

# Synchronization

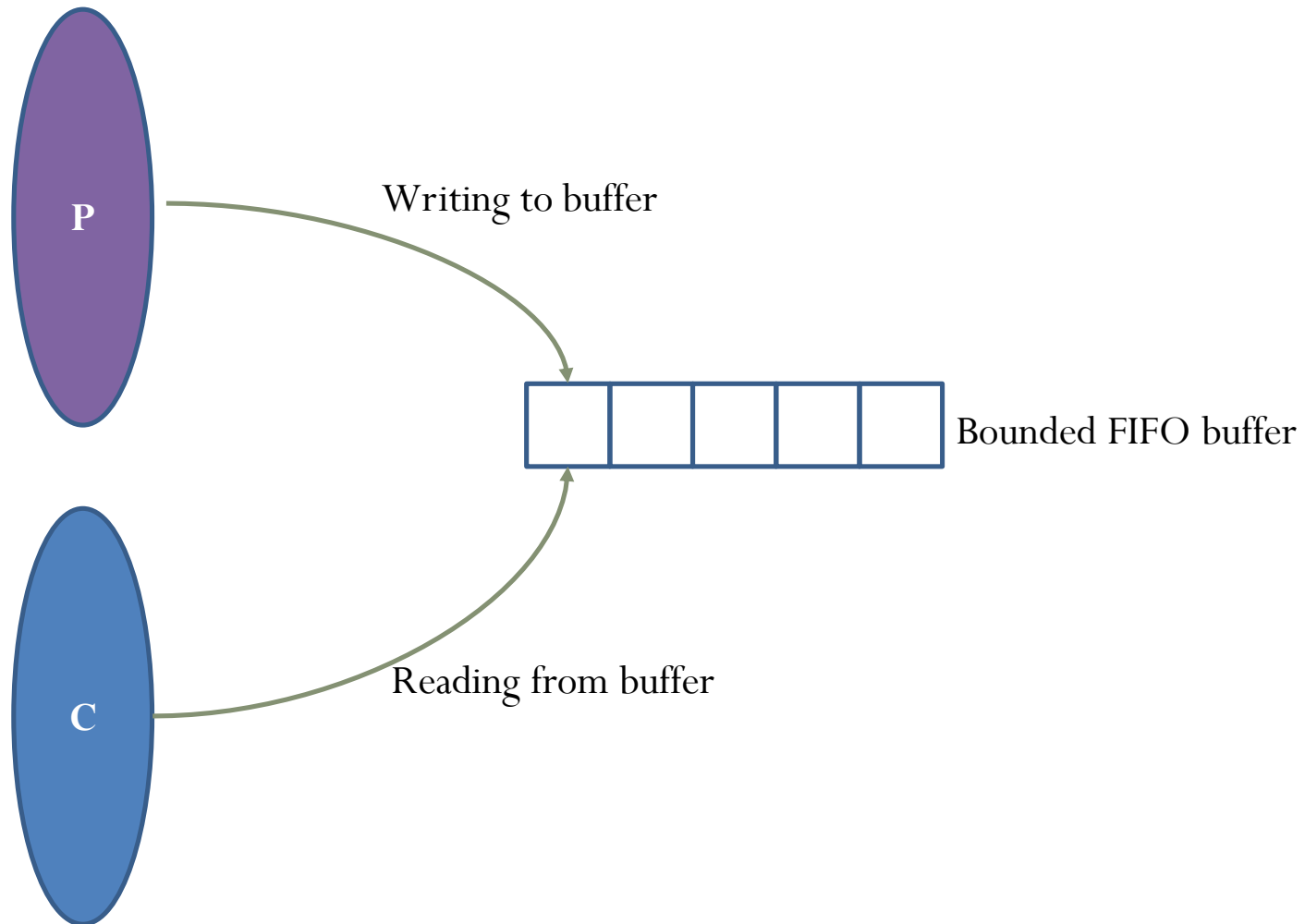
Instructor: William Zheng

Email:

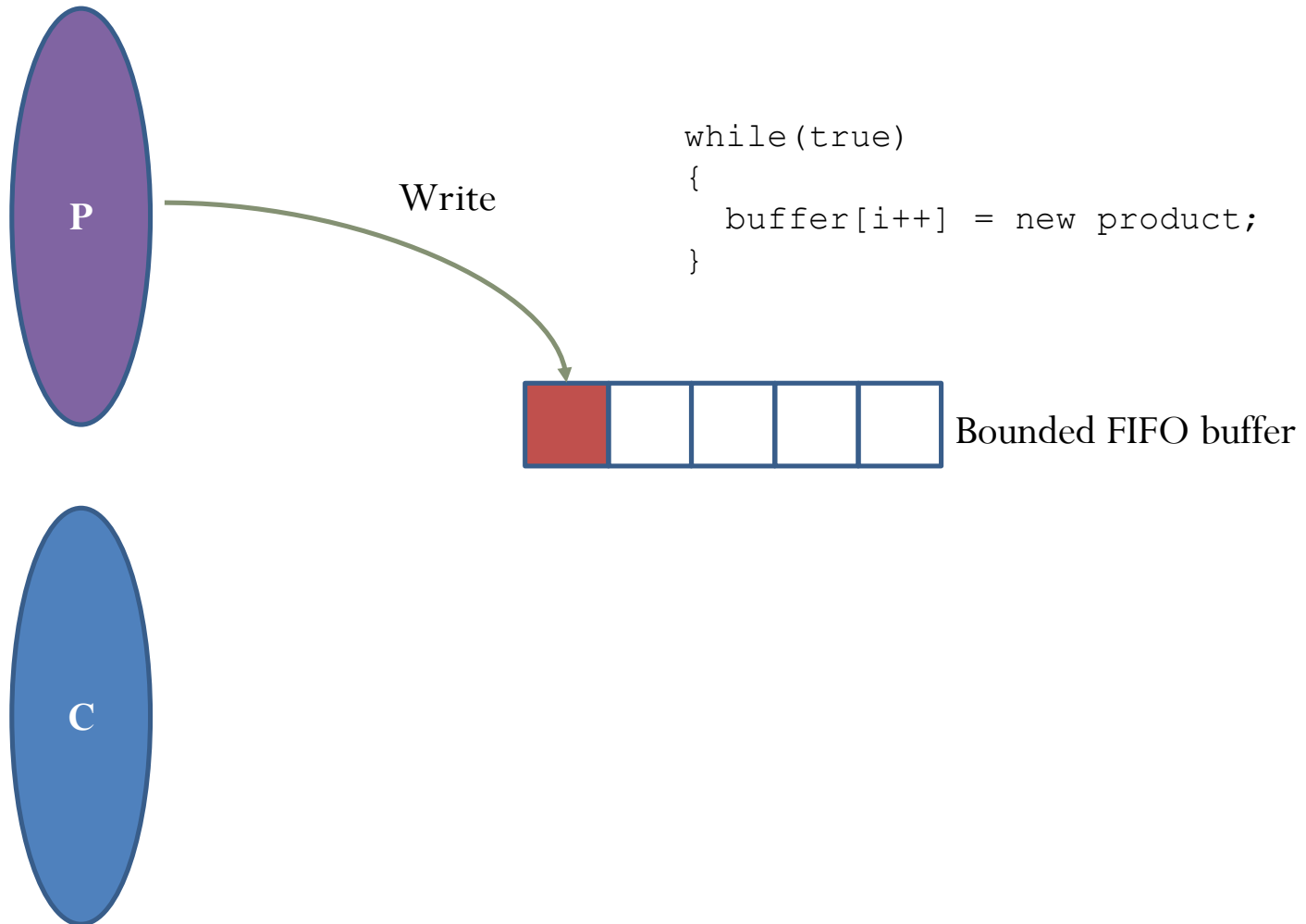
[william.zheng@digipen.edu](mailto:william.zheng@digipen.edu)

PHONE EXT: 1745

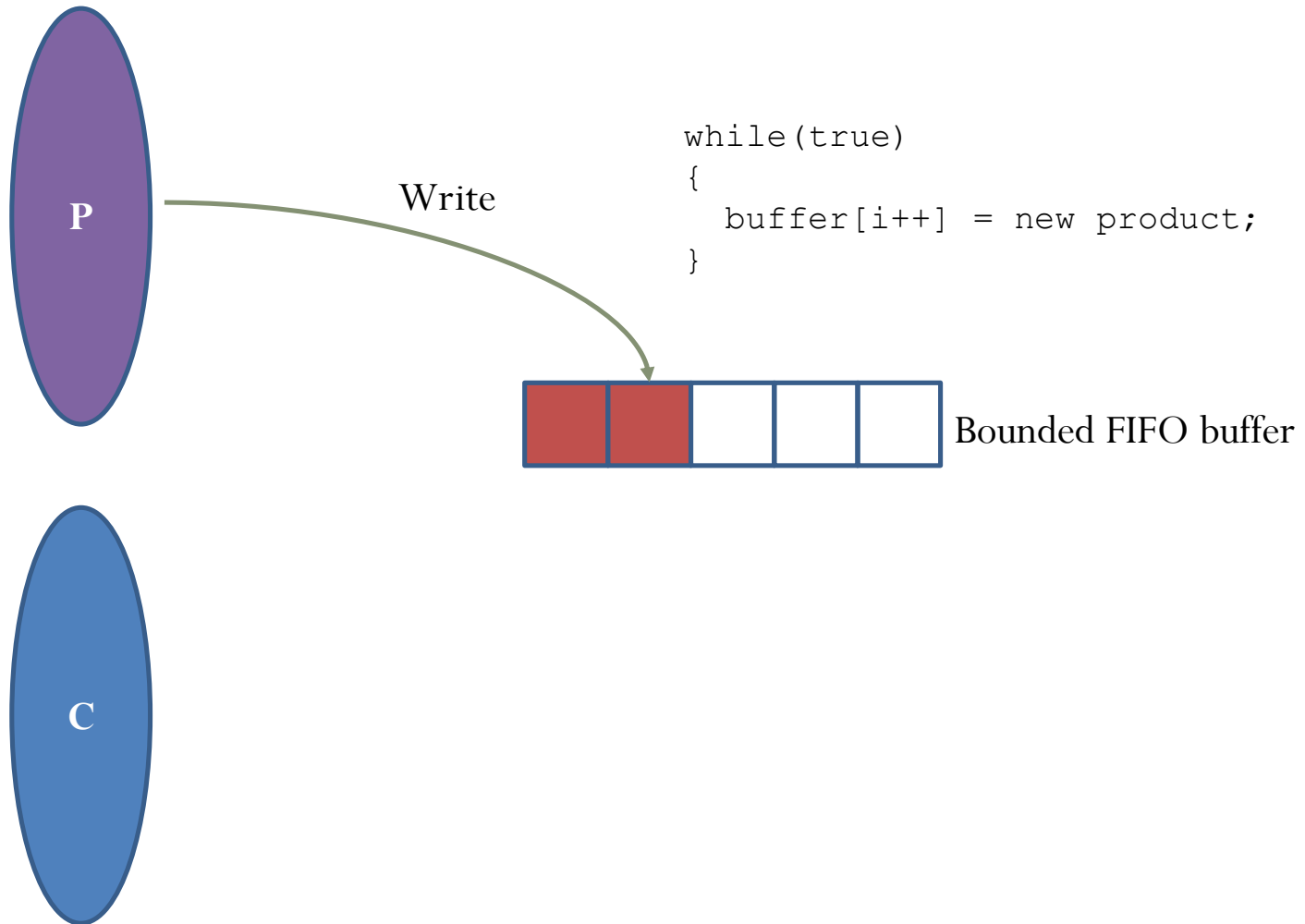
# Producer – Consumer Problem



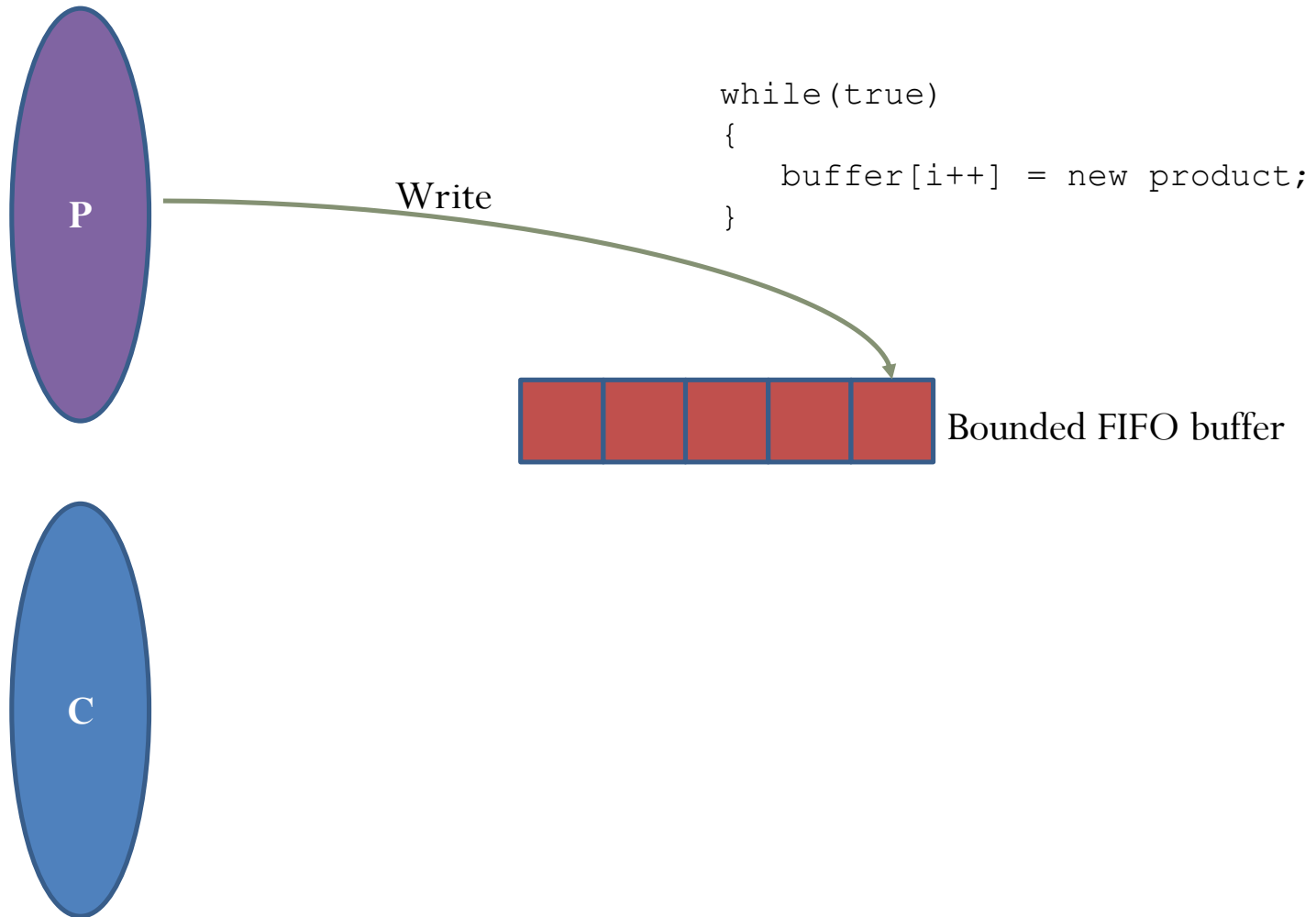
# Producer writes to buffer



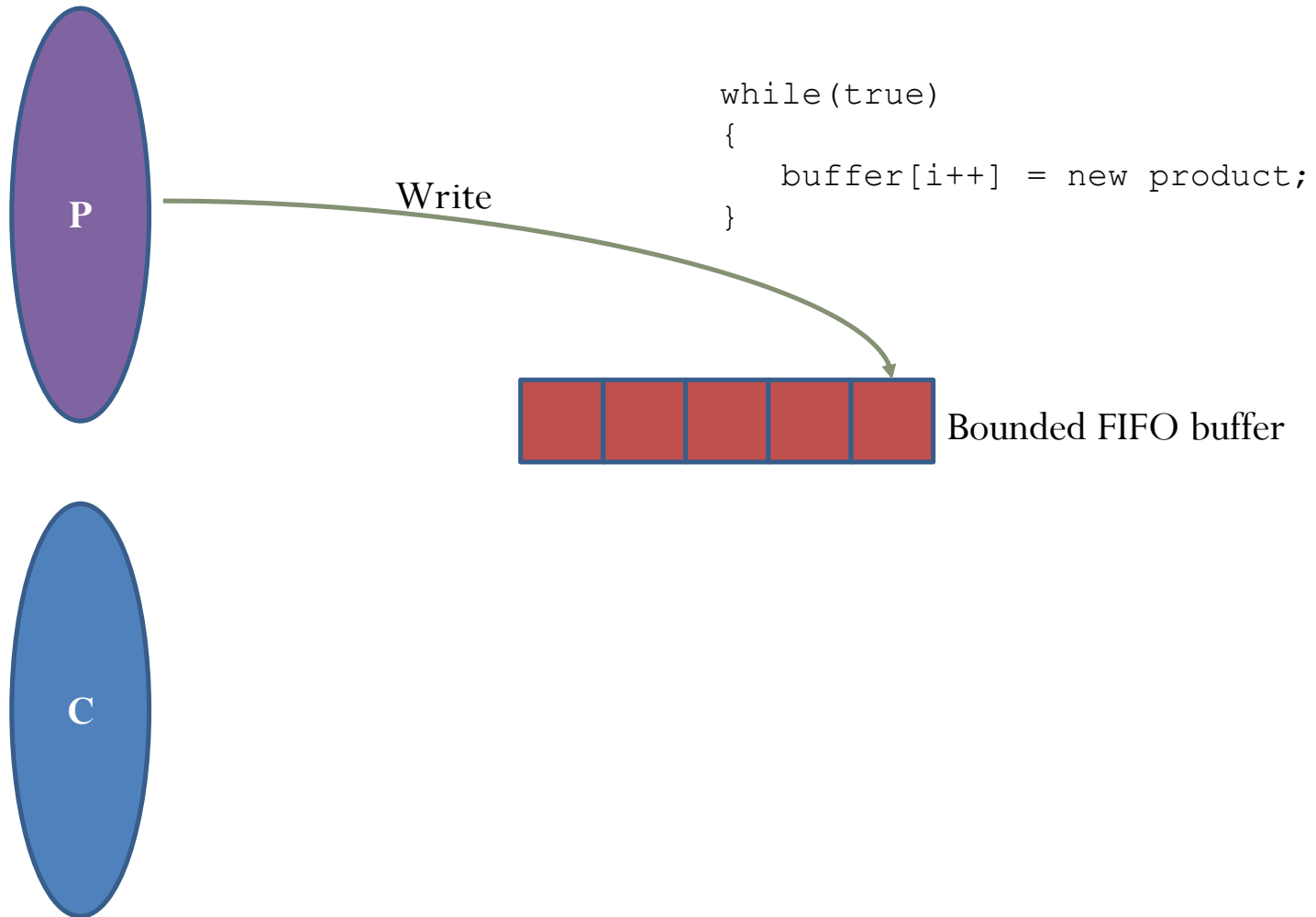
# Buffer filling



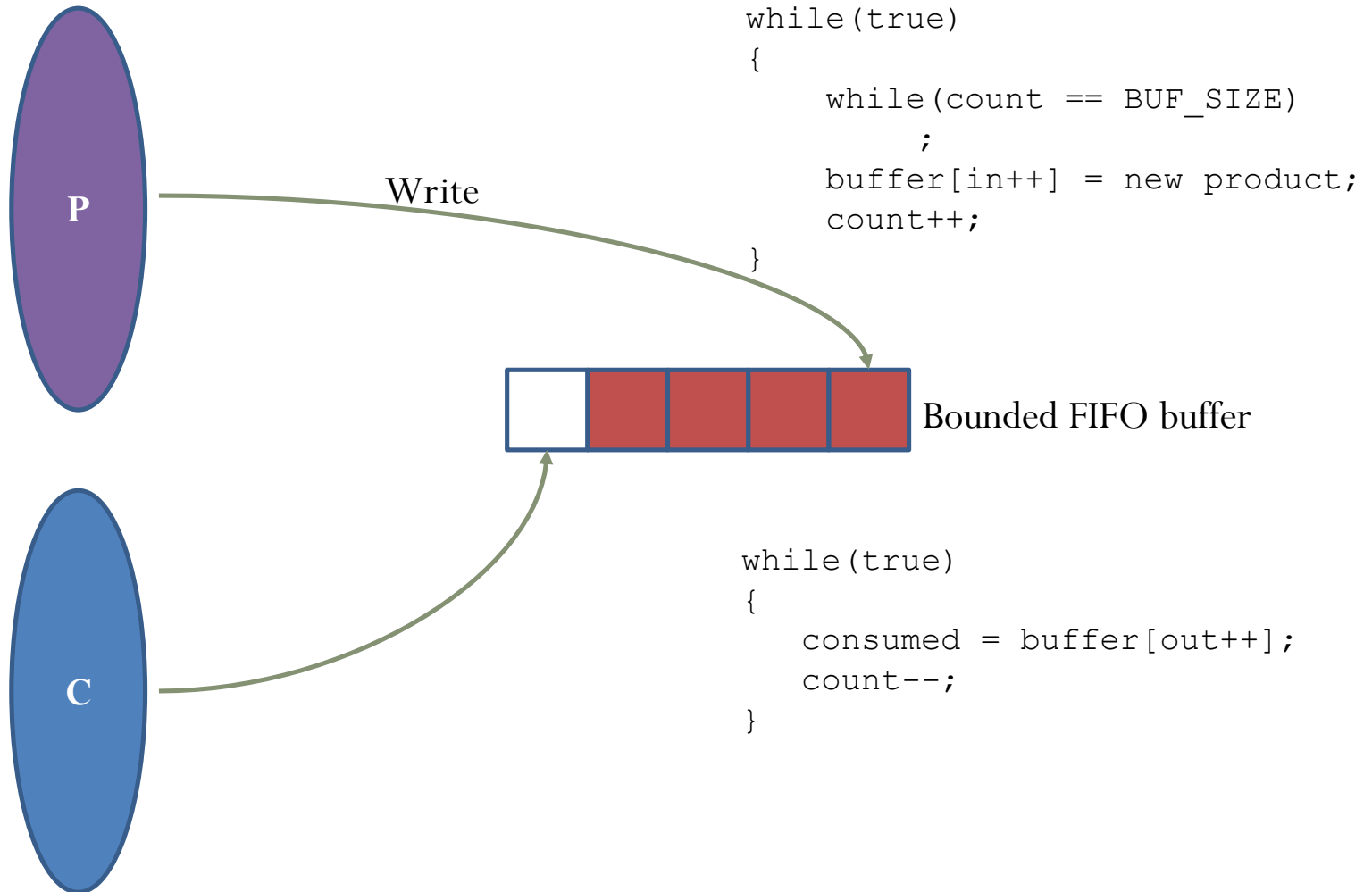
# Stop when buffer is full!



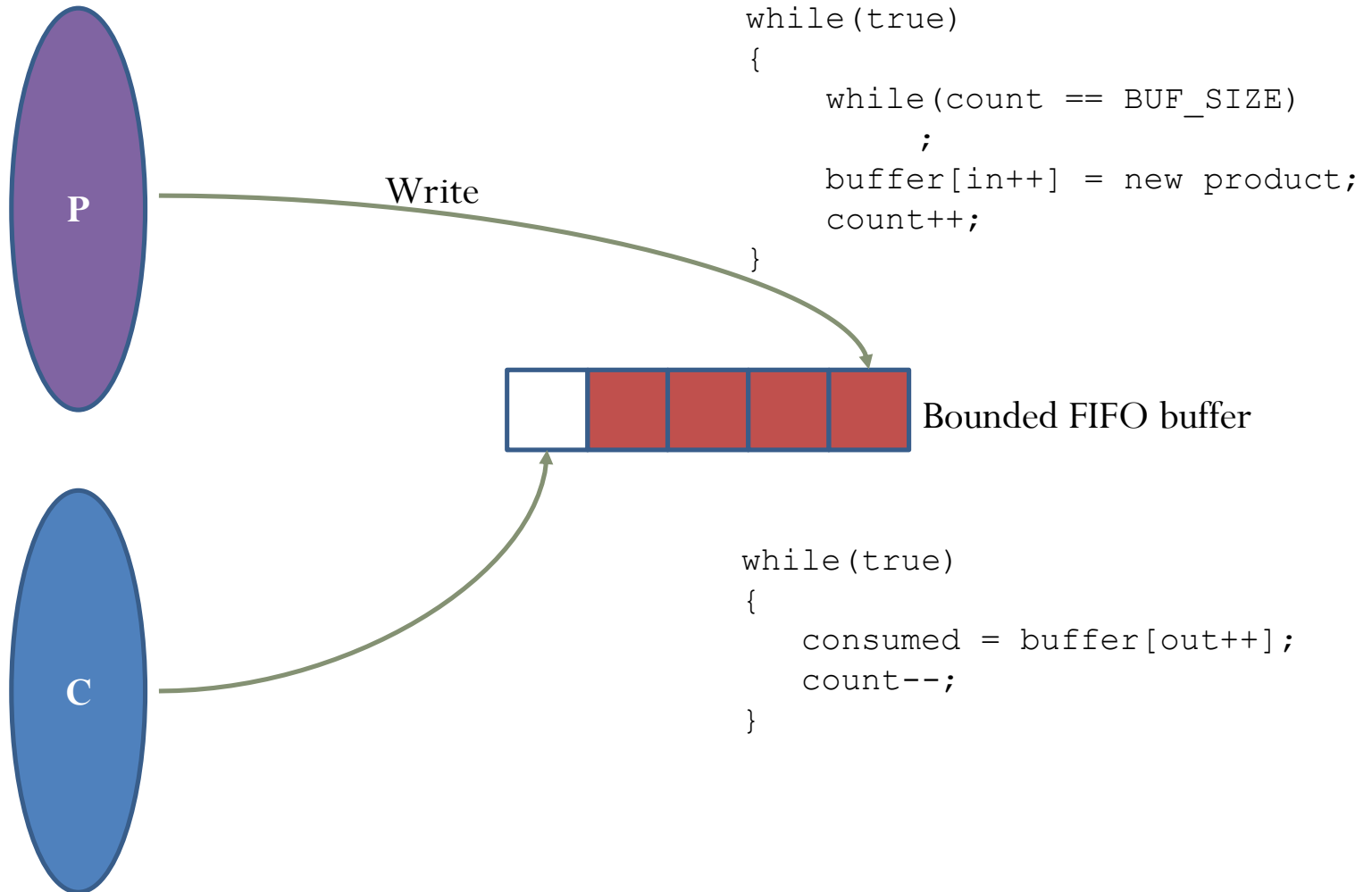
# Stop when buffer is full!



# Consumer reads buffer

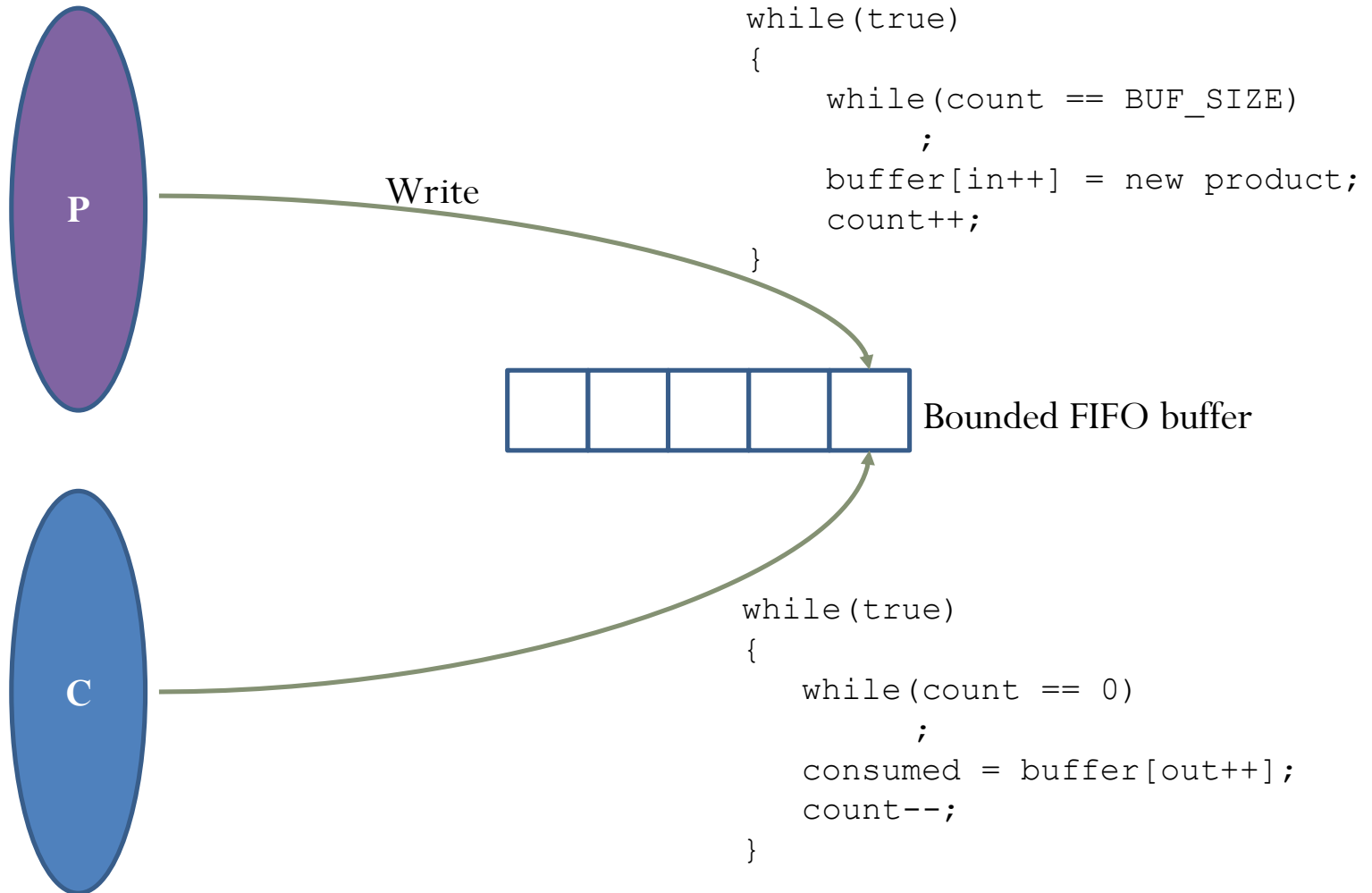


# Consumer reads buffer

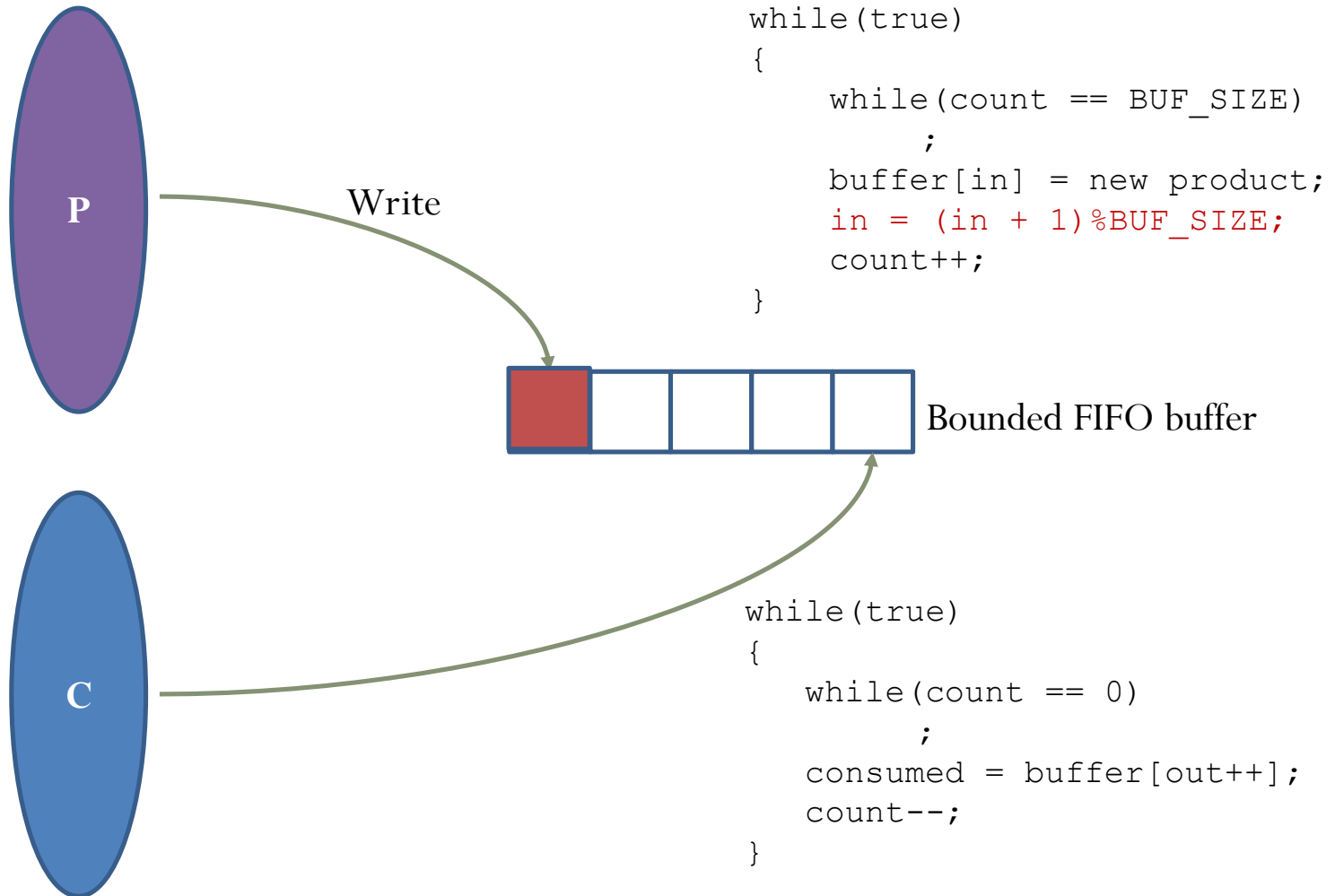




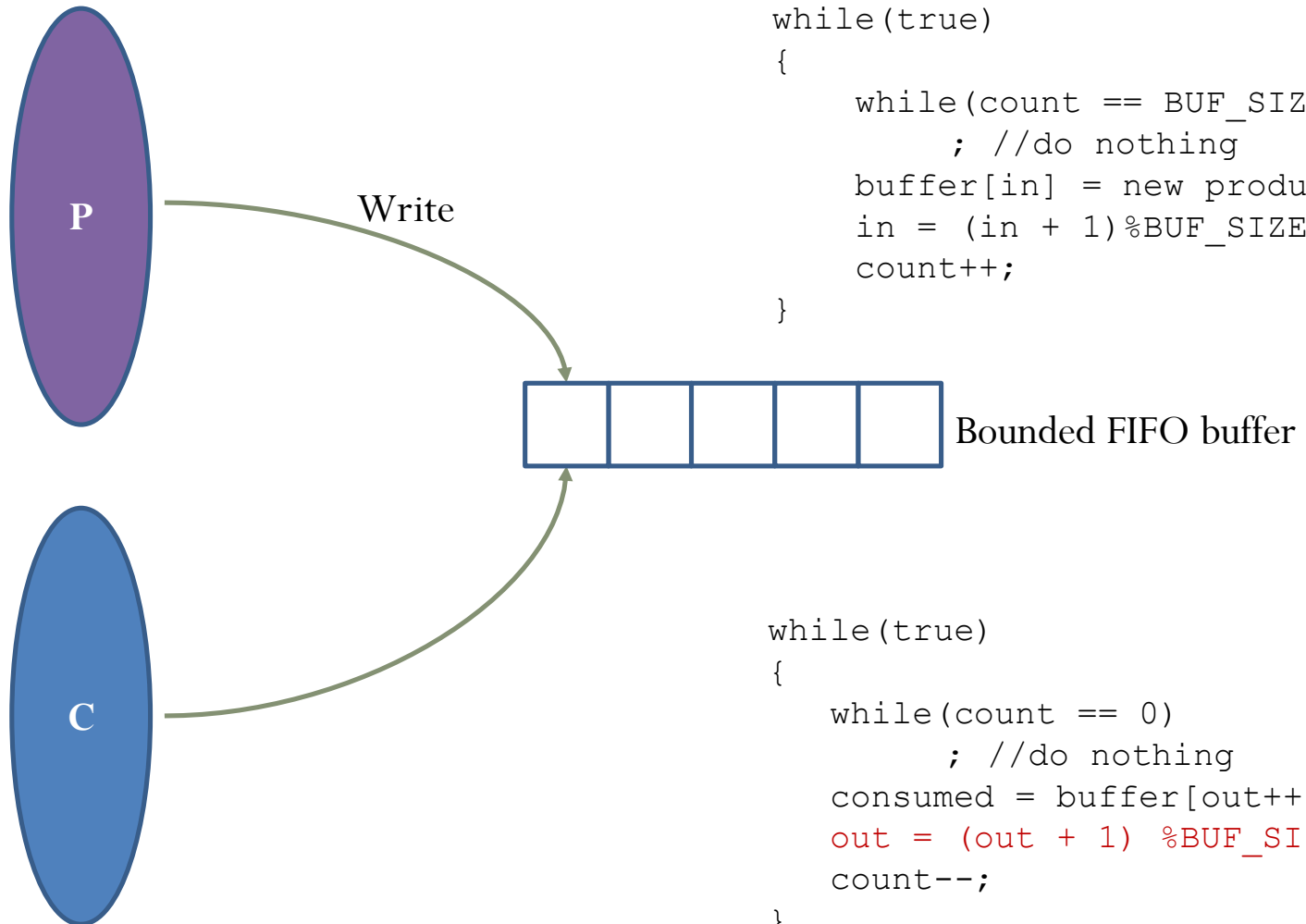
# Stop if buffer is empty!



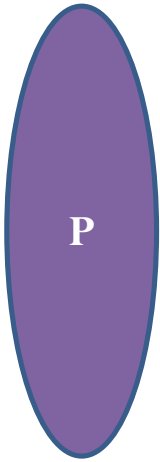
# Wrap around - writing



# Wrap around - reading

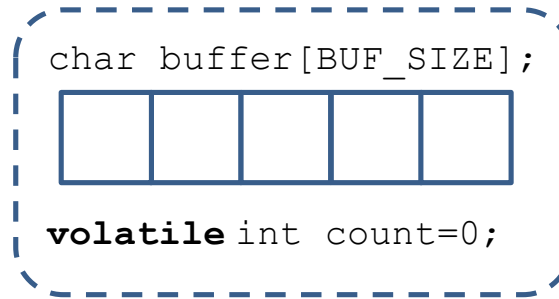


# Producer – consumer Problem



Producer:

1. Insert item (wrap around)
2. Should stop when buffer is full



Shared Memory



Consumer:

1. Read item (wrap around)
2. Should stop when buffer is empty


# Examples

- Traffic simulation
- Event queues
- Streaming (e.g., video)
- Pipes between 2 processes

# What's the problem?

## Consumer


```
while(true)
{
    while(count == 0)
        ; //do nothing
    consumed = buffer[out++];
    out = (out + 1) %BUF_SIZE;
    count--;
}
```



```
load count, r0    r0<-count
sub r0, r0, 1      r0<-r0-1
store r0, count    count<-r0
```

## Producer

```
while(true)
{
    while(count == BUF_SIZE)
        ;
    buffer[in] = new product;
    in = (in + 1) %BUF_SIZE;
    count++;
}
```

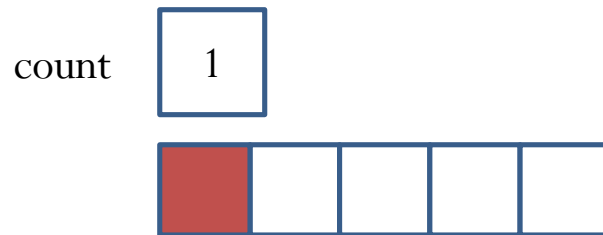


```
load count, r0    r0<-count
add r0, r0, 1      r0<-r0+1
store r0, count    count<-r0
```

**count** is in the memory. **r0** is the register.

Main problem: updating of shared memory “count” is **non-atomic**

# Illustration of problem - I



Scenario:

Producer has just put one  
item in buffer

count is 1

Consumer's turn

Consumer

```
(1)  load count, r0
(2)  sub r0, r0, 1
      store r0, count
```

Producer

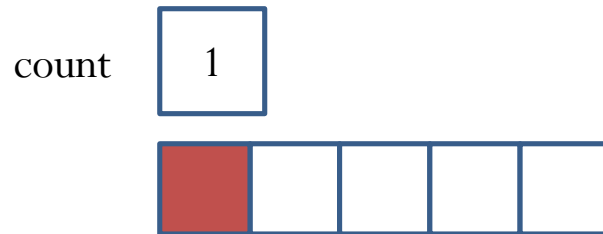
```
load count, r0
add r0, r0, 1
store r0, count
```

# Illustration of problem - II

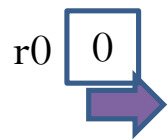
Scenario continued:

Consumer has executed 2 instructions

Before storing back, interrupt happens



Consumer



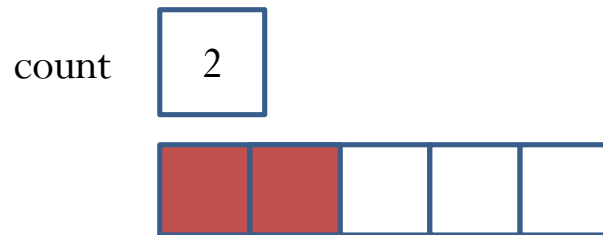
- (1) `load count, r0`
- (2) `sub r0, r0, 1`  
`store r0, count`

Producer

- (3) `load count, r0`  
`add r0, r0, 1`  
`store r0, count`



# Illustration of problem - III



Scenario continued:

Producer successfully

incremented count to 2

Interrupt occurs and switch

back to consumer

Consumer

r0

A small blue-outlined box containing the number '0'.

- (1) load count, r0
- (2) sub r0, r0, 1
- (6) store r0, count

Producer

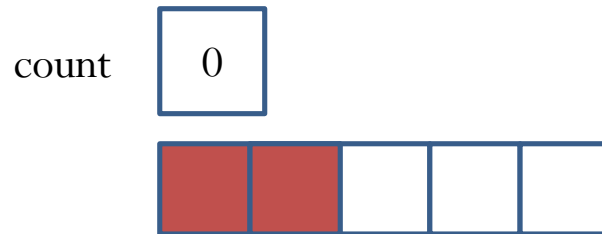
- (3) load count, r0
- (4) add r0, r0, 1
- (5) store r0, count

# Illustration of problem - IV

Scenario continued:

Consumer writes 0 into count

**Wrong value!**



Consumer

r0

0
---

- (1) load count, r0
- (2) sub r0, r0, 1
- (6) store r0, count

Producer

- (3) load count, r0
- (4) add r0, r0, 1
- (5) store r0, count

# The problem

- Non- atomicity
  - Divisible operation
  - Interruptible
- Instruction interleaving

# Critical Section (CS)

## Consumer

```
while(true)
{
    while(count == 0)
        ; //do nothing
    consumed = buffer[out++];
    out = (out + 1) %BUF_SIZE;
    count--;
```

## Producer

```
while(true)
{
    while(count == BUF_SIZE)
        ;
    buffer[in] = new product;
    in = (in + 1) %BUF_SIZE;
    count++;
```

critical section:

Segments of code (in different threads or processes) sharing access to shared objects (e.g., files, variables, arrays etc)

There's more than 1 CS here! How?

# General structure for CS solutions

```
while (true) {
```

```
    entry section e.g., entryCS()
```

→ Code for entry request

```
    critical section
```

```
    exit section e.g., leaveCS()
```

→ Code that “may” release  
someone to enter CS

```
    remainder section
```

```
}
```

# Solution criteria

- Criteria
  - Mutual exclusion
  - Progress
  - Bounded Waiting
- Assumptions
  - Speed independence
  - Progress assumed in CS

# Mechanisms for CS solution

- No enhanced support
  - Peterson's algorithm
- Hardware mechanisms
  - TestAndSet and Swap
- Operating system support
  - Semaphores

# SW Solution 1: Peterson's algorithm

```
int turn;
int interested[2];
void EnterCS(int proc)
{
    int other;
    other = proc ^ 0x1; //toggle
    interested[proc] = true;
    turn = other;
    while((turn==other) && interested[other]);
}

void LeaveCS(int proc)
{
    interested[proc]= false;
}
```



# Peterson's algorithm

**P<sub>0</sub>** proc=0

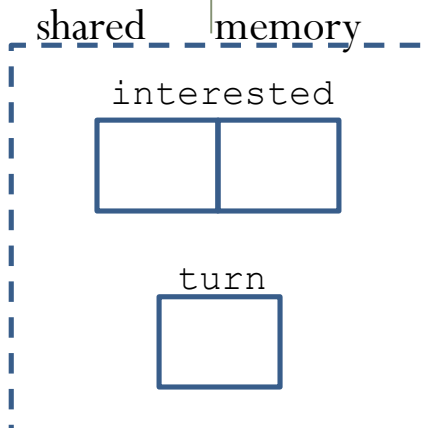
```
void EnterCS (...)  
{  
    int other;  
    other = 1;  
    interested[0] = true;  
    turn = 1;  
    while((turn==1) &&  
          interested[1]);  
}
```

```
void LeaveCS (...)  
{  
    interested[0]= false;  
}
```

**P<sub>1</sub>** proc=1

```
void EnterCS (...)  
{  
    int other;  
    other = 0; //toggle  
    interested[1] = true;  
    turn = 0;  
    while((turn==0) &&  
          interested[0]);  
}
```

```
void LeaveCS (...)  
{  
    interested[1]= false ;  
}
```



# Can both go through?

**P<sub>0</sub>** proc=0

```
void EnterCS (...)  
{  
    int other;  
    other = 1;  
    interested[0] = true;  
    turn = 1;  
    while((turn==1) &&  
          interested[1]);  
}
```

```
void LeaveCS (...)  
{  
    interested[0] = false ;  
}
```

**P<sub>1</sub>** proc=1

```
void EnterCS (...)  
{  
    int other;  
    other = 0; //toggle  
    interested[1] = true;  
    turn = 0;  
    while((turn==0) &&  
          interested[0]);  
}
```

```
void LeaveCS (...)  
{  
    interested[1] = false ;  
}
```

shared memory

interested	
true	true

turn
?

# Memory order

$P_0$  proc=0

Expected ordering

```
store 1, interested[0];  
store 0, turn;  
load r0, interested[1];  
Load r1, turn;
```



```
load r0, interested[1];  
store 1, interested[0];  
store 0, turn;  
load r1, turn;
```

Hardware messes it up during run-time!

$P_1$  proc=1

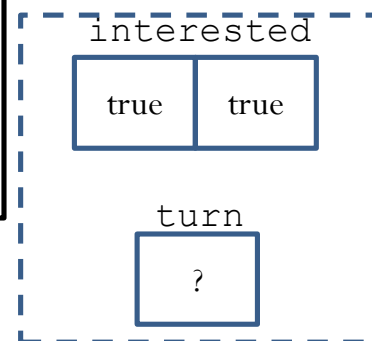
Expected ordering

```
store 1, interested[1];  
store 1, turn;  
load r0, interested[0];  
Load r1, turn;
```



```
load r0, interested[0];  
store 1, interested[1];  
store 0, turn;  
load r1, turn;
```

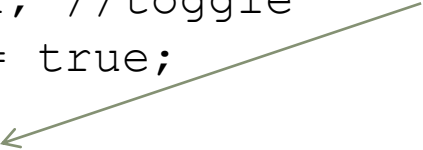
shared memory



# Peterson's algorithm (Modern version)

```
int turn;
Int interested[2];
void EnterCS(int proc)
{
    int other;
    other = proc ^ 0x1; //toggle
    interested[proc] = true;
    turn = other;
    __asm__ ("mfence");
    while((turn==other) && interested[other]);
}
```

Memory barrier:  
No memory reordering before  
this instruction



```
void LeaveCS(int proc)
{
    interested[proc]= false ;
}
```

# HW Solution 1: Disable Interrupts

```
while(true)
{
    Disable interrupts;
    //Critical Section
    ...
    Enable interrupts;
    //Remainder Section
}
```

- Requirements
  - Computer Instruction
  - Usually kernel-mode
- Caveat
  - Uniprocessor only
  - Scalability issues

# HW Solution 2: Test And Set

```
bool TestAndSet(bool *tgt)    do
{                               {
    bool rv = *tgt;           while(TestAndSet(&lock));

    *tgt = true;              // critical section

    return rv;                lock = false;

                               // remainder section
                               } while (true);
}
```

# HW Solution 3: Compare and Swap

```
int CompareAndSwap(
    int *value,
    int expected
    int new_value)
{
    int temp = *value;

    if(*value == expected)
        *value = new_value;

    return temp;
}

do {
    while (CompareAndSwap(&lock,
        0, 1) !=0);
    // critical section

    lock = 0;

    // remainder section
} while (true);
```

# HW Solutions

- TestAndSet and CompareAndSwap are HW instructions!
- Atomic
- Require hardware design
- Fails bounded waiting requirement (Refer to textbook chap 6.4 )

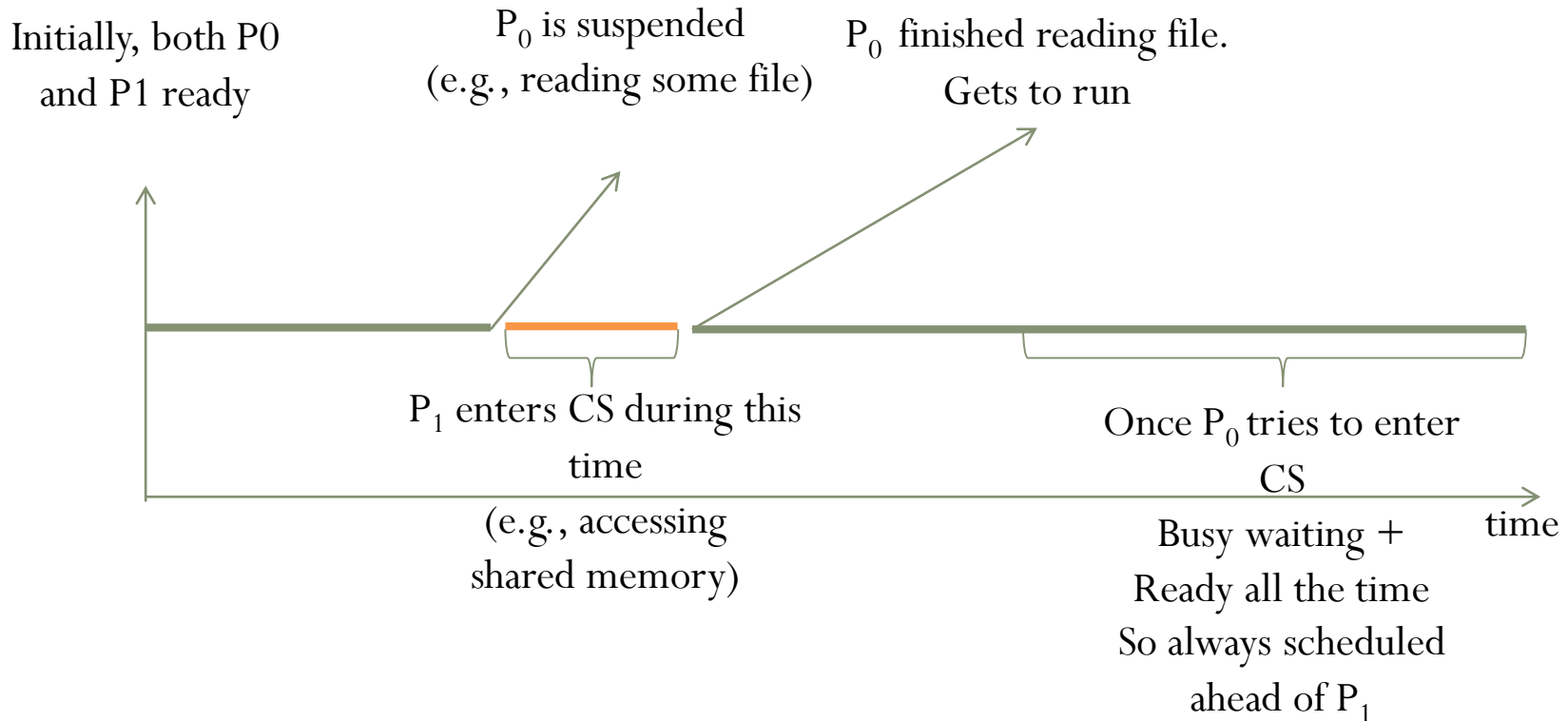


# Busy waiting

- Who's busy waiting?
  - Peterson, TestAndSet, CompareAndSwap
- Cons
  - Low CPU Utilization
  - Priority Inversion Problem (Uniprocessor)

# Priority Inversion (Uniprocessor version)

$P_0$   Priority of  $P_0 >$  Priority of  $P_1$   
 $P_1$  



# Sleep and wakeup

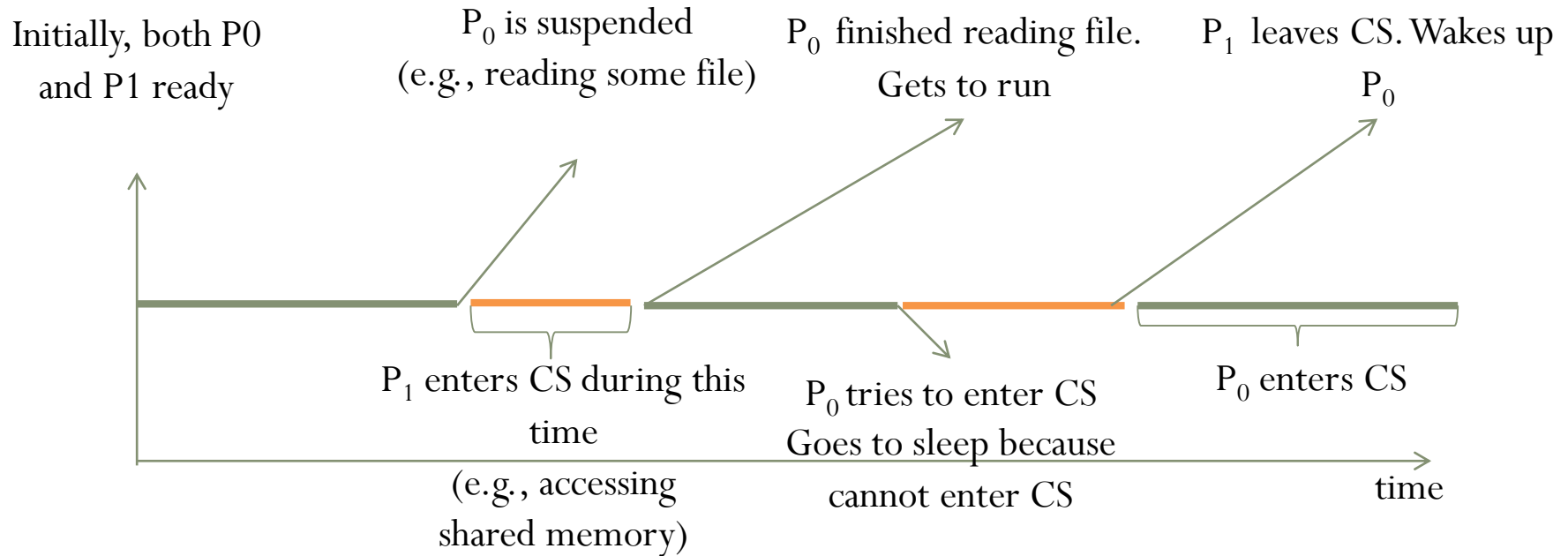
```
EnterCS()  
{  
    if cannot enter CS  
        block calling process;  
}
```

```
LeaveCS()  
{  
    When leaving CS,  
    wakeup one of any  
    blocking process in  
    EnterCS  
}
```

- Pros
  - Better CPU Utilization
  - Avoids priority inversion (?!)
- Cons
  - Less Efficient
  - Requires OS support

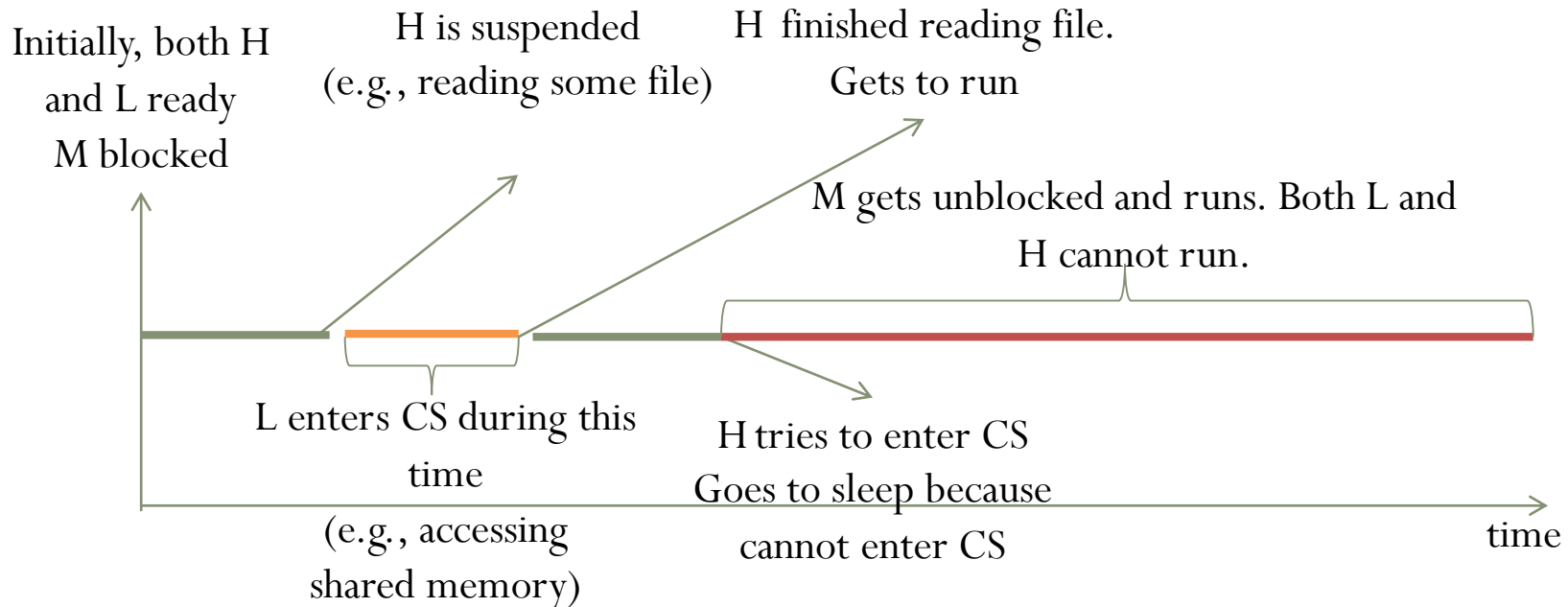
# Priority Inversion avoided (Uniprocessor version)

$P_0$   Priority of  $P_0 >$  Priority of  $P_1$   
 $P_1$  



# Priority Inversion comes back with a vengeance!

H —————  
M —————  
L —————



# Semaphores – initial definition

```
class Semaphore
{
    void wait ()
    {
        while(s <=0) ;
        s--;
    }
    void signal()
    {
        s++;
    }
private:
    int s;
}
```

Busy-waiting

```
class Semaphore
{
    void wait ()
    {
        if(s <= 0)
            block this process
        s--;
    }
    void signal()
    {
        s++;
        wake up one of blocking
        processes
    }
private:
    int s;
}
```

Sleep-wakeup

# Types of semaphore

- Counting/General semaphores
  - value of semaphore initialized to N
- Binary semaphore
  - value semaphore initialized to 1

# Using semaphores

```
Semaphore s(1);
```

```
while(true)
{
    s.wait();
    //critical section
    s.signal();
    //remainder section;
}
```



Only 1 in CS each time

```
Semaphore s(N);
```

```
while(true)
{
    s.wait();
    //critical section
    s.signal();
    //remainder section;
}
```



Up to N in CS each time



# Producer-Consumer Problem Revisited

## Consumer

```
while(true)
{
    while(count == 0)
        ; //do nothing
    consumed = buffer[out++];
    out = (out + 1) %BUF_SIZE;
    count--;
}
```

## Producer

```
while(true)
{
    while(count == BUF_SIZE)
        ;
    buffer[in] = new product;
    in = (in + 1)%BUF_SIZE;
    count++;
}
```

# Producer-Consumer Problem Revisited

## Consumer

```
while(true)
{
    while(count == 0)
        ; //do nothing
    mutex.wait();
    consumed = buffer[out++];
    out = (out + 1) %BUF_SIZE;
    mutex.signal();
    count--;
}
```

## Producer

```
while(true)
{
    while(count == BUF_SIZE)
        ;
    mutex.wait();
    buffer[in] = new product;
    in = (in + 1)%BUF_SIZE;
    mutex.signal();
    count++;
}
```

# Not in the same process!

Process 1

```
while(true)
{
    S1;
    synch.signal();
}
```

Process 2

```
while(true)
{
    synch.wait();
    S2;
}
```

Shared memory

```
Semaphore synch;
```

# Consumer should block when empty...

## Consumer

```
while(true)
{
    while(count == 0)
        ; //do nothing
    mutex.wait();
    consumed = buffer[out++];
    out = (out + 1) %BUF_SIZE;
    mutex.signal();
    count--;
}
```

## Producer


```
while(true)
{
    while(count == BUF_SIZE)
        ;
    mutex.wait();
    buffer[in] = new product;
    in = (in + 1)%BUF_SIZE;
    mutex.signal();
    count++;
}
```

# Consumer should block when empty...

Consumer


```
while(true)
{
    empty.wait();
    mutex.wait();
    consumed = buffer[out++];
    out = (out + 1) % BUF_SIZE;
    mutex.signal();
    count--;
}
```

should block  
when  
buffer is empty!



Producer

```
while(true)
{
    while(count == BUF_SIZE)
        ;
    mutex.wait();
    buffer[in] = new product;
    in = (in + 1) % BUF_SIZE;
    mutex.signal();
    empty.signal();
}
```




increment available  
buffer count

# Producer should block when buffer is full!

## Consumer

```
while(true)
{
    empty.wait();
    mutex.wait();
    consumed = buffer[out++];
    out = (out + 1) % BUF_SIZE;
    mutex.signal();
    full.signal();
}
```


increment available  
buffer count



## Producer

```
while(true)
{
    full.wait();
    mutex.wait();
    buffer[in] = new product;
    in = (in + 1) % BUF_SIZE;
    mutex.signal();
    empty.signal();
}
```

should block  
when  
buffer is full!



# Semaphores – sleep and wakeup

```
class Semaphore
{
    void wait ()
    {
        if(s <=0)
        {
            add self-process to queue;
            block();
        }
        s--;
    }
    void signal()
    {
        s++;
        if queue is not empty
            wake up any process
            waiting in queue
    }
private:
    int s;
}
```

- So can we eliminate busy waiting entirely?

# Semaphores - critical section

```
class Semaphore
{
    void wait ()
    {
        if(s <=0)
        {
            add self-process to queue;
            block();
        }
        s--;
    }
    void signal()
    {
        s++;
        if queue is not empty
            wake up any process
            waiting in queue
    }
private:
    int s;
}
```

- So can we eliminate busy waiting entirely?



# Implementation of Semaphores

## (REVISED)

```
void wait()
{
    while (TestAndSet(&lock));
    if (s <= 0)
    {
        add self-process to
        queue;
        lock = false;
        block(&lock);
    }
    s--;
    lock = false;
}
```

```
void signal()
{
    while (TestAndSet(&lock));
    s++;
    if (queue is not empty)
        wake up any process
        waiting in queue
    lock = false;
}
```

# Sleeping barber problem

- A barbershop has  $N$  chairs and one barber
- The barber does one of two things
  - If there is at least one customer, he chooses one and cuts his hair
  - If there are no customers, he goes to sleep (waits for a customer)
- When a customer enters
  - If there is at least one seat available, he seats himself and tells the barber he would like a haircut, and waits for a haircut
  - If there are no seats available, he leaves

# Solution for sleeping barber

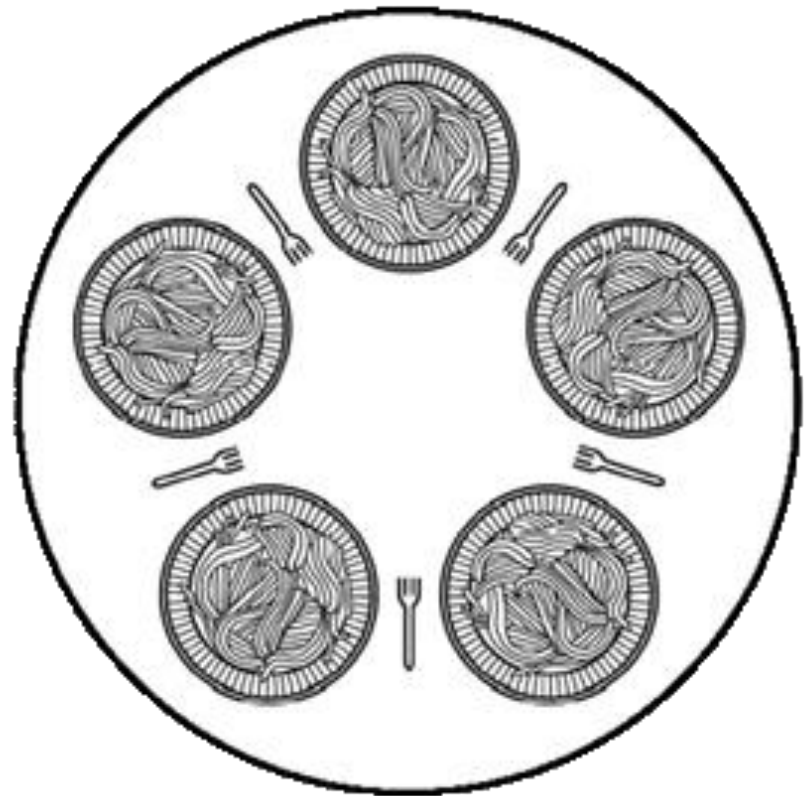
```
Semaphore barbers = 0;  
Semaphore mutex = 1;  
Semaphore customers = 0;  
int nFreeWRSeats = N;
```

```
void Barber(){  
    while (1) {  
        wait(customers);  
        wait(mutex);  
        nFreeWRSeats ++;  
        signal(barbers);  
        signal(mutex);  
        haircut();  
    }  
}
```

```
void Customer() {  
    wait(mutex);  
    if (nFreeWRSeats > 0) {  
        nFreeWRSeats --;  
        signal(customers);  
        signal(mutex);  
        wait(barber);  
        get_haircut();  
    }  
    else {  
        signal(mutex);  
        //leaveWR();  
    }  
}
```

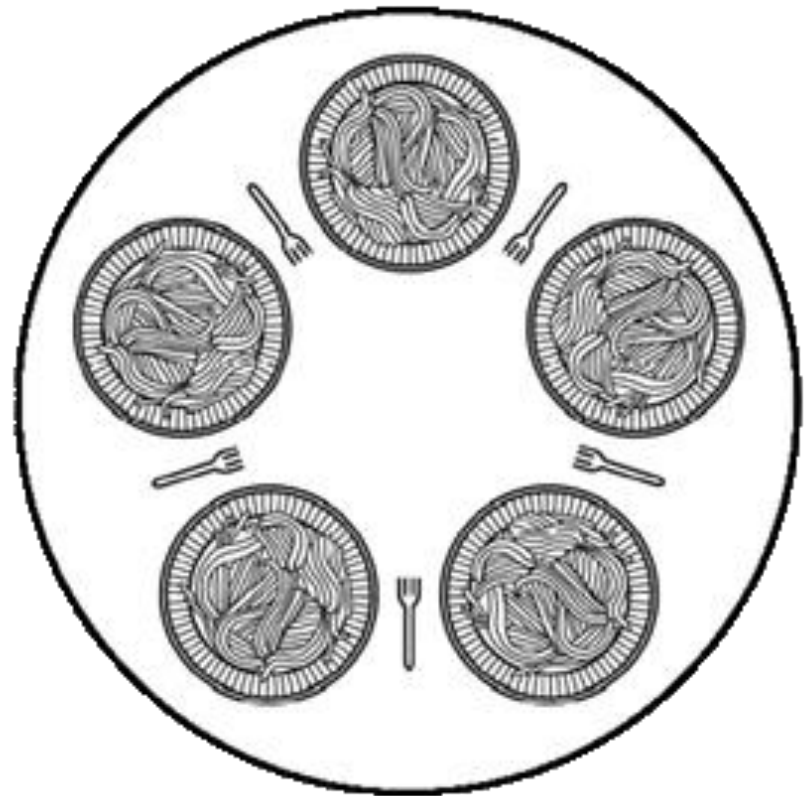
# Dining Philosopher's Problem

```
while (true)
{
    get_left();
    get_right();
    eat();
    think();
}
```



# Dining Philosopher's Problem

```
Semaphore chopsticks[N];  
  
while (true)  
{  
    wait(chopsticks[i]);  
    get_left();  
    wait(chopsticks[(i+1)%N]);  
    get_right();  
    eat();  
    signal(chopsticks[i]);  
    signal(chopsticks[(i+1)%N]);  
    think();  
}
```



# 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

$P_0$   
`wait(S) ;`  
`wait(Q) ;`  
`...`  
`signal(S) ;`  
`signal(Q) ;`

$P_1$   
`wait(Q) ;`  
`wait(S) ;`  
`...`  
`signal(Q) ;`  
`signal(S) ;`

**Starvation – indefinite blocking**

A process may never be removed from the semaphore queue in which it is suspended

**Priority Inversion** – Scheduling problem when lower-priority process holds a lock needed by higher-priority process

# Deadlock and Livelock

- **DEADLOCK** a condition in which a task waits indefinitely for conditions that can never be satisfied
  - task claims exclusive control over shared resources
  - task holds resources while waiting for other resources to be released
  - tasks cannot be forced to relinquish resources
  - a circular waiting condition exists
- **LIVELOCK**
  - State of the processes involved in the livelock constantly change with regard to one another
- Live lock happens when process are in ready or running state while deadlock deals with waiting state

# Deadlock & Livelock Examples

```
/* PROCESS 0 */
flag[0] = true;
while (flag[1]) /* do nothing */;
/* CS */
...
flag[0] = false;

/* PROCESS 1 */
flag[1] = true;
while (flag[0]) /* do nothing */;
/* CS */
...
flag[1] = false;
```

```
/* PROCESS 0 */
flag[0] = true;
while (flag[1]) {
    flag[0] = false;
    sleep(10);
    flag[0] = true;
}
/*CS*/
...
flag[0] = false;

/* PROCESS 1 */
flag[1] = true;
while (flag[0]) {
    flag[1] = false;
    sleep(10);
    flag[1] = true;
}
/*CS*/
...
flag[1] = false;
```

P0 sets flag[0] to true.  
P1 sets flag[1] to true.  
P0 checks flag[1].  
P1 checks flag[0].  
P0 sets flag[0] to false.  
P1 sets flag[1] to false.  
P0 sets flag[0] to true.  
P1 sets flag[1] to true.

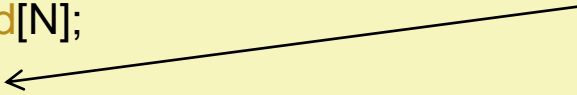


# Race condition

```
/* A threaded program with a race */
int main()
{
    pthread_t tid[N];
    int i;

    for (i = 0; i < N; i++)
        Pthread_create(&tid[i], NULL, thread, &i);
    for (i = 0; i < N; i++)
        Pthread_join(tid[i], NULL);
    exit(0);
}
```

N threads are  
sharing i

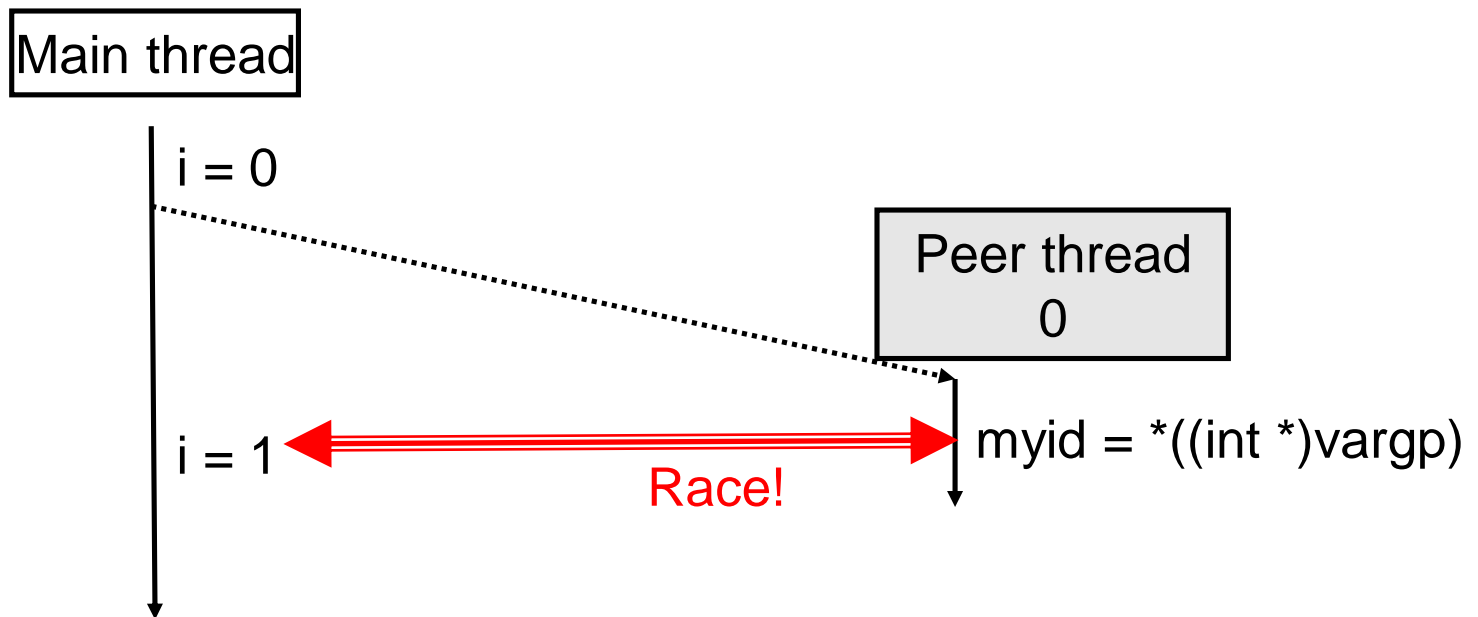


```
/* Thread routine */
void *thread(void *vargp)
{
    int myid = *((int *)vargp);
    printf("Hello from thread %d\n", myid);
    return NULL;
}
```

A *race* occurs when correctness of the program depends on one thread reaching point x before another thread reaches point y

# Race Illustration

```
for (i = 0; i < N; i++)  
    Pthread_create(&tid[i], NULL, thread, &i);
```



- Race between increment of  $i$  in main thread and deref of `vargp` in peer thread:
  - If deref happens while  $i = 0$ , then OK
  - Otherwise, peer thread gets wrong id value