Synchronization (I)

Operating Systems

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(with slides borrowed from Prof. Jerry Chou)

Outline

- Background
- Critical section
- Synchronization hardware
- Semaphores

Background

Background

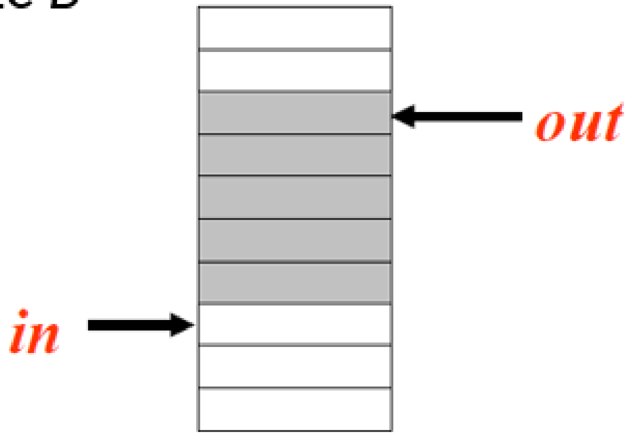
- **Concurrent access** to **shared data** may result in **data inconsistency**

- Maintaining data consistency requires mechanism to ensure the **orderly execution** of cooperating processes

Consumer & Producer Problem

- Determine whether buffer is empty or full
  - Use ***in***, ***out*** position

- Buffer as a circular array with size *B*
  - Next free: *in*
  - First available: *out*
  - Empty: *in = out*
  - Full: *(in + 1) % B = out*



- The solution allows at most (B - 1) item in the buffer
  - Otherwise, cannot tell the buffer is empty or full

Consumer & Producer Problem (cont.)

- Determine whether buffer is empty or full
  - Use ***count*** value

```
/* Producer */
while (true) {
    // produce an item in next produced.
    while (counter == BUFFER_SIZE);
        // do nothing.
    buffer[in] = next_produced;
    in = (in + 1) % BUFFER_SIZE;
    counter++;
}
```

```
/* Consumer */
while (true) {
    while (counter == 0);
        // do nothing.
    next_consumed = buffer[out];
    out = (out + 1) % BUFFER_SIZE;
    counter--;
    // consume the item in next consumed.
}
```

Concurrent Operations on Counter

- The statement “counter++” may be implemented in machine language as

    move ax, counter

    add ax, 1

    move counter, ax

- The statement “counter--” may be implemented as

    move bx, counter

    sub bx, 1

    move counter, bx

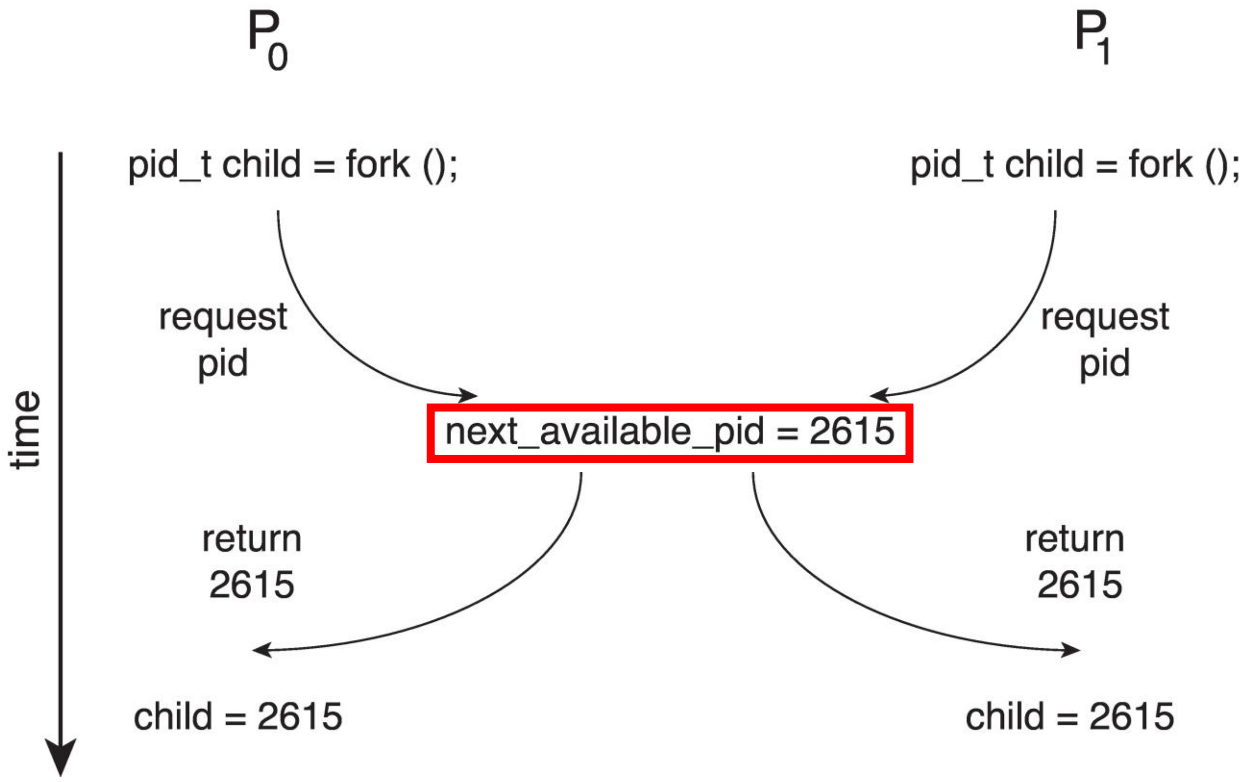
Instruction Interleaving

- Assume counter is initially 5. One interleaving of statement is

producer: move ax, counter	➔ ax = 5
producer: add ax, 1	➔ ax = 6
context switch	
consumer: move bx, counter	➔ bx = 5
consumer: sub bx, 1	➔ bx = 4
context switch	
producer: move counter, ax	➔ counter = 6
context switch	
consumer: move counter, bx	➔ counter = 4

Another Example

- An example in the kernel



Race Condition

- The situation where several processes access and manipulate **shared** data concurrently.
- **The final value of the shared data depends upon which process finishes last**
- To prevent race condition, concurrent processes must be **synchronized**
  - On a single-processor machine, we could disable interrupt or use non-preemptive CPU scheduling
  - But how about on **multi-processor** machines and **preemptive** scheduling?
- We need a mechanism to solve the synchronization issue, commonly described as **critical section problem**

Critical Section

The Critical-Section Problem

- **Purpose**
  - A **protocol** for processes to cooperate

- **Problem description**
  - *N* processes are competing to use some **shared** data
  - Each process has a **code segment**, called **critical section**, in which the shared data is accessed
  - Ensure that when one process is executing in its critical section, **no other process is allowed** to execute in its critical section

  ➔ **mutually exclusive !**

The Critical-Section Problem (cont.)

- **General code section structure**
  - Only one process can be in a critical section

```
do {
    entry section        →  get entry permission
      critical section   →  modified shared data
    exit section         →  release entry permission
      remainder section
} while (1);
```

Critical-Section Requirements

- **Mutual exclusion**
  - If a process *P* is executing in its critical section (CS), no other processes can be executing in their CS
- **Progress**
  - If no process is executing in its CS and there exist some processes that wish to enter their CS, there processes cannot be postponed indefinitely
- **Bounded Waiting**
  - A **bound** must exist on the number of times that other processes are allowed to enter their CS after a process has made a request to enter its CS
- How to design **entry** and **exit section** to satisfy the above requirement?

CS Solutions and Synchronization Tools

- Software solution
- Synchronization hardware
- Semaphore
- Monitor

Algorithm for Two Processes

- Only 2 processes P_0 and P_1
- Shared variables
  - int *turn*; // initially *turn* = 0
  - *turn* == *i* ➔ P_i can enter its critical section

```
/* Process 0 */
do {
    while (turn != 0);      — entry section
        critical section
    turn = 1;               — exit section
        remainder section
} while (1);
```

```
/* Process 1 */
do {
    while (turn != 1);      — entry section
        critical section
    turn = 0;               — exit section
        remainder section
} while (1);
```

mutual exclusion? **Y** progress? **N** bounded-wait? **Y**

Peterson's Solution for Two Processes

- Shared variables
  - int *turn*; // initially *turn* = 0
  - *turn* == *i* ➔ P_i can enter its critical section
  - boolean *flag[2]*; // initially *flag[0]* = *flag[1]* = *false*
  - *flag[i]* == *true* ➔ P_i is ready to enter its critical section

```
/* Process i */
do {
    flag[i] = true;
    turn = j;                          — entry section
    while (flag[j] && turn == j);
        critical section
    flag[i] = false;                   — exit section
        remainder section
} while (1);
```

Proof of Peterson's Solution

- **Mutual exclusion**
  - If P_0 in CS ➔ *flag[1] == false || turn == 0*
  - If P_1 in CS ➔ *flag[0] == false || turn == 1*
  - Assume both processes in CS ➔ *flag[0] == flag[1] == true*

    ➔ turn == 0 for P_0 to enter, *turn == 1* for P_1 to enter

    ➔ turn will be either 0 or 1, so P_0, P_1 cannot in CS at the same time

```
/* Process 0 */
do {
    flag[0] = true;
    turn = 1;
    while (flag[1] && turn == 1);
        critical section
    flag[0] = false;
        remainder section
} while (1);
```

```
/* Process 1 */
do {
    flag[1] = true;
    turn = 0;
    while (flag[0] && turn == 0);
        critical section
    flag[1] = false;
        remainder section
} while (1);
```

Proof of Peterson's Solution

- **Progress (e.g., P_0 withes to enter its CS)**
  - (1) If P_1 is not ready ➔ *flag[1] = false* ➔ P_0 can enter
  - (2) If both are ready ➔ *flag[0] == flag[1] == true*

    ➔ If *turn == 0* then P_0 enters, otherwise P_1 enters
  - Either cases, some waiting process can enter CS

```
/* Process 0 */
do {
        flag[0] = true;
        turn = 1;
        while (flag[1] && turn == 1);
            critical section
        flag[0] = false;
            remainder section
} while (1);
```

```
/* Process 1 */
do {
        flag[1] = true;
(2)     turn = 0;
        while (flag[0] && turn == 0);
            critical section
(1)     flag[1] = false;
            remainder section
} while (1);
```

Proof of Peterson's Solution

- **Bounded waiting (e.g., P_0 withes to enter its CS)**
  - (1) Once P_1 exits CS ➔ *flag[1] == false* ➔ P_0 can enter
  - (2) If P_1 exits CS and reset *flag[1] = true*

    ➔ *turn == 0* (overwrite P_0 setting) ➔ P_0 can enter
  - P_0 won't wait infinitely

```
/* Process 0 */
do {
        flag[0] = true;
        turn = 1;
        while (flag[1] && turn == 1);
            critical section
        flag[0] = false;
            remainder section
} while (1);
```

```
/* Process 1 */
do {
(2)     flag[1] = true;
        turn = 0;
        while (flag[0] && turn == 0);
            critical section
(1)     flag[1] = false;
            remainder section
} while (1);
```

Peterson’s Solution and Modern Architecture

- Peterson’s solution is **not guaranteed** to work on modern architectures
  - To improve performance, processors and/or compilers may **reorder operations** that have no **dependencies**
- For **single-threaded process** this is **OK** as the result will always be the same
- For **multi-threaded process** the reordering may produce inconsistent or unexpected results

Peterson's Solution and Modern Architecture (cont.)

- Example:
  - Two threads share the data:

    bool flag = true;
    int x = 0;

  - Thread1 performs

    while (!flag);
    print x;

  - Thread2 performs

    x = 100;
    flag = true;

  - Expected output will be 100

Peterson's Solution and Modern Architecture (cont.)

- Example (cont.):
  - Because the variables ***flag*** and ***x*** are independent of each other, the instructions:

    x = 100;
    flag = true;

    for Thread2 may be reordered

  - If this occurs, the output may be 0!

Peterson's Solution and Modern Architecture (cont.)

```
/* Process 0 */
do {
    flag[0] = true;
    turn = 1;
    while (flag[1] && turn == 1);
        critical section
    flag[0] = false;
        remainder section
} while (1);
```

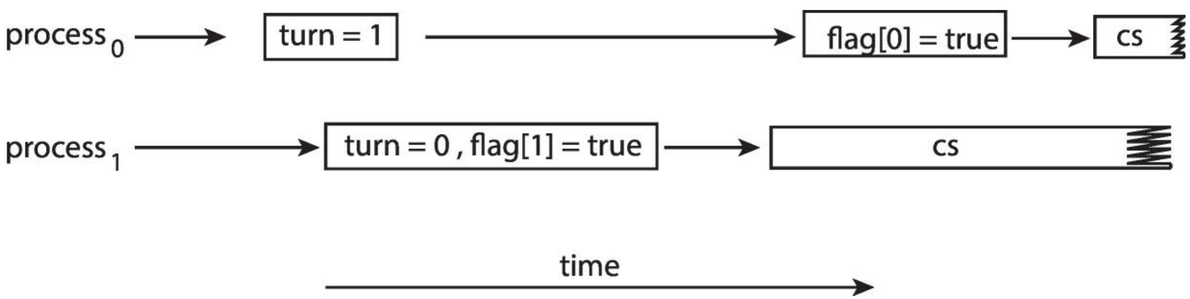
```
/* Process 1 */
do {
    flag[1] = true;
    turn = 0;
    while (flag[0] && turn == 0);
        critical section
    flag[1] = false;
        remainder section
} while (1);
```

The variables *flag[]* and *turn* are independent, so they might be reordered

Peterson's Solution and Modern Architecture (cont.)

```
/* Process 0 */
do {
    turn = 1;
    flag[0] = true;
    while (flag[1] && turn == 1);
        critical section
    flag[0] = false;
        remainder section
} while (1);
```

```
/* Process 1 */
do {
    turn = 0;
    flag[1] = true;
    while (flag[0] && turn == 0);
        critical section
    flag[1] = false;
        remainder section
} while (1);
```



Both processes will enter their CS !

We can use **Memory Barrier** to ensure the correctness

Memory Barrier

- When a memory barrier instruction is performed, the system ensures that **all loads and stores are completed before any subsequent loads or stores operations are performed**
- Recall previous example:

```
/* Thread 1 */
while (! flag) ;   load
print x
```

```
/* Thread 2 */
x = 100;           store
flag = true;
```

Memory Barrier (cont.)

- When a memory barrier instruction is performed, the system ensures that **all loads and stores are completed before any subsequent loads or stores operations are performed**
- Modification:

```
/* Thread 1 */
while (! flag) ;
memory_barrier();
print x
```

```
/* Thread 2 */
x = 100;
memory_barrier();
flag = true;
```

For Thread 1, we are guaranteed that the value of *flag* is loaded before the value of *x*

Memory Barrier (cont.)

- When a memory barrier instruction is performed, the system ensures that **all loads and stores are completed before any subsequent load or store operations are performed**
- Modification:

```
/* Thread 1 */
while (! flag) ;
memory_barrier();
print x
```

```
/* Thread 2 */
x = 100;
memory_barrier();
flag = true;
```

For Thread 2, we are guaranteed that the assignment to *x* occurs before the assignment to *flag*

Producer & Consumer Problem

```
/* Producer process 0 */
while (true) {
        entry section
        nextItem = getItem();
        while (counter == BUFFER_SIZE);
        buffer[in] = nextItem;
        in = (in + 1) % BUFFER_SIZE;
        counter++;
        computing();
        exit section
}
```

```
/* Consumer process 0 */
while (true) {
        entry section
        while (counter == 0);
        item = buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        counter--;
        computing();
        exit section
}
```

Incorrect. Deadlock if consumer enters the CS first

Producer & Consumer Problem (cont.)

```
/* Producer process 0 */
while (true) {
        nextItem = getItem();
        while (counter == BUFFER_SIZE);
        buffer[in] = nextItem;
        in = (in + 1) % BUFFER_SIZE;
        entry section
        counter++;
        computing();
        exit section
}
```

```
/* Consumer process 0 */
while (true) {
        while (counter == 0);
        item = buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        entry section
        counter--;
        computing();
        exit section
}
```

Correct but **poor performance**

Producer & Consumer Problem (cont.)

```
/* Producer process 0 */
while (true) {
        nextItem = getItem();
        while (counter == BUFFER_SIZE);
        buffer[in] = nextItem;
        in = (in + 1) % BUFFER_SIZE;
        entry section
        counter++;
        exit section
        computing();
}
```

```
/* Consumer process 0 */
while (true) {
        while (counter == 0);
        item = buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        entry section
        counter--;
        exit section
        computing();
}
```

Correct and **maximize concurrent performance**

Bakery Algorithm (*n* processes)

- Before entering its CS, each process receives a **number (#)**
- **Holder of the smallest # enters CS**
- The numbering scheme always generates # in **non-decreasing order**; i.e., 1, 2, 3, 3, 4, 5, 5, 5 …
- If processes P_i and P_j receive the same #, if $i < j$, then P_i is served first
- Notation:
  - $(a, b) < (c, d)$ if
    - $a < c$ or
    - $a == c$ && $b < d$

Bakery Algorithm (*n* processes) (cont.)

get ticket

FCFS

release ticket

```
// Process i:
do {
    choosing[i] = true;
    num[i] = max (num[0], num[1], …num[n-1]) + 1;
    choosing[i] = false;
    for (j = 0; j < n; j++) {
        while (choosing[j]);
        while ((num[j] != 0) && ((num[j], j) < (num[i], i)));
    }
    critical section
    num[i] = 0;
    remainder section
}
```

Bounded waiting because processes enter CS on a **first come, first served** basis

Bakery Algorithm (*n* processes) (cont.)

- Why cannot compare when num is being modified?
- Without locking
  - Let 5 be the current maximum number
  - If P_1 and P_4 take number together, but P_4 finishes before P_1
    - $P_1 = 0$, $P_4 = 6$ ➔ P_4 will enter the CS
  - After P_1 takes the number
    - $P_1 = P_4 = 6$ ➔ P_1 will enter the CS as well !
- With locking
  - P_4 will have to wait until P_1 finish taking the number
  - Both P_1 & P_4 will have the new number "6" before comparison

Pthread Lock/Mutex Routines

- To use mutex, it must be declared as of type *pthread_mutex_t* and initialized with *pthread_mutex_init()*
- A mutex is destroyed with *pthread_mutex_destroy()*
- A critical section can then be protected using *pthread_mutex_lock()* and *pthread_mutex_unlock()*

```
#include "pthread.h"
pthread_mutex   mutex;
pthread_mutex_init(&mutex, NULL);
pthread_mutex_lock(&mutex);          ⟵ enter critical section
critical section
pthread_mutex_unlock(&mutex);        ⟵ exit critical section
pthread_mutex_destroy(&mutex);
```

Condition Variables

- **Condition variables (CV)** represent some condition that a **thread** can
  - **Wait on**, until the condition occurs; or
  - **Notify** other waiting threads that the condition has occurred
- Three operations on condition variables
  - **wait()** – block until another thread calls **signal()** or **broadcast()** on the CV

    pthread_cond_wait(&theCV, &someLock)
  - **signal()** – wake up one thread waiting on the CV

    pthread_cond_signal(&theCV)
  - **broadcast()** – wake up all threads waiting on the CV

    pthread_cond_broadcast(&theCV)

Condition Variables (cont.)

- Example
  - A thread is designed to take action when *x == 0*
  - Another thread is responsible for decrementing the counter

```
pthread_cont_t      cond;
pthread_cond_init(cond, NULL);
pthread_mutex_t mutex;
pthread_mutex_init(mutex, NULL);
```

```
action() {
    pthread_mutex_lock(&mutex);
    if (x != 0)
        pthread_cond_wait(cond, mutex);
    pthread_mutex_unlock(&mutex);
    take_action();
}
```

```
counter() {
    pthread_mutex_lock(&mutex);
    x--;
    if (x == 0)
        pthread_cond_signal(cond);
    pthread_mutex_unlock(&mutex);
}
```

Using Condition Variables

```
action() {
    pthread_mutex_lock(&mutex);
    if (x != 0)
        pthread_cond_wait(cond, mutex);
    pthread_mutex_unlock(&mutex);
    take_action();
}
```

```
counter() {
    pthread_mutex_lock(&mutex);
    x--;
    if (x == 0)
        pthread_cond_signal(cond);
    pthread_mutex_unlock(&mutex);
}
```

Lock mutex

Using Condition Variables

```
action() {
    pthread_mutex_lock(&mutex);
    if (x != 0)
        pthread_cond_wait(cond, mutex);
    pthread_mutex_unlock(&mutex);
    take_action();
}
```

```
counter() {
    pthread_mutex_lock(&mutex);
    x--;
    if (x == 0)
        pthread_cond_signal(cond);
    pthread_mutex_unlock(&mutex);
}
```

Lock mutex

Wait()

- Put the thread into **sleep** and **releases the lock**

Lock mutex

Using Condition Variables

```
action() {
    pthread_mutex_lock(&mutex);
    if (x != 0)
        pthread_cond_wait(cond, mutex);
    pthread_mutex_unlock(&mutex);
    take_action();
}
```

```
counter() {
    pthread_mutex_lock(&mutex);
    x--;
    if (x == 0)
        pthread_cond_signal(cond);
    pthread_mutex_unlock(&mutex);
}
```

Lock mutex

Wait()

- Put the thread into **sleep** and **releases the lock**
- **Waked up**, but the thread is locked

Lock mutex

Signal()

Using Condition Variables

```
action() {
    pthread_mutex_lock(&mutex);
    if (x != 0)
        pthread_cond_wait(cond, mutex);
    pthread_mutex_unlock(&mutex);
    take_action();
}
```

```
counter() {
    pthread_mutex_lock(&mutex);
    x--;
    if (x == 0)
        pthread_cond_signal(cond);
    pthread_mutex_unlock(&mutex);
}
```

Lock mutex

Wait()

- Put the thread into **sleep** and **releases the lock**
- **Waked up**, but the thread is locked
- **Re-acquire lock** and resume execution

Lock mutex

Signal()

Release the lock

Using Condition Variables

```
action() {
    pthread_mutex_lock(&mutex);
    if (x != 0)
        pthread_cond_wait(cond, mutex);
    pthread_mutex_unlock(&mutex);
    take_action();
}
```

```
counter() {
    pthread_mutex_lock(&mutex);
    x--;
    if (x == 0)
        pthread_cond_signal(cond);
    pthread_mutex_unlock(&mutex);
}
```

Lock mutex

Wait()

- Put the thread into **sleep** and **releases the lock**
- **Waked up**, but the thread is locked
- **Re-acquire lock** and resume execution

Release the lock

Lock mutex

Signal()

Release the lock

ThreadPool Implementation

- **Task structure**

```
typedef struct {
    void (*function)(void *);
    void *argument;
} threadpool_task_t;
```

- **ThreadPool structure**

```
struct threadpool_t {
    pthread_mutex_t lock;
    pthread_cond_t notify;
    pthread_t *threads;
    threadpool_task_t *queue;
    int thread_count;
    int queue_size;
    int head;
    int tail;
    int count;
    int shutdown;
    int started;
};
```

- **Allocate thread and task queue**

```
/* Allocate thread and task queue */
pool->threads = (pthread_t *) malloc(sizeof(pthread_t) * thread_count);
pool->queue = (threadpool_task_t *) malloc(sizeof(threadpool_task_t) * queue_size);
```

ThreadPool Implementation (cont.)

```
static void *threadpool_thread(void *threadpool)
 {
     threadpool_t *pool = (threadpool_t *)threadpool;
     threadpool_task_t task;

     for(;;) {
         /* Lock must be taken to wait on conditional variable */
         pthread_mutex_lock(&(pool->lock));

         /* Wait on condition variable, check for spurious wakeups.
            When returning from pthread_cond_wait(), we own the lock. */
         while((pool->count == 0) && (!pool->shutdown)) {
             pthread_cond_wait(&(pool->notify), &(pool->lock));
         }
```

ThreadPool Implementation (cont.)

```
    /* Grab our task */
    task.function = pool->queue[pool->head].function;
    task.argument = pool->queue[pool->head].argument;
    pool->head += 1;
    pool->head = (pool->head == pool->queue_size) ? 0 : pool->head;
    pool->count -= 1;

    /* Unlock */
    pthread_mutex_unlock(&(pool->lock));

    /* Get to work */
    (*(task.function))(task.argument);
}
```

Synchronization Hardware

Hardware Support

- The CS problem occurs because the modification of a shared variable may be **interrupted**
- If disable interrupts when in CS
  - Not feasible in multiprocessor machine
  - Clock interrupts cannot fire in any machine
- **HW support solution: atomic instructions**
  - atomic: as one **uninterruptible** unit
  - Example: **TestAndSet(var)** and **Swap(a, b)**

Atomic TestAndSet()

```
bool TestAndSet (bool &lock) {
    bool value = lock;
    lock = true;
    return value;
}
```

execute atomically:
return the value of “lock” and **set** “lock” to true

```
shared data: bool lock;    // initially lock = false
```

```
// P0
do {
    while (TestAndSet (lock));
    critical section
    lock = false;
    remainder section
} while (1);
```

```
// P1
do {
    while (TestAndSet (lock));
    critical section
    lock = false;
    remainder section
} while (1);
```

mutual exclusion? **Y** progress? **Y** bounded-wait? **N**

Atomic Swap()

Enter CS if lock == false

```
shared data: bool lock;    // initially lock = false

// P0                                  // P1
do {                                   do {
    key0 = true;                           key1 = true;
    while (key0 == true)                   while (key1 == true)
        Swap(lock, key0);                      Swap(lock, key1);
    critical section                       critical section
    lock = false;                          lock = false;
    remainder section                      remainder section
} while (1);                           } while (1);
```

mutual exclusion? **Y** progress? **Y** bounded-wait? **N**

Atomic CompareAndSwap()

```
int CompareAndSwap (int &value, int expected, int new_value) {
    int temp = value;
    if (value == expected)
        value = new_value;
    return temp;
}
shared data: int lock;     // initially lock = 0
// P0
do {
    while (CompareAndSwap (lock, 0, 1) != 0);
    critical section
    lock = 0;
    remainder section
} while (1);
```

mutual exclusion? **Y** progress? **Y** bounded-wait? **N**

Atomic Variables

- **Atomic variable** is another tool that provides atomic (uniterruptible) updates on basic data types such as integers and Booleans
- Usually built with atomic instructions such as ***CompareAndSwap***
- Example:
  - Let ***sequence*** be an atomic variable
  - Let ***increment()*** be an operation for incrementing the atomic variable ***sequence***
  - The command ***increment(&sequence)*** ensures ***sequence*** is incremented without interruption

Atomic Variables (cont.)

- The ***increment()*** function can be implemented as follows

```
                                 5
void increment (atomic_int &v) {
    int temp;
    do {
        temp = v;
    }     5
    while (temp != (CompareAndSwap (v, temp, temp+1));
}           5                      5   5     6
```

```
int CompareAndSwap (int &value, int expected, int new_value) {
    int temp = value;            5         5            6
    if (value == expected)
        value = new_value;
    return temp;
}
```

Atomic Variables (cont.)

- The ***increment()*** function can be implemented as follows

5

```
bool increment (atomic_int &v) {
        int temp;
        do {
                temp = v;
        }       5
        while (temp != (CompareAndSwap (v, temp, temp+1));
}              5                        3    5       6
```

v is modified

```
int CompareAndSwap (int &value, int expected, int new_value) {
        int temp = value;           3          5           6
        if (value == expected)
                value = new_value;
        return temp;
}
```

Atomic Variables (cont.)

- The ***increment()*** function can be implemented as follows

```
bool increment (atomic_int &v) {
      int temp;
      do {
            temp = v;
      }     3
      while (temp != (CompareAndSwap (v, temp, temp+1));
}                 3                          3    3     4
```

v is modified

```
int CompareAndSwap (int &value, int expected, int new_value) {
      int temp = value;             3         3           4
      if (value == expected)
            value = new_value;
      return temp;
}
```

Semaphores

Semaphores

- A tool to generalize the synchronization problem
- More specifically
  - A **record** of **how many units of a particular resource is available**
    - If # record = 1 ➔ binary semaphore, **mutex lock**
    - If # record > 1 ➔ counting semaphore
  - Accessed only through 2 **atomic** operations: **wait** & **signal**
- **Spinlock** implementation
  - Semaphore ***S*** is an integer variable

```
wait (S) {
    while (S <= 0);
    S--;
}
```

busy waiting

```
signal (S) {
    S++;
}
```

POSIX Semaphore

- Semaphore is part of **POSIX standard** BUT it is not belonged to pthread
  - It can be used with or without thread
- POSIX Semaphore routines

```
#include <semaphore.h>
sem_t sem;
sem_init(&sem);
sem_wait(&sem);
critical section
sem_signal(&sem);
sem_destroy(&sem);
```

n-Process CS Problem Revisit

- Shared data:

  semaphore mutex; *// initially mutex = 1*

- Process P_i :

```
do {
        wait(mutex);            // pthread_mutex_lock(&mutex)
        critical section
        signal(mutex);          // pthread_mutex_unlock(&mutex)
        remainder section
} while (1);
```

progress? **Y**

bounded-wait? **depends on the implementation of wait()**

Semaphores with Non-busy Waiting

- Semaphore is a **data structure with queue**
  - May use any queuing strategy (FIFO, FILO, etc)

```
typedef struct {
    int value;    // init to # resource
    struct process *L;  // PCB queue
} semaphore;
```

- **wait()** and **signal()**
  - Use system calls: **block()** and **wakeup()**
  - Must be **executed atomically**

```
void wait (semaphore S) {
    S.value--;  // subtract first
    if (S.value < 0) {
        add this process to S.L;
        sleep();
} }
```

```
void signal (semaphore S) {
    S.value++;
    if (S.value <= 0) {
        remove this process from S.L;
        wakeup(P);
} }
```

How to Ensure Atomic Wait & Signal Ops?

- Hardware support
  - TestAndSet
  - Swap

- Software solution
  - Peterson’s solution
  - Bakery algorithm

Semaphore with Critical Section

```
void wait (semaphore S) {
    entry section
    S.value--;
    if (S.value < 0) {
        add this process to S.L;
        exit section
        sleep();
    } else {
        exit section
    }
}
```

```
void signal (semaphore S) {
    entry section
    S.value++;
    if (S.value <= 0) {
        remove this process from S.L;
        exit section
        wakeup(P);
    } else {
        exit section
    }
}
```

Cooperation Synchronization

- P1 executes S1; P2 executes S2
  - S2 will be executed only after …

- Implementation

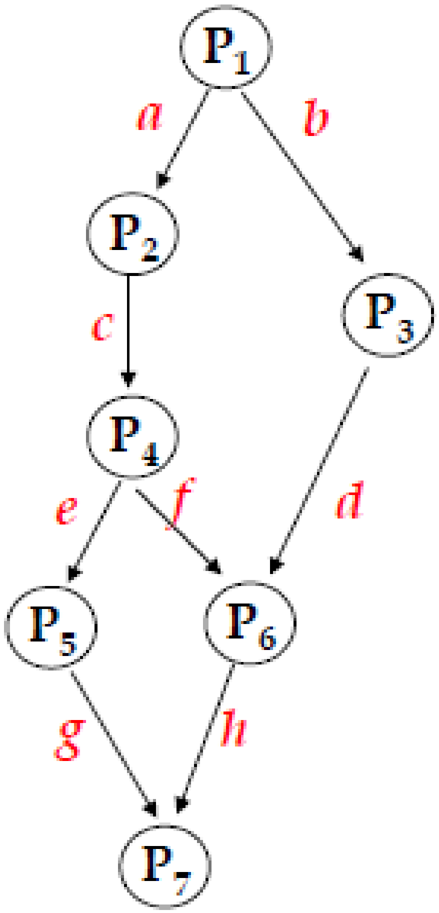
  Shared variable:

  semaphore sync; *// initially sync = 0*

P1:	***P2:***
S1;	*wait (sync);*
signal (sync);	*S2;*

A More Complicated Example

- Initially, all semaphores are 0
- Begin
  - P1: S1; signal(a); signal(b);
  - P2: wait(a); S2; signal(c);
  - P3: wait(b); S3; signal(d);
  - P4: wait(c); S4; signal(e); signal(f);
  - P5: wait(e); S5; signal(g);
  - P6: wait(f); wait(d); S6; signal(h);
  - P7: wait(g); wait(h); S7;
- End



Deadlocks and Starvation

- **Deadlock**
  - Two processes are waiting indefinitely for each other to release resources
- **Starvation**
  - Some processes (threads) wait infinitely

P_0	P_1
wait(S);	*wait*(Q);
wait(Q);	*wait*(S);
⋮	⋮
signal(S);	*signal*(Q);
signal(Q)	*signal*(S);