Concurrency and Synchronisation

Learning Outcomes

• Understand concurrency is an issue in operating systems and multithreaded applications
• Know the concept of a critical region.
• Understand how mutual exclusion of critical regions can be used to solve concurrency issues – including how mutual exclusion can be implemented correctly and efficiently.
• Be able to identify and solve a producer consumer bounded buffer problem.
• Understand and apply standard synchronisation primitives to solve synchronisation problems.

Textbook

• Sections 2.3 - 2.3.7 & 2.5

Concurrent Example

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

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

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

count is a global variable shared between two threads.

Inter-Thread and Process Communication

We have a race condition

Two processes want to access shared memory at same time

Making Single-Threaded Code Multithreaded

Conflicts between threads over the use of a global variable
Critical Regions

- 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,...

Identifying critical regions

- Critical regions are regions of code that:
  - Access a shared resource,
  - And correctness relies on the shared resource not being concurrently modified by another thread/process/entity.

Example critical regions

```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;
}
```

Example Race

```c
void insert(struct *item)
{
    item->next = head;
    head = item;
}
```
Critical Regions Solutions

Also called critical sections

Conditions required of any solution to the critical region problem

- Mutual Exclusion:
  - No two processes simultaneously in critical region
- 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?

```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();
    lock = 0
    non_critical();
}
```

Observation

- Unfortunately, it is usually easier to show something does not work, than it is to prove that it does work.
  - Easier to provide a counter example
  - Ideally, we’d like to prove, or at least informally demonstrate, that our solutions work.

Mutual Exclusion by Taking Turns

```c
while (TRUE) {
    while (turn == 0) /* loop */;
    critical_region();
    turn = 1;
    noncritical_region();
}   

(a)  (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.
    - 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.

```
Producer
X X X X
Consumer
```

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);
    }
}
```

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
  - **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

```
Producer
X X X X
Consumer
```

Concurrent uncontrolled access to the buffer
Problems

```c
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);
    }
}
```

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

Concurrent uncontrolled access to the counter

Proposed Solution

• Let's use a locking primitive based on test-and-set to protect the concurrent access

```c
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);
    }
}
```

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

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);
    }
}
```

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

Wakeup without a matching sleep is lost

Proposed solution?

```c
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);
    }
}
```

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

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);
    }
}
```

```c
con() {
    while(TRUE) {
        if (count == 0)
            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:

```c
acquire_lock();
if (count == N)
    sleep();
release_lock();
acquire_lock();
if (count == 1)
    wakeup();
release_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.
- 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
  - E.g. interrupts are disabled for each.

Semaphore as a General Synchronization Tool

- Execute `B` in `Pj` only after `A` executed in `Pi`.
- Use semaphore `count` initialized to 0.
- Code:
  ```
  P_i P_j 
  \[ \]
  A \rightarrow \text{wait(flag)} \quad \text{signal(flag)} \rightarrow B
  ```

Semaphore Implementation of a Mutex

- Mutex is short for Mutual Exclusion.
  - Can also be called a lock.
  ```
  semaphore mutex; 
  mutex.count = 1; /* initialize 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 => mutex.count initialised as 1.

Solving the producer-consumer problem with semaphores

```c
#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

```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.

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.

Monitors

- 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

```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();
}
```

```c
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);
}
```

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();
}
```

```c
procedure inc() {
    P(count_mutex);
    count = count + 1;
    V(count_mutex);
}
procedure dec() {
    P(count_mutex);
    count = count -1;
    V(count_mutex);
}
```

Example of Condition Variables

```c
struct cv *cv_create(const char *name);
void cv_destroy(struct cv *); 
void cv_wait(struct cv *cv, struct lock *lock);
void cv_signal(struct cv *cv, struct lock *lock);
void cv_broadcast(struct cv *cv, struct lock *lock);
```

```c
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 “waker” scheduled after signaller releases the lock will re-acquire the lock
```

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 /* buf size */
prod() {
    item = produce()
    lock_acquire()
    while (count == N)
        cv_wait(full, l);
    insert_item(item);
    count++;
    if (count == N)
        cv_signal(empty, l);
lock_release()
}
```

```c
con() {
    
```
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
#define LEFT (n-1)%N
#define RIGHT (n+1)%N
#define THINKING 0
#define HUNGRY 1

typedef int semaphore;

semaphore mutex = 1;
int semaphores_per_philosopher = 2;

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

A nonsolution to the dining philosophers problem

Solution to dining philosophers problem (part 1)

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

A solution to the readers and writers problem