Synchronisation and Concurrency II

Summarising Semaphores

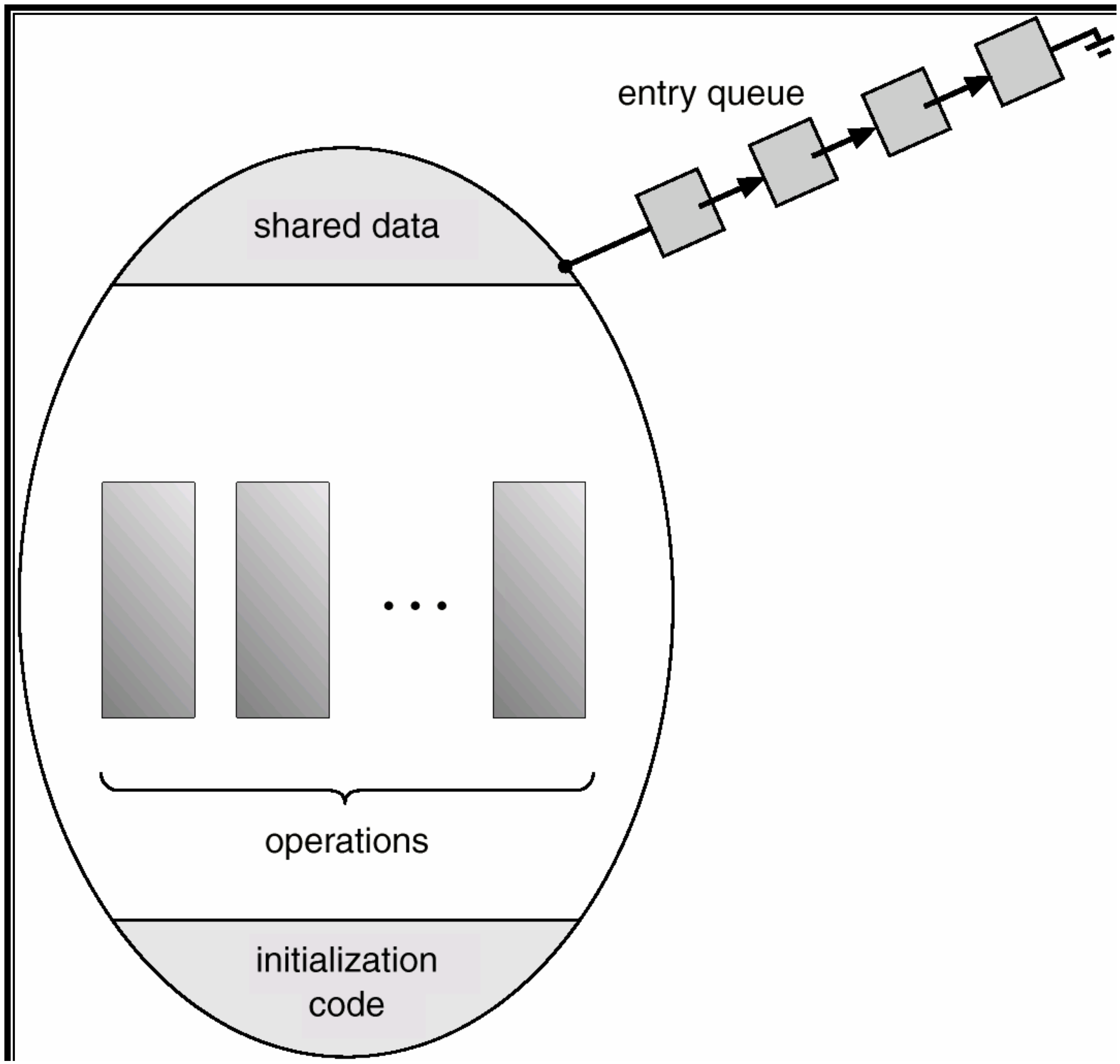
- Semaphores can be used to solve a variety of concurrency problems
- However, programming with then can be error-prone
  - E.g. must *signal* for every *wait* for mutexes
    - Too many, or too few signals or waits, or signals and waits in the wrong order, can have catastrophic results

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

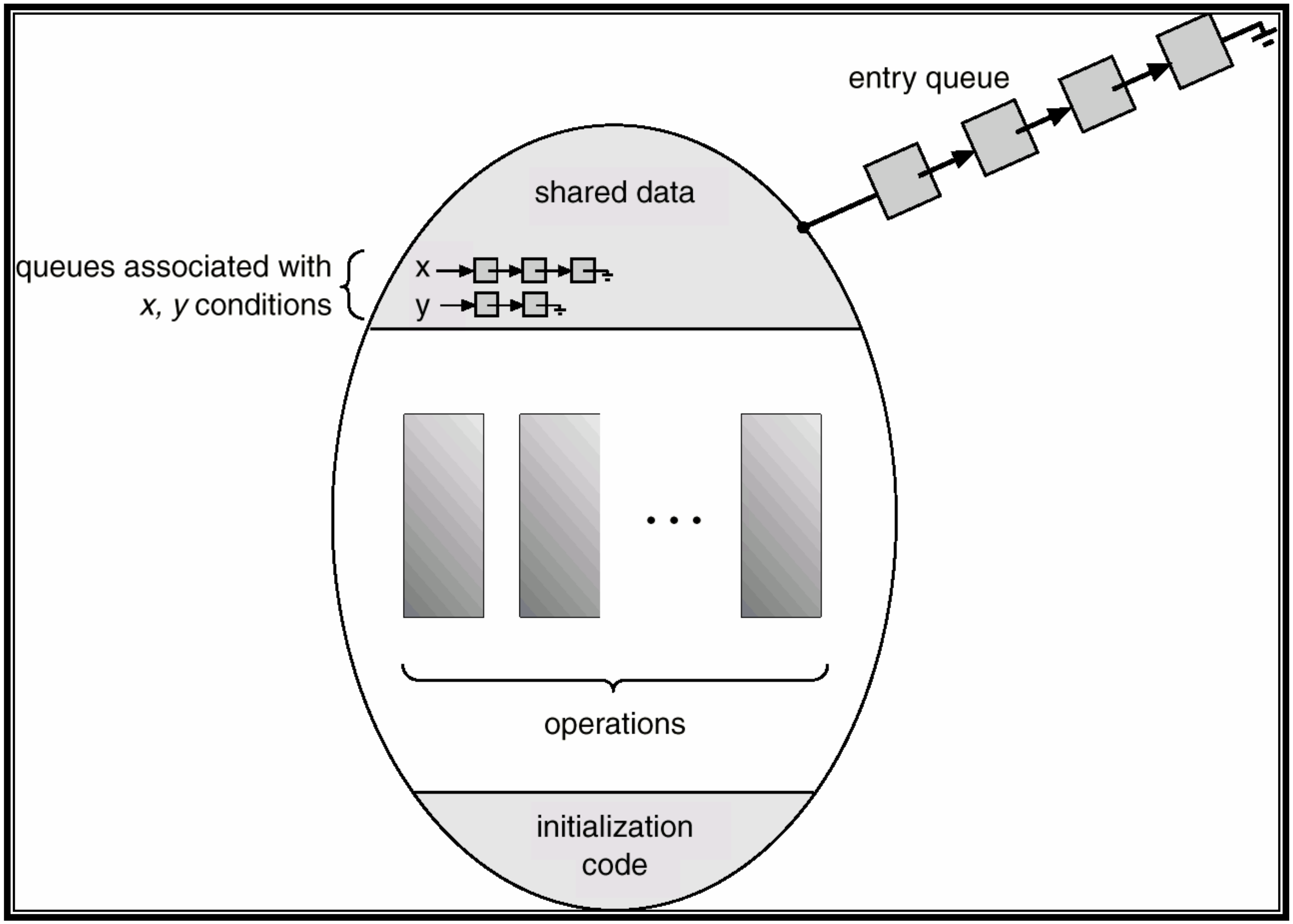
        x.wait();

      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);
```

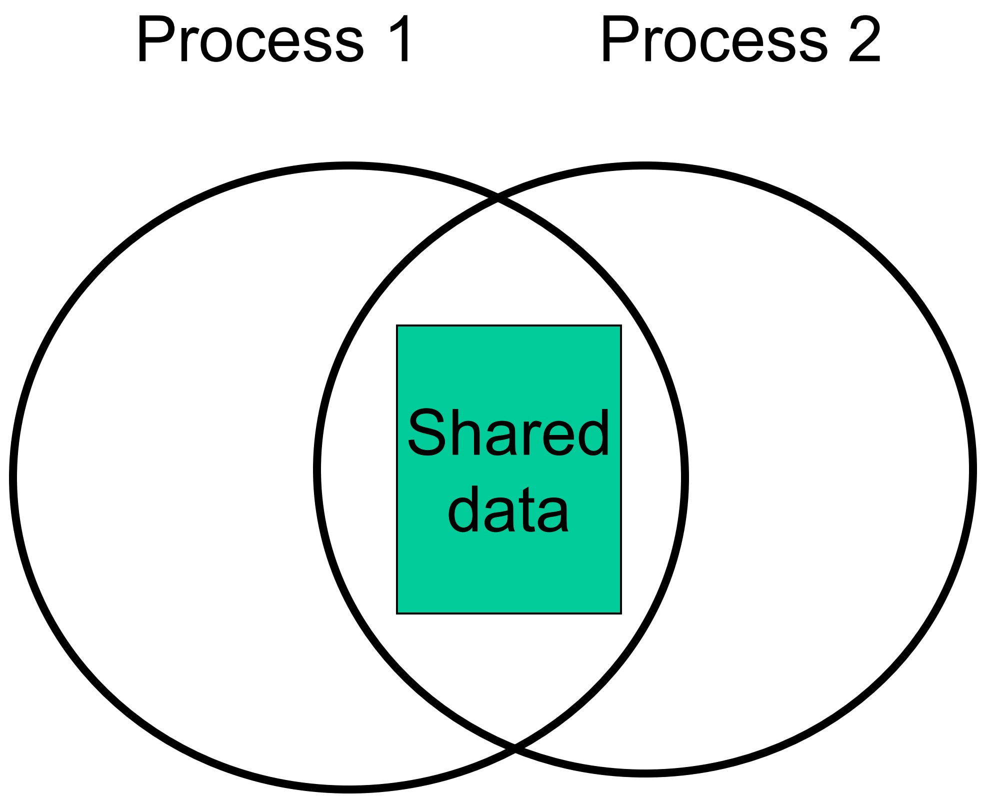
A Producer-Consumer Solution Using OS/161 CVs

```
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);
   }
}
```

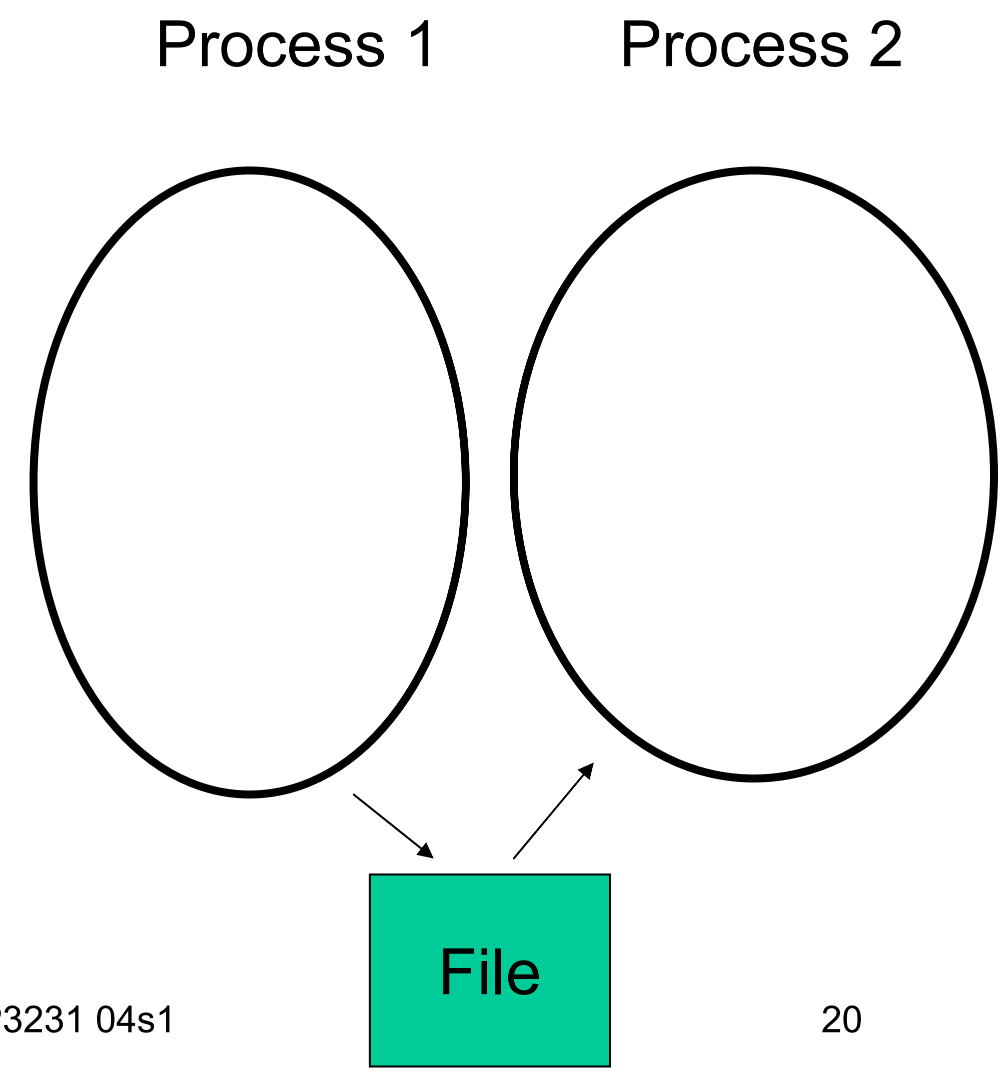
Interprocess Communication

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



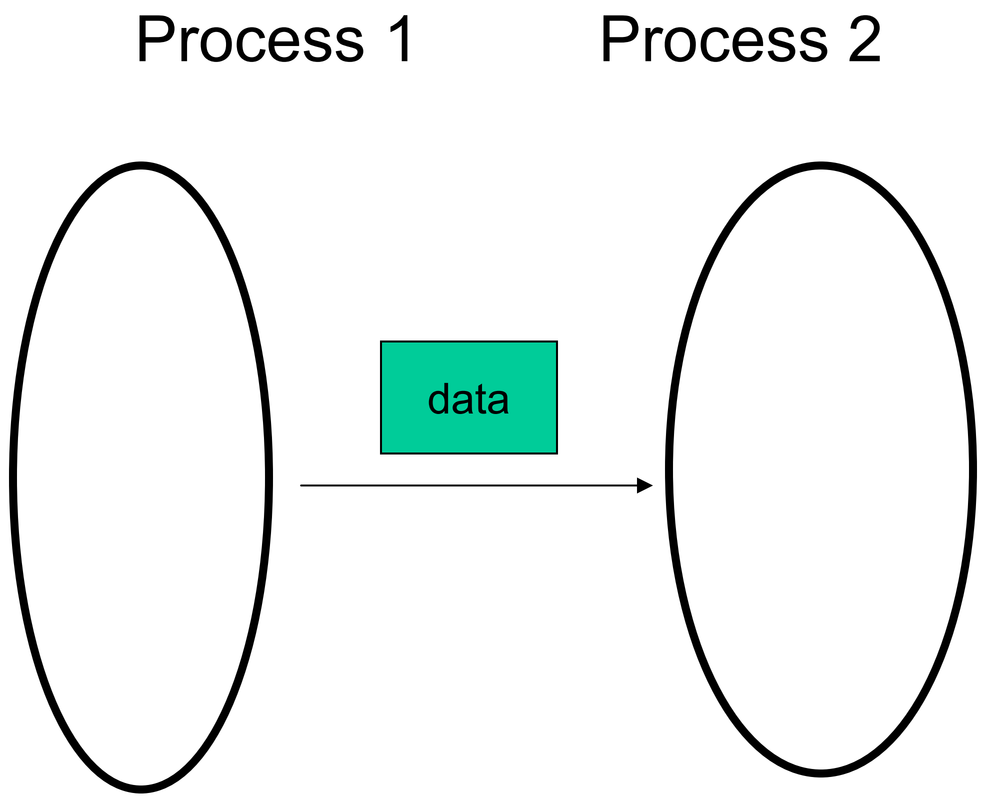
Interprocess Communication

- 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

- 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

- 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 $\Rightarrow$ 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.

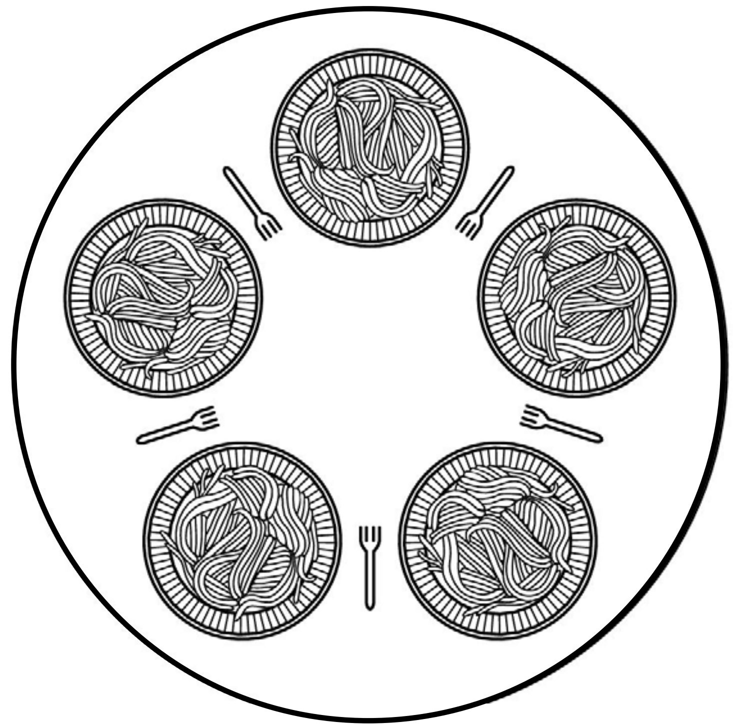
Message Passing

```
#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.