer Consumer: **Blocking Version**

- `wait(notFull)` : Forces producers to go to sleep
- `wait(notEmpty)` : Forces consumers to go to sleep
- `signal(notFull)` : 1 consumer wakes up 1 producer
- `signal(notEmpty)` : 1 producer wakes up 1 consumer
- Evaluation:
 - This code correctly solve the problem
 - No busy-waiting, “unwanted” producer/consumer will go to sleep on respective semaphores

Readers Writers: Specification

- Processes share a data structure **D**:
 - Reader: Retrieves information from **D**
 - Writer: Modifies information in **D**
- Writer must have exclusive access to **D**
- Reader can access with other readers



Readers Writers: Simple Version

```
while (TRUE) {  
  
    wait( roomEmpty );  
  
    Modifies data  
  
    signal( roomEmpty );  
}
```

Writer Process

■ Initial Values:

- ❑ roomEmpty = S(1)
- ❑ mutex = S(1)
- ❑ nReader = 0

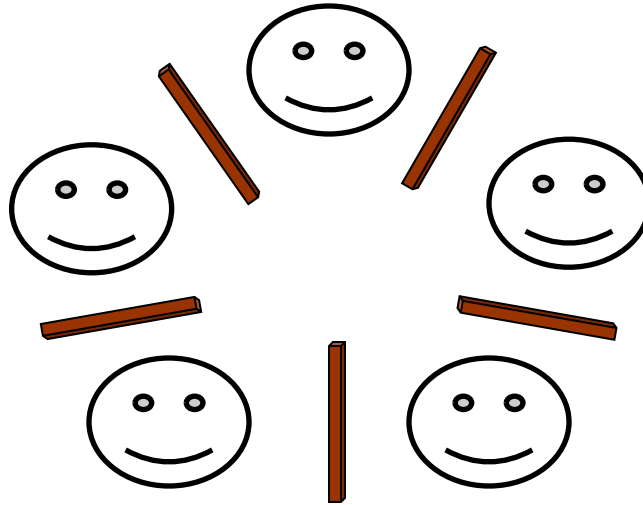
```
while (TRUE) {  
  
    wait( mutex );  
    nReader++;  
    if (nReader == 1)  
        wait( roomEmpty );  
    signal( mutex );  
  
    Reads data  
  
    wait( mutex );  
    nReader--;  
    if (nReader == 0)  
        signal( roomEmpty );  
    signal( mutex );  
  
}
```

Reader Process

Readers Writers: **Evaluation**

- Convince yourself that the solution satisfies the specification
- However:
 - It has one problem
 - (hint: Something to do with writer....)

Dining Philosophers: Specification



- Five philosophers are seated around a table
 - There are five single chopstick placed between each pair of philosopher
 - When any philosopher wants to eat, he/she will have to acquire both chopsticks from his/her left and right
- Devise a **deadlock-free** and **starve-free** way to allow the philosopher to eat freely

Dining Philosophers: **Attempt 1**

```
#define N 5
#define LEFT i
#define RIGHT ((i+1) % N)

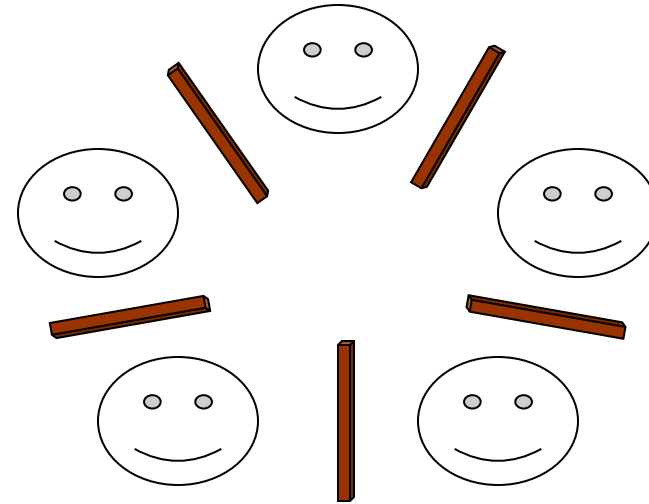
//For philosopher i
while (TRUE){

    Think( );
    //hungry, need food!
    takeChpStk( LEFT );
    takeChpStk( RIGHT );

    Eat( );

    putChpStk( LEFT );
    putChpStk( RIGHT );

}
```



■ Can you figure out the problem?

Dining Philosophers: **Attempt 1**

■ Deadlock:

- ❑ All philosopher simultaneously takes up the left chopstick, and none can proceed

■ Fix attempt:

- ❑ Make the philosopher to put down the left chopstick if right chopstick cannot be acquired
 - Try again later
- ❑ No deadlock:
 - Livelock: All philosopher take up left chopstick, put it down, take it up, put it down,

Dining Philosopher: **Attempt 2**

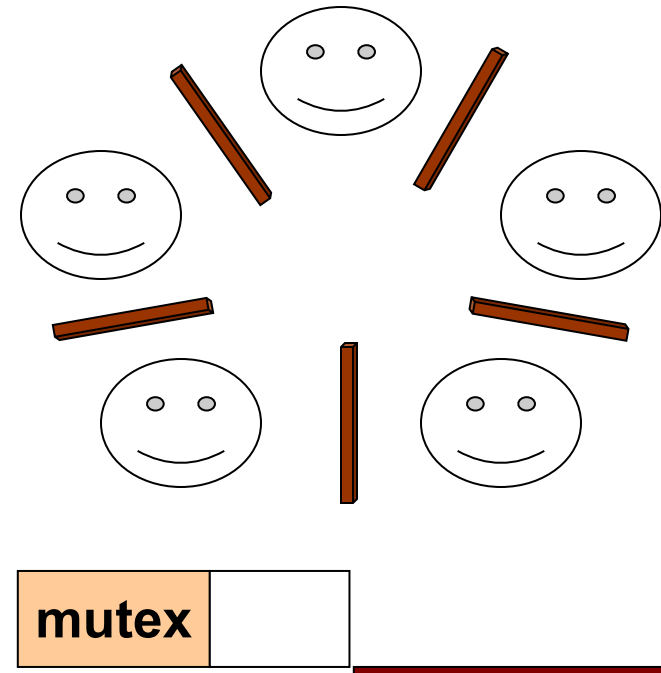
```
#define N 5
#define LEFT i
#define RIGHT ((i+1) % N)

//For philosopher i
while (TRUE){
    Think( );

    wait( mutex );

    takeChpStk( LEFT );
    takeChpStk( RIGHT );
    Eat( );
    putChpStk( LEFT );
    putChpStk( RIGHT );

    signal( mutex );
}
```



- Two questions:
 - ❑ Does it work?
 - ❑ Is it good?

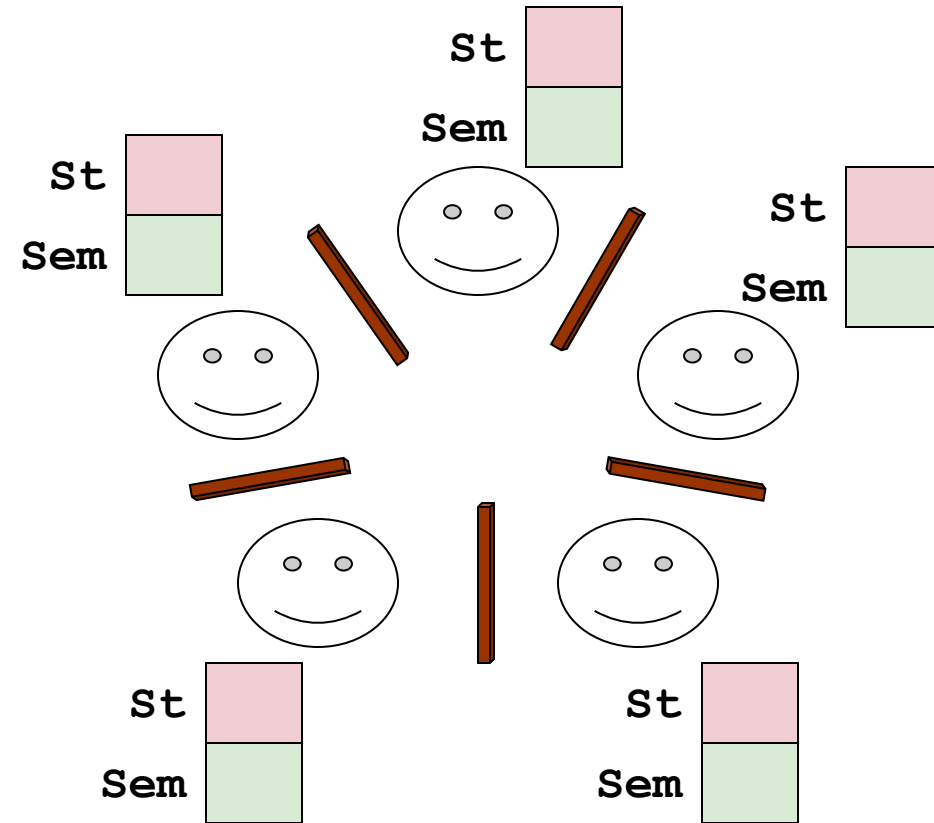
Dining Philosopher: **Tanenbaum Solution**

```
#define N 5
#define LEFT ((i+N-1) % N)
#define RIGHT ((i+1) % N)

#define THINKING 0
#define HUNGRY 1
#define EATING 2

int state[N];
Semaphore mutex = 1;
Semaphore s[N];

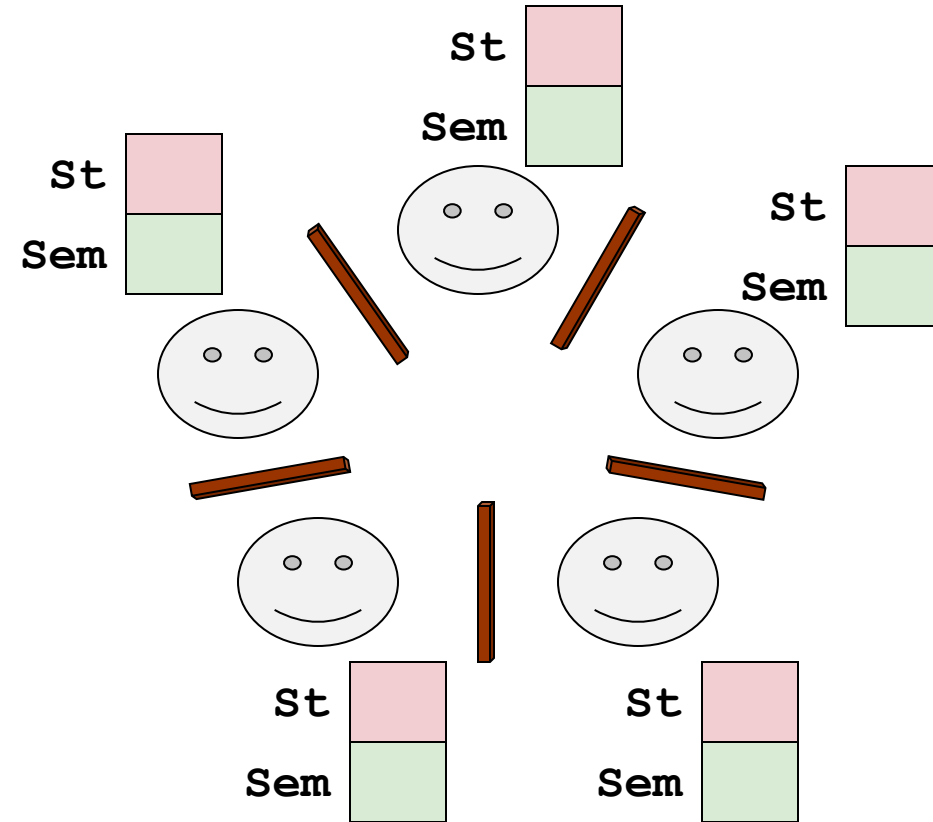
void philosopher( int i ){
    while (TRUE){
        Think( );
        takeChpStcks( i );
        Eat( );
        putChpStcks( i );
    }
}
```



Dining Philosopher: Tanenbaum Solution

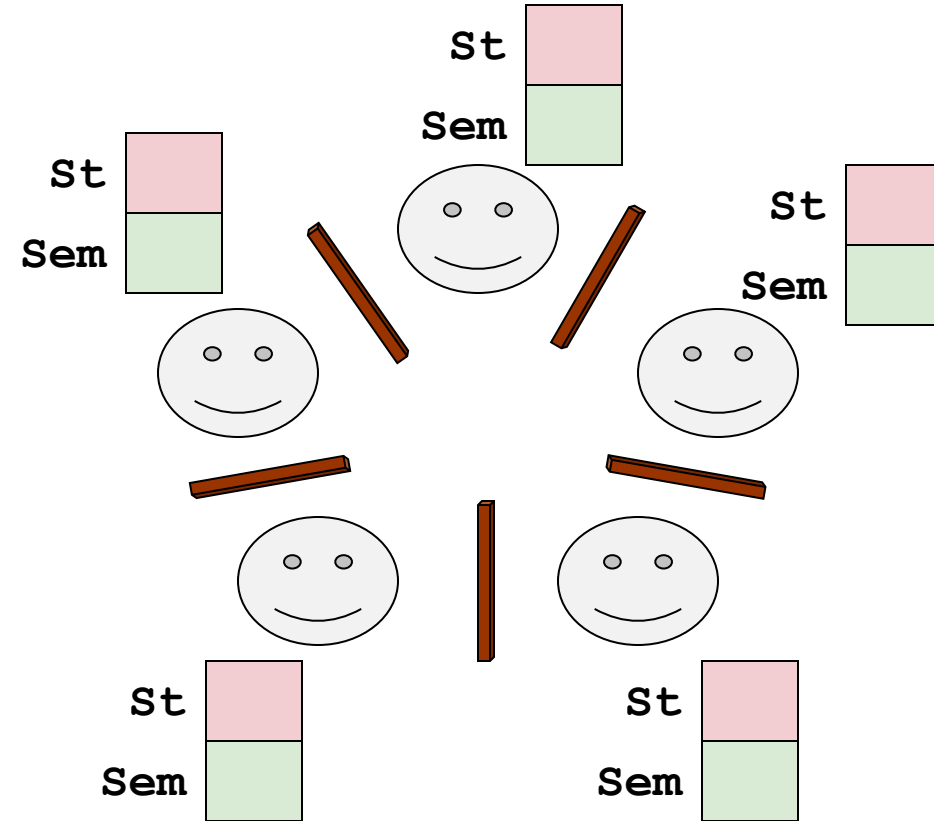
```
void takeChpStcks( i )  
{  
    wait( mutex );  
    state[i] = HUNGRY;  
    safeToEat( i );  
    signal( mutex );  
    wait( s[i] );  
}
```

```
void safeToEat( i )  
{  
    if( (state[i] == HUNGRY) &&  
        (state[LEFT] != EATING) &&  
        (state[RIGHT] != EATING) ) {  
        state[ i ] = EATING;  
        signal( s[i] );  
    }  
}
```



Dining Philosopher: **Tanenbaum Solution**

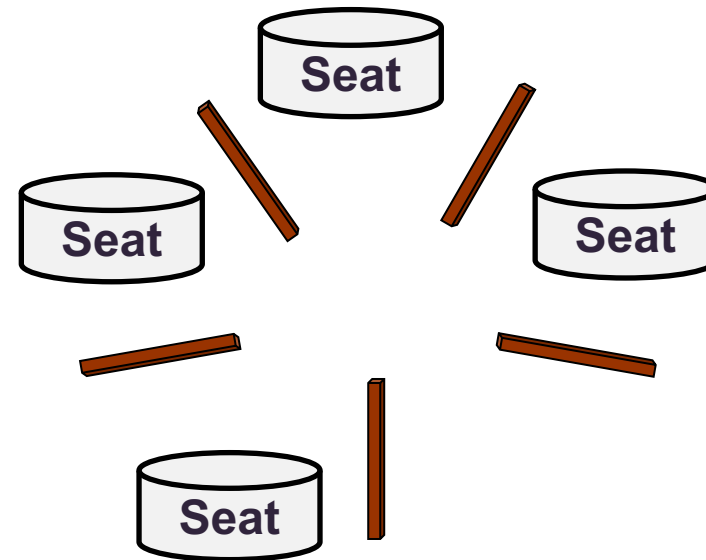
```
void putChpStcks( i )  
{  
    wait( mutex );  
  
    state[i] = THINKING;  
    safeToEat( LEFT );  
    safeToEat( RIGHT );  
  
    signal( mutex );  
}
```



Dining Philosopher: **Limited Eater**

- If at most 4 philosophers are allowed to sit at the table (leaving one empty seat)
➔ **Deadlock is impossible!**

```
void philosopher( int i ){  
    while (TRUE){  
        Think( );  
        wait( seats );  
        wait( chpStk[LEFT] );  
        wait( chpStk[RIGHT] );  
        Eat( );  
        signal( chpStk[LEFT] );  
        signal( chpStk[RIGHT] );  
        signal( seats );  
    }  
}
```



- Initial Values:
 - ❑ `seats = S(4)`
 - ❑ `chpStk = S(1)[5]`

SYNCHRONIZATION IMPLEMENTATIONS

POSIX Semaphore

- Popular implementation of semaphore under Unix
- Header File:
 - ❑ `#include <semaphore.h>`
- Compilation Flag:
 - ❑ `gcc something.c -lrt`
 - ❑ Stand for "real time library"
- Basic Usage:
 - ❑ Initialize a semaphore
 - ❑ Perform `wait()` or `signal()` on semaphore

pthread Mutex and Conditional Variables

- Synchronization mechanisms for pthreads
- Mutex (`pthread_mutex`):
 - ❑ Binary semaphore (i.e., equivalent `Semaphore(1)`).
 - ❑ Lock: `pthread_mutex_lock()`
 - ❑ Unlock: `pthread_mutex_unlock()`
- Conditional Variables(`pthread_cond`):
 - ❑ Wait: `pthread_cond_wait()`
 - ❑ Signal: `pthread_cond_signal()`
 - ❑ Broadcast: `pthread_cond_broadcast()`

Others

- Programming languages with thread support will have some forms of synchronization mechanisms
- Examples:
 - ❑ **Java**: all object has built-in lock (mutex), **synchronized** method access, etc.
 - ❑ **Python**: supports mutex, semaphore, conditional variable, etc.
 - ❑ **C++**: Added built-in thread in C++11; Support mutex, conditional variable

Summary

■ Synchronization:

- ❑ Problem: Race condition
- ❑ Solution: Critical Section
- ❑ Criteria of good solution:
 - Mutual Exclusion, progress, bounded waiting time, independence
- ❑ Important High Level Construct: Semaphore

■ Classic Synchronization problems:

- ❑ Producer + Consumer
- ❑ Reader + Writer
- ❑ Dining Philosophers

Reference

- Modern Operating System (3rd Edition)
 - Chapter 2.4
- Operating System Concepts (7th Edition)
 - Chapter 5
- Edgar W. Dijkstra, “Note No.123: Cooperating Sequential Processes”
 - <http://www.cs.utexas.edu/users/EWD/ewd01xx/EWD123.PDF>