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 the same time

We have a race condition
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

```c
struct node {
    int data;
    struct node *next;
};
struct node *head;

void init(void) {
    head = NULL;
}

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;
}

• Simple last-in-first-out queue implemented as a linked list.
```
Example critical sections

```c
struct node {
    int data;
    struct node *next;
};
struct node *head;

void init(void) {
    head = NULL;
}

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 must wait 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?

```c
while(TRUE) {
    while(lock == 1);
    lock = 1;
    critical();
    lock = 0
    non_critical();
}
```

```c
while(TRUE) {
    while(lock == 1);
    lock = 1;
    critical();
    lock = 0
    non_critical();
}
A problematic execution sequence

```c
while(TRUE) {
    while(lock == 1);
    lock = 1;
    critical();
    lock = 0
    non_critical();
}
```

```c
while(TRUE) {
    while(lock == 1);
    lock = 1;
    critical();
    lock = 0
    non_critical();
}
```
Observation

• Unfortunately, it is usually easier to show something does not work, than it is to prove that it does work.
  – 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 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

```c
int count = 0;
#define N 4 /* buf size */
prod() {
    while(TRUE) {
        item = produce()
        if (count == N)
            sleep();
        remove_item();
        count --;
        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

```c
int count = 0;
#define N 4 /* buf size */

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

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?

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

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

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

con() {
    while(TRUE) {
        if (count == 0)
            wakeup without a matching sleep is lost
        sleep();
        acquire_lock();
        insert_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

```c
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
  
  ```c
  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

\[
\text{\textit{wait}}(S):
\begin{align*}
&\text{S.count}--; \\
&\quad \text{if } (\text{S.count} < 0) \{ \\
&\quad\quad \text{add this process to S.L;} \\
&\quad\quad \text{sleep;} \\
&\quad\} \\
\end{align*}
\]

\[
\text{\textit{signal}}(S):
\begin{align*}
&\text{S.count}++; \\
&\quad \text{if } (\text{S.count} \leq 0) \{ \\
&\quad\quad \text{remove a process P from S.L;} \\
&\quad\quad \text{wakeup(P);} \\
&\quad\} \\
\end{align*}
\]

• 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:

  $P_i$          $P_j$
  \[ \vdots \quad \vdots \]
  \[ A \quad \text{wait(flag)} \]
  \[ \text{signal(flag)} \quad B \]
Semaphore Implementation of a Mutex

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

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

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

  Blahblah();

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

Notice that the initial count determines how many waits can progress before blocking and requiring a signal \( \Rightarrow \) mutex.count initialised as 1
Solving the producer-consumer problem with semaphores

#define N = 4

semaphore mutex = 1;

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

/* count full slots */
semaphore full = 0;
Solving the producer-consumer problem with semaphores

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

con() {
    while(TRUE) {
        wait(full);
        wait(mutex);
        remove_item();
        signal(mutex);
        signal(empty);
    }
}
```
Solving the producer-consumer problem with semaphores

```c
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);
    }
}
```
Solving the producer-consumer problem with semaphores

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

con() {
    while(TRUE) {
        wait(full);
        wait(mutex);
        remove_item();
        signal(mutex);
        signal(empty);
    }
}
```
Solving the producer-consumer problem with semaphores

```c
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

```c
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

![Diagram showing a system with shared data, queues associated with x, y conditions, operations, and initialization code. There's an entry queue at the top right.]
Monitors

```plaintext
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

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

- Functions to acquire and release them

```c
void lock_acquire(struct lock *);
void lock_release(struct lock *);
```
Example use of locks

```c
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

```c
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

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

Solution

```c
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

```c
int count = 0;
#define N 4 /* buf size */
prod() {
    while(TRUE) {
        item = produce()
        lock_acquire(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

```c
#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;
int state[N];
semaphore mutex = 1;
semaphore s[N];

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

Solution to dining philosophers problem (part 1)
#define N 5

void philosopher(int i)
{
    while (TRUE) {
        think();
        take_fork(i);
        take_fork((i+1) % N);
        eat();
        put_fork(i);
        put_fork((i+1) % N);
    }
}

/* number of philosophers */
/* i: philosopher number, from 0 to 4 */
/* philosopher is thinking */
/* take left fork */
/* take right fork; % is modulo operator */
/* yum-yum, spaghetti */
/* put left fork back on the table */
/* put right fork back on the table */

A nonsolution to the dining philosophers problem
Dining Philosophers

void take_forks(int i)  
{  
    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)  
{  
    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)  
{  
    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

```c
typedef int semaphore;       /* use your imagination */
semaphore mutex = 1;         /* controls access to 'rc' */
semaphore db = 1;            /* controls access to the database */
ing 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);       /* access the data */
        read_data_base();/* get exclusive access to 'rc' */
        down(&mutex);     /* one reader fewer now */
        rc = rc - 1;      /* if this is the last reader ... */
        if (rc == 0) up(&db); /* release exclusive access to 'rc' */
        up(&mutex);       /* noncritical region */
        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
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); /* access the data */
        read_data_base(); /* get exclusive access to 'rc' */
        down(&mutex); /* access the data */
        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