Concurrency and Synchronisation

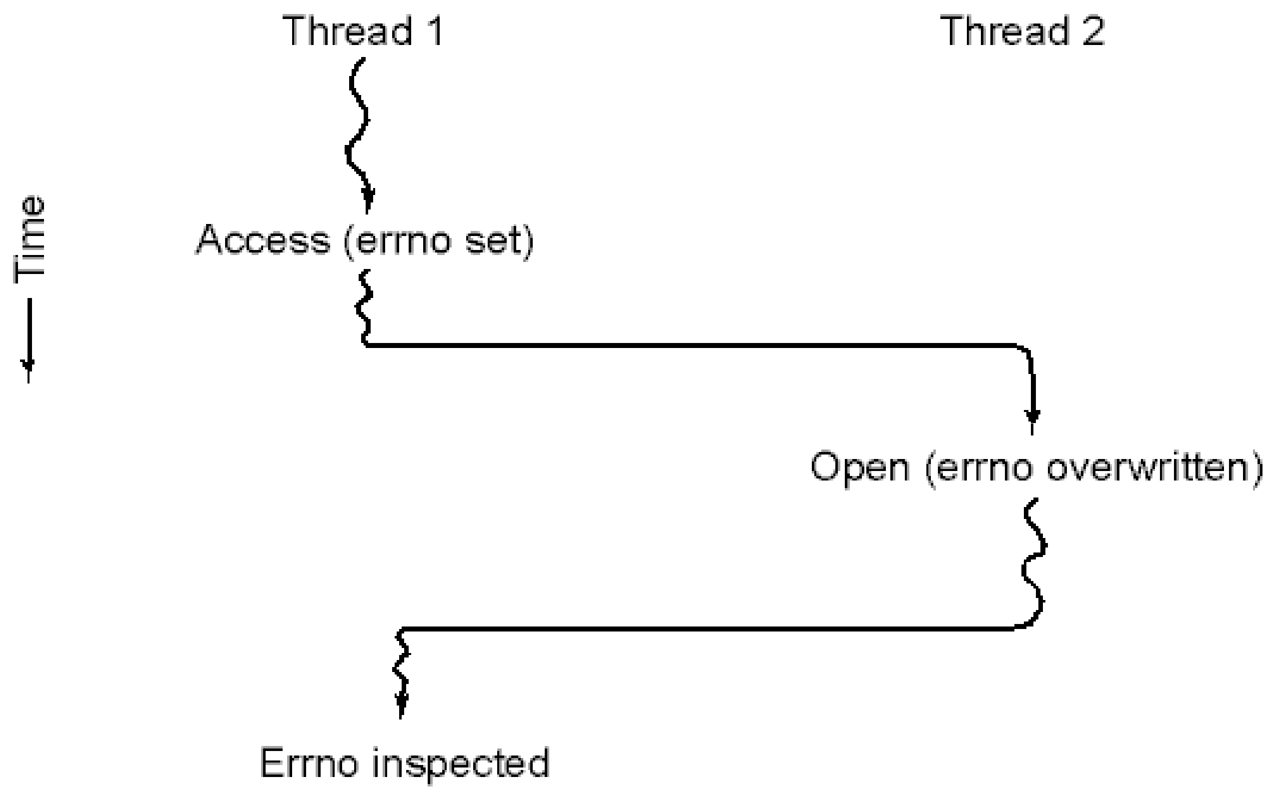
Learning Outcomes

- 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

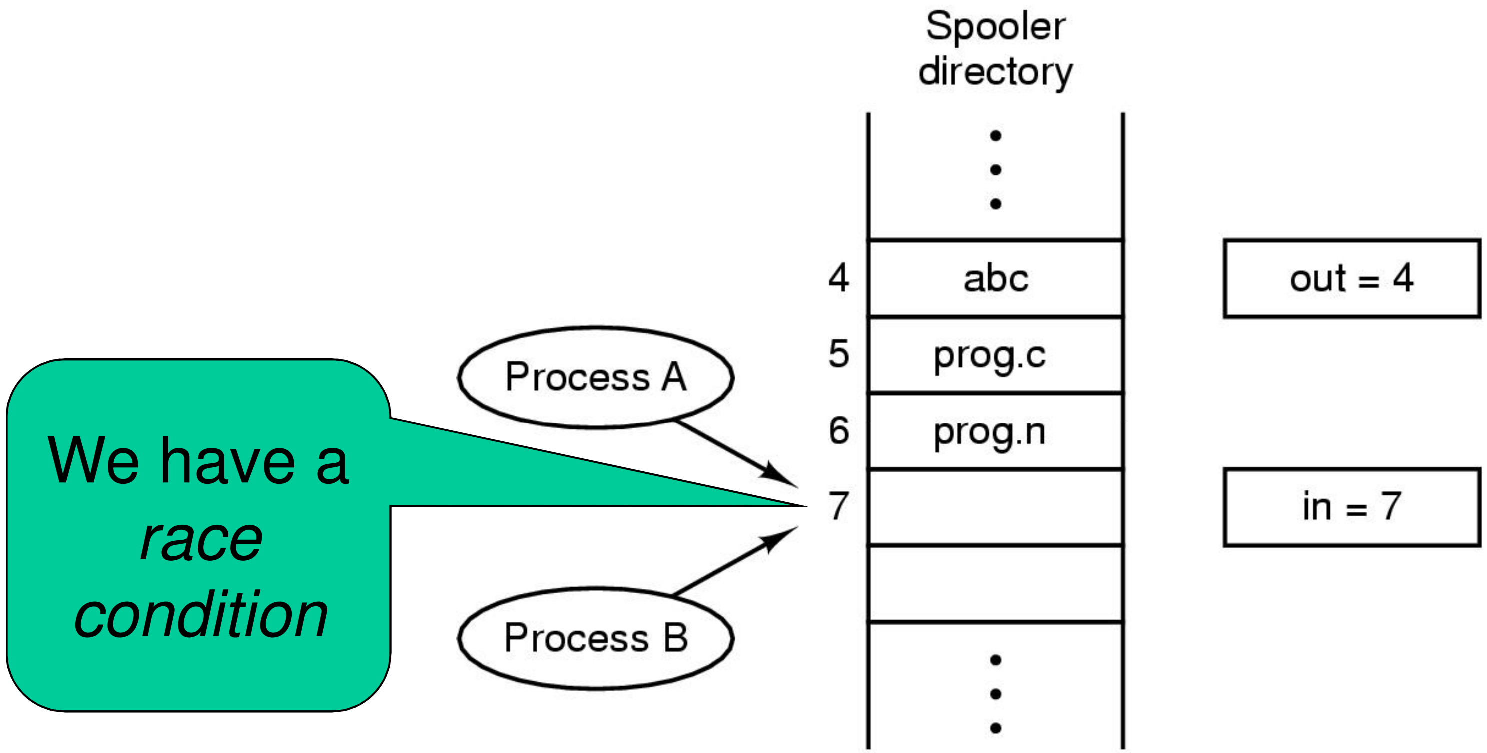
- Sections 2.3 & 2.5

Making Single-Threaded Code Multithreaded



Conflicts between threads over the use of a global variable

Inter- Thread and Process Communication



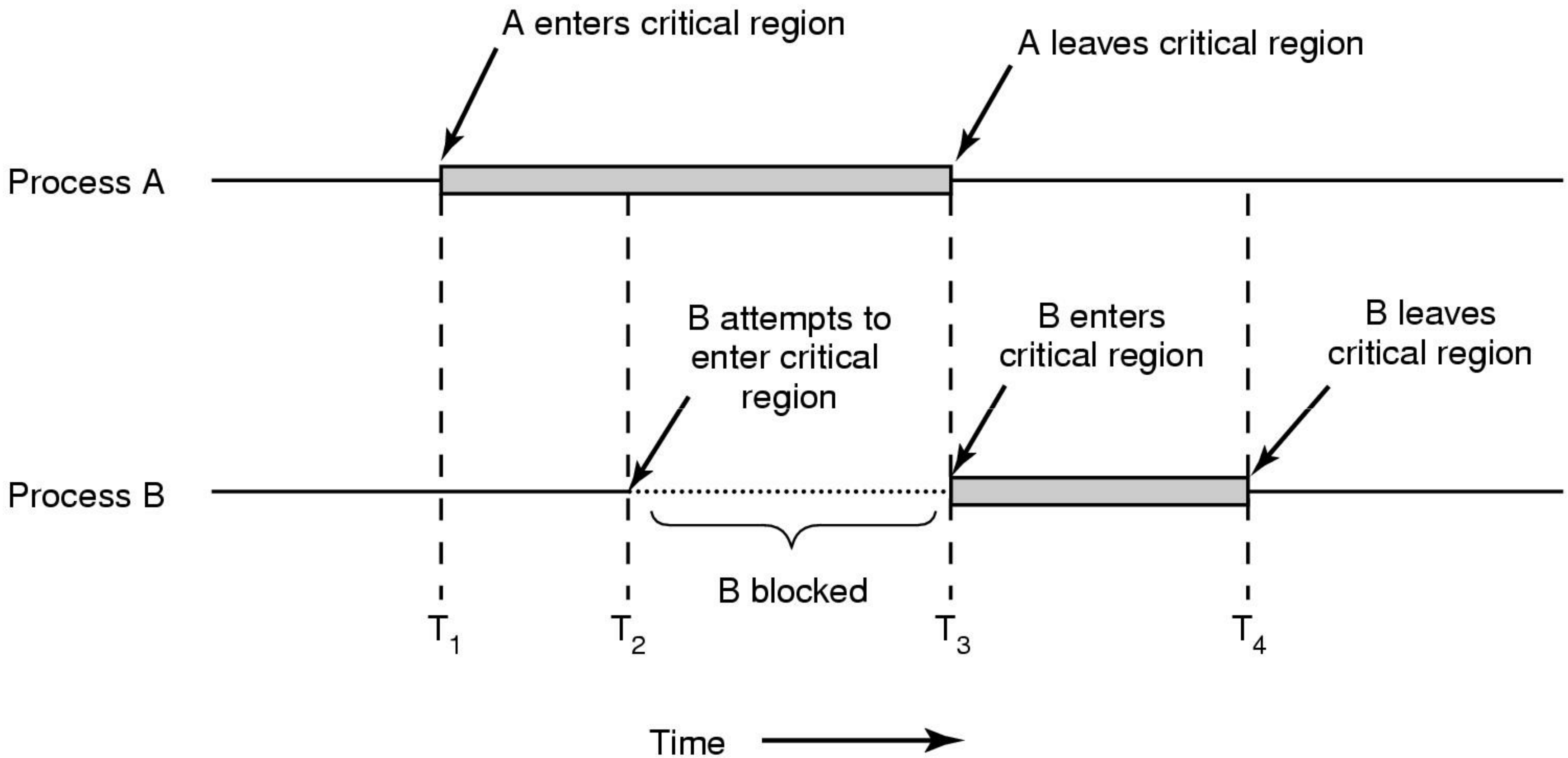
Two processes want to access shared memory at same time

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

Example critical sections

```
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 sections

```
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;
}
```

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Critical Regions

Also called *critical sections*

Conditions required of any solution to the critical region problem

- Mutual Exclusion:
  - No two processes simultaneously in critical region
- No assumptions made about speeds or numbers of CPUs
- Progress
  - No process running outside its critical region may block another process
- 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.
  - 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

- See the textbook

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

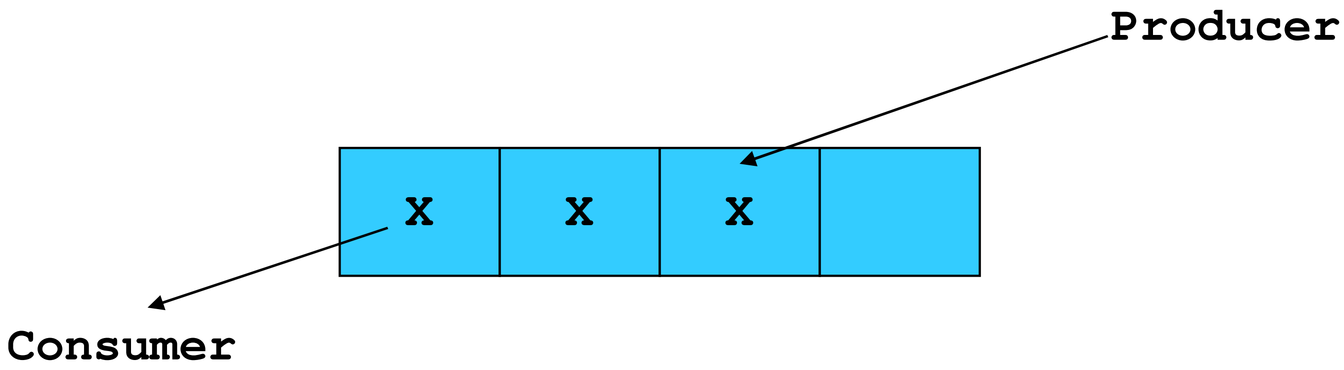
- Pros
  - Simple (easy to show it's correct)
  - Available at user-level
    - To any number of processors
    - To implement any number of lock variables
- Cons
  - Busy waits (also termed a *spin lock)*
    - Consumes CPU
    - Livelock in the presence of priorities
      - If a low priority process has the lock and a high priority process attempts to get it, the high priority process will busy-wait forever.
    - 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 the event happens, the event generator (another process) calls wakeup to unblock the sleeping process.

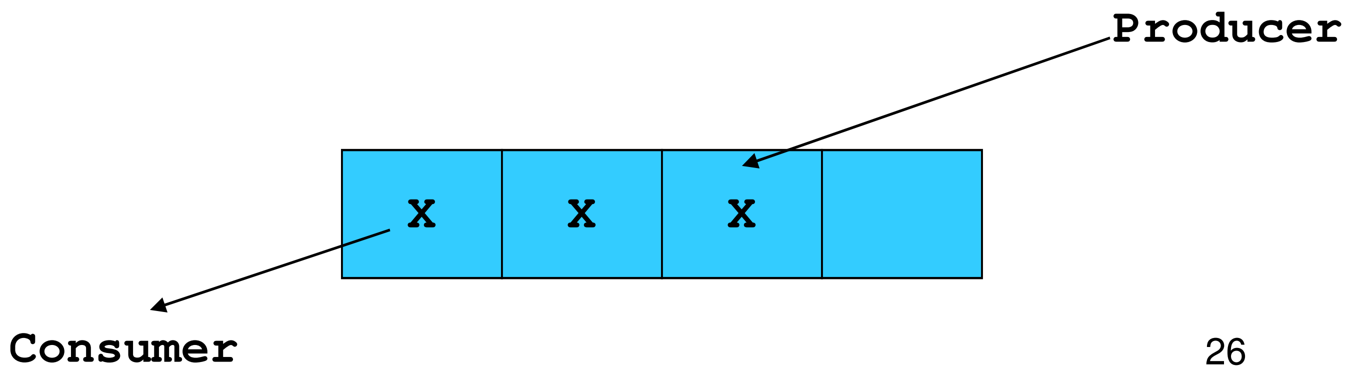
The Producer-Consumer Problem

- 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

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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

```
                                      con() {
                                          while(TRUE) {
                                              if (count == 0)
prod() {
    while(TRUE) {
        item = produce()
        if (count == N)
            sleep();
        acquire_lock()
        insert_item();
        count++;
        release_lock()
        if (count == 1)
            wakeup(con);
```

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

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

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*

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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

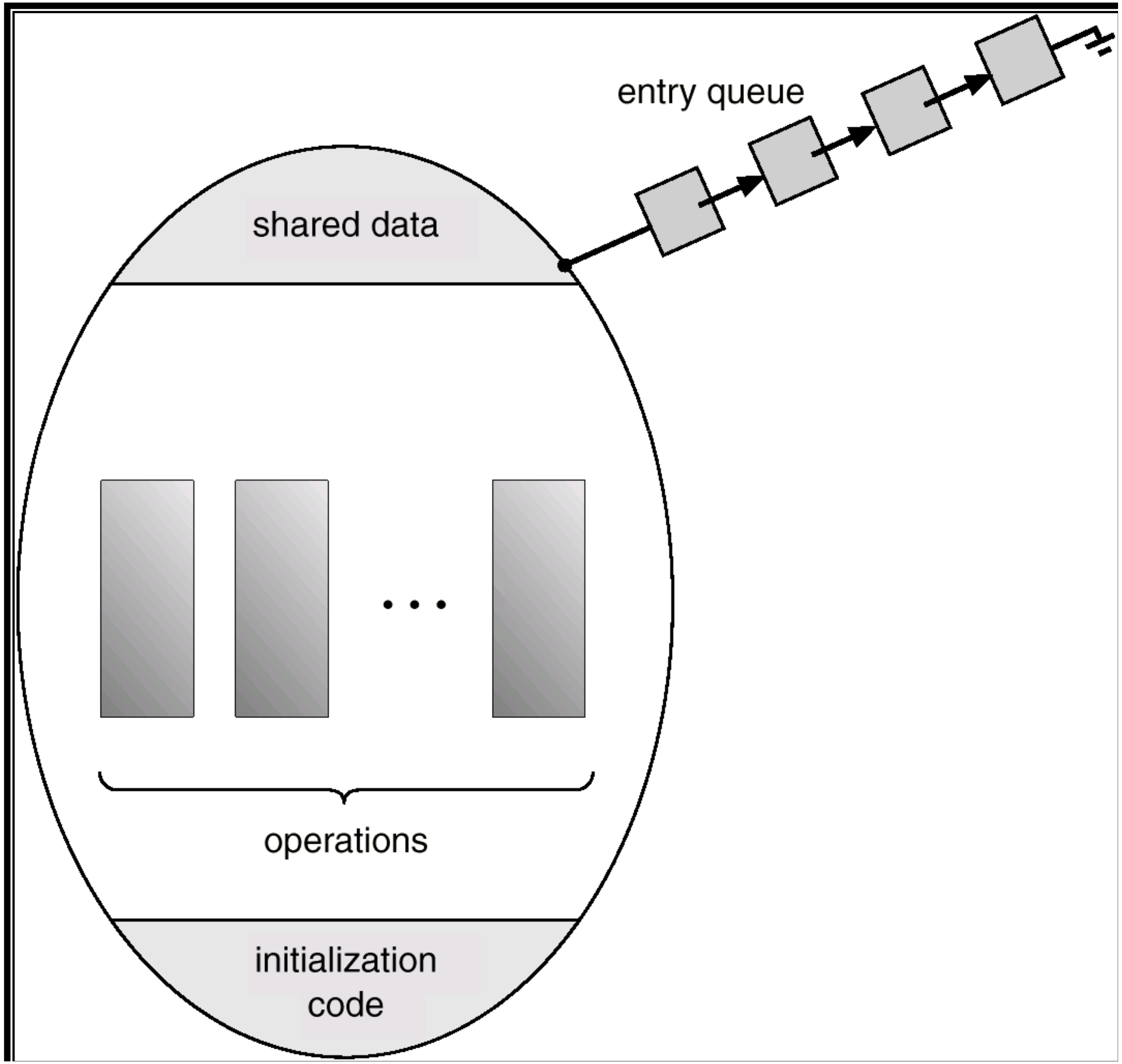
- Semaphores can be used to solve a variety of concurrency problems
- However, programming with then can be error-prone
  - E.g. must *signal* for every *wait* for mutexes
    - Too many, or too few signals or waits, or signals and waits in the wrong order, can have catastrophic results

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;

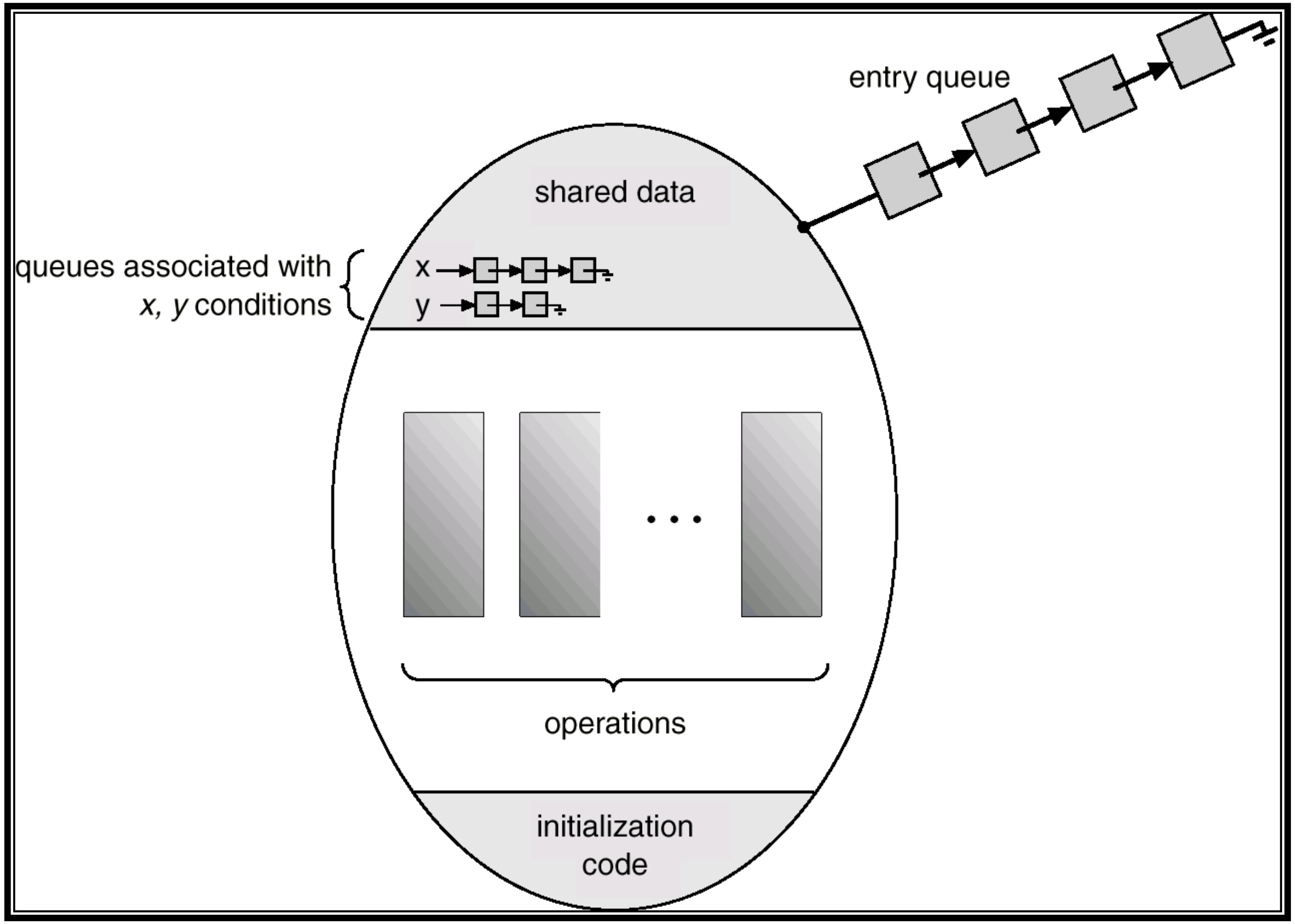
- Condition variable can only be used with the operations **wait** and **signal**.
  - The operation

    x.wait();

    means that the process invoking this operation is suspended until another process invokes

    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);
```

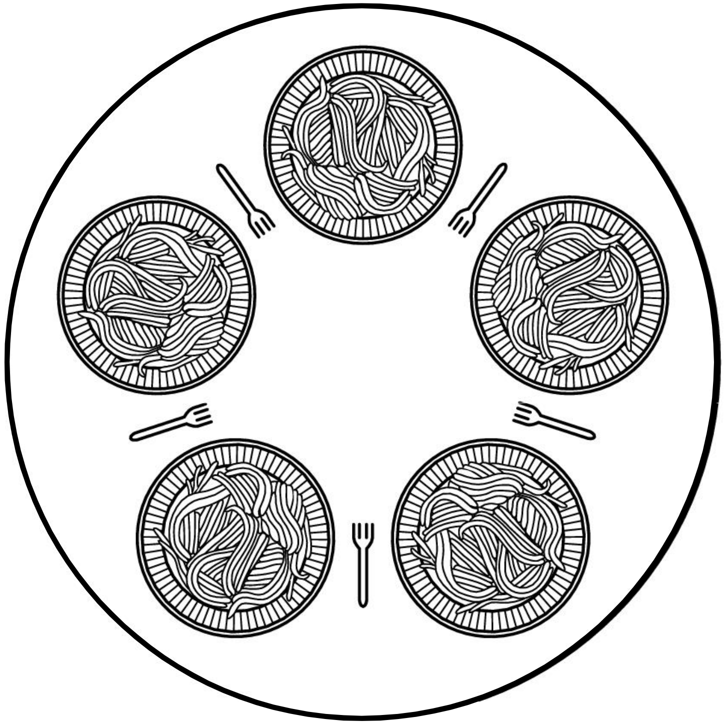
A Producer-Consumer Solution Using OS/161 CVs

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

```
con() {
   while(TRUE) {
        lock_acquire(l)
        while (count == 0)
                cv_wait(e,l);
        item = remove_item();
        count--;
        if (count == N-1)
                cv_signal(f,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