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

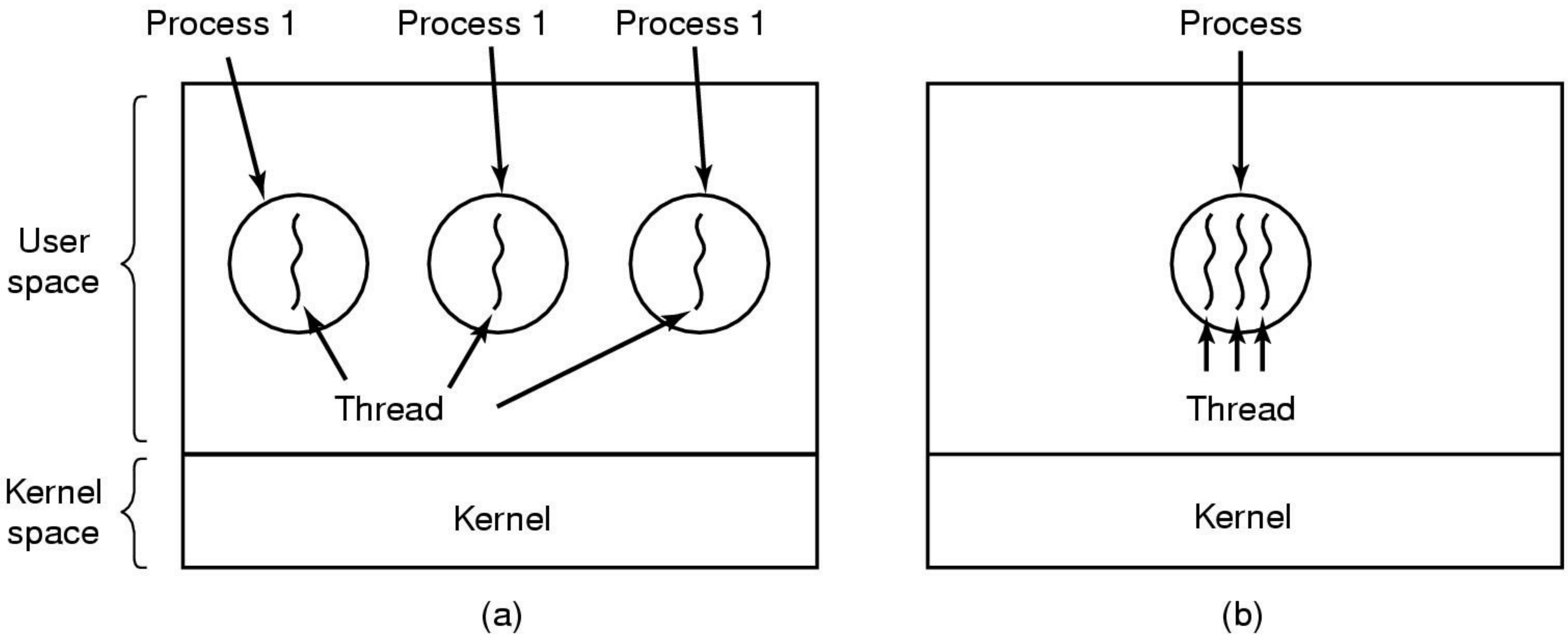
`count` is a global variable shared between two threads, `t` is a local variable. After increment and decrement complete, what is the value of count?

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

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

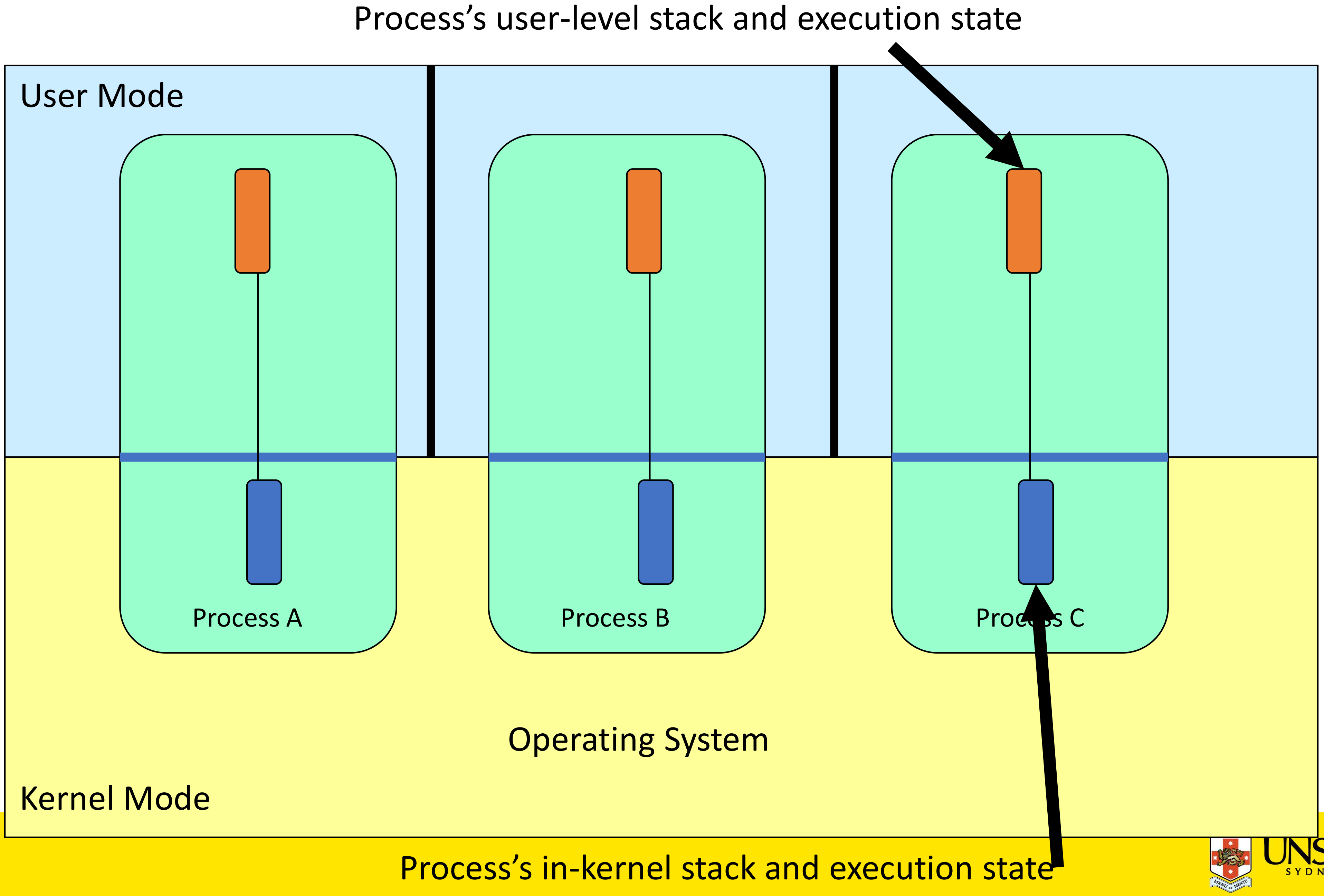
We have a *race condition*

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.

$\Rightarrow$ 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

  $\Rightarrow$ Incorrect behaviour, deadlock, lost work,…

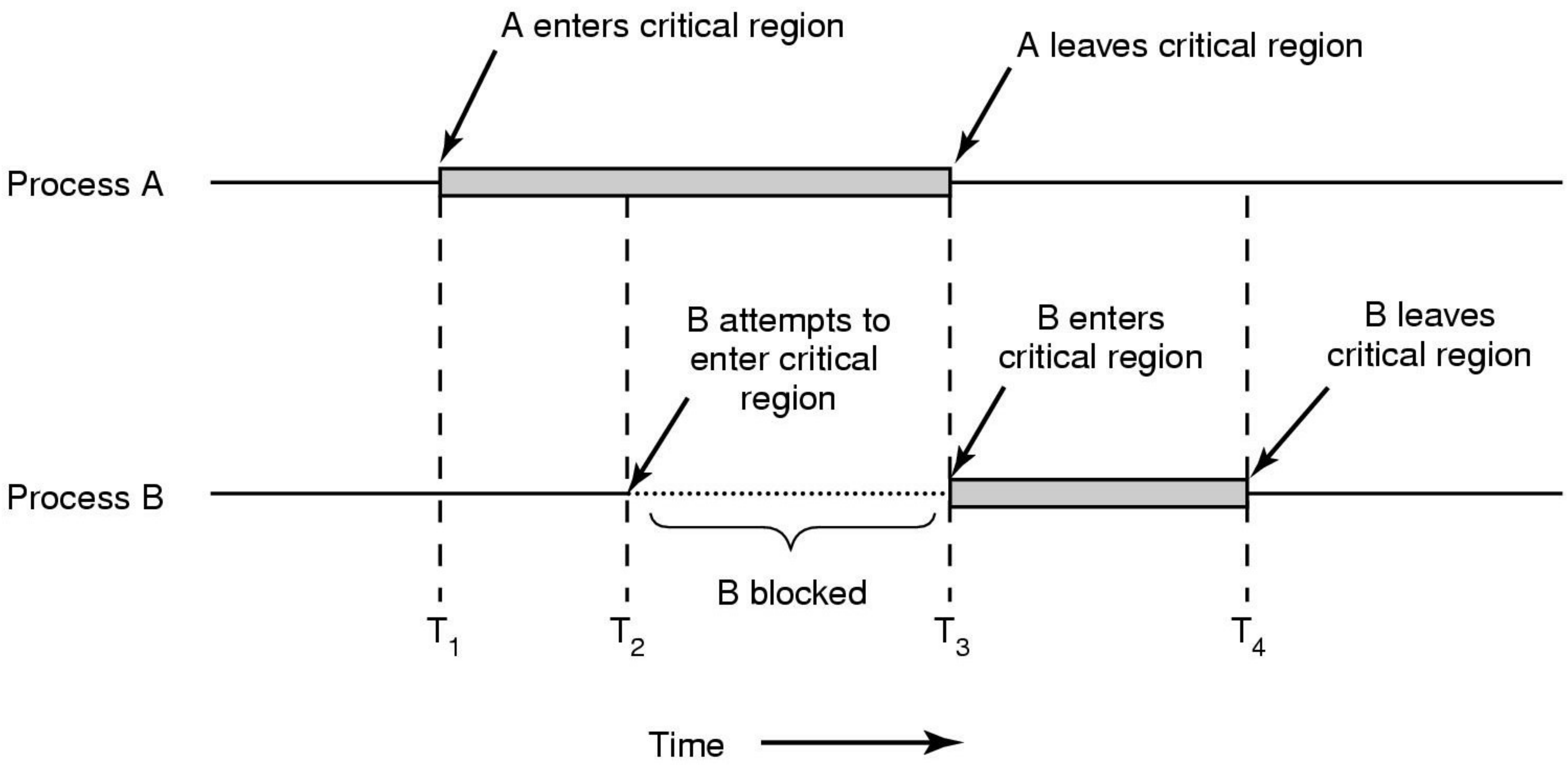
Identifying critical regions

- 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. 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(TRUE) {
                                          while(lock == 1);
 while(lock == 1);
 lock = 1;
                                          lock = 1;
 critical();                              critical();
 lock = 0
 non_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

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
  - 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
  - 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

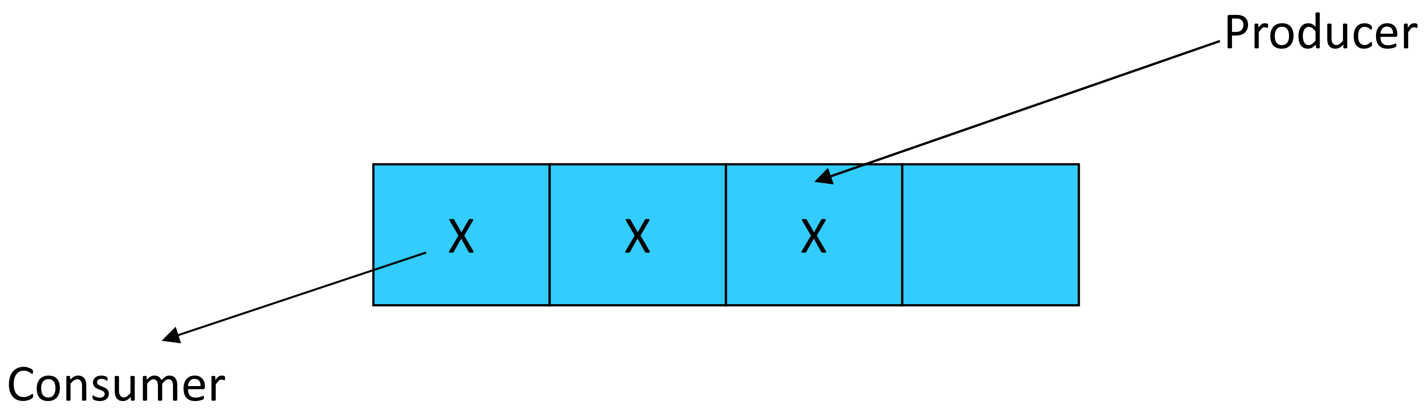
- Pros
  - Simple (easy to show it's correct)
  - Available at user-level
    - To any number of processors
    - To implement any number of lock variables
- Cons
  - Busy waits (also termed a *spin lock)*
    - Consumes CPU
    - Starvation is possible when a process leaves its critical section and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

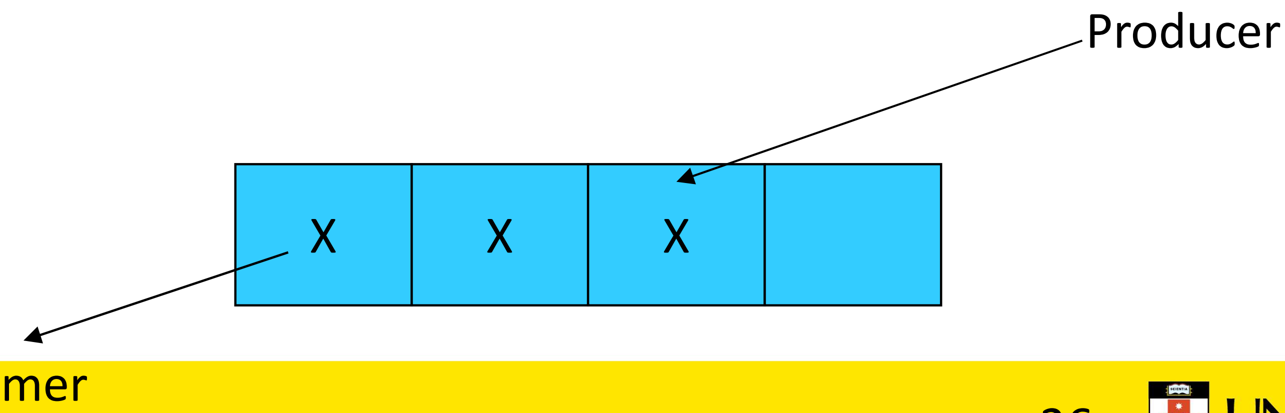
The Producer-Consumer Problem

- 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
    - 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)
            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(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)
```

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

The lock is held while asleep
$\Rightarrow$ count will never change

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 (P) and signal (V) 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 critcal 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

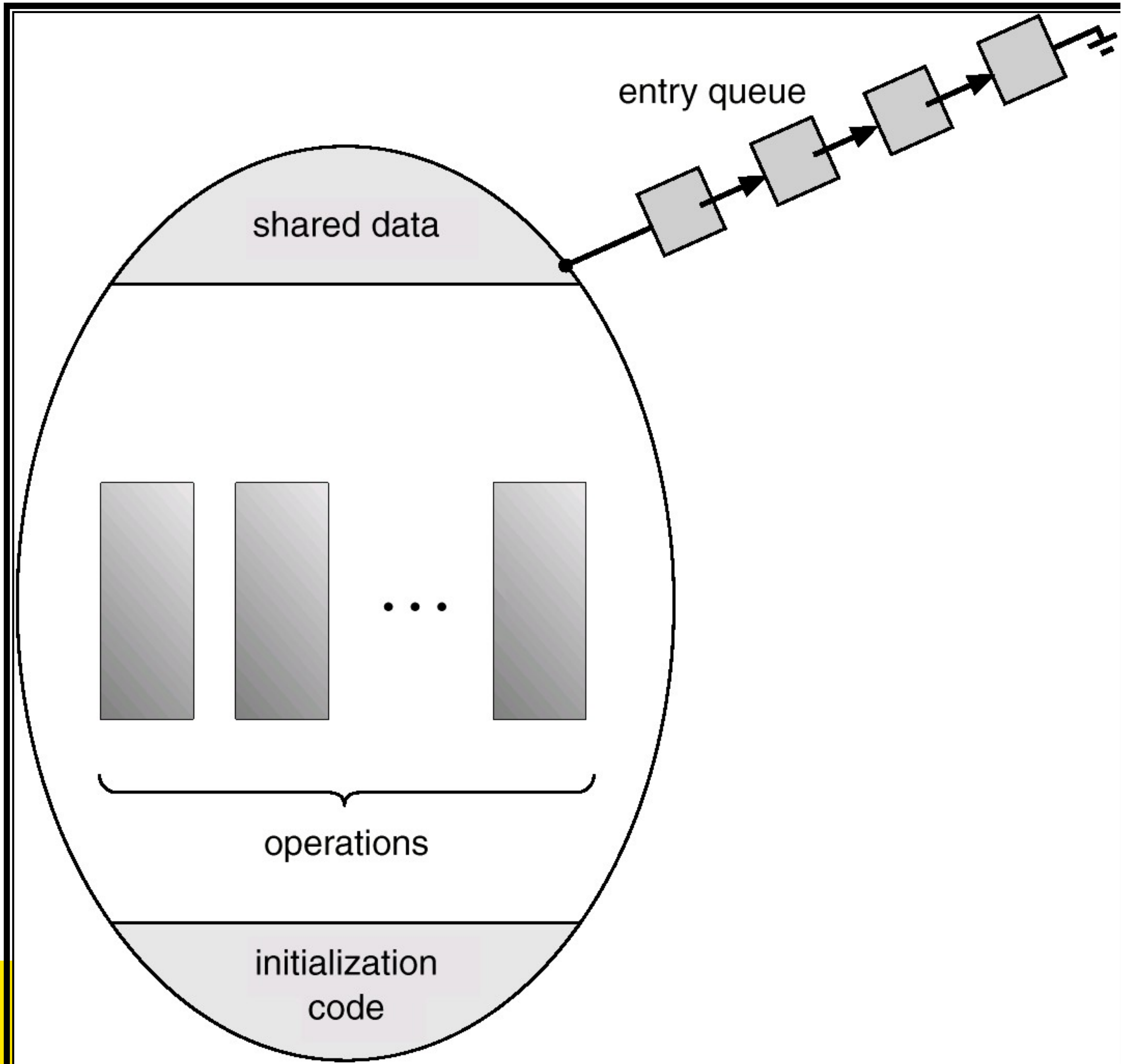
- Semaphores can be used to solve a variety of concurrency problems
- However, programming with then can be error-prone
  - E.g. must *signal* for every *wait* for mutexes
    - Too many, or too few signals or waits, or signals and waits in the wrong order, can have catastrophic results

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

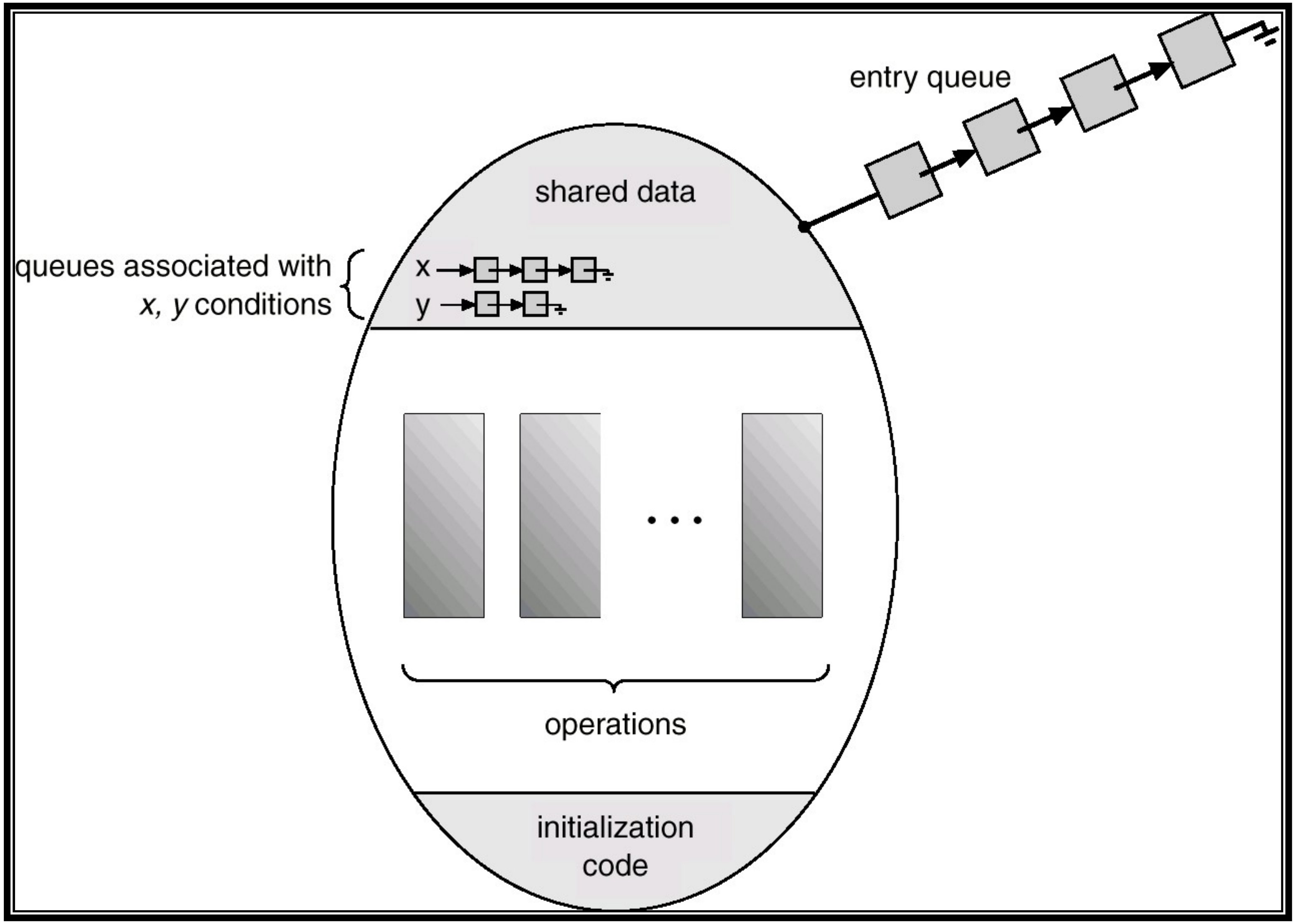
    x.wait();

    - 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;
```

- 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);
```

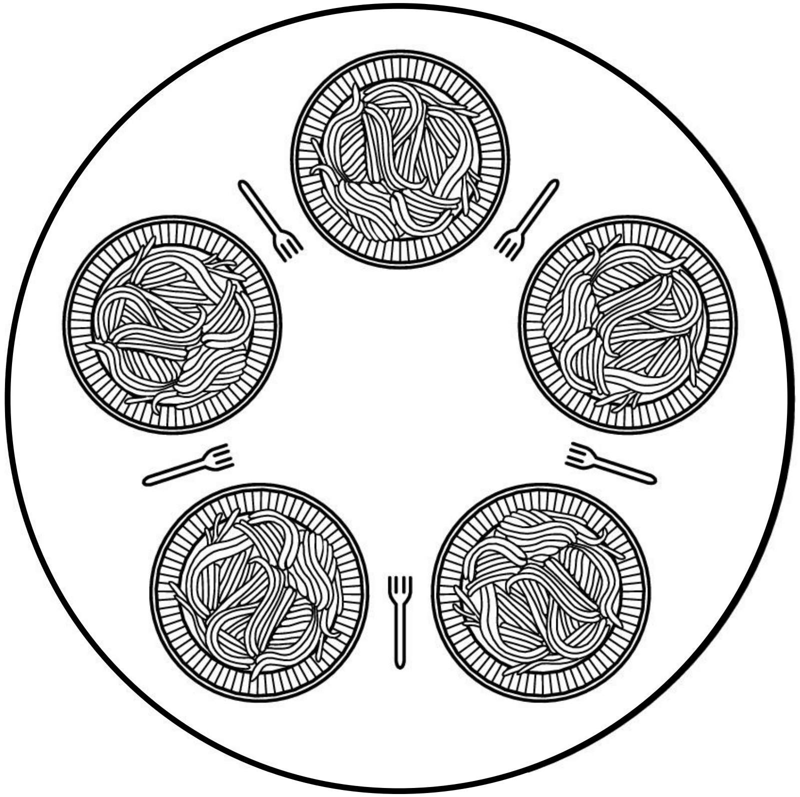
Alternative Producer-Consumer Solution Using OS/161 CVs

```
int count = 0;
#define N 4 /* buf size */
prod() {
  while(TRUE) {
        item = produce()
        lock_aquire(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 <u>non</u>solution 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