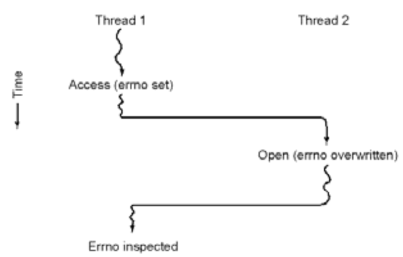
Concurrency and Synchronisation

Textbook

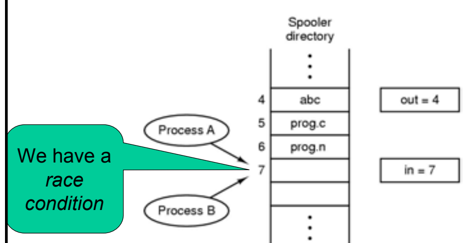
- Sections 2.3 & 2.4

Making Single-Threaded Code Multithreaded



Conflicts between threads over the use of a global variable

Inter- Thread and Process Communication



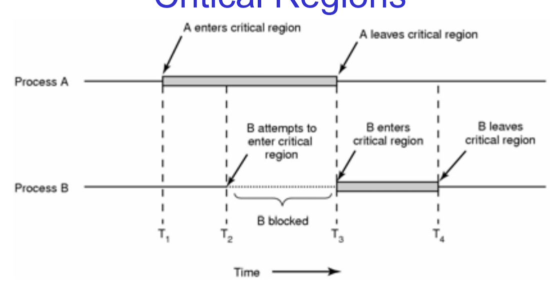
Two processes want to access shared memory at same time

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

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 non-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 non-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
    - If lock == 1
      - return 1
  - 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

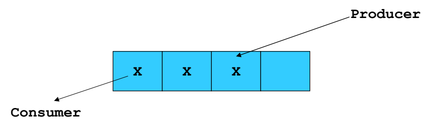
- Pros
  - Simple (easy to show it's correct)
  - Available at user-level
    - To any number of processors
    - To implement any number of lock variables
- Cons
  - Busy waits (also termed a *spin lock)*
    - Consumes CPU
    - Deadlock in the presence of priorities
      - If a low priority process has the low 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 *something to do* 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 $\Rightarrow$ 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);
  }
}
```

FYI

- Counting semaphores versus binary semaphores:
  - In a counting semaphore, *count* can take arbitrary integer values
  - In a binary semaphore, *count* can only be 0 or 1
    - Can be easier to implement
  - Counting semaphores can be implemented in terms of binary semaphores (how?)
- Strong semaphores versus weak semaphores:
  - In a strong semaphore, the *queue* adheres to the FIFO policy
  - In a weak semaphore, any process may be taken from the *queue*
  - Strong semaphores can be implemented in terms of weak semaphores (how?)

Summarising

- 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 can have catastrophic results