Synchronisation and Concurrency II

Summarising Semaphores

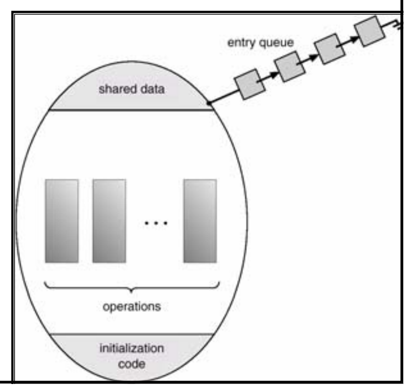
- Semaphores can be used to solve a variety of concurrency problems
- However, programming with then can be error-prone
  - E.g. must *signal* for every *wait* for mutexes
    - Too many, or too few signals or waits, or signals and waits in the wrong order, can have catastrophic results

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

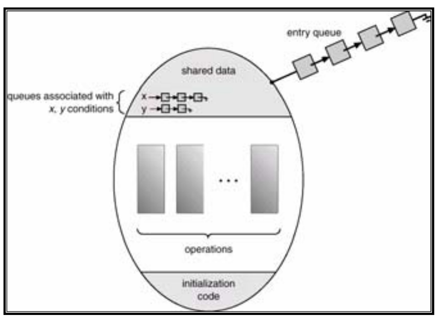
  condition x, y;
- Condition variable can only be used with the operations **wait** and **signal**.
  - The operation

    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);
```

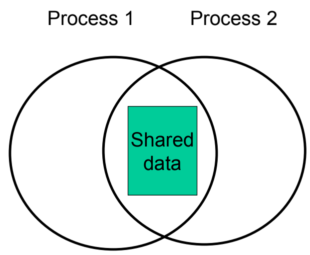

A Producer-Consumer Solution Using OS/161 CVs

```
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);
   }
}
```

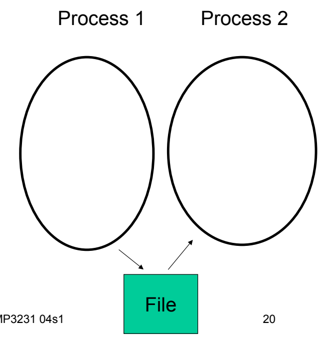
Interprocess Communication

- Shared Memory
  - Region of memory appears in each process
  - Communication via modifications to shared region
  - Requires concurrency control (semaphores, mutexes, monitors…



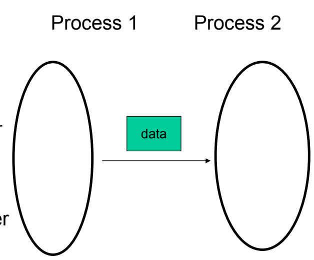
Interprocess Communication

- Shared files
  - Cumbersome



Interprocess Communication

- Message Passing
  - "real" IPC
- Requires two facilities
  - *send(message)*
    - Message may be fixed or variable in size
  - *receive(message)*
- OS ships the data from the sender to the receiver



Interprocess Communication (IPC)

- Mechanism for processes to communicate and to *synchronize* their actions.
- Message system – processes communicate with each other without resorting to shared variables.
- If *P* and *Q* wish to communicate, they need to:
  - establish a *communication link* between them
  - exchange messages via send/receive

IPC design issues

- Is the communication synchronous or asynchronous?
- How are links established?
- Can a link be associated with more than two processes?
- How many links can there be between every pair of communicating processes?
- What is the capacity of a link?
- Is the size of a message that the link can accommodate fixed or variable?
- Is the message format fixed or variable?
- Is a link unidirectional or bi-directional?

Blocking vs. Non-blocking

Blocking

- Send
  - Operation blocks until partner is ready to receive
    - Rendezvous model
    - Send and receiver execute their system at the same time (synchronously)
- Receive
  - Operation blocks until message is available
    - synchronous

Non-blocking

- Send
  - Kernel receives message and delivers when receiver is ready
    - Asynchronous
- Receive
  - System call returns immediately if no message is available
    - Asynchronous (polling)

Blocking vs. Non-blocking

- Non-blocking IPC
  - Requires buffering of messages in the kernel
    - May fail due to buffer full
    - Overhead (copying, allocation)
  - Higher level of concurrency
  - Requires a separate synchronisation primitive
- Blocking IPC
  - May lead to threads blocked indefinitely
    - Can use *timeouts* prevent this
    - Zero-timeout ⇒ non-blocking receive

Direct Communication

- Processes (or threads) must name each other explicitly using their unique process (or thread) ID:
  - **send** (*P, message*) – send a message to process P
  - **receive**(*Q, message*) – receive a message from process Q
- Properties of communication link
  - Links are established automatically (implicitly).
  - A link is associated with exactly one pair of communicating processes.
  - Between each pair there exists exactly one link.
  - The link may be unidirectional, but is usually bi-directional.

Indirect Communication

- Messages are directed to and received from mailboxes (also referred to as ports).
  - Each mailbox has a unique id.
  - Processes can communicate only if they share a mailbox.
  - E.g. Mach
- Properties of communication link
  - Link established only if processes share a common mailbox
    - OS mechanism required to establish mailbox sharing
  - A link may be associated with many processes.
  - Each pair of processes may share several communication links.
  - Link may be unidirectional or bi-directional.

Indirect Communication

- Operations
  - create a new mailbox
  - send and receive messages through mailbox
  - destroy a mailbox
- Primitives are defined as:

  send(*A, message*) – send a message to mailbox A

  receive(*A, message*) – receive a message from mailbox A

Indirect Communication

- Mailbox sharing
  - P_1, P_2, and P_3 share mailbox A.
  - P_1, sends; P_2 and P_3 receive.
  - Who gets the message?
- Solutions
  - Allow a link to be associated with at most two processes.
  - Allow only one process at a time to execute a receive operation (Mach).
  - Allow the system to select arbitrarily the receiver.
  - First come, first served.

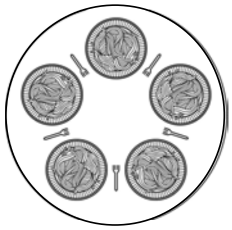
Message Passing

```
#define N 100                            /* number of slots in the buffer */

void producer(void)
{
    int item;
    message m;                           /* message buffer */

    while (TRUE) {
        item = produce_item( );          /* generate something to put in buffer */
        receive(consumer, &m);           /* wait for an empty to arrive */
        build_message(&m, item);         /* construct a message to send */
        send(consumer, &m);              /* send item to consumer */
    }
}

void consumer(void)
{
    int item, i;
    message m;

    for (i = 0; i < N; i++) send(producer, &m);  /* send N empties */
    while (TRUE) {
        receive(producer, &m);           /* get message containing item */
        item = extract_item(&m);         /* extract item from message */
        send(producer, &m);              /* send back empty reply */
        consume_item(item);              /* do something with the item */
    }
}
```

The producer-consumer problem with N messages

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 */

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

```
#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

```
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

The Sleeping Barber Problem

The Sleeping Barber Problem

```
#define CHAIRS 5                    /* # chairs for waiting customers */

typedef int semaphore;              /* use your imagination */

semaphore customers = 0;            /* # of customers waiting for service */
semaphore barbers = 0;              /* # of barbers waiting for customers */
semaphore mutex = 1;                /* for mutual exclusion */
int waiting = 0;                    /* customers are waiting (not being cut) */

void barber(void)
{
    while (TRUE) {
        down(&customers);           /* go to sleep if # of customers is 0 */
        down(&mutex);               /* acquire access to 'waiting' */
        waiting = waiting − 1;      /* decrement count of waiting customers */
        up(&barbers);               /* one barber is now ready to cut hair */
        up(&mutex);                 /* release 'waiting' */
        cut_hair( );                /* cut hair (outside critical region) */
    }
}

void cu
{
    down(&mutex);                   /* enter critical region */
    if (waiting < CHAIRS) {         /* if there are no free chairs, leave */
        waiting = waiting + 1;      /* increment count of waiting customers */
        up(&customers);             /* wake up barber if necessary */
        up(&mutex);                 /* release access to 'waiting' */
        down(&barbers);             /* go to sleep if # of free barbers is 0 */
        get_haircut( );             /* be seated and be serviced */
    } else {
        up(&mutex);                 /* shop is full; do not wait */
    }
```

See the textbook

Solution to sleeping barber problem.