

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 and solve a *producer consumer bounded buffer* problem.
- Understand and apply standard synchronisation primitives to solve synchronisation problems.

Textbook

- Sections 2.3 - 2.3.7 & 2.5

Concurrency Example

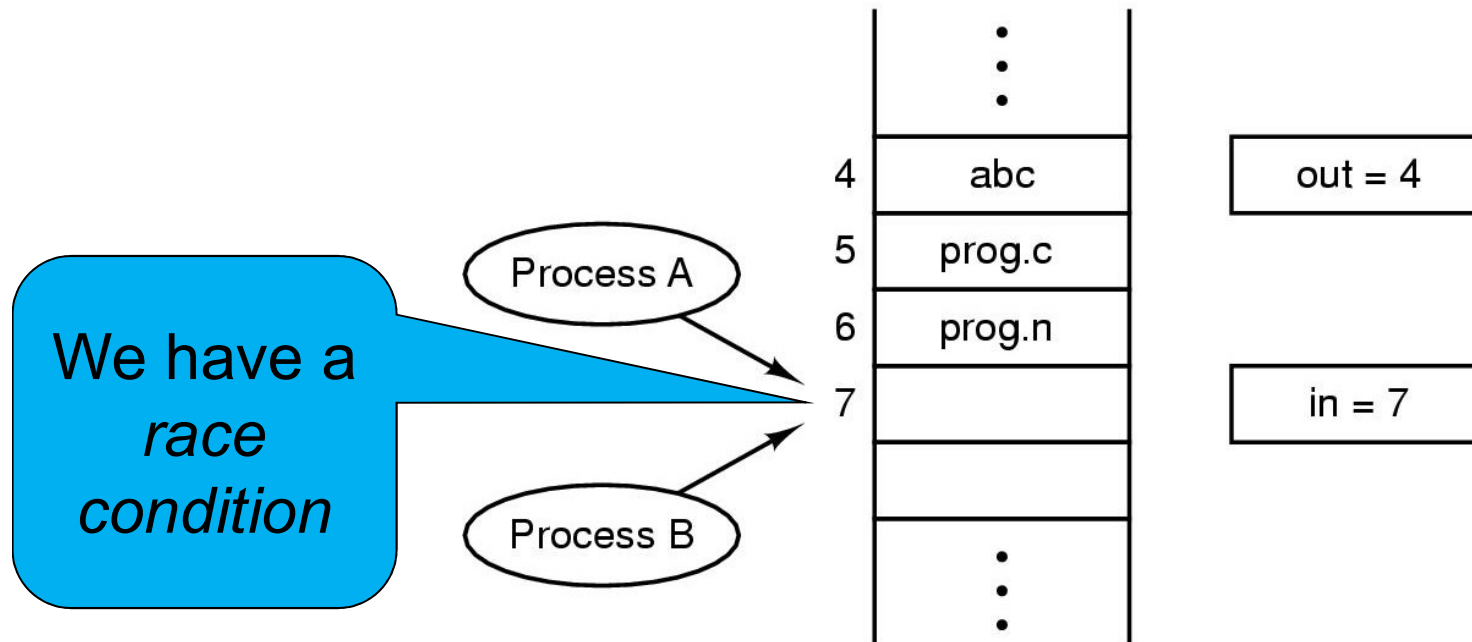
count is a global variable shared between two threads.

After increment and decrement complete, what is the value of count?

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

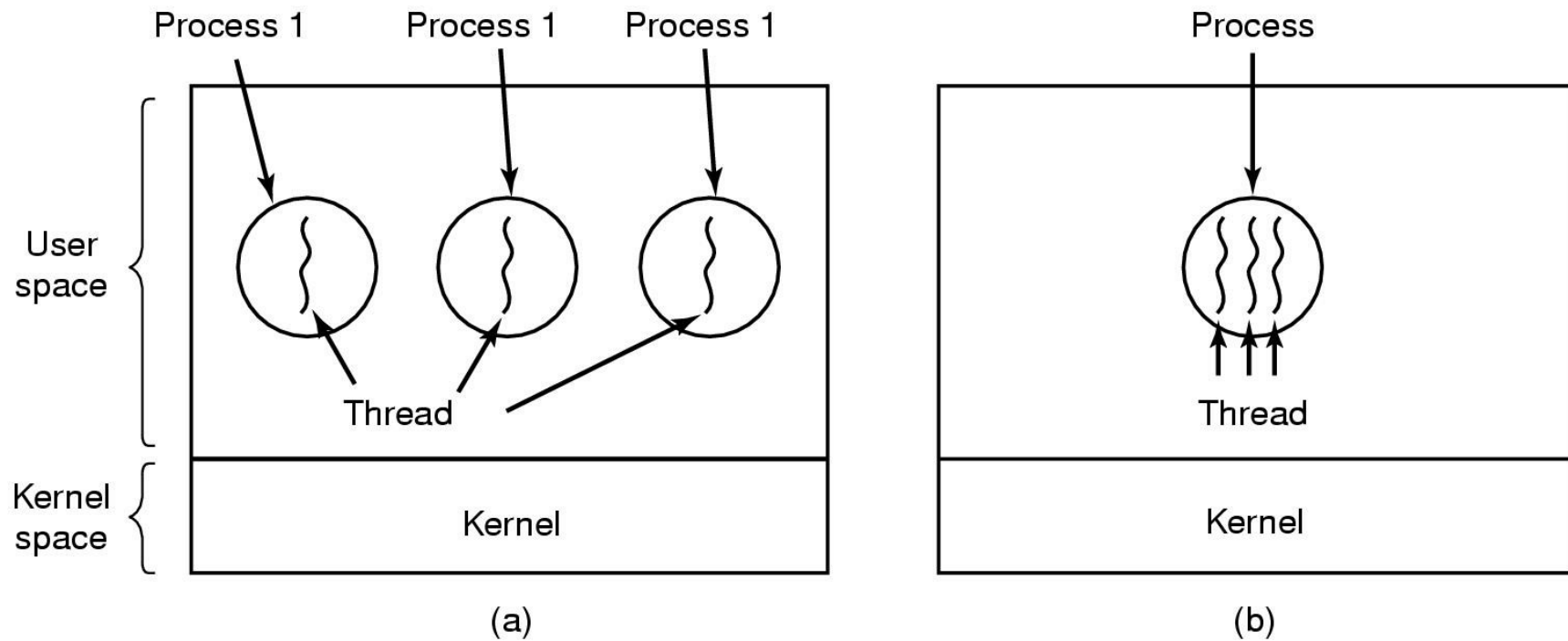
```
void decrement ()
{
    int t;
    t = count;
    t = t - 1;
    count = t;
}
```

Concurrency on a shared data structure



Two processes want to access shared memory at same time

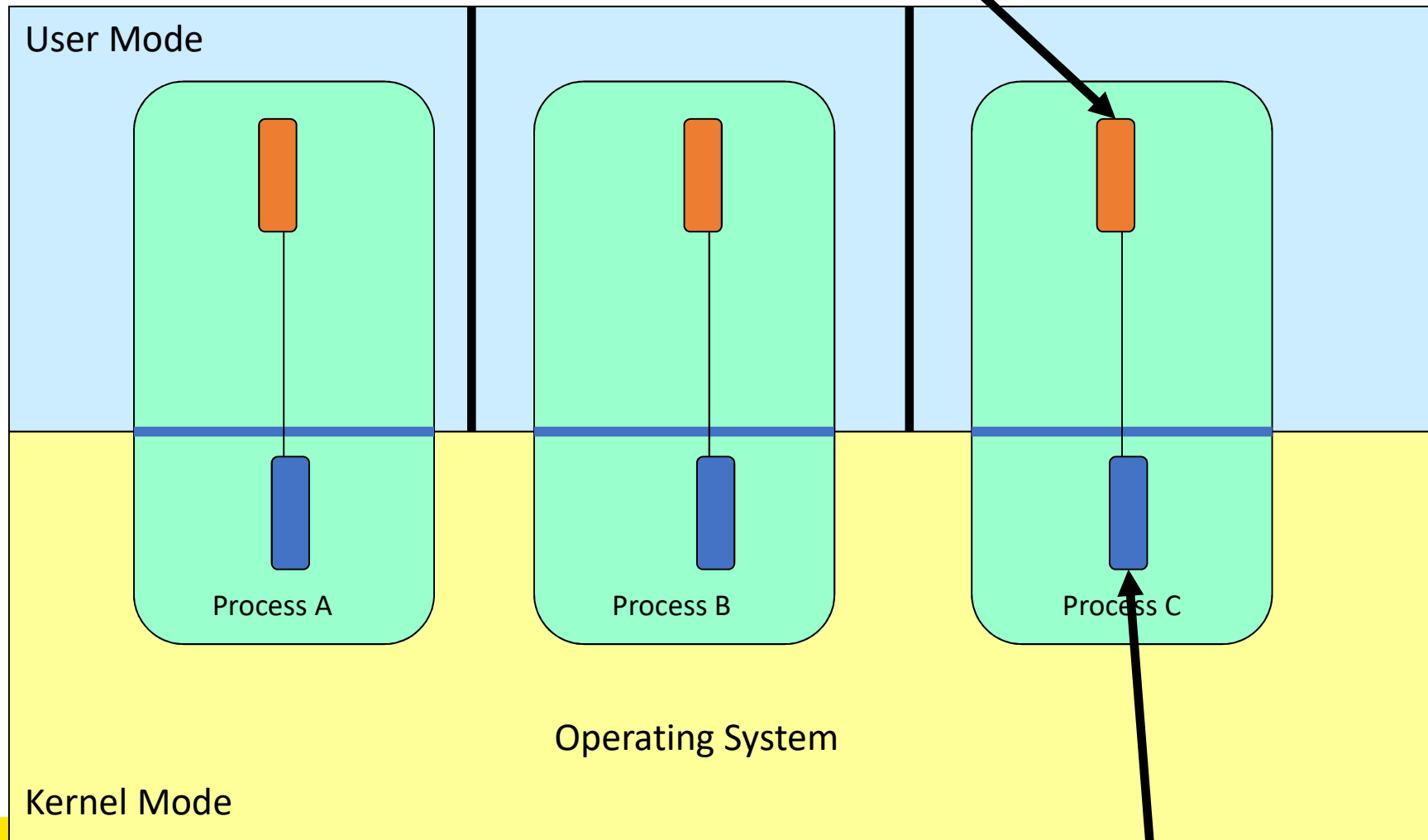
Where is the concurrency?



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

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

Process's user-level stack and execution state



Process's in-kernel stack and execution state

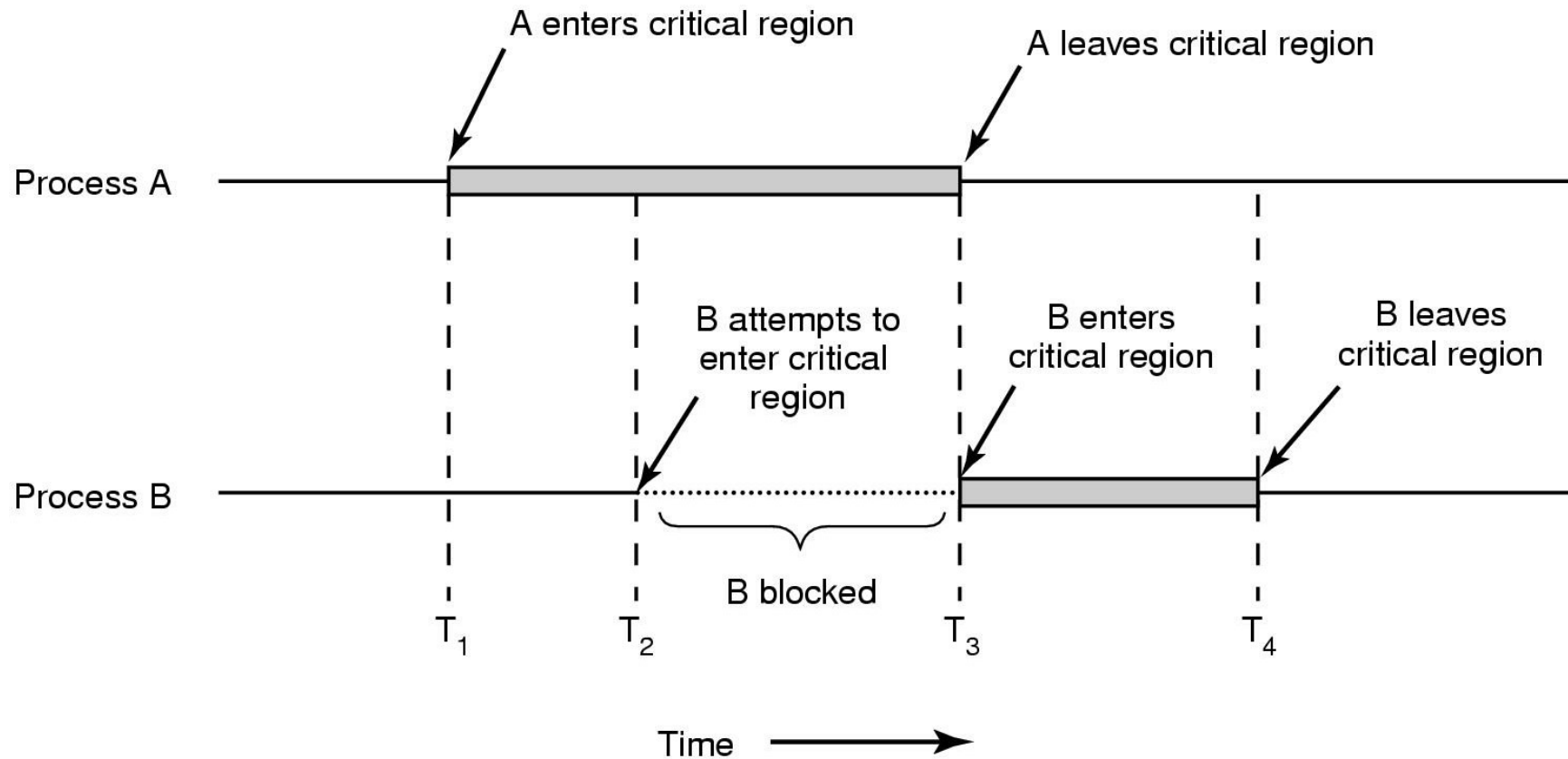
Critical Region

- 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,...

Critical Regions



Mutual exclusion using critical regions

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.

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. Bounded
 - 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.

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

Peterson's Solution

- For the curious
- Avoids strict alternation
 - see the textbook
 - or Internet

Mutual Exclusion by Disabling Interrupts

- Before entering a critical region, disable interrupts
- After leaving the critical region, enable interrupts
- Pros
 - simple
- Cons
 - Only available in the kernel
 - Blocks 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
 - 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

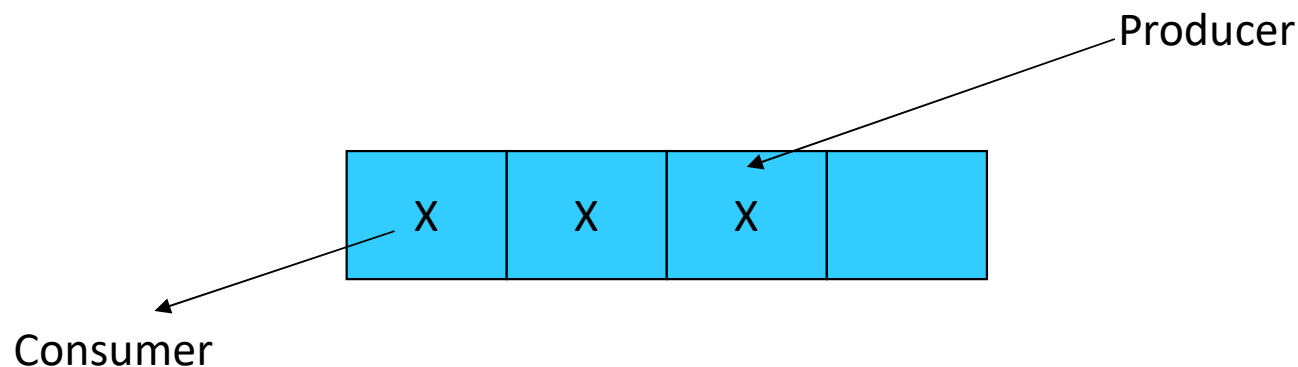
- Pros
 - Simple (easy to show it's correct)
 - Available at user-level
 - To any number of processors
 - To implement any number of lock variables
- Cons
 - Busy waits (also termed a *spin lock*)
 - Consumes CPU
 - Starvation is possible when a process leaves its critical section and more than one process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

Tackling the Busy-Wait Problem

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

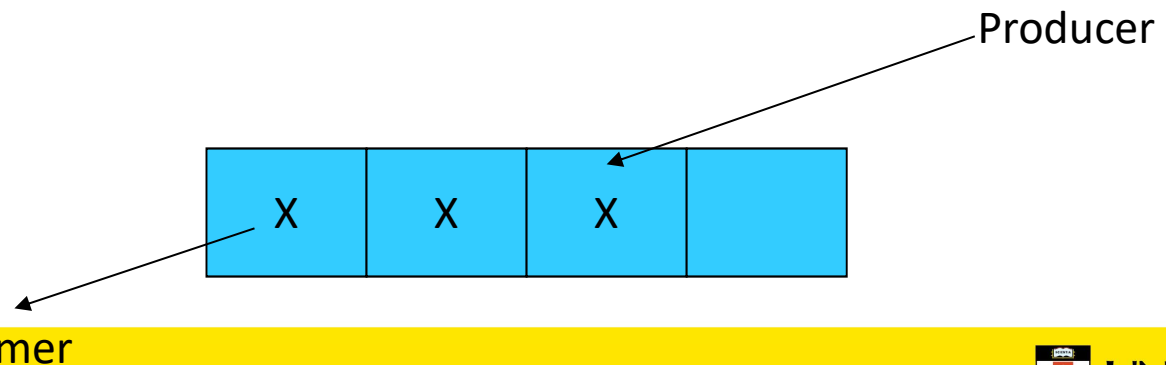
The Producer-Consumer Problem

- 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
 - can 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
 - Can 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

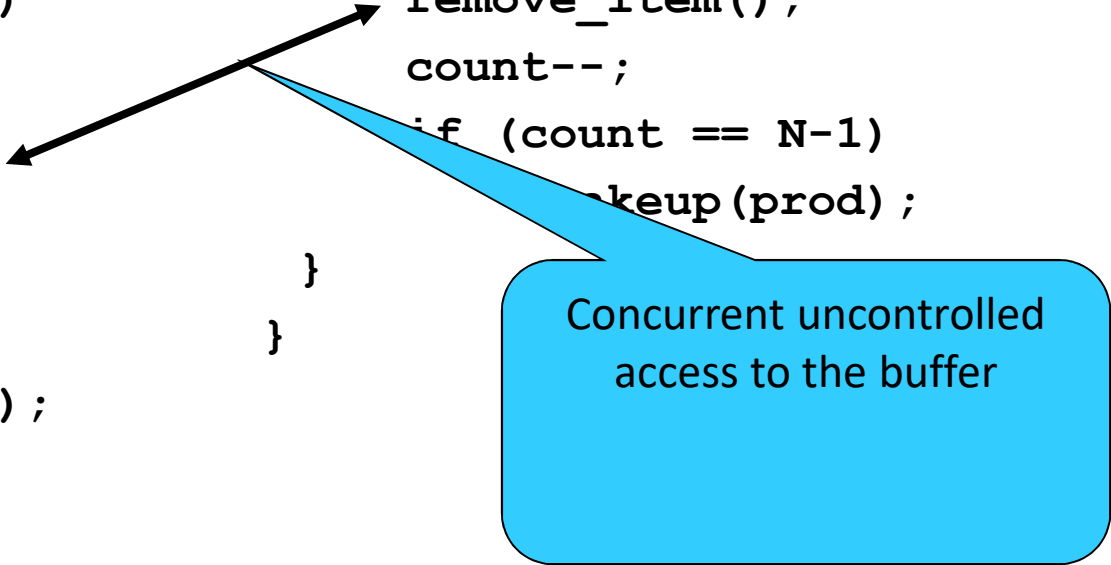
```
int count = 0;
#define N 4 /* buf size */
prod() {
    while(TRUE) {
        item = produce()
        if (count == N)
            sleep();
        insert_item();
        count++;
        if (count == 1)
            wakeup(con);
    }
}

con() {
    while(TRUE) {
        if (count == 0)
            sleep();
        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();
        insert_item();
        count++;
        if (count == 1)
            wakeup(con);
    }
}

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

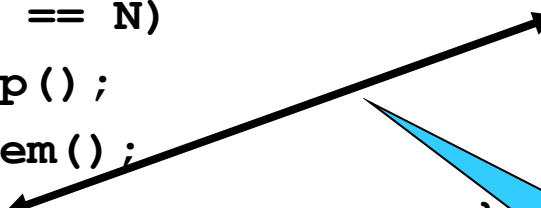


Concurrent uncontrolled access to the buffer

Problems

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

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

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

Problematic execution sequence

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

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

wakeup without a
matching sleep is lost

```
      sleep();  
      acquire_lock()  
      remove_item();  
      count--;  
      release_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()  
if (count == N)  
    sleep();  
release_lock()
```

The lock is held while asleep
⇒ count will never change

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

Semaphores

- Dijkstra (1965) introduced two primitives that are more powerful than simple sleep and wakeup alone.
 - P(): *proberen*, from Dutch to *test*.
 - V(): *verhogen*, from Dutch to *increment*.
 - Also called *wait & signal*, *down & up*.

How do they work

- If a resource is not available, the corresponding semaphore blocks any process **waiting** for the resource
- Blocked processes are put into a process queue maintained by the semaphore (avoids busy waiting!)
- When a process releases a resource, it **signals** this by means of the semaphore
- Signalling resumes a blocked process if there is any
- Wait and signal operations cannot be interrupted
- Complex coordination can be implemented by multiple semaphores

Semaphore Implementation

- Define a semaphore as a record

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

- Assume two simple operations:
 - **sleep** suspends the process that invokes it.
 - **wakeup(P)** resumes the execution of a blocked process **P**.

- Semaphore operations now defined as

wait(S):

```
S.count--;  
if (S.count < 0) {  
    add this process to S.L;  
    sleep;  
}
```

signal(S):

```
S.count++;  
if (S.count <= 0) {  
    remove a process P from S.L;  
    wakeup(P);  
}
```

- Each primitive is atomic
 - E.g. interrupts are disabled for each

Semaphore as a General Synchronization Tool

- Execute B in P_j only after A executed in P_i
- Use semaphore *count* initialized to 0
- Code:

P_i	P_j
⋮	⋮
A	$wait(flag)$
$signal(flag)$	B

Semaphore Implementation of a Mutex

- Mutex is short for Mutual Exclusion
 - Can also be called a lock

```
semaphore mutex;  
mutex.count = 1; /* initialise mutex */  
  
wait(mutex); /* enter the critical region */  
  
Blahblah();  
  
signal(mutex); /* exit the critical region */
```

Notice that the initial count determines how many waits can progress before blocking and requiring a signal \Rightarrow mutex.count initialised as 1

Solving the producer-consumer problem with semaphores

```
#define N = 4

semaphore mutex = 1;

/* count empty slots */
semaphore empty = N;

/* count full slots */
semaphore full = 0;
```

Solving the producer-consumer problem with semaphores

```
prod() {  
    while(TRUE) {  
        item = produce()  
        wait(empty);  
        wait(mutex)  
        insert_item();  
        signal(mutex);  
        signal(full);  
    }  
}
```

```
con() {  
    while(TRUE) {  
        wait(full);  
        wait(mutex);  
        remove_item();  
        signal(mutex);  
        signal(empty);  
    }  
}
```

Summarising Semaphores

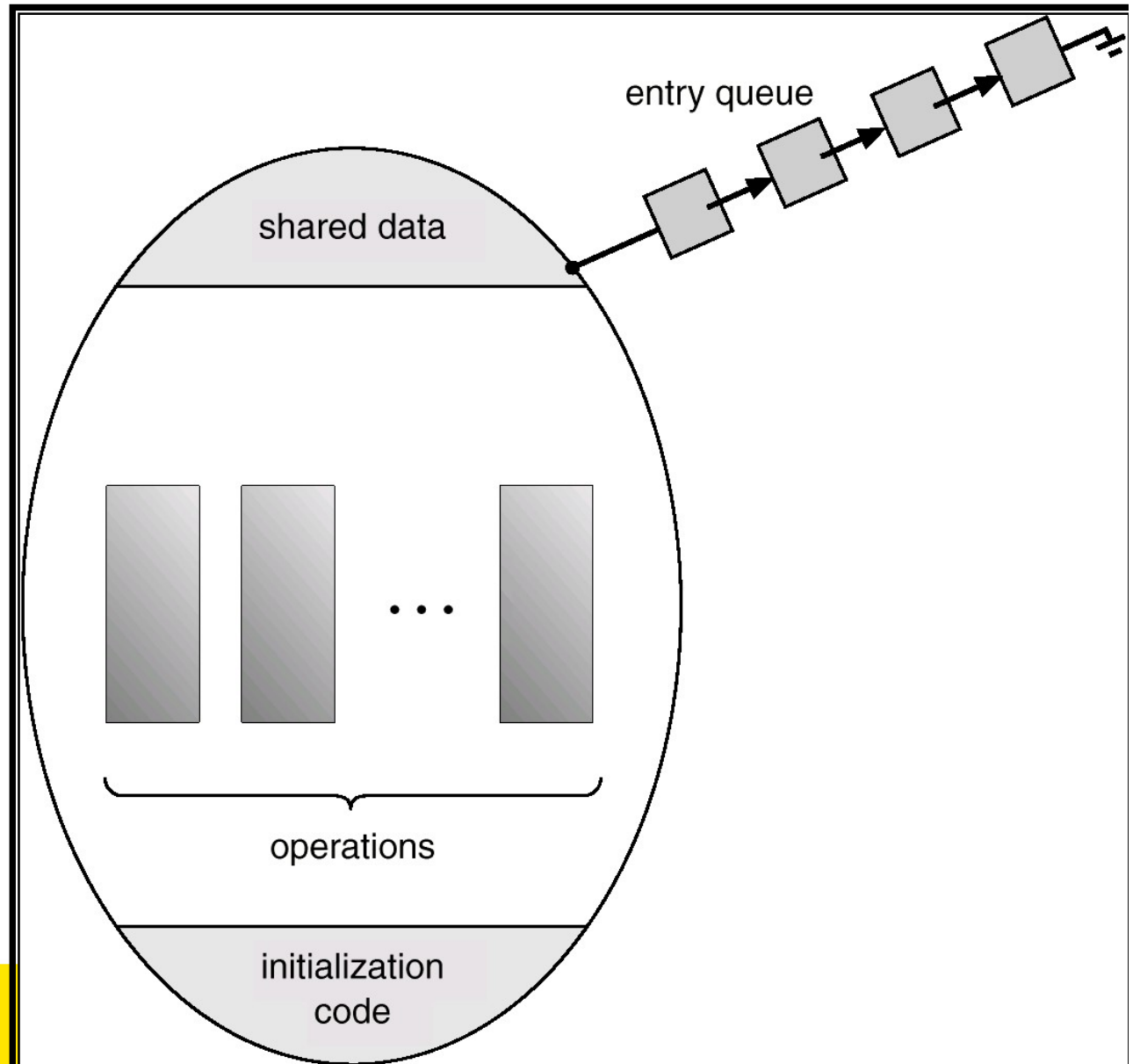
- Semaphores can be used to solve a variety of concurrency problems
- However, programming with them can be error-prone
 - E.g. must *signal* for every *wait* for mutexes
 - Too many, or too few signals or waits, or signals and waits in the wrong order, can have catastrophic results

Monitors

- To ease concurrent programming, Hoare (1974) proposed *monitors*.
 - A higher level synchronisation primitive
 - Programming language construct
- Idea
 - A set of procedures, variables, data types are grouped in a special kind of module, a *monitor*.
 - Variables and data types only accessed from within the monitor
 - Only one process/thread can be in the monitor at any one time
 - Mutual exclusion is implemented by the compiler (which should be less error prone)

Monitor

- When a thread calls a monitor procedure that has a thread already inside, it is queued and it sleeps until the current thread exits the monitor.



Monitors

```
monitor example  
  integer i;  
  condition c;  
  
  procedure producer( );  
  .  
  .  
  .  
  end;  
  
  procedure consumer( );  
  .  
  .  
  .  
  end;  
end monitor;
```

Example of a monitor

Simple example

```
monitor counter {  
    int count;  
    procedure inc() {  
        count = count + 1;  
    }  
    procedure dec() {  
        count = count -1;  
    }  
}
```

Note: “paper” language

- Compiler guarantees only one thread can be active in the monitor at any one time
- Easy to see this provides mutual exclusion
 - No race condition on **count**.

How do we block waiting for an event?

- We need a mechanism to block waiting for an event (in addition to ensuring mutual exclusion)
 - e.g., for producer consumer problem when buffer is empty or full
- *Condition Variables*

Condition Variable

- To allow a process to wait within the monitor, a **condition** variable must be declared, as

condition x, y;

- Condition variable can only be used with the operations **wait** and **signal**.

- The operation

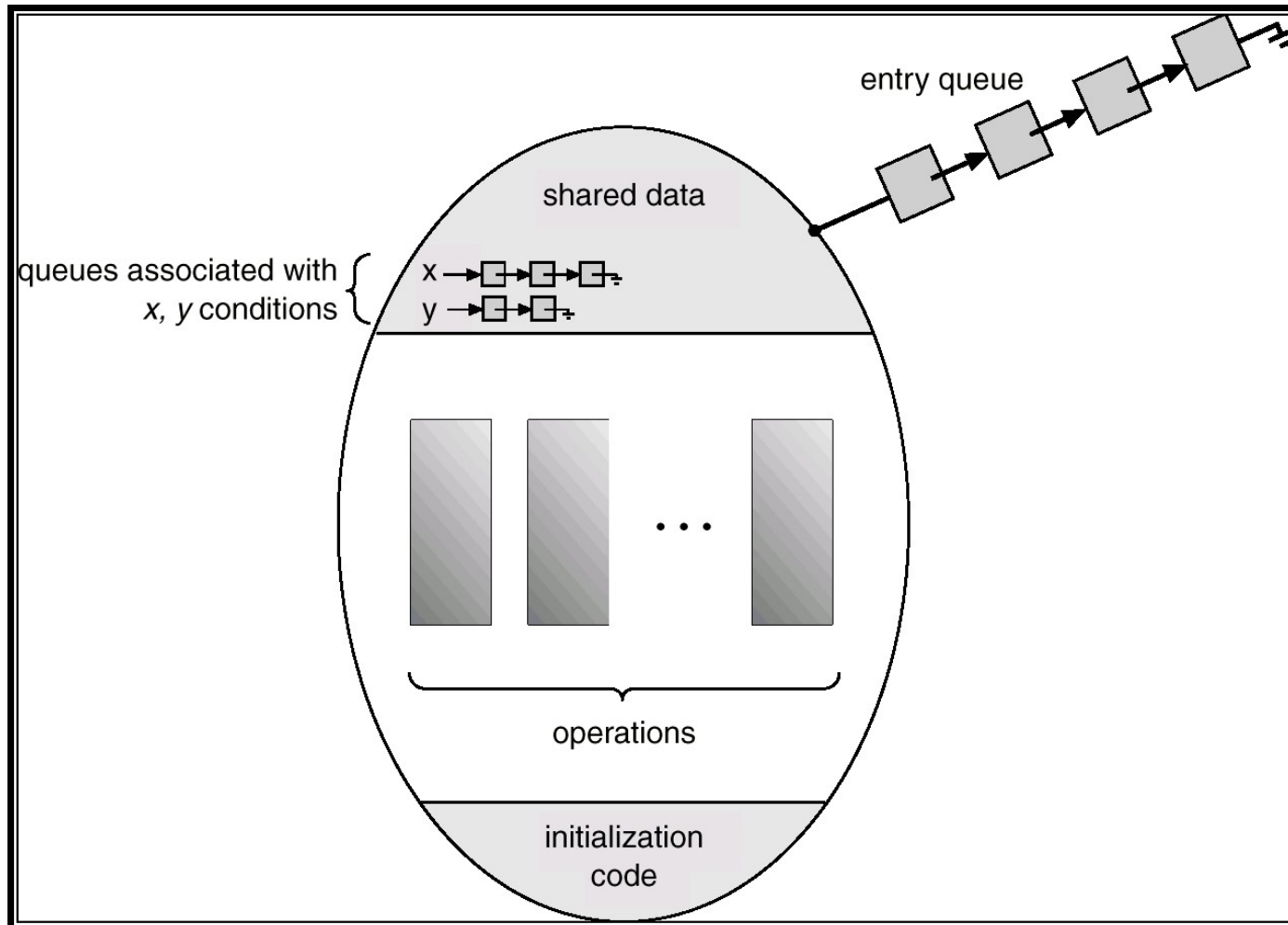
x.wait();

- means that the process invoking this operation is suspended until another process invokes
- Another thread can enter the monitor while original is suspended

x.signal();

- The **x.signal** operation resumes exactly one suspended process. If no process is suspended, then the **signal** operation has no effect.

Condition Variables



Monitors

```
monitor ProducerConsumer
  condition full, empty;
  integer count;
  procedure insert(item: integer);
  begin
    if count = N then wait(full);
    insert_item(item);
    count := count + 1;
    if count = 1 then signal(empty)
  end;
  function remove: integer;
  begin
    if count = 0 then wait(empty);
    remove = remove_item;
    count := count - 1;
    if count = N - 1 then signal(full)
  end;
  count := 0;
end monitor;
```

```
procedure producer;
begin
  while true do
    begin
      item = produce_item;
      ProducerConsumer.insert(item)
    end
  end;
procedure consumer;
begin
  while true do
    begin
      item = ProducerConsumer.remove;
      consume_item(item)
    end
  end;
end;
```

- Outline of producer-consumer problem with monitors
 - only one monitor procedure active at one time
 - buffer has N slots

OS/161 Provided Synchronisation Primitives

- Locks
- Semaphores
- Condition Variables

Locks

- Functions to create and destroy locks

```
struct lock *lock_create(const char *name);  
void          lock_destroy(struct lock *);
```

- Functions to acquire and release them

```
void          lock_acquire(struct lock *);  
void          lock_release(struct lock *);
```

Example use of locks

```
int count;
struct lock *count_lock

main() {
    count = 0;
    count_lock =
        lock_create("count
lock");
    if (count_lock == NULL)
        panic("I'm dead");
    stuff();
}
```

```
procedure inc() {
    lock_acquire(count_lock);
    count = count + 1;
    lock_release(count_lock);
}

procedure dec() {
    lock_acquire(count_lock);
    count = count - 1;
    lock_release(count_lock);
}
```

Semaphores

```
struct semaphore *sem_create(const char *name, int
                             initial_count);

void              sem_destroy(struct semaphore *);

void              P(struct semaphore *);
void              V(struct semaphore *);
```


Example use of Semaphores

```
int count;
struct semaphore
    *count_mutex;

main() {
    count = 0;
    count_mutex =
        sem_create("count",
                  1);
    if (count_mutex == NULL)
        panic("I'm dead");
    stuff();
}

procedure inc() {
    P(count_mutex);
    count = count + 1;
    V(count_mutex);
}

procedure dec() {
    P(count_mutex);
    count = count - 1;
    V(count_mutex);
}
```

Condition Variables

```
struct cv *cv_create(const char *name);  
void      cv_destroy(struct cv *);
```

```
void      cv_wait(struct cv *cv, struct lock *lock);
```

- Releases the lock and blocks
- Upon resumption, it re-acquires the lock
 - Note: we must recheck the condition we slept on

```
void      cv_signal(struct cv *cv, struct lock *lock);
```

```
void      cv_broadcast(struct cv *cv, struct lock *lock);
```

- Wakes one/all, does not release the lock
- First “waiter” scheduled after signaller releases the lock will re-acquire the lock

Note: All three variants must hold the lock passed in.

Condition Variables and Bounded Buffers

Non-solution

```
lock_acquire(c_lock)
if (count == 0)
    sleep();
remove_item();
count--;
lock_release(c_lock)
;
```

Solution

```
lock_acquire(c_lock)
while (count == 0)
    cv_wait(c_cv, c_lock);
remove_item();
count--;
lock_release(c_lock);
```

A Producer-Consumer Solution Using OS/161 CVs

```
int count = 0;
#define N 4 /* buf size */
prod() {
    while(TRUE) {
        item = produce()
        lock_acquire(l)
        while (count == N)
            cv_wait(full,l);
        insert_item(item);
        count++;
        if (count == 1)
            cv_signal(empty,l);
        lock_release(l)
    }
}
```

```
con() {
    while(TRUE) {
        lock_acquire(l)
        while (count == 0)
            cv_wait(empty,l);
        item = remove_item();
        count--;
        if (count == N-1)
            cv_signal(full,l);
        lock_release(l);
        consume(item);
    }
}
```

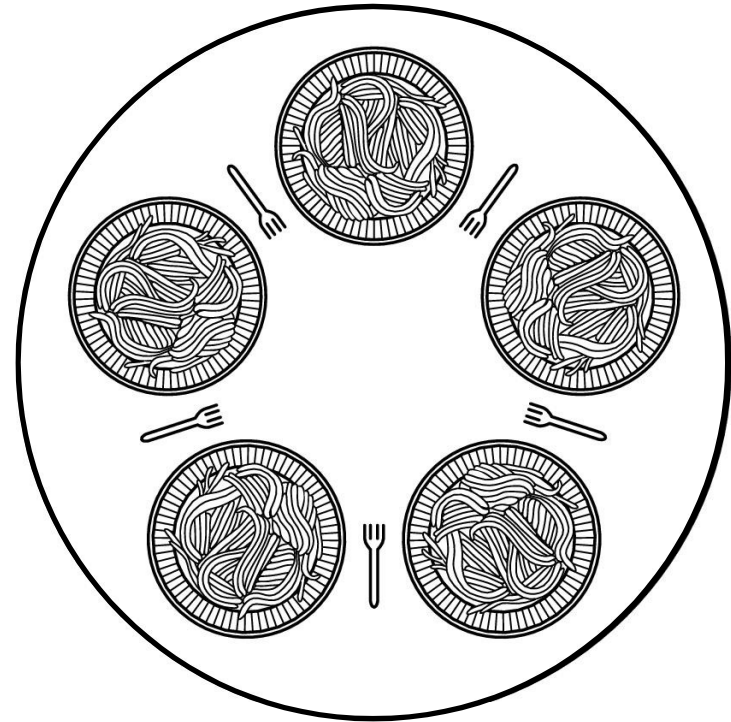
Alternative Producer-Consumer Solution Using OS/161 CVs

```
int count = 0;
#define N 4 /* buf size */
prod() {
    while(TRUE) {
        item = produce()
        lock_acquire(l)
        while (count == N)
            cv_wait(full,l);
        insert_item(item);
        count++;
        cv_signal(empty,l);
        lock_release(l)
    }
}

con() {
    while(TRUE) {
        lock_acquire(l)
        while (count == 0)
            cv_wait(empty,l);
        item = remove_item();
        count--;
        cv_signal(full,l);
        lock_release(l);
        consume(item);
    }
}
```

Dining Philosophers

- Philosophers eat/think
- Eating needs 2 forks
- Pick one fork at a time
- How to prevent deadlock



Dining Philosophers

```
#define N          5          /* number of philosophers */
#define LEFT      (i+N-1)%N  /* number of i's left neighbor */
#define RIGHT     (i+1)%N    /* number of i's right neighbor */
#define THINKING  0          /* philosopher is thinking */
#define HUNGRY    1          /* philosopher is trying to get forks */
#define EATING    2          /* philosopher is eating */
typedef int semaphore;      /* semaphores are a special kind of int */
int state[N];              /* array to keep track of everyone's state */
semaphore mutex = 1;       /* mutual exclusion for critical regions */
semaphore s[N];           /* one semaphore per philosopher */

void philosopher(int i)    /* i: philosopher number, from 0 to N-1 */
{
    while (TRUE) {        /* repeat forever */
        think();          /* philosopher is thinking */
        take_forks(i);    /* acquire two forks or block */
        eat();            /* yum-yum, spaghetti */
        put_forks(i);     /* put both forks back on table */
    }
}
```

Solution to dining philosophers problem (part 1)

Dining Philosophers

```
#define N 5                                     /* number of philosophers */

void philosopher(int i)                         /* i: philosopher number, from 0 to 4 */
{
    while (TRUE) {
        think( );                             /* philosopher is thinking */
        take_fork(i);                          /* take left fork */
        take_fork((i+1) % N);                 /* take right fork; % is modulo operator */
        eat( );                               /* yum-yum, spaghetti */
        put_fork(i);                          /* put left fork back on the table */
        put_fork((i+1) % N);                 /* put right fork back on the table */
    }
}
```

A nonsolution to the dining philosophers problem

Dining Philosophers

```
void take_forks(int i)                /* i: philosopher number, from 0 to N-1 */
{
    down(&mutex);                    /* enter critical region */
    state[i] = HUNGRY;               /* record fact that philosopher i is hungry */
    test(i);                         /* try to acquire 2 forks */
    up(&mutex);                      /* exit critical region */
    down(&s[i]);                     /* block if forks were not acquired */
}

void put_forks(i)                    /* i: philosopher number, from 0 to N-1 */
{
    down(&mutex);                    /* enter critical region */
    state[i] = THINKING;            /* philosopher has finished eating */
    test(LEFT);                     /* see if left neighbor can now eat */
    test(RIGHT);                    /* see if right neighbor can now eat */
    up(&mutex);                      /* exit critical region */
}

void test(i)                         /* i: philosopher number, from 0 to N-1 */
{
    if (state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING) {
        state[i] = EATING;
        up(&s[i]);
    }
}
```

Solution to dining philosophers problem (part 2)



The Readers and Writers Problem

- Models access to a database
 - E.g. airline reservation system
- Can have more than one concurrent reader
 - To check schedules and reservations
- Writers must have exclusive access
 - To book a ticket or update a schedule

The Readers and Writers Problem

```
typedef int semaphore;           /* use your imagination */
semaphore mutex = 1;           /* controls access to 'rc' */
semaphore db = 1;              /* controls access to the database */
int rc = 0;                     /* # of processes reading or wanting to */

void reader(void)
{
    while (TRUE) {              /* repeat forever */
        down(&mutex);           /* get exclusive access to 'rc' */
        rc = rc + 1;            /* one reader more now */
        if (rc == 1) down(&db); /* if this is the first reader ... */
        up(&mutex);             /* release exclusive access to 'rc' */
        read_data_base();       /* access the data */
        down(&mutex);           /* get exclusive access to 'rc' */
        rc = rc - 1;            /* one reader fewer now */
        if (rc == 0) up(&db);   /* if this is the last reader ... */
        up(&mutex);             /* release exclusive access to 'rc' */
        use_data_read();        /* noncritical region */
    }
}

void writer(void)
{
    while (TRUE) {              /* repeat forever */
        think_up_data();        /* noncritical region */
        down(&db);              /* get exclusive access */
        write_data_base();      /* update the data */
        up(&db);                /* release exclusive access */
    }
}
```

A solution to the readers and writers problem