Concurrency and Synchronisation

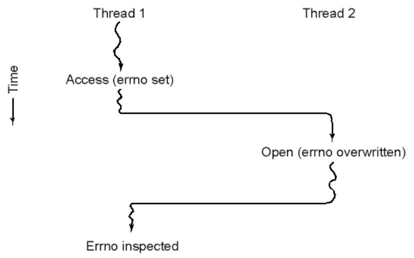
Learning Outcomes

- 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

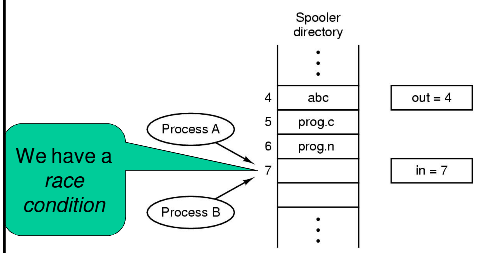
- Sections 2.3 & 2.5

Making Single-Threaded Code Multithreaded



Conflicts between threads over the use of a global variable

Inter- Thread and Process Communication



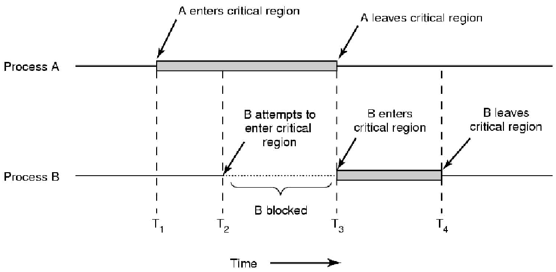
Two processes want to access shared memory at same time

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;
}
```


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

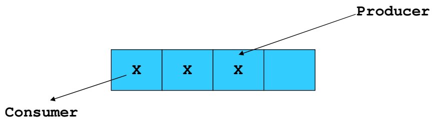
- Pros
  - Simple (easy to show it's correct)
  - Available at user-level
    - To any number of processors
    - To implement any number of lock variables
- Cons
  - Busy waits (also termed a *spin lock)*
    - Consumes CPU
    - Livelock in the presence of priorities
      - If a low priority process 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.

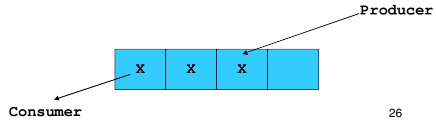
The Producer-Consumer Problem

- 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

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);
                                                sleep();
                                        acquire_lock()
                                        remove_item();
                                        count--;
                                        release_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

```
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*

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 ⇒ 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

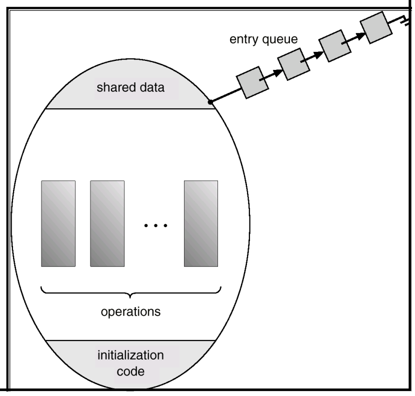
- Semaphores can be used to solve a variety of concurrency problems
- However, programming with then can be error-prone
  - E.g. must *signal* for every *wait* for mutexes
    - Too many, or too few signals or waits, or signals and waits in the wrong order, can have catastrophic results

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

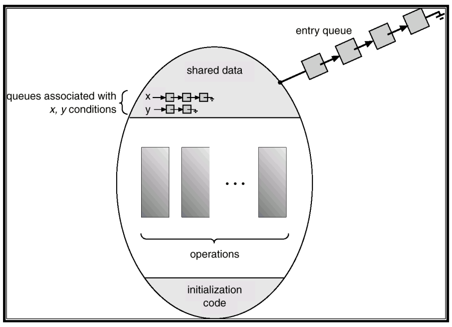
  condition x, y;
- Condition variable can only be used with the operations **wait** and **signal**.
  - The operation

    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);
```

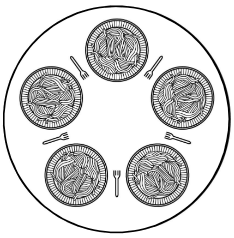

A Producer-Consumer Solution Using OS/161 CVs

```
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 <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