# Concurrency and Synchronisation

Part II

# Learning Outcomes

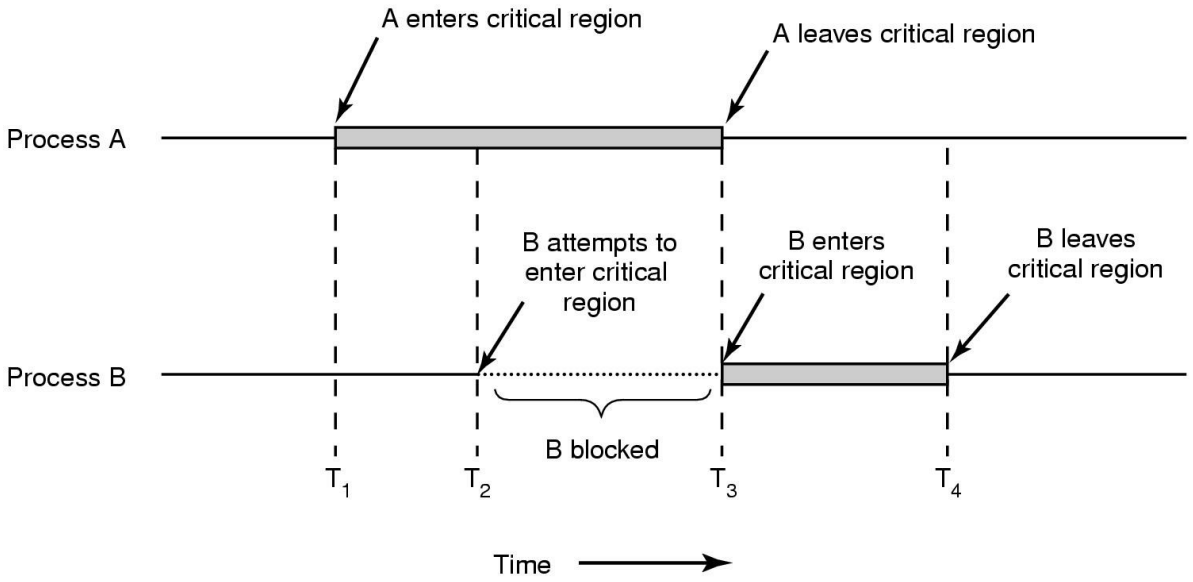
- Understand concurrency is an issue in operating systems and multithreaded applications
- Know the concept of a *critical region*.
- Understand how mutual exclusion of critical regions can be used to solve concurrency issues
  - Including how mutual exclusion can be implemented correctly and efficiently.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

# Recap: Critical Regions

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




Mutual exclusion using critical regions

# Recap: Test-and-Set

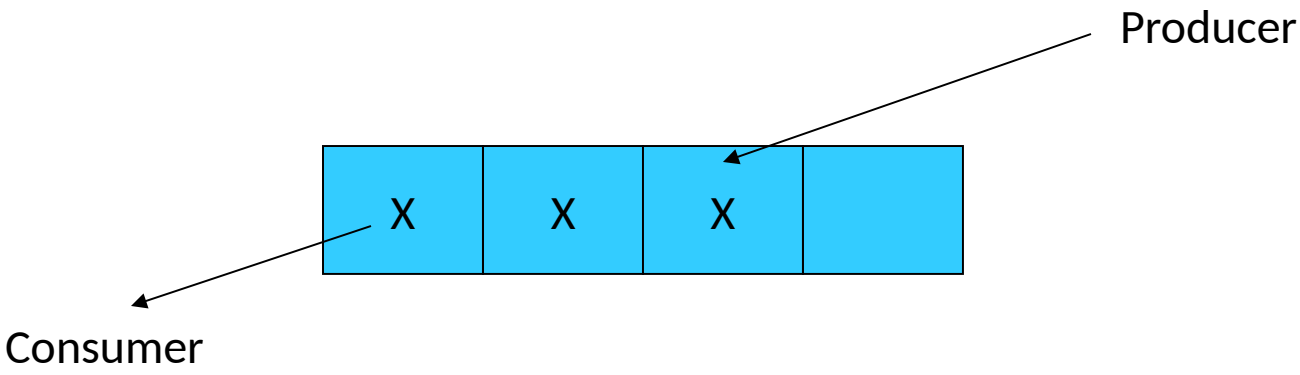
- We can use test-and-set to implement lock() and unlock() primitives
- Pros
  - Simple (easy to show it's correct)
  - Available at user-level
    - To any number of processors
    - To implement any number of lock variables
- Cons
  - Busy waits (also termed a *spin lock)*
    - Consumes CPU
    - 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.

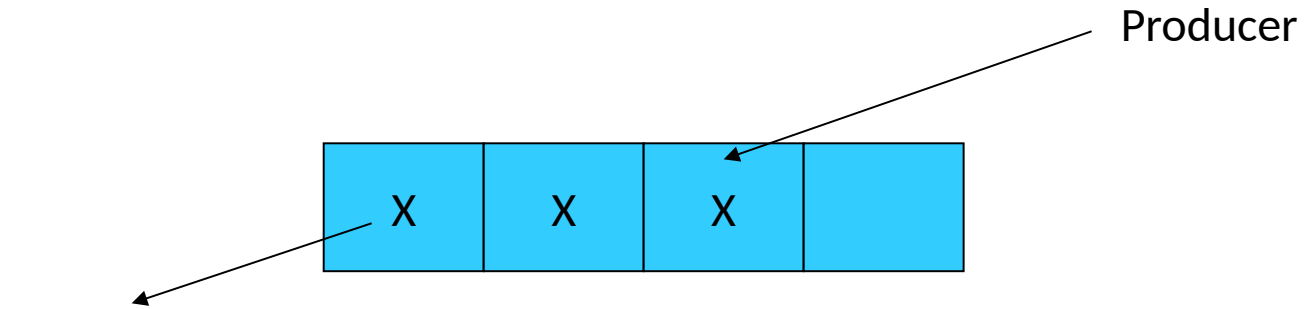
# The Producer-Consumer Problem

- 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(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(item);
      count++;
      if (count == 1)
           wakeup(con);
 }
}
```

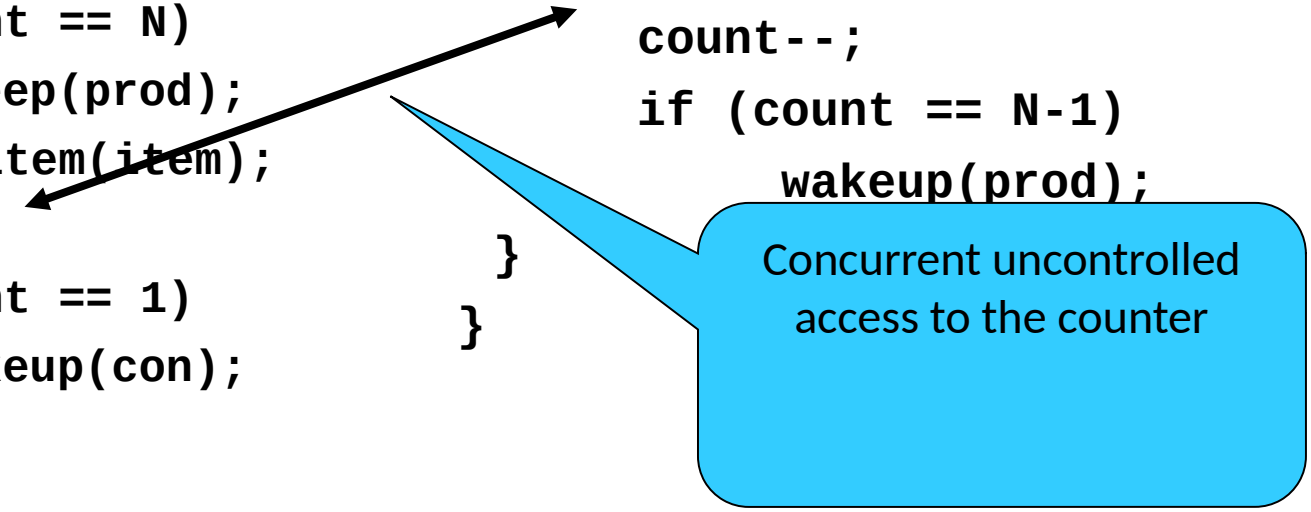
```
con() {
 while(TRUE) {
      if (count == 0)
           sleep(con);
      remove_item();
      count--;
      if (count == N-1)
           wakeup(prod);
 }
}
```

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(item);
      count++;
      if (count == 1)
           wakeup(con);
 }
}
```

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



# 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(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

```
prod() {
  while(TRUE) {
        item = produce()
        if (count == N)
              sleep(prod);
        acquire_lock(buf_lock)
        insert_item(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);
  }
}
```

wakeup without a matching sleep is lost

# Problem

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

The lock is held while asleep ⇒ count will never change

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

```
acquire_lock(buf_lock)
...
if (count == N - 1)
            wakeup(prod);
...
release_lock(buf_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, or stores the signal to be read by the next waiting task
- 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*):

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

*signal*(*S*):

```
S.count++;
if (S.count <= 1) {
  remove a process P from S.L;
  wakeup(P);
}
```

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

# Semaphore Implementation of a Mutex

```
/* initialise mutex */
semaphore mutex;
mutex.count = 1;

/* enter the critcal region */
wait(mutex);

critical();

/* exit the critical region */
signal(mutex);
```

A semaphore can restrict a region to access by N threads.

If N=1, this implements mutual exclusion.

- A mutex object.
- Also called a lock.

# 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

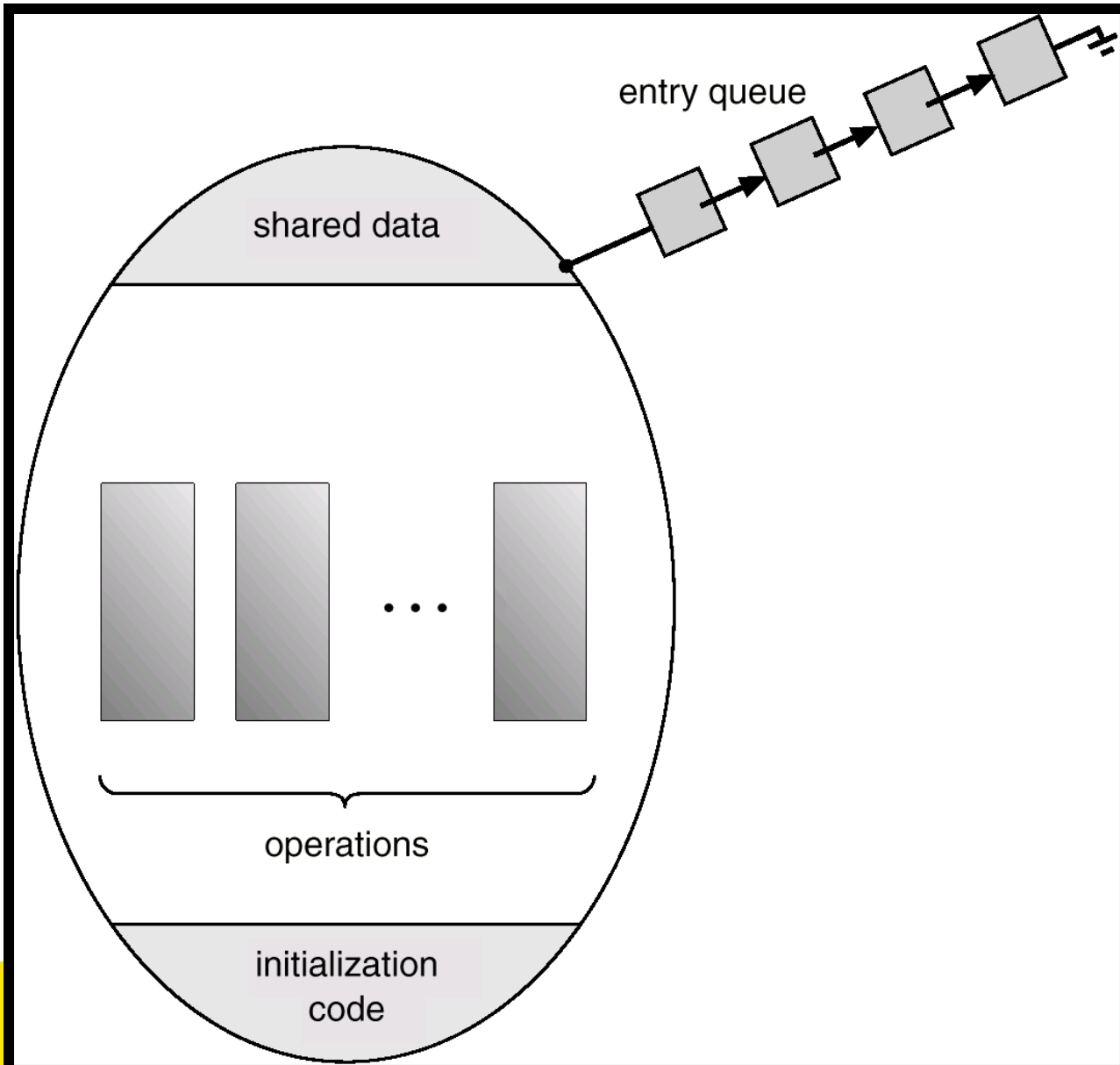
- Semaphores can be used to solve a variety of concurrency problems
- However, programming with them can be error-prone
  - E.g. must *signal* for every *wait* for mutexes
    - Too many, or too few signals or waits, or signals and waits in the wrong order, can have catastrophic results

# 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`**.
- For instance, **synchronized** methods in Java.

# How do we block waiting for an event?

- We can use locks to block waiting for an object, held by another task
- We can use semaphores to solve the producer/consumer problem directly
- We would like a mechanism to block waiting for a kind of event (and also respect mutual exclusion)
  - e.g. in the producer-consumer problem
    - produce events
    - consume events
  - A blocked consumer is not waiting on just one producer
- *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

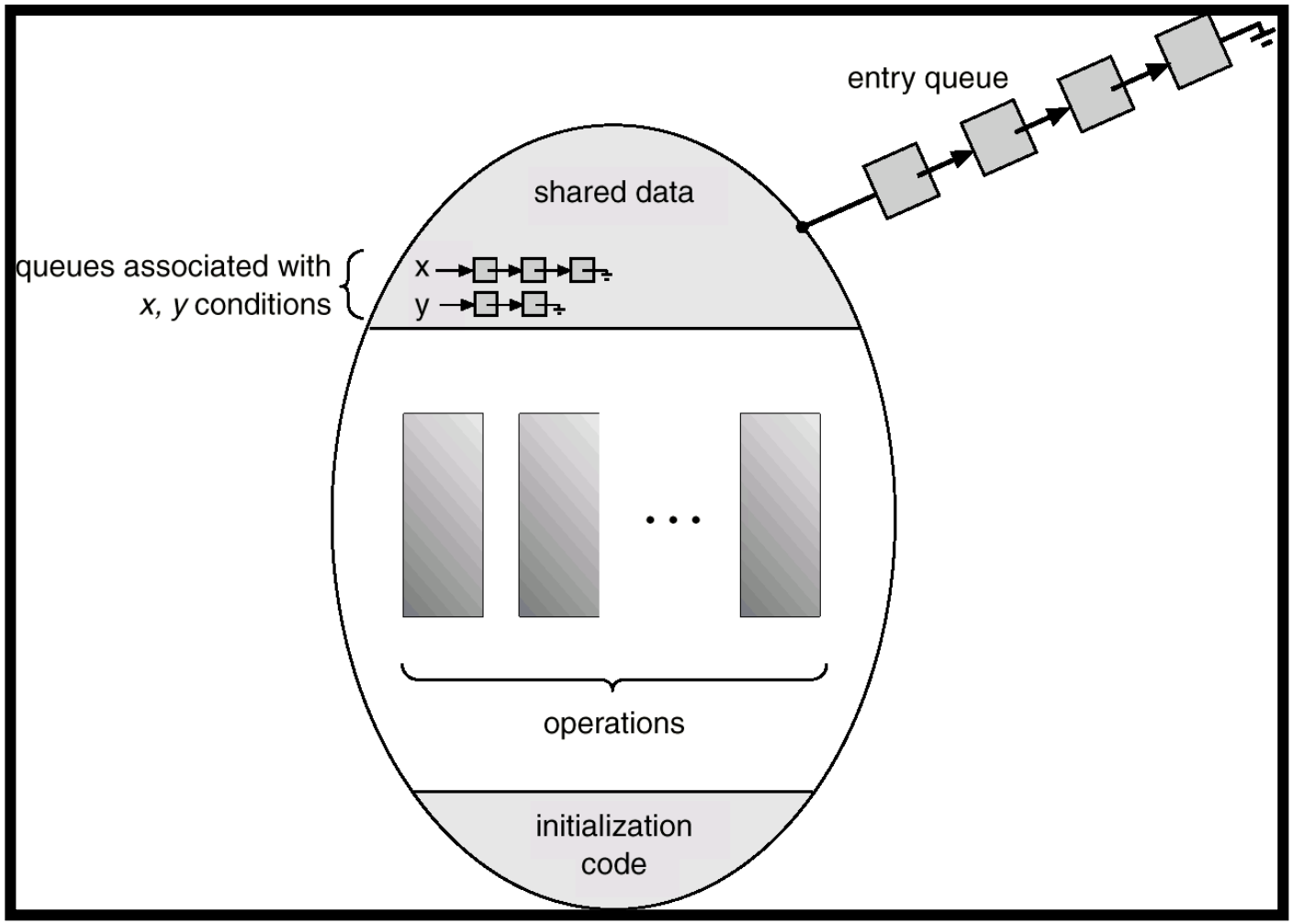
    **x.wait();**

    - means that the process invoking this operation is suspended until another process invokes signal
    - 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 functions 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);
  }
}
```

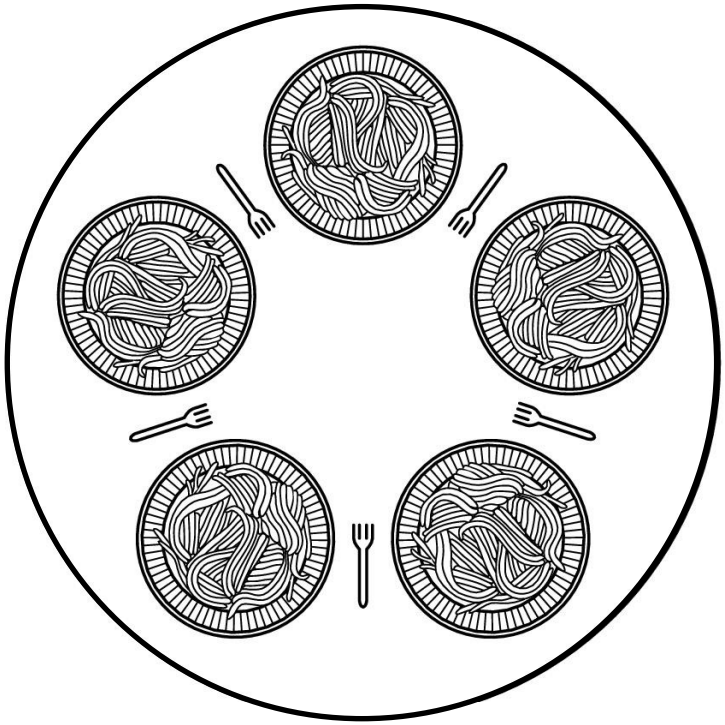
# More Concurrency Puzzles

Some more concurrency puzzles to think about (which may appear again in tutorials):

- Dining philosophers
- Readers/Writers

# Dining Philosophers

- Philosophers eat/think
- Eating needs 2 forks
- Pick one fork at a time
- How do we 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

# This Lecture

- Synchronisation Mechanisms:
  - Locks
  - Semaphores
  - Monitors (not present in OS/161)
  - Condition Variables
- Concurrency Scenarios:
  - Producer/Consumer
  - Dining Philosophers
  - Readers/Writers