

Part 4: Process Synchronization

- Race Condition & Critical-Section
- User-level Solutions
- OS-level Solutions
 - Synchronization Hardware
 - Semaphores
- Classical Problems of Synchronization

* Important but difficult 😊

Background

- Access to shared data from concurrent processes may result in **data inconsistency**
 - **Inconsistent Data:** Data value depends on the order of instruction executions from concurrent processes
 - That is, data value depends on **when context switches occur between the concurrent processes**
- Maintaining data consistency requires mechanisms to ensure the orderly execution of concurrent processes
 - **Causal ordering (sequencing) of reads and writes to the shared data from concurrent processes**

Example: Producer-Consumer (with bounded buffer)

- `#define BUFFER_SIZE 10`
- `typedef struct { . . . } item;`
- `int in=0;` //the next-to-fill empty slot (producer variable)
- `int out=0;` //the next-to-process item (consumer variable)
- Shared Data
 - `item buffer[BUFFER_SIZE];`
 - `int counter = 0;` // Number of items in buffer

Example: Producer-Consumer (with bounded buffer)

- Producer process

```
item nextProduced;  
while (1) {  
    while (counter == BUFFER_SIZE); // wait for space  
    buffer[in] = nextProduced; // produce item  
    in = (in + 1) % BUFFER_SIZE; // prepare for next item  
    counter++;  
}
```

Example: Producer-Consumer (with bounded buffer)

- **Consumer process**

```
item nextConsumed;  
while (1) {  
    while (counter == 0); // wait for buffer to receive an item  
    nextConsumed = buffer[out]; // Consume the item  
    out = (out + 1) % BUFFER_SIZE; // Prepare for next item  
    counter--;  
}
```

Example: Producer-Consumer (with bounded buffer)

- Lets take a close look at these instructions
 - *Producer process: counter++;*
 - *Consumer process: counter--;*
- They may create inconsistent value for variable counter due to *race condition*
 - The actual value depends on when the producer or consumer process context switches

Race Condition

In Producer counter++ implemented as:

```
register1 = counter  
register1 = register1 + 1  
counter = register1
```

In Consumer counter-- implemented as:

```
register2 = counter  
register2 = register2 - 1  
counter = register2
```

With “counter = 5” initially, suppose we execute producer and consumer once using the following interleaving

1. Producer executes `register1 = counter` {register1 = 5}
2. Producer executes `register1 = register1 + 1` {register1 = 6}
3. **Context switch occurs from Producer to Consumer**
4. Consumer executes `register2 = counter` {register2 = 5}
5. Consumer executes `register2 = register2 - 1` {register2 = 4}
6. **Context switch occurs from Consumer to Producer**
7. Producer executes `counter = register1` {counter = 6 }
8. **Context switch occurs from Producer to Consumer**
9. Consumer executes `counter = register2` {counter = 4}

Counter value is 4 instead of 5!

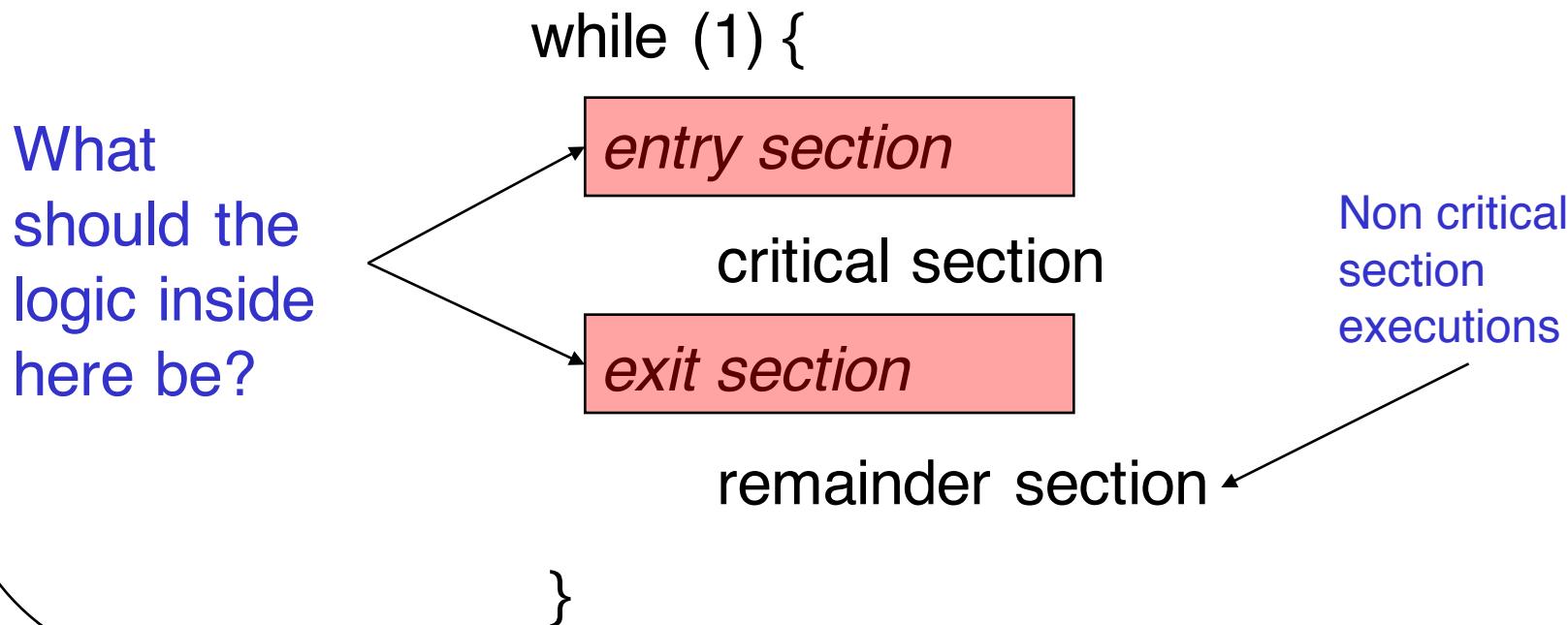
The Critical-Section Problem

- n processes all competing to use some shared data
- Each process has a code segment, called *critical section*, in which the shared data is accessed
 - Process may be changing shared variables, updating a shared table, writing a shared file, etc.
 - At least one process modifies (writes to) the shared data
- **Problem:** Design protocol to ensure that when one process is executing in its critical section, no other process is allowed to execute in its critical section

Generic Solution Structure for the Critical-Section Problem

1. Entry section: Ask permission to enter critical section
2. Exit section: Exit critical section (notify other processes)

Generic Process Structure



Desired Properties of Solutions to the Critical-Section Problem

- Assumptions of critical and remainder sections
 - Each process is guaranteed to make progress over time in these sections
 - No assumption about relative execution speed of different processes in these sections (may execute at different speeds)
- Desired Properties of entry and exit sections
 1. Mutual Exclusion: If a process is executing in its critical section, then no other process can be executing in its critical section at the same time

Desired Properties of Solutions to the Critical-Section Problem (Cont.)

2. **Progress:** If no process is executing in its critical section and there exist processes that wish to enter their critical section, then the **selection of the next process to enter the critical section cannot be postponed indefinitely**
3. **Bounded Waiting:** After a process has requested to enter its critical section and before that request is granted, other processes are allowed to enter their critical section only a bounded number of times

These two properties together ensure that a process is not stuck in the entry section forever

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- **User-level Solutions**
- OS-level Solutions
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Initial Attempts to Solve the Problem

- Generic structure of process

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

- We start with only 2 processes P_0 and P_1
 - Although P_0 and P_1 have the same generic structure, they may have **different implementations for the four sections**
- We look at **user-level software approaches w/o OS support**

Algorithm 1

- Variable shared between processes:

int turn; // initially turn=0

– $turn = i \Rightarrow P_i$ can enter critical section

- Process P_i : while (1){

Entry Section → **while (turn != i);**

critical section

Exit Section → **turn = k;**

remainder section

}

Process P_0

while (1){

while (turn != 0);

 critical section

turn = 1;

 remainder section

}

Process P_1

while (1){

while (turn != 1);

 critical section

turn = 0;

 remainder section

}

Algorithm 1: Property Analysis

1. Mutual Exclusion? ☺

- Suppose **turn = 0** and P_0 enters critical section
- **turn** is only updated in exit section, when P_0 exits critical section
- Process P_1 therefore cannot enter its critical section

2. Progress? ☹

- **turn = 0** and P_0 is in a long remainder section (think `while(1)` loop or blocked I/O), and P_1 wants to enter critical section

3. Bounded Waiting? ☺

- Assuming **turn** is updated in a fair (e.g., round-robin) manner among the two concurrent processes

Algorithm 2

- Variables shared: **boolean $flag[2]$** ;
 - Initially $flag[0] = flag[1] = false$
 - $flag[i] = true \Rightarrow P_i$ ready to enter its critical section

- Process P_i : `while (1) {`

Entry Section

```
flag[i] = true;  
while (flag[k]);
```

critical section

Exit Section

```
flag[i] = false;
```

remainder section

}

Algorithm 1 had an issue that it did not know if a process wants to enter its critical section

- **Issue solved in Algorithm 2 by using one flag for each process to express interest**

Algorithm 2: Property Analysis

1. Mutual Exclusion? ☺

- Suppose P_0 enters critical section, then **flag [1] = false** and **flag [0] = true**
- **flag [0]** is only updated to false in the exit section of P_0
- Process P_1 therefore cannot enter its critical section

2. Progress? ☹ Consider the following interleaving:

1. P_0 executes **flag [0] = true;**
2. **Context switch to P_1**
3. P_1 executes **flag [1] = true;**

Both P_0 and P_1 are stuck in an infinite while loop now!

3. Bounded Waiting? ☺

- Once P_0 sets **flag [0] = true**, process P_1 cannot enter its critical section

Algorithm 3

- Variables are a combination of Algorithms 1 and 2
 - $flag[i] = true \Rightarrow P_i$ ready to enter its critical section
 - $turn = i \Rightarrow P_i$ can enter critical section
- Proc. P_i : $while(1)$ {

Entry Section →

```
flag [ i ] = true;  
turn = k;  
while (flag [ k ] and turn = k);
```

critical section

Exit Section →

```
flag [ i ] = false;
```

remainder section

}

Algorithm 2 could not choose between two processes that wanted to enter their critical section at the same time

- **Issue solved in Algorithm 3 by using turn variable to denote whose turn it is**

Algorithm 3: Property Analysis

1. Mutual Exclusion? ☺

- If P_0 enters critical section, then $\text{flag}[0] = \text{true}$
- If P_1 now wants to enter critical section, then it will first set $\text{turn} = 0$
- P_1 then cannot enter because $\text{turn} = 0$ and $\text{flag}[0] = \text{true}$

2. Progress? ☺ Suppose P_0 wants to enter critical section

- If P_1 is in remainder section then $\text{flag}[1] = \text{false}$ and P_0 can enter
- If P_1 is in entry section, then access is granted either to P_0 or P_1 depending on the latest value of turn

3. Bounded Waiting? ☺ Assuming turn is updated fairly

How to extend Algorithm 3 for say three processes?

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- **OS-level Solutions**
 - **Synchronization Hardware**
 - **Semaphores**
- Classical Problems of Synchronization

OS Support for Synchronization

- Previous **software approaches** are difficult to implement for more than two processes
 - Solution: **Operating system support**
- OS has the following three kinds of support for the critical section problem (low level to high level)
 - **Synchronization hardware**
 - **Semaphore**
 - **Monitor**

Synchronization Hardware

- Modern processors provide special atomic hardware instructions
 - **Atomic** = non-interruptible (no context switches)
- **TestAndSet**: Test and modify the content of a main memory word **atomically** ([nice video](#))

```
boolean TestAndSet (boolean *target) {
```

Get current value → boolean *rv* = **target*;

Store true → **target* = *true*;

Return old value → return *rv*;

```
}
```

Interrupt is disabled

No context switches allowed during this execution

Interrupt is enabled

Critical-Section with Test-and-Set

- Variable shared: **boolean lock**;
 - Initially lock = false
 - If TestAndSet on lock returns false, then process can enter critical section (because it set lock to true)

- Process P_i : while (1) {

Entry Section

while(TestAndSet(&lock));

Acquire lock

critical section

Exit Section

lock = false;

Release lock

remainder section

}

TestAndSet: Property Analysis

1. Mutual Exclusion? ☺

- A process enters critical section → **lock = false** immediately before it executes TestAndSet(&lock) and **lock = true** thereafter
- **lock** is reset to false **only** in the exit section of the process
- No process can thereafter enter critical section since **lock = true**

2. Progress? ☺

- If **lock = false**, then the first process that executes TestAndSet(&lock) will immediately enter critical section

3. Bounded Waiting? ☹ See next slide

- More complex solution with TestAndSet that satisfies bounded waiting is in the textbook (pages 261-262) – **not examinable**

Bounded Waiting fails with TestAndSet

- Process P_0

1. Initialization code

2. while (1) {

3. while(TestAndSet(&lock));

4. critical section

5. lock = false;

6. }

- Process P_1

1. while (1) {

2. while(TestAndSet(&lock));

3. critical section

4. lock = false;

5. }

Context switch points

- Suppose for P_0 lines 1-3 take 10ms and 2-6 also take 10ms
- Suppose we use round-robin scheduling with quantum 10ms
- Whenever P_0 context switches out, it holds the lock (is in critical section)



Semaphore

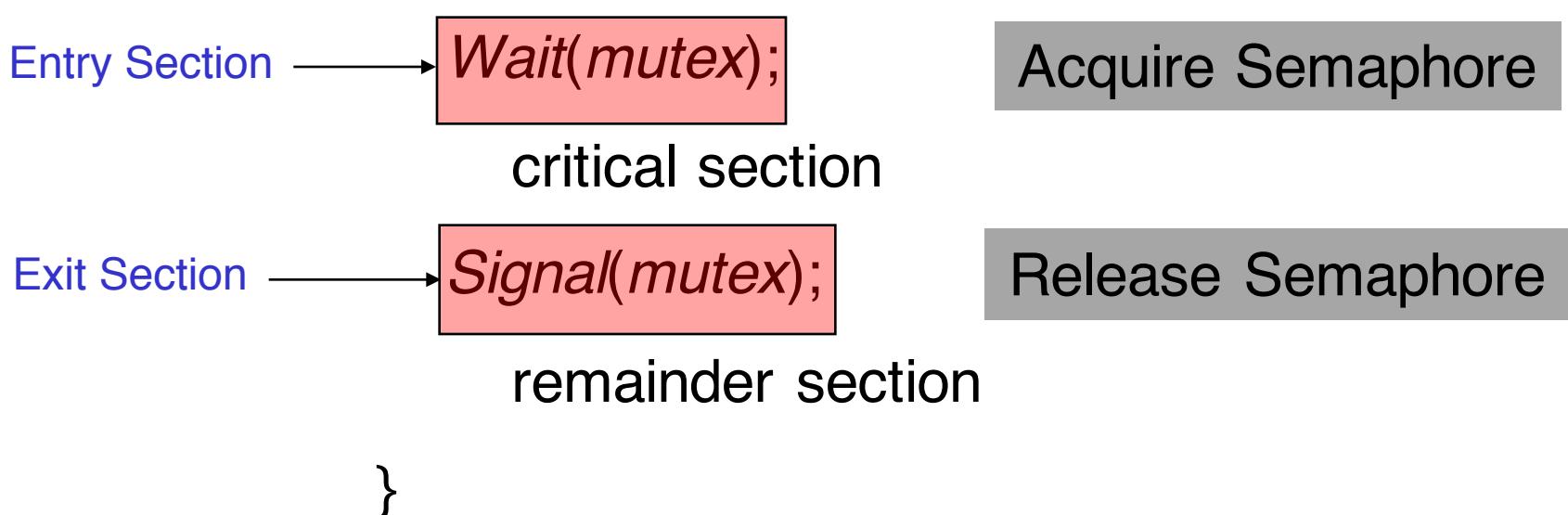
- **Semaphore S :** Integer shared variable
- **Only** accessible by two **atomic** operations: *Wait* and *Signal*
 - *Wait (S): if $S>0$, $S--$; else, wait();*
 - *Signal (S): $S++;$*
- Two types of semaphores
 - *Counting semaphore:* Integer value can range over an unrestricted domain
 - *Binary semaphore:* Integer value can never be greater than 1

Enter waiting state
or busy loop waiting

Semaphore Solution for the Critical Section Problem

- Variable shared: **semaphore mutex**; // initially $mutex=1$
 - If $mutex=1$ and process executes `Wait(mutex)`, then it can enter critical section

- Process P_i : `while(1) {`



Classical Semaphore Implementation (Busy Waiting)

- *Wait (S):*

```
while (S <= 0)  
; // busy wait  
  
S--;
```

- *Signal (S):*

```
S++;
```

- **Pros:** No context switch overhead (busy waiting)
- **Cons:** Inefficient if critical sections are long
 - Busy waiting wastes CPU cycles

Assembly for Wait(S):

```
loop1: ldr ax, [S]  
       cmp ax, 0  
       jle loop1  
       sub ax, 1  
       str [S], ax
```

Assembly for Signal(S):

```
ldr ax, [S]  
add ax, 1  
str [S], ax
```

Busy Waiting Semaphore (Property Analysis)

1. To avoid race condition, S++ and S-- must be atomic

2. Wait(S) must be atomic to ensure mutual exclusion

- Consider the following with S>0 initially
 1. Process P_0 executes **while ($S \leq 0$);** and exits busy wait
 2. **Context switch from P_0 to P_1**
 3. Process P_1 executes **while ($S \leq 0$);** and **S--;**
 4. **Context switch from P_1 to P_0**
 5. Process P_0 executes **S--;**
 6. *Mutual Exclusion? ☹*

Assembly for Wait(S):

```
loop1: ldr ax, [S]
       cmp ax, 0
       jle loop1
       sub ax, 1
       str [S], ax
```

} **while ($S \leq 0$);**
} **S--;**

Assembly for Signal(S):

```
ldr ax, [S]
add ax, 1
str [S], ax
```

} **S++;**

Current Semaphore Implementation (Blocking)

- Define a semaphore as a record

```
typedef struct {  
    int value;  
    struct process *L;  
} semaphore;
```

L is a queue that stores the processes waiting on this semaphore (in the form of PCB list)

- Need two simple operations
 - *block()*: blocks the current process
 - *wakeup()*: resumes the execution of a blocked process in list L

Blocking Semaphore Implementation

block() and wakeup()

block():

1. Dequeue current process from ready queue
2. Enqueue the process to list L
3. Change state of the process to **waiting**

wakeup():

1. Dequeue a process from list L
2. Enqueue the process to the ready queue
3. Change state of the process to **ready**

Will lead to a context switch

Blocking Semaphore Implementation

Wait(S) and Signal(S)

Wait(S):

```
S.value--;  
if (S.value < 0)  
{  
    block( );  
}
```

Signal(S):

```
S.value++;  
if (S.value <= 0)  
{  
    wakeup(P);  
}
```

If $S.value = -2$, how many processes are waiting in list L? **2**

Blocking Semaphore Implementation

Wait and Signal must still be atomic?

Wait(S): **S.value--;**

```
if (S.value < 0)  
{ block(); }
```

Signal(S): **S.value++;**

```
if (S.value <= 0)  
{ wakeup(P); }
```

1. Initially, **S.value = 1**
2. Process P_0 executes **S.value--;**
3. **Context switch from P_0 to P_1**
4. Process P_1 executes **S.value--;** and blocks since **S.value = -1**
5. **Context switch from P_1 to P_0**
6. Process P_0 also blocks
7. *Progress for P_0 and P_1 ?* ☹

1. Initially, **S.value = -1** (P_2 blocked for **S**)
2. Process P_0 executes **S.value++;**
3. **Context switch from P_0 to P_1**
4. Process P_1 executes **S.value++;** and exits. No **wakeup(P);** since **S.value = 1**
5. **Context switch from P_1 to P_0**
6. Process P_0 also exits without **wakeup(P);**
7. *Progress for P_2 ?* ☹

Also lead to mutual exclusion violation due to -- and ++

All updates and checks for S must be atomic

Blocking Semaphore Implementation

S.value-- at the end of Wait(S)?

Wait(S):

```
if (S.value <= 0)
{
    block();
}
S.value--;
```

Problems:

1. This would require a context switch between `block()`; and `S.value--`; if the process blocks
2. If this context switch is allowed, mutual exclusion will be violated
 - Say `S.value = -1` and P_0 executes `block()`;
 - P_1 uses `Signal(S)` twice to increment `S.value` and executes `wakeup(P_0)`;
 - P_2 executes `Wait(S)`, locks `S`, enters critical section
 - P_0 executes `S.value--`; and enters critical section

Part 4: Process Synchronization

- The Critical-Section Problem
- User-level Solutions
- OS-level Solutions
 - Synchronization Hardware
 - Semaphores
- **Classical Problems of Synchronization**

Best Practices for Semaphores

- **Step 1:** Understand the application scenario and identify the following:
 - Shared variables/data
 - Shared resources
- **Step 2:** Protect the shared variables
 - Identify the critical section
 - Use binary semaphore, and add entry section (Wait) and exit section (Signal)
- **Step 3:** Protect the shared resources
 - Identity each kind of resource; **one semaphore for one kind**
 - Initial value: number of resource instances
 - When the resource is requested/consumed: Wait
 - When the resource is released: Signal

Semaphore as General Synchronization Tool

- We wish to execute code segment B in process P_k only after code segment A in process P_i ,

– Use a semaphore *flag* initialized to 0

– Code: P_i

⋮

A

Signal(flag)

P_k

⋮

Wait(flag)

B

Deadlocks (Incorrect Semaphore Use)

- **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	P_1
<i>Wait(S);</i>	<i>Wait(Q);</i>
<i>Wait(Q);</i>	<i>Wait(S);</i>
\vdots	\vdots
<i>Signal(S);</i>	<i>Signal(Q);</i>
<i>Signal(Q);</i>	<i>Signal(S);</i>

Consider the following interleaving:

1. P_0 executes ***Wait(S);***
2. **Context switch from P_0 to P_1**
3. P_1 executes ***Wait(Q);*** and ***Wait(S);***
4. **Context switch from P_1 to P_0**
5. P_0 executes ***Wait(Q);***

Starvation (Incorrect Semaphore Use)

- **Starvation:** Indefinite postponement (no progress)
 - A process may never have a chance to be removed from the semaphore queue (list L) due to queue discipline
 - Examples of queue disciplines that can cause starvation
 - * **Priority-based:** Low priority process may starve if higher priority processes keep joining the queue
 - * **Last-In-First-Out policy**

Classical Problems of Synchronization

- Bounded-Buffer (Producer-Consumer) Problem
- Dining-Philosophers Problem
- Readers and Writers Problem

Producer-Consumer with Bounded-Buffer

- Consider multiple producers/consumers
 - We used **counter**, **in** and **out** variables for a producer-consumer pair
 - **in/out** are also shared variables now (**in** - producers, **out** - consumers)
- Shared data and resources (Step 1)
 - **item buffer[n];**
 - buffer is a shared data structure
 - Slots in buffer are shared resources
- Semaphores to be used
 - semaphore full, empty, mutex;**
 - full = 0; empty = n; mutex = 1;**

Binary semaphore for mutual exclusion to update buffer

- **in** replaced with **empty**
- **out** replaced with **full**
- **counter** not used (why?)
- **mutex** introduced to control access to buffer

Counting semaphore for consumers to identify full buffer to consume

Counting semaphore for producers to identify empty buffer to fill

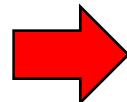
Bounded-Buffer Problem (Cont.)

Producer process (Step 2)

Protect Shared Data:

Without synchronization:

```
item nextProduced;  
while (1) {  
    ...  
    produce nextProduced;  
    ...  
    add nextProduced to buffer;  
    ...  
}
```



```
item nextProduced;  
while (1) {  
    ...  
    produce nextProduced;  
    ...  
Wait(mutex);  
    ...  
    add nextProduced to buffer;  
    ...  
Signal(mutex);  
}
```

Bounded-Buffer Problem (Cont.)

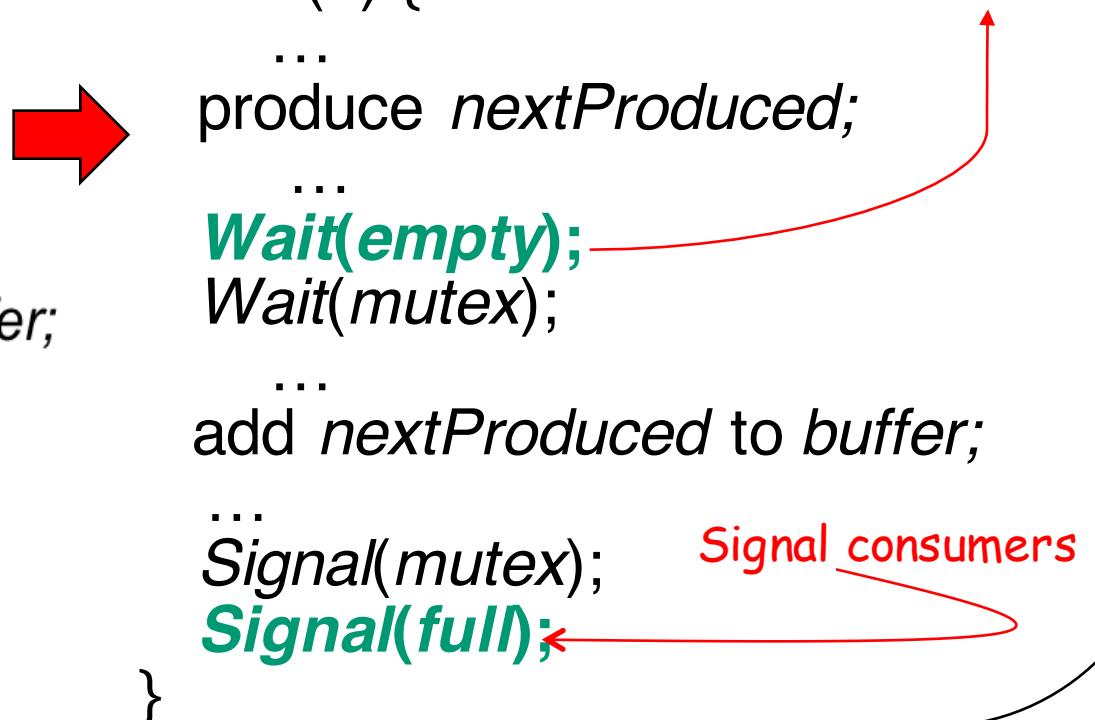
Producer process (Step 3)

Protect Shared Data:

```
item nextProduced;  
while (1) {  
    ...  
    produce nextProduced;  
    ...  
    wait(mutex);  
    ...  
    add nextProduced to buffer;  
    ...  
    signal(mutex);  
}
```

Manage Shared Resources:

```
item nextProduced;  
while (1) {  
    ...  
    produce nextProduced;  
    ...  
    Wait(empty);  
    Wait(mutex);  
    ...  
    add nextProduced to buffer;  
    ...  
    Signal(mutex);  
    Signal(full);
```



Bounded-Buffer Problem (Cont.)

Consumer process

Protect Shared Data and Manage Shared Resources:

```
item nextConsumed;  
while (1) {  
    Wait(full); Consume one  
full slot  
    Wait(mutex);  
    ...  
    nextConsumed = item from buffer;  
    ...  
    Signal(mutex);  
    Signal(empty); → Signal producers  
    ...  
    consume the item nextConsumed;  
}
```

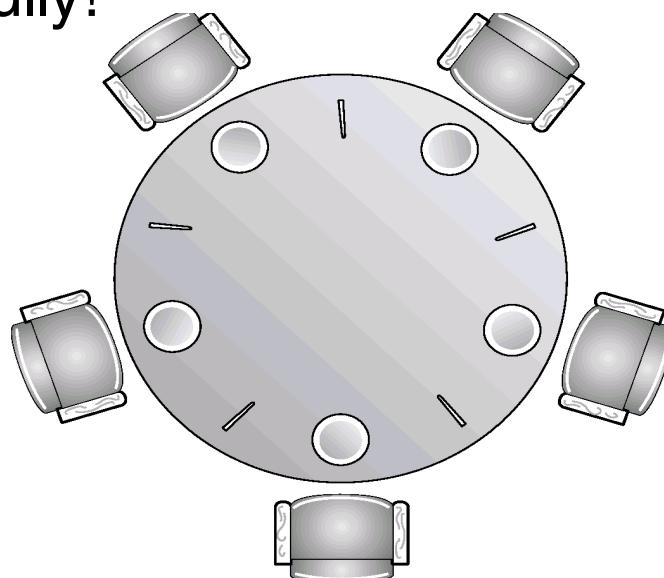
What if we swap
as below?

Wait(mutex);
Wait(full);

**DEADLOCK if
buffer is empty!**

Dining-Philosophers Problem

- Five philosophers seated in a round table alternating between eating and thinking
- Five plates (one for each philosopher) and **only five chopsticks (one between each plate)**
- **Problem:** Devise a strategy to enable the philosophers to eat peacefully!



Dining-Philosophers Problem (Cont.)

- Initial Solution
 - Each philosopher is a process
 - Each chopstick is a shared resource protected by a binary semaphore (**chopstick [5]**);
 - Initially, for all i , **chopstick [i] = 1**;
- Code (Philosopher i)

```
while (1) {
    Wait(chopstick [  $i$  ]);
    Wait(chopstick [ ( $i+1$ )%5 ]);
    eat
    Signal(chopstick [  $i$  ]);
    Signal(chopstick [ ( $i+1$ )%5 ]);
    think
}
```

Dining-Philosophers Problem (Cont.)

- Does the above solution have a problem?
- Consider the following interleaving (P_i =Philosopher i):
 1. P_0 executes **Wait(0)**; and then **context switch** to P_1
 2. P_1 executes **Wait(1)**; and then **context switch** to P_2
 3. P_2 executes **Wait(2)**; and then **context switch** to P_3
 4. P_3 executes **Wait(3)**; and then **context switch** to P_4
 5. P_4 executes **Wait(4)**;

**Each philosopher has 1 chopstick and needs another to eat
Deadlock!**

Dining-Philosophers Problem (Cont.)

There are several possible remedies to avoid the above deadlock problem

- Allow at most four philosophers to be hungry simultaneously
- Allow a philosopher to pick up his chopsticks only if both chopsticks are available
- Use an asymmetric solution
 - * An **odd** philosopher picks up **first his left chopstick and then his right chopstick**
 - * An **even** philosopher picks up **first his right chopstick and then his left chopstick**

Readers-Writers Problem

- Problem: Scenario in a database or file
 - A writer requires exclusive access
 - Multiple readers can concurrently access
 - * The first reader: Before reading, it must **block the writers**
 - * The last reader: After reading, it can **allow writers**
 - * Readers given **preference** (writer preference also possible)
 - If a reader is in database, more readers can access it
- Shared data
 - **int readcount =0;** // Tracks #readers in the database
 - Database itself
- Semaphores to be used
 - **mutex=1;** → Binary semaphore protects access to **readcount**
 - **wrt=1;** → Binary semaphore for mutual exclusion to database

Readers-Writers Problem

Writer process

Wait(wrt);

...

writing is performed

...

Signal(wrt);

Readers-Writers Problem (Cont.)

Reader process

When a reader comes

Wait(mutex);
readcount ++;
if (*readcount == 1*) **Wait(wrt);**

The first reader?
Request access to database

Signal(mutex);

...

reading is performed

...

Wait(mutex);

readcount --;

if (*readcount == 0*) **Signal(wrt);**

The last reader?
Release database

When a reader leaves

Signal(mutex);

Monitor

- High-level synchronization construct that allows the sharing of variables among concurrent processes
- Monitor is a collection of procedures and data
- Processes may call procedures within monitor to access and update the data
- Only one process can be active in the monitor at any one time (i.e., only one process can be executing a monitor procedure at any one time)
- Data within monitor can only be accessed by procedures within it

This slide is not examinable