Concurrency and Synchronisation

Learning Outcomes

- Understand concurrency is an issue in operating systems and multithreaded applications
- Know the concept of a *critical region*.
- Understand how mutual exclusion of critical regions can be used to solve concurrency issues
  - Including how mutual exclusion can be implemented correctly and efficiently.
- Be able to identify a *producer consumer bounded buffer* problem.

Textbook

- Sections 2.3 - 2.3.7 & 2.5

Concurrency Example

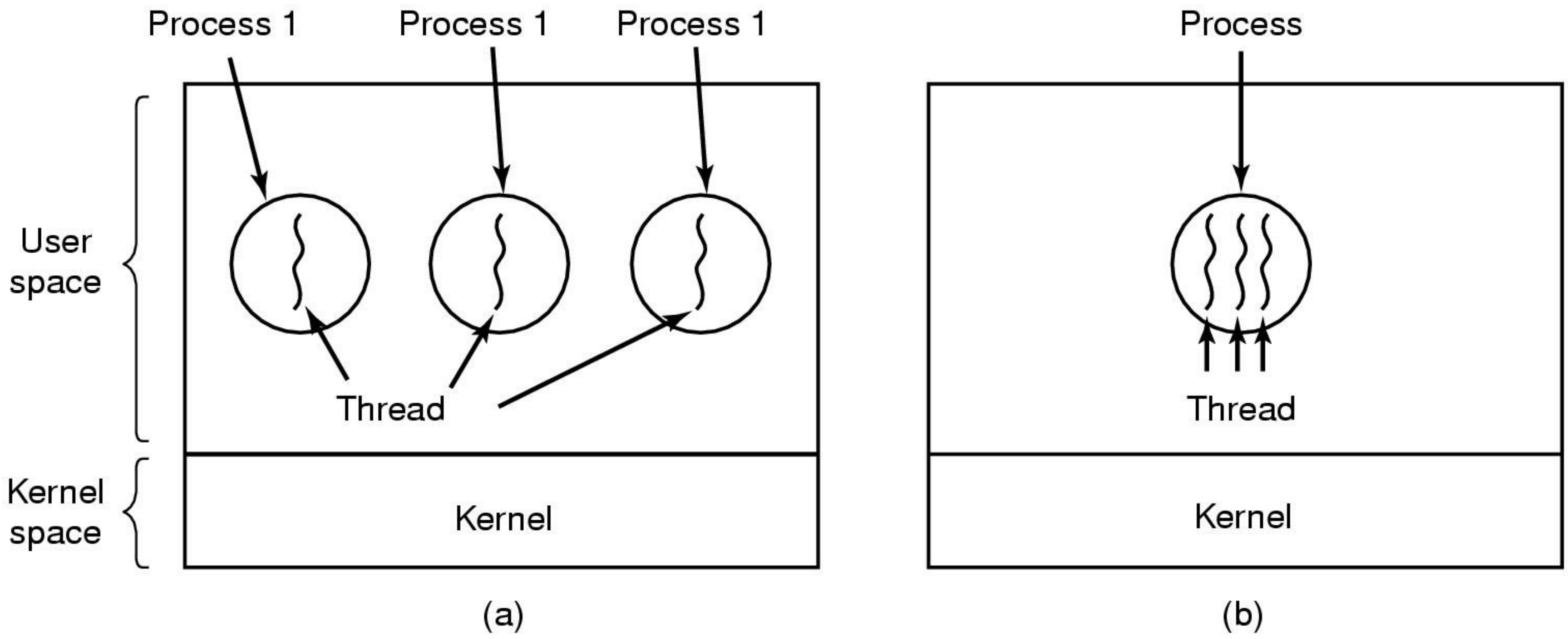
`count` is a global variable shared between two threads, `t` is a local variable. After increment and decrement complete, what is the value of count?

```
void increment ()
{
     int t;
     t = count;
     t = t + 1;
     count = t;
}
```

```
void decrement ()
{
 int t;
 t = count;
 t = t - 1;
 count = t;
}
```

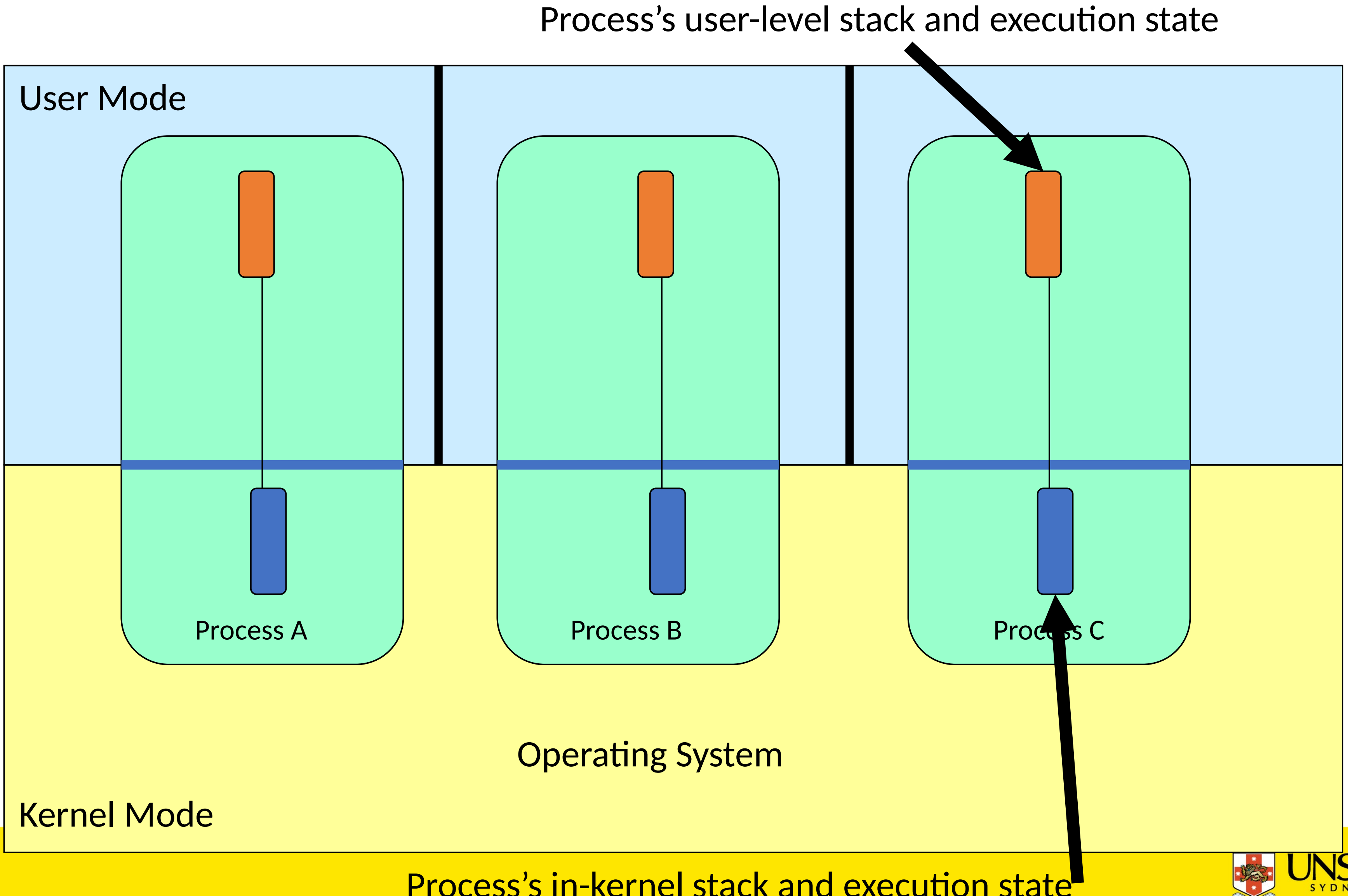
We have a *race condition*

Where is the concurrency?



- (a) Three processes each with one thread
- (b) One process with three threads

There is in-kernel concurrency even for single-threaded processes



Critical Region

- We can control access to the shared resource by controlling access to the code that accesses the resource.

⇒ A *critical region* is a region of code where shared resources are accessed.

  - Variables, memory, files, etc…

- Uncoordinated entry to the critical region results in a race condition

  ⇒ Incorrect behaviour, deadlock, lost work,…

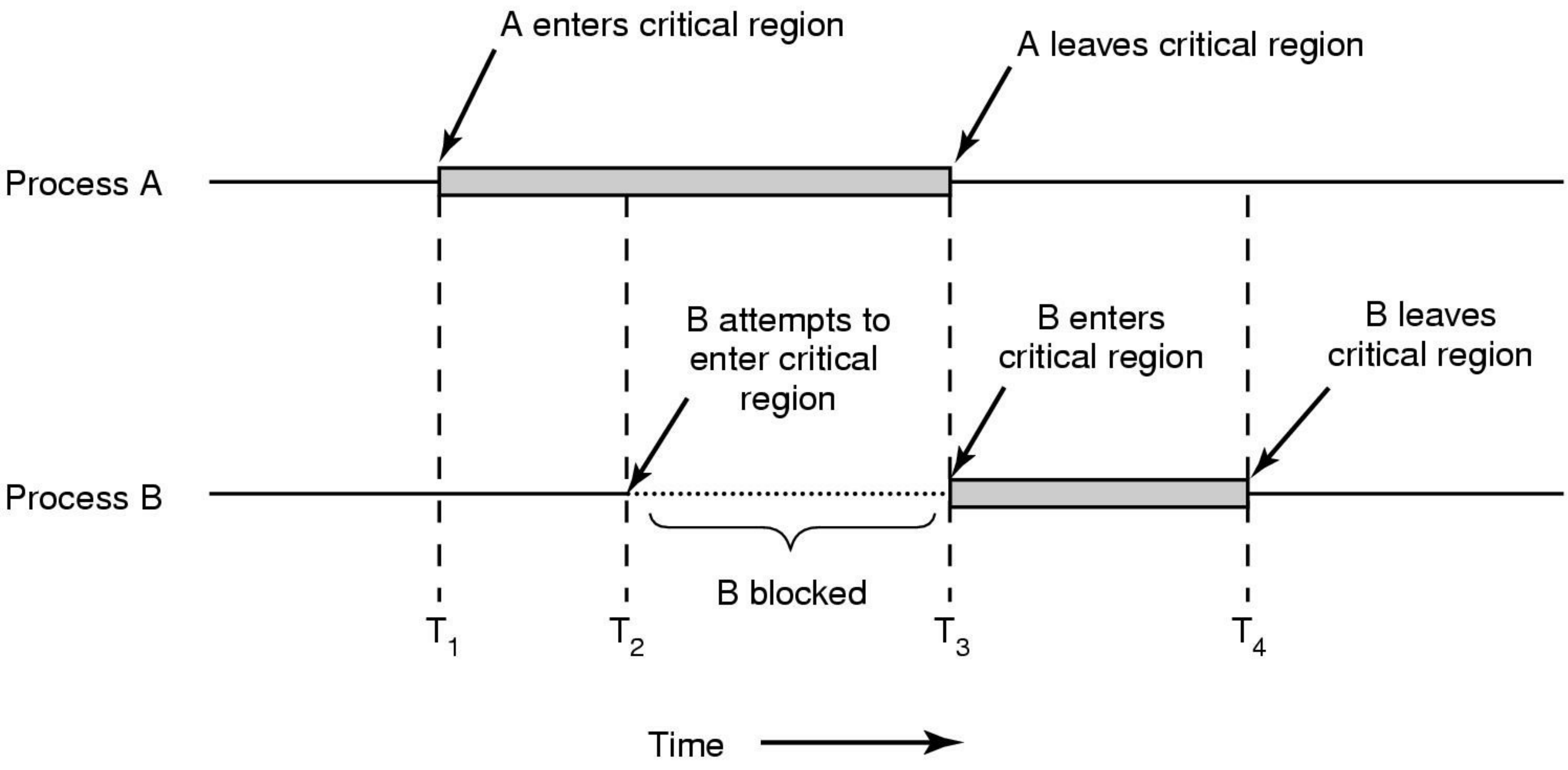
Identifying critical regions

- Critical regions are regions of code that:
  - Access a shared resource,
  - and correctness relies on the shared resource not being concurrently modified by another thread/process/entity.

```
void increment ()
{
    int t;
    t = count;
    t = t + 1;
    count = t;
}
```

```
void decrement ()
{
    int t;
    t = count;
    t = t - 1;
    count = t;
}
```

Accessing Critical Regions



Mutual exclusion using critical regions

Example critical regions

```
struct node {
  int data;
  struct node *next;
};
struct node *head;

void init(void)
{
  head = NULL;
}
```

- Simple last-in-first-out queue implemented as a linked list.

```
void insert(struct *item)
{
  item->next = head;
  head = item;
}

struct node *remove(void)
{
  struct node *t;
  t = head;
  if (t != NULL) {
  head = head->next;
  }
  return t;
}
```

Example Race

```
void insert(struct *item)
{
 item->next = head;
 head = item;
}
```

```
void insert(struct *item)
{
   item->next = head;
   head = item;
}
```

Example critical regions

```
struct node {
  int data;
  struct node *next;
};
struct node *head;

void init(void)
{
  head = NULL;
}
```

- Critical sections

```
void insert(struct *item)
{
  item->next = head;
  head = item;
}

struct node *remove(void)
{
  struct node *t;
  t = head;
  if (t != NULL) {
  head = head->next;
  }
  return t;
}
```

Critical Regions Solutions

- We seek a solution to coordinate access to critical regions.
  - Also called critical sections
- Conditions required of any solution to the critical region problem
  1. Mutual Exclusion:
     - No two processes simultaneously in critical region
  2. No assumptions made about speeds or numbers of CPUs
  3. Progress
     - No process running outside its critical region may block another process
  4. Non-Starvation
     - No process waits forever to enter its critical region

A solution?

- A lock variable
  - If lock == 1,
    - somebody is in the critical section and we must wait
  - If lock == 0,
    - nobody is in the critical section and we are free to enter

A solution?

```
while(TRUE) {
 while(lock == 1)
  ;
 lock = 1;
 critical();
 lock = 0
 non_critical();
}
```

```
while(TRUE) {
 while(lock == 1)
  ;
 lock = 1;
 critical();
 lock = 0
 non_critical();
}
```

A problematic execution sequence

```
while(TRUE) {

 while(lock == 1)
  ;
 lock = 1;

 critical();
 lock = 0
 non_critical();
}
```

```
while(TRUE) {
 while(lock == 1)
  ;

 lock = 1;
 critical();

 lock = 0
 non_critical();
}
```

Observation

- Unfortunately, it is usually easier to show something does not work, than it is to prove that it does work.
  - Easier to provide a counter example
  - Ideally, we'd like to prove, or at least informally demonstrate, that our solutions work.

- Some of our problematic sequences are quite unlikely
  - e.g. Timer interrupt arrives exactly after we read the lock variable.
  - Testing for concurrency errors is really tricky.

Mutual Exclusion by Taking Turns

```
while (TRUE) {
    while (turn != 0)        /* loop */ ;
    critical_region( );
    turn = 1;
    noncritical_region( );
}
```

(a)

```
while (TRUE) {
    while (turn != 1)        /* loop */ ;
    critical_region( );
    turn = 0;
    noncritical_region( );
}
```

(b)

Proposed solution to critical region problem

(a) Process 0. (b) Process 1.

Mutual Exclusion by Taking Turns

- Works due to *strict alternation*
  - Each process takes turns
- Cons
  - Busy waiting
  - Process must wait its turn even while the other process is doing something else.
    - With many processes, must wait for everyone to have a turn
      - Does not guarantee progress if a process no longer needs a turn.
    - Poor solution when processes require the critical section at differing rates

Mutual Exclusion by Disabling Interrupts

- Before entering a critical region, disable interrupts
- After leaving the critical region, enable interrupts

```
while(TRUE) {
 disable_interrupts();
 critical();
 enable_interrupts();
 non_critical();
}
```

```
while(TRUE) {
 disable_interrupts();
 critical();
 enable_interrupts();
 non_critical();
}
```

Mutual Exclusion by Disabling Interrupts

- Pros
  - simple
- Cons
  - Only available in the kernel
  - Delays everybody else, even with no contention
    - Slows interrupt response time
  - Does not work on a multiprocessor

Hardware Support for mutual exclusion

- Test and set instruction
  - Test memory cell X and set memory cell X
  - Can be used to implement lock variables correctly
    - It loads the value of the lock
    - If lock == 0,
      - set the lock to 1
      - return the result 0 – we acquire the lock
    - If lock == 1
      - return 1 – another thread/process has the lock
  - Hardware guarantees that the instruction executes atomically.
    - Atomically: As an indivisible unit.

Mutual Exclusion with Test-and-Set

```
enter_region:
    TSL REGISTER,LOCK           | copy lock to register and set lock to 1
    CMP REGISTER,#0             | was lock zero?
    JNE enter_region            | if it was non zero, lock was set, so loop
    RET | return to caller; critical region entered

leave_region:
    MOVE LOCK,#0                | store a 0 in lock
    RET | return to caller
```

Entering and leaving a critical region using the

TSL instruction

Test-and-Set

- Pros
  - Simple (easy to show it's correct)
  - Available at user-level
    - To any number of processors
    - To implement any number of lock variables
- Cons
  - Busy waits (also termed a *spin lock)*
    - Consumes CPU
    - Starvation is possible when a process leaves its critical section and more than one process is waiting.

Variants of Test-and-Set

More general operations than test-and-set are provided by modern processors

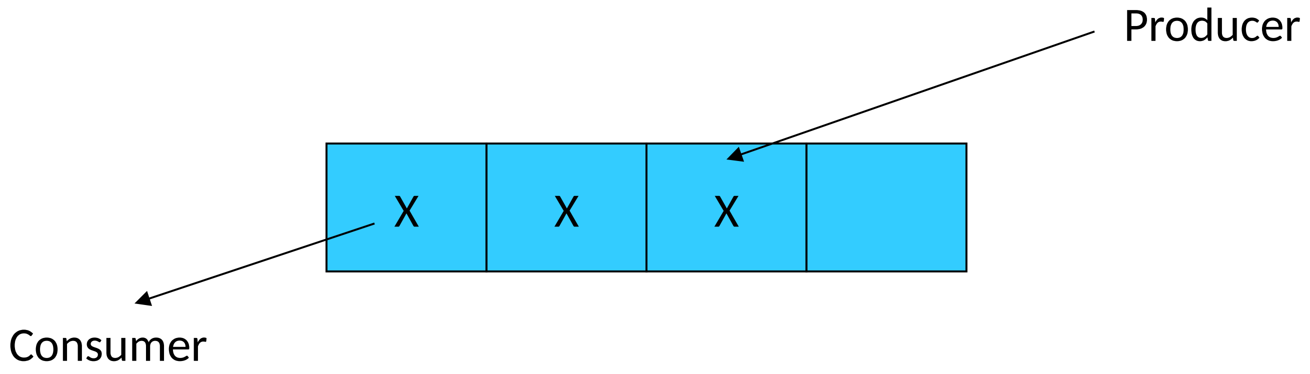
- Compare-and-Swap
  - Check the contents of X is Y, and if so write Z
- Load-Link, Store-Exclusive
  - The store fails if the linked memory address has been accessed
- Atomic Arithmetic
  - e.g. Atomic Increment by 1.

Tackling the Busy-Wait Problem

- Sleep / Wakeup
  - The idea
    - When process is waiting for an event, it calls sleep (a system call) to block, instead of busy waiting.
    - When the event happens, the event generator (another process) calls wakeup to unblock the sleeping process.
    - Waking a ready/running process has no effect.

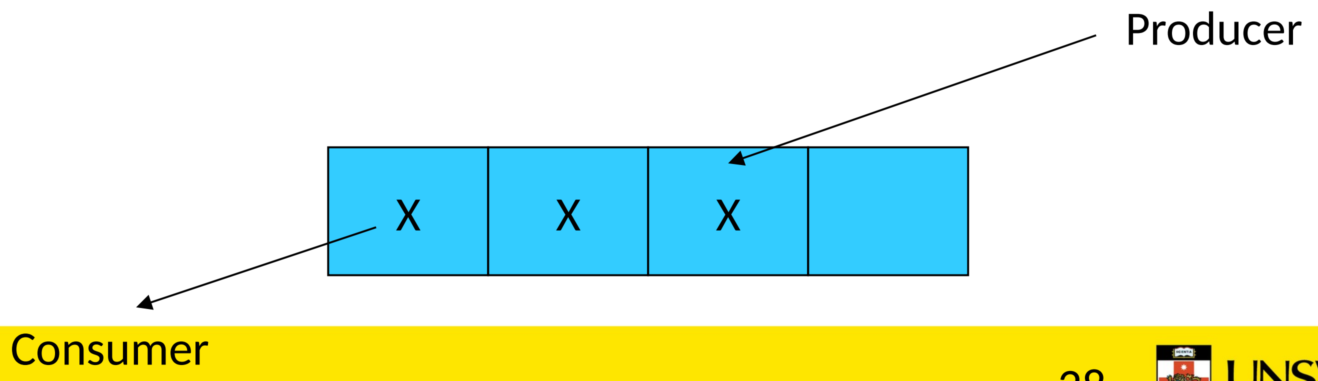
The Producer-Consumer Problem

- Also called the *bounded buffer* problem
- A producer produces data items and stores the items in a buffer
- A consumer takes the items out of the buffer and consumes them.



Issues

- We must keep an accurate count of items in buffer
  - Producer
    - should sleep when the buffer is full,
    - and wakeup when there is empty space in the buffer
      - The consumer can call wakeup when it consumes the first entry of the full buffer
  - Consumer
    - should sleep when the buffer is empty
    - and wake up when there are items available
      - Producer can call wakeup when it adds the first item to the buffer



Pseudo-code for producer and consumer

```
int count = 0;
#define N 4 /* buf size */
prod() {
 while(TRUE) {
      item = produce()
      if (count == N)
           sleep(prod);
      insert_item();
      count++;
      if (count == 1)
           wakeup(con);
 }
}
```

```
con() {
 while(TRUE) {
      if (count == 0)
           sleep(con);
      remove_item();
      count--;
      if (count == N-1)
           wakeup(prod);
 }
}
```

Problems

```
int count = 0;
#define N 4 /* buf size */
prod() {
 while(TRUE) {
	item = produce()
	if (count == N)
		sleep(prod);
	insert_item();
	count++;
	if (count == 1)
		wakeup(con);
 }
}
```

```
con() {
 while(TRUE) {
	if (count == 0)
		sleep(con);
	remove_item();
	count--;
	if (count == N-1)
		   up(prod);
 }
}
```

Concurrent uncontrolled access to the buffer

Problems

```
int count = 0;
#define N 4 /* buf size */
prod() {
 while(TRUE) {
      item = produce()
      if (count == N)
           sleep(prod);
      insert_item();
      count++;
      if (count == 1)
           wakeup(con);
 }
}
```

```
con() {
 while(TRUE) {
      if (count == 0)
           sleep(con);
      remove_item();
      count--;
      if (count == N-1)
           wakeup(prod);
 }
}
```

Concurrent uncontrolled access to the counter

Proposed Solution

- Lets use a locking primitive based on test-and-set to protect the concurrent access

Proposed solution?

```
int count = 0;
lock_t buf_lock;
#define N 4 /* buf size */
prod() {
  while(TRUE) {
        item = produce()
        if (count == N)
              sleep(prod);
        acquire_lock(buf_lock)
        insert_item();
        count++;
        release_lock(buf_lock)
        if (count == 1)
              wakeup(con);
  }
}
```

```
con() {
  while(TRUE) {
        if (count == 0)
              sleep(con);
        acquire_lock(buf_lock)
        remove_item();
        count--;
        release_lock(buf_lock);
        if (count == N-1)
              wakeup(prod);
  }
}
```

Problematic execution sequence

```
con() {
  while(TRUE) {
  if (count == 0)
```

```
prod() {
  while(TRUE) {
        item = produce()
        if (count == N)
              sleep(prod);
        acquire_lock(buf_lock)
        insert_item();
        count++;
        release_lock(buf_lock)
        if (count == 1)
              wakeup(con);
```

wakeup without a matching sleep is lost

```
  sleep(con);
  acquire_lock(buf_lock)
  remove_item();
  count--;
  release_lock(buf_lock);
  if (count == N-1)
  wakeup(prod);
  }
}
```

Problem

- The test for *some condition* and actually going to sleep needs to be atomic
- The following does not work:

```
acquire_lock(buf_lock)
if (count == N)
          sleep();
release_lock(buf_lock)
```

The lock is held while asleep ⇒ count will never change

```
acquire_lock(buf_lock)
if (count == 1)
          wakeup();
release_lock(buf_lock)
```

Today

- Concurrency.
- Critical sections and mutual exclusion.
- Test-and-set operations and locks.
- The producer/consumer problem.
  - More on that later, when we return to concurrency management.