Synchronization Primitives

2023-2024 Fall COMP3230A

Contents

- mutual exclusion – mutex lock
- Using atomic instructions to build spin-waiting mutex lock
- Condition variables – a synchronization primitive
- Semaphores – another synchronization primitive that can serve as mutex lock and condition variables

Related Learning Outcomes

- ILO 2c – describe the principles and **techniques** used by OS to support concurrency and synchronization control.
- ILO 4 – **[Practicability]** demonstrate knowledge in applying system software and tools available in modern operating system

Readings & References

- Required Readings
  - Chapter 28 – **Locks** (except sections 28.10, 28.11, 28.15, 28.16)
    - http://pages.cs.wisc.edu/~remzi/OSTEP/threads-locks.pdf
  - Chapter 30 – **Condition Variables**
    - http://pages.cs.wisc.edu/~remzi/OSTEP/threads-cv.pdf
  - Chapter 31 – **Semaphores**
    - http://pages.cs.wisc.edu/~remzi/OSTEP/threads-sema.pdf
- References
  - Chapter 27 – **Interlude: Thread API**
    - http://pages.cs.wisc.edu/~remzi/OSTEP/threads-api.pdf

Mutual Exclusion

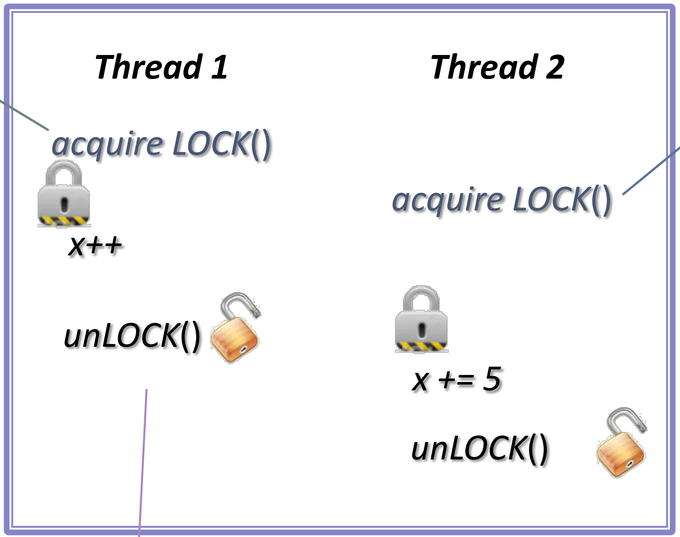
- We need a mechanism to inform OS that the thread is going to enter its critical section
- Here comes the concept of using a "lock"
  - A lock is a data structure used for **indicating** the start and end of **a critical section**
    - Indicate shared data is about to be accessed and **ask for the system** to provide necessary protection

Mutual Exclusion – Lock

- A lock is either available (free or unlocked) or held (locked or acquired)

A thread wants to access a shared item, it tries to acquire a lock

If no other thread holds the lock, this thread gets the lock (becomes the **owner**) and enters critical section



If the lock is held by another thread, this thread will not return and block until the lock changes to free; **then** it acquires the lock and enters critical section

The owner calls unlock( ) to free the lock when exits critical section

Evaluation Criteria for Locks

- Correctness
  - Does it provide mutual exclusion, preventing multiple threads from entering the critical section?
- Fairness
  - Do all threads contending for the lock get a fair shot? Any starvation?
- Performance
  - What time overheads added by using the lock?
  - Overheads in cases of 1) single thread, 2) multiple threads on a single CPU, and 3) multiple threads on multiple CPUs

Building Locks

- The main cause of the indeterministic outcome is *uncontrolled scheduling*
  - Can we avoid being preempted when the thread is in critical section?

```
/* lock( )*/
disable interrupts

/* unlock( )*/
enable interrupts
```

- **Disabling interrupts**
  - Prevents current executing thread from being preempted, as without interrupts, scheduler will not be invoked; thus, no other threads will be able to turn to running state
- Works only on systems with single core
- Being used rarely, mostly used in kernel under privilege mode

Atomic Instructions

- Modern machines provide special atomic hardware instructions
- **Test-and-Set** Instruction
  - It enables us to test the old value ***while simultaneously set*** the variable to a new value
    - The instruction ***returns the old value*** and **simultaneously updates the value** to new in an **atomic way**

Guarantee execution till end without interruption

```
int TestAndSet(int *ptr, int new) {
    int old = *ptr;         //get current value
    *ptr = new;             //set to new value
    return old;    //return old value
}
```

- **Compare-and-Swap** Instruction
  - Test whether the content of a variable is equal to expected; if so, update the variable to a new value; otherwise, do nothing
    - The instruction **always returns the current value** of the variable

Guarantee execution till end without interruption

```
void CompareAndSwap(int *ptr, int expected, int new)
{
    int temp = *ptr;        //get current value
    if (temp == expected)
        *ptr = new;
    return temp;
}
```

Test-and-Set

```
int TestAndSet(int *ptr, int new) {
    int old = *ptr;         //get current value
    *ptr = new;             //set to new value
    return old;    //return old value
}
```

- Implementing Mutual Exclusion
  - Based on **checking** of the value of a shared variable to decide whether a process can enter its Critical Section
  - Uses **busy waiting** (spin-wait or spin-lock) to test whether it can enter its Critical Section

(1) If another thread is in critical section, flag is 1; in that case, TestAndSet( ) will return 1

(2) If no thread is in critical section, flag is 0; in that case, TestAndSet( ) will return 0 and will atomically modify flag to 1

```
int flag = 0;        //when flag = 0, lock is free

while (TestAndSet(&flag, 1) == 1);      //lock( )

// into the critical section

flag = 0;     //unlock( )
```

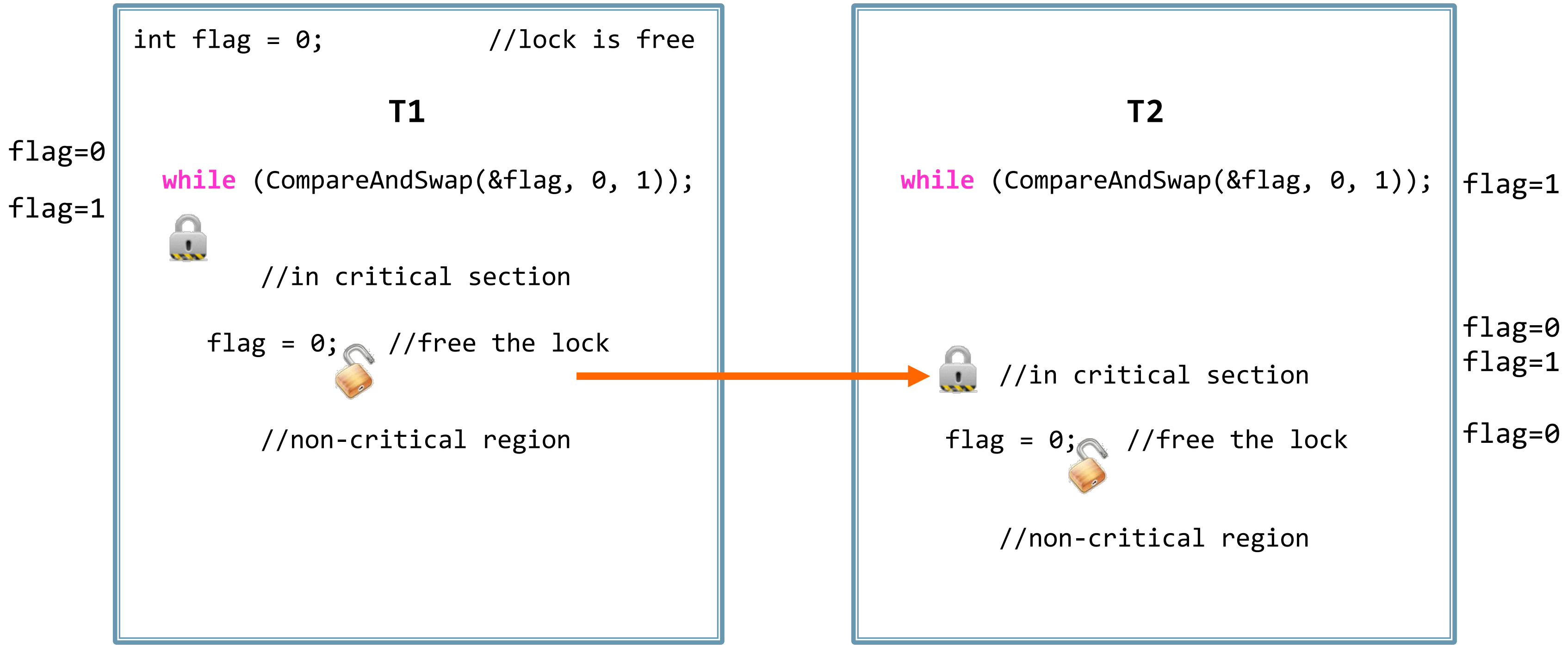
Test-and-Set

- With the guarantee of atomic update of a shared variable
  - This guarantees mutual exclusion as only one thread can set the shared flag to 1, others have to spin-wait for the flag to turn back to 0
- Spin-wait / Busy-waiting
  - However, the processor is essentially doing nothing but just executes the while() loop
  - Wastes significant processor time
    - those threads may just spin-waiting until the time quantum expires
- Spin-waiting cannot avoid indefinite postponement; thus, do not provide fairness guarantee
  - e.g., when two threads T1 & T2 contend for entering to critical sections, because of uncontrolled scheduling, it is possible that T1 always be the lucky one & T2 always finds that the flag is always 1

```
void CompareAndSwap(int *ptr, int expected, int new)
{
    int temp = *ptr;          //get current value
    if (temp == expected)
        *ptr = new;
    return temp;
}
```

Compare-And-Swap

- Example: Intel IA-32 and IA-64 contain an CMPXCHG instruction
- Implementing Mutual Exclusion
  - Again, using spin-waiting



```
int flag = 0;              //lock is free

              T1
flag=0
    while (CompareAndSwap(&flag, 0, 1));
flag=1

           //in critical section

       flag = 0;   //free the lock

           //non-critical region
```

```
              T2

    while (CompareAndSwap(&flag, 0, 1));   flag=1

                                            flag=0
                                            flag=1
       //in critical section

    flag = 0;   //free the lock             flag=0

       //non-critical region
```

Fetch-And-Add

- fetch-and-add instruction
  - Atomically increment a value while returning the old value
- Ticket Lock
  - ticket: the calling thread's turn
  - turn: determine which thread's turn it is
- Fairness: Ensures progress for all threads
  - Every thread attempting to acquire the lock with be assigned a ticket value, and will be scheduled at some point in the future

Guarantee execution till end without interruption

```
int FetchAndAdd(int *ptr) {
    int old = *ptr;
    *ptr = old + 1;
    return old;    //return old value
}
```

```
lock->ticket = 0;
lock->turn = 0;
```

```
int myturn = FetchAndAdd(&lock->ticket);
while (lock->turn != myturn); // spin
```

```
lock->turn = lock->turn + 1;
```

MutEx – Hardware Instructions

- Atomic instructions
  - Applicable to any number of processes/threads on either a single processor or multiple processors sharing main memory
- Machine-language instructions cannot provide a good mutual exclusion solution on its alone
  - For example, possibility of having indefinite postponement if more than one thread is waiting
- Unfortunately, Spin-waiting consumes processor time
- The Crux
  - How can we develop a lock that does not **needlessly waste time** spinning on the CPU as well as **maintain fairness**?
- The answer is: we need OS support.

Why/How to Avoid Spinning?

- Performance: Spin-wait does nothing but waste CPU time
- OS Support:
  - #1: Yield to give up CPU: yield() moves the caller from running to ready
  - #2: Use queues to sleep and wait instead of spinning: park() to put the calling thread to sleep; unpark() to wake up a thread
- Two-phase lock: Spin-wait once (or for a fixed amount of time) and go to sleep if not getting the lock
  - A hybrid approach (Linux Lock)
- Correctness: priority inversion
  - A higher-priority thread gets stuck waiting for a lock held by a lower-priority thread, which won't get a chance to run and thus cannot release the lock.

Pthread Lock

- In POSIX library, the lock data type is called mutex
- mutex variables must be declared with type
  - pthread_mutex_t

- Must be initialized before they can be used

- Two operations on mutex variables
  - pthread_mutex_lock() and pthread_mutex_unlock()
    - OS **blocks the calling thread** if the request lock is not available

- When finished using a mutex, deletes it with
  - pthread_mutex_destroy(&lock);

Not for examination

Concurrent Data Structure

- Locked-based concurrent data structure
  - Add locks to make a data structure **thread-safe**
- How to add locks correctly and efficiently?
  - Correct: Add a single lock to the data structure: "Big kernel lock"
  - Scalable: Use more "local" (to CPU/memory) locks to increase concurrency
- An example: Concurrent counters
- More data structures: linked list, queues, hash table, B-tree...
- No-blocking data structures: Non-lock-based

```
typedef struct __counter_t {
  int value;
  pthread_mutex_t lock;
} counter_t;

void init(counter_t *c) {
  c->value = 0;
  Pthread_mutex_init(&c->lock, NULL);
}

void increment(counter_t *c) {
  Pthread_mutex_lock(&c->lock);
  c->value++;
  Pthread_mutex_unlock(&c->lock);
}

void decrement(counter_t *c) {
  Pthread_mutex_lock(&c->lock);
  c->value--;
  Pthread_mutex_unlock(&c->lock);
}

int get(counter_t *c) {
  Pthread_mutex_lock(&c->lock);
  int rc = c->value;
  Pthread_mutex_unlock(&c->lock);
  return rc;
}
```

An unreal real-life example: Common Room Free Coffee Problem

- The CS Department is running a FREE Coffee Plan for its staff and students. The coffees are kept in the refrigerator in the Common Room in the CYC building (only one refrigerator there). The staffs in the General Office are responsible to make sure the refrigerator is always well stocked with coffee. Any staff can check the refrigerator and, if it is found empty, he/she can go and buy coffee and refill the refrigerator.
- With such responsible staffs, we can imagine, using the concurrency thinking we've developed in this course, a scenario where more than one staffs go and buy coffees, leading to a waste as the refrigerator has a limited capacity.
- The goals in solving this problem are two-fold:
  - 1) Make sure at most one person buys coffee;
  - 2) If coffee is needed, someone will eventually buy it.
- We decide to solve the problem by modeling each person as a thread, and refrigerator as shared variable (`coffee`). In the following, you will be asked to develop your solutions to ensure the two goals. A helper function named `Buy()` is provided, which simply changes `coffee` to `1`.

An unreal real-life example: Common Room Free Coffee Problem

- Let us first simplify the problem a bit by assuming that only two staffs are responsible for the free coffee plan. They believe they can leave a note on the refrigerator before going to buy coffee.
- Two threads, Thread A and Thread B, should be implemented for the two staffs respectively. You can use the following global variables in your code:
- - (int) `coffee`: indicate whether coffee is running out: `1` – well stocked; `0` – out of stock.
- - (int) `noteA`: leave note of staff A, value 1 means a note is left to buy coffee and 0 means none.
- - (int) `noteB`: leave note of staff B, same as `noteA` but for Thread B.
- As threads may be preempted at any time, make sure your solution support the above two goals.

```
// code here for thread A
noteA = 1;
while (noteB == 1);

if (coffee == 0) {
    Buy();
}
noteA = 0;
```

```
// code for thread B
noteB = 1;
if (noteA == 0) {
    if (coffee == 0) {
        Buy();
    }
}
noteB = 0;
```

An unreal real-life example: Common Room Free Coffee Problem

- Someone suggests that we could padlock the Common Room when going to buy coffee. Assume that there can be any number of staffs responsible for buying coffee (we don’t know the exact number as some of them may be on leave and some work from home). Use the knowledge we learn about mutex locks and present a solution using mutex locks. Still use the variable `coffee` to indicate the status of coffee availability and name your lock as `mutex`.

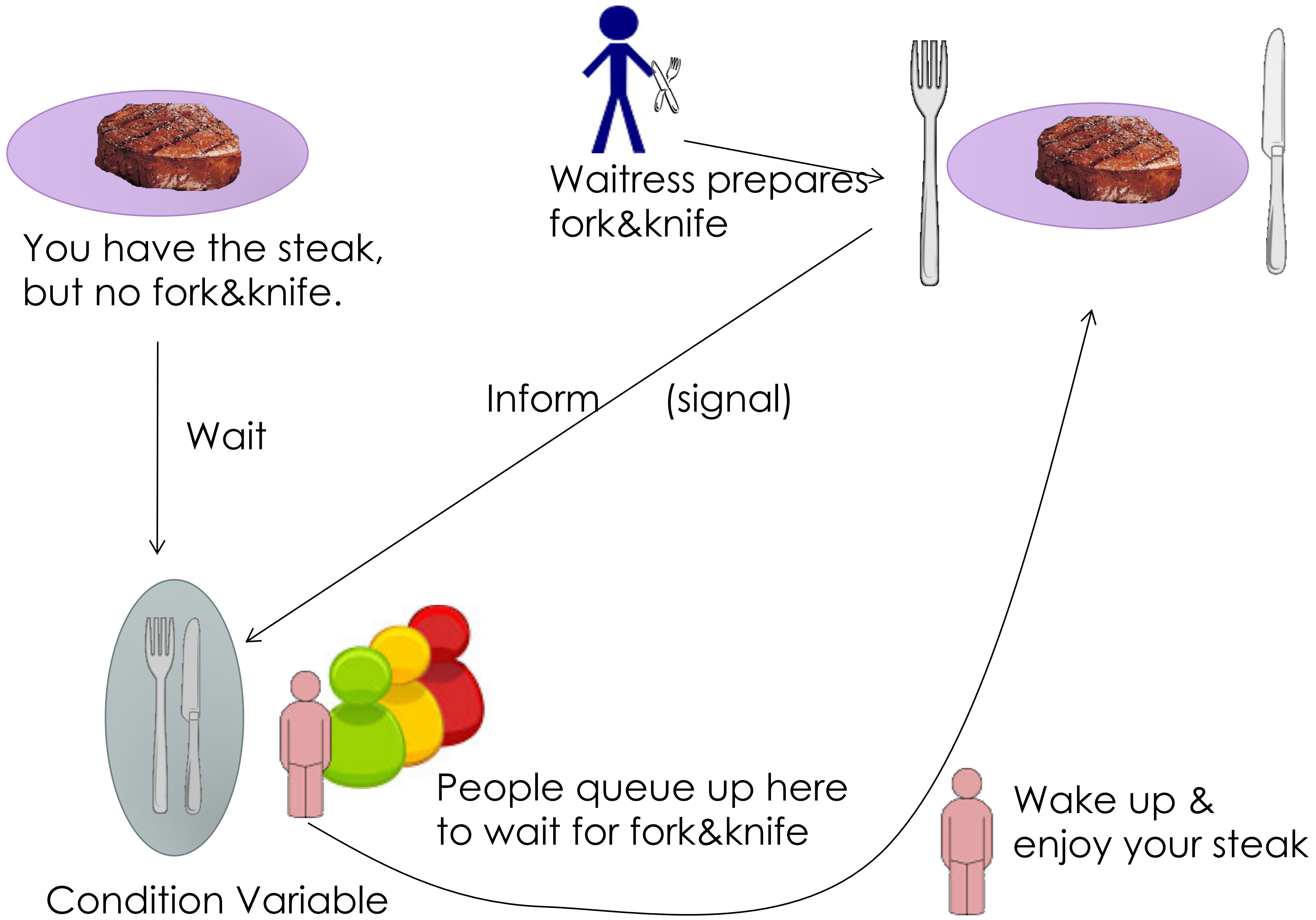
```
Pthread_mutex_lock(&mutex);

if (coffee == 0) {
    Buy();
}

Pthread_mutex_unlock(&mutex);
```

Control Synchronization

- Another typical interaction between threads is the control synchronization
  - a thread (A) should perform some action **only after** some other threads have performed specific actions (or have detected an event/condition)
  - **Thread A has to be waited and some other thread has to notify A** about the occurrence of the event/condition
- A simple approach – Thread A just spins until the condition becomes true
  - this is inefficient and wastes CPU cycles.

Condition Variables

- A data type explicitly designed to support synchronization between threads (without wasting CPU cycles)
  - it has **a queue** that threads can wait over there when some condition/event is not met
  - some other thread, once detects the condition/event, inform (signal) those waiting threads and wake one of those waiting threads
  - when using condition variables, each condition variable can only be associated to a distinct condition/event

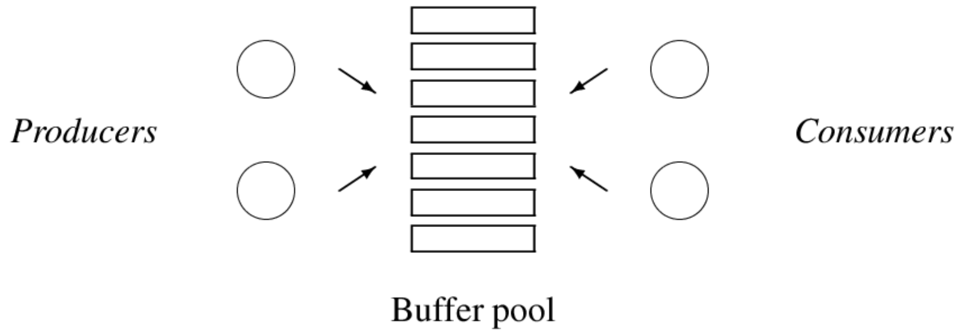

You have the steak, but no fork&knife.
Waitress prepares fork&knife
Wait
Inform (signal)
People queue up here to wait for fork&knife
Wake up & enjoy your steak
Condition Variable

Pthread Condition Variables

- Must be declared with type pthread_cond_t, and must be initialized before they can be used
- To wait for a condition
  - pthread_cond_wait()
    - When call this function, the calling thread is blocked until wake up by other using pthread_cond_signal()
- To inform others that the condition/event has happened
  - pthread_cond_signal()
  - pthread_cond_broadcast()
- Finish using a condition variable
  - pthread_cond_destroy(&cond);

Producer-consumer problem

- Classical synchronization problem, also known as Bounded-Buffer Problem
  - The system has a **finite buffer pool** shared by one or more producers and one or more consumers
    - Each buffer is capable of holding one unit of information
  - Producers produce data items and wish to place them in buffers
    - A producer thread produces a data item and places it into the next available buffer in the buffer pool
  - Consumers take out data items from buffer and consume/process the data item in some way
    - A consumer thread consumes a data item by removing it out of the buffer pool



Producer-consumer problem

- Synchronization requirements
  - Buffer pool is shared resource, producers and consumers need to use some method to coordinate the access to the pool
  - A producer must not overwrite a buffer when buffer pool is full
  - A consumer must not consume an empty buffer when buffer pool is empty
  - Mutual exclusion
  - Information must be consumed in FIFO order

A Solution to Producer-consumer problem

```
buffer[sizeofbuffer];
mutex_t mv;
cond_t notFULL, notEMPTY;
count = 0;

Producer( ){
        while (1)
        {
                d = generating_data();
                lock(mv);                                //try acquire the mutex lock
                while (count == sizeofbuffer)            //while buffer pool is full
                        cond_wait(notFULL, mv);          //wait for free space
                append(d, buffer);                       //update the count
                cond_signal(notEMPTY);                   //data is available in buffer
                unlock(mv);                              //release the lock
                remaining_work();
        }
}
```

To wait for buffer pool becomes NOT FULL

To wait for data/job in buffer pool

- Before waiting, it releases the mv lock.
- Then queues in the cond queue.
- Upon waking up, it gets back the mv lock before return

Buffer is definitely NOT FULL

Buffer pool is definitely NOT EMPTY. Inform waiting threads if any

A Solution to Producer-consumer problem

```
Consumer( ) {
        while (1)
        {
                lock(mv);                             //try acquire the mutex lock
                while (count == 0)                    //while buffer pool is empty
                        cond_wait(notEMPTY, mv);      //wait for data item
                d = take(buffer);                     //update the count
                cond_signal(notFULL);                 //one more free buffer space
                unlock(mv);                           //release the lock
                consume_data(d);
                remaining_work();
        }
```

Buffer is definitely NOT EMPTY

Buffer pool is definitely NOT FULL. Inform waiting threads if any

- Before waiting, it releases the mv lock.
- Then queues in the cond queue.
- Upon waking up, it gets back the mv lock before return

A Failure "Improvement": Using *if*

```
buffer[sizeofbuffer];
mutex_t mv;
cond_t notFULL, notEMPTY;
count = 0;
```

```
Producer( ){
while (1)
    {
        d = generating_data();
        lock(mv);
        if (count == sizeofbuffer)
            cond_wait(notFULL, mv);
        append(d, buffer);
        cond_signal(notEMPTY);
        unlock(mv);

        remaining_work();
    }
}
```

```
Consumer( ) {
while (1)
    {

        lock(mv);                    //try acquire the mutex lock
        if (count == 0)              //if buffer pool is empty
            cond_wait(notEMPTY, mv);//wait for data item
        d = take(buffer);            //update the count
        cond_signal(notFULL);        //one more free buffer space
        unlock(mv);                  //release the lock
        consume_data(d);
        remaining_work();
    }
}
```

A Failure “Improvement”: Using Single CV

```
buffer[sizeofbuffer];
mutex_t mv;
cond_t FULLEMPTY ~~notFULL~~, ~~notEMPTY~~;
count = 0;
```

```
Producer( ){
while (1)
    {
        d = generating_data();
        lock(mv);
        while (count == sizeofbuffer)
            cond_wait(FULLEMPTY, mv);
        append(d, buffer);
        cond_signal(FULLEMPTY);
        unlock(mv);

        remaining_work();
    }
}
```

```
Consumer( ) {
while (1)
    {

        lock(mv);                    //try acquire the mutex lock
        while (count == 0)           //while buffer pool is empty
            cond_wait(FULLEMPTY, mv);//wait for data item
        d = take(buffer);            //update the count
        cond_signal(FULLEMPTY);      //one more free buffer space
        unlock(mv);                  //release the lock
        consume_data(d);
        remaining_work();
    }
}
```

Two More Terms

- Mesa semantics [1980]
  - Signaling a thread ONLY wakes it up, but no guarantee that when the woken thread runs, the signaled state will still be as desired
  - Thus the issue of using "if" statement
  - Coined in the first research building a condition variable in such a manner using Mesa language (Butler W. Lampson, Turing Award 1992)
- Hoare semantics [1974]
  - Provides a stronger guarantee that the woken thread will run immediately upon being woken, but harder to implement
  - Named after its author Tony Hoare (Turing Award 1980)

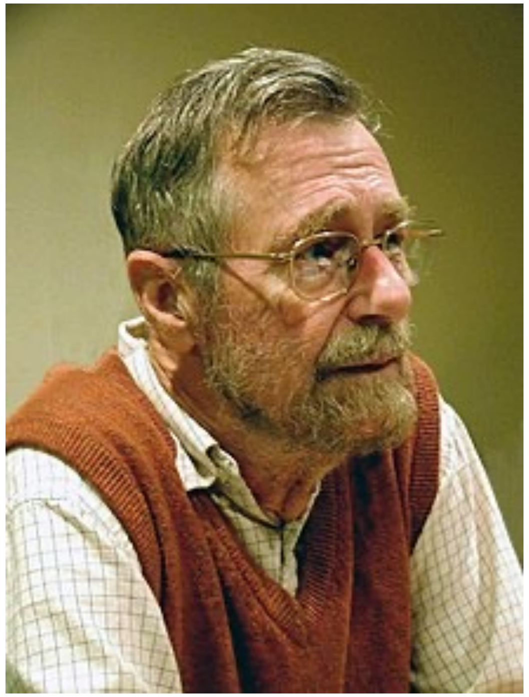
Semaphores

- Another synchronization tool that can serve as mutex locks or use for control synchronization
  - Invented as a single (generalized) primitive for all things of sync.

- A semaphore is an object with an internal protected integer variable
- Must be declared with type **sem_t**

- The range of integer values stored in the semaphore determines its behavior

- To initialize semaphore, **sem_t** *k*, to a value of *x*
  - sem_init(&*k*, 0, *x*);
  - **sem_init(sem_t ****sem*, **int** *pshared*, **unsigned int** *value***);**



Edsger W. Dijkstra
Turing Award 1972

Semaphores (2)

- The protect integer value **can only be** accessed via two atomic operations
  - sem_wait(&*k*) and sem_post(&*k*)
  - Also called **P()** (or wait or down) and **V()** (or signal or up), respectively

sem_wait(&*k*)

```
sem_wait(&k) {
    decrement the value of semaphore k by 1

    if value of semaphore k < 0
        place the thread in k's waiting queue
}
```

sem_post(&*k*)

```
sem_post(&k) {
    increment the value of semaphore k by 1

    if any threads are waiting on k's queue
        wake up one thread
}
```

MutEx – Binary Semaphores

- Semaphores that work like a mutex lock
- Binary – semaphore can have the value **one or zero only**
  - allow only one thread in its critical section at once
  - sem_t *lock* is **initially set to one only**

```
sem_t lock;
sem_init(&lock, 0, 1);

              Thread 1

while (1) {            lock = 1
    sem_wait(&lock);   lock = 0

    //in critical section

    sem_post(&lock);

    //other code fragment
}
```

```
              Thread 2

while (1) {

    sem_wait(&lock);    lock = -1


    //in critical section    lock = -1

    sem_post(&lock);

    //other code fragment
}
```

```
              Thread 3

while (1) {

    sem_wait(&lock);    lock = -2



    //in critical section    lock = 0

    sem_post(&lock);    lock = 1
```

Semaphores for Ordering

- Semaphores can be used to notify other threads that specific event/condition have occurred/reached

- Example: Another example of common synchronization problems is **order of execution** of operations of different threads
  - Thread1 wants to wait for both Thread2 and Thread3 to finish their tasks before its operation

```
sem_t order;
sem_init(&order, 0, 0);    //initialize to 0

   Thread1                        Thread2                    Thread3
      :                              :                          :
      :                              :                          :
sem_wait(&order);            computation2( );           computation3( );
sem_wait(&order);            sem_post(&order);          sem_post(&order);
computation1( );                     :                          :
      :                              :                          :
```

Readers-Writers Problem

- Another classic synchronization problem
- Consists of a set of threads accessing some shared data
  - Readers – threads that only reads the data
  - Writers – threads that modifies the data
- Typical example – Database access, linked list update and lookup
- Synchronization requirements
  - Many readers can perform reading concurrently
  - Reading is prohibited while a writer is updating
  - Only one writer can perform updating at any time

A Solution using Binary Semaphore

```
Semaphore semMutex = 1;
Semaphore readMutex = 1;
int readcount = 0;
```

```
Reader() {
    StartRead();
    do_reading();
    EndRead();
}
```

```
Writer() {
    StartWrite();
    do_writing();
    EndWrite();
}
```

```
StartRead() {
    P(readMutex); //Get the readMutex
    readcount++; //Count the number of readers
    if (readcount == 1) //If is the first reader
        P(semMutex); //Get the access right
    V(readMutex); //Release, others can update readcount
}
```

```
StartWrite() {
    P(semMutex);
}
```

```
EndRead() {
    P(readMutex); //Finish reading, try decrement readcount
    readcount--;
    if (readcount == 0) //If is last reader, free access semaphore
        V(semMutex);
    V(readMutex);
}
```

```
EndWrite() {
    V(semMutex);
}
```

General Semaphores

- Also known as Counting Semaphores
- Can be used to control access to a pool of identical resources
  - Initialized with sem_t *pool* to the resource count
  - Decrement the semaphore when taking resource from pool – sem_wait*(&pool)* operation
  - Increment the semaphore when returning it to pool – sem_post*(&pool)* operation
  - If no resources are available, thread is blocked until a resource becomes available

Producer/Consumer Problem

```
sem_t empty, full, mutex;

sem_init(&empty, 0, MAX); // MAX buffers are empty initially
sem_init(&full, 0, 0); // 0 buffers are full
sem_init(&mutex, 0, 1); // mutex = 1 because it is a lock (binary semaphore)
```

```
Producer()
{
    while (1)
    {
        P(&empty); /* block if buffer unavail */
        P(&mutex); /* lock */

        // critical section
        <<< Put item into shared buffer >>>

        V(&mutex);
        V(&full);
    }
}
```

```
Consumer()
{
    while (1)
    {
        P(&full);
        P(&mutex);

        // critical section
        <<< Remove item from shared buffer >>>

        V(&mutex);
        V(&empty);
    }
}
```

Summary

- To avoid race condition, such that only one thread can be in critical section, we need to use mutual exclusion primitives, such as, mutex lock or binary semaphore, as a guard for accessing/modifying the shared data

- For spin-wait locks, in uniprocessor, because of the busy waiting, performance overhead can be quite painful

- By the use of condition variables, thread can have a non-busy waiting mechanism, by put itself into sleep and wait for other thread to wake it when the desire condition is met

- Semaphores are a powerful and flexible primitive that support both synchronization and mutual execution

Semaphores Considered Harmful#

# Quoted from semaphore's inventor, Dijkstra's nice article with a great title "Goto Statements Considered Harmful"

- Just side information for fun

- Semaphores are slow
- Semaphores are stateful, while condition variables are stateless
- Codes using semaphores are not as self-documenting and easy to read as those using locks & condition variables

- Understanding semaphores is still important because 1) it is a nice idea and 2) real-world codes do use it.