CSCI 3753
Operating Systems

Classic Synchronization Problems (Producer-Consumer, Readers-Writers, Dining Philosophers)

Lecture Notes By

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Classic Synchronization Problems

- Bounded Buffer Producer-Consumer Problem
- Readers-Writers Problem
  - First Readers Problem
- Dining Philosophers Problem
- These are not just abstract problems
  - They are representative of several classes of synchronization problems commonly encountered in the real world when trying to synchronize access to shared resources among multiple processes or threads

Producer consumer problem

- We have already seen this problem with one producer and one consumer
- General problem: multiple producers and multiple consumers
- Producers puts new information in the buffer.
- Consumers takes out information from the buffer.

Semaphore empty = 0, full = MAX, m = 1;

```
producer()
    produce_info(item);
    P(full);
      P(m);
        enter_info(item);
      V(m);
    V(empty);
```

```
consumer ()
    P(empty);
       P(m);
          remove_info(item);
       V(m);
    V(full);
    consume_info(item);
```

Semaphores empty and full are used for maintaining counter values and signaling between producer and consumer processes.

Semaphore mutex1 is used for mutual exclusion among producer processes and mutex2 is used for mutual exclusion among consumer processes.

Pthreads Synchronization

- Mutex locks
  - Used to protect critical sections
- Some implementations provide semaphores through POSIX SEM extension
  - Not part of Pthreads standard

```
#include <pthread.h>
pthread_mutex_t m; //declare a mutex object
Pthread_mutex_init (&m, NULL); // initialize mutex object
```

```
//thread 1
pthread_mutex_lock (&m);
   //critical section code for th1
pthread_mutex_unlock (&m);
```

```
//thread 2
pthread_mutex_lock (&m);
   //critical section code for th2
pthread_mutex_unlock (&m);
```

From pthreads handout

odd function

```
…
  pthread_mutex_lock(&m);
  for (i = 0; i < 10000; i++)
    printf("odd\n");
  pthread_mutex_unlock(&m);
…
```

even function

```
…
  pthread_mutex_lock(&m);
  for (i = 0; i < 10000; i++)
    printf("even\n");
  pthread_mutex_unlock(&m);
…
```

main function

```
…
  pthread_mutex_lock(&m);
  for (i = 0; i < 10000; i++)
    printf("main\n");
  pthread_mutex_unlock(&m);
…
```

All three functions are writing to the standard output

What can happen if we do not use mutexes?

- *try it*

Binary Semaphores

Similar to semaphores with one key difference

- value can be only 0 or 1

```
typedef struct {
    int value;
    struct process *list;
} bin_semaphore;
```

```
P(bin_semaphore *s) {
    if (s→value == 0) {
        add this process to s→list;
        sleep ( );
    }
    else s→value = 0;
}
```

```
V(bin_semaphore *s) {
    if (s→list is not empty) {
        remove a process P from s→list;
        wakeup (P);
    }
    else s→value = 1;
}
```

Both P and V operations are atomic

Pthread mutex and binary semaphores

- Like binary semaphores, pthread mutexes can have only one of two states: lock or unlock
- But, there is a key difference
  - Mutex ownership: Only the thread that locks a mutex can unlock that mutex, while any thread can call the V operation on a binary semaphore irrespective of which thread called the P operation on that binary semaphore
  - So, mutexes are strictly used for mutual exclusion while binary semaphores can also be used for synchronization between two threads

POSIX semaphores

#include <semaphore.h>

int sem_init(sem_t *sem, int pshared, unsigned int value);
//pshared: 0 (among threads); 1 (among processes)

int sem_wait(sem_t **sem*); //P( ) operation

int sem_post(sem_t *sem); //V( ) operation

sem_getvalue( ), sem_close( ),

Kernel Synchronization

- At any time, many kernel mode processes may be active
  - Share kernel data structures
  - Notice that even though user processes have their own address spaces, race conditions can still arise when they execute in kernel mode, e.g. executing a system call
- Preemptive and non-preemptive kernels
  - Preemptive kernel: allows a process to be preempted while running in kernel mode
    - Race conditions can occur
  - Non-preemptive kernel: does not allow a process to be preempted while running in kernel mode
    - Race conditions cannot occur

Windows Synchronization

- Kernel level
  - Singe processor system: temporarily mask interrupts for all interrupt handlers that may also access a shared resource
  - Multiprocessor system: use spin lock (busy waiting)
- User level
  - Dispatcher objects: mutex locks, semaphores, …

Linux Synchronization

- Kernel level
  - Prior to version 2.6, non-preemptive kernel, but later versions are fully preemptive
  - Atomic integers: all math operations on atomic integers are performed without interruptions

```
atomic_t counter;
atomic_set(&counter, 5);
atomic_add(10, &counter);
…
```

  - Mutex locks, spin locks and semaphores, enabling/ disabling interrupts on single processor systems
- User level
  - Futex, semop( ): system call

Readers writers problem

- A database is accessed by two types of processes: reader processes and writer processes.
- Readers only read information from the database.
- Writers modify the database.

- Constraints
  - Writers must have exclusive access to the database.
  - Multiple readers can access the database concurrently.

Readers-Writers Problem: First Attempt

Semaphore mutex = 1;

```
Reader( )
{
   P(mutex);
      read database
   V(mutex);
}
```

```
Writer( )
{
   P(mutex);
      write database
   V(mutex);
}
```

Exclusive access to the writer processes is provided
BUT: No concurrency among reader processes

Readers-Writers Problem: Second Attempt

```
int rc = 0; /* Number of readers in the database */
Semaphore db = 1; /* controls access to database for writers */
Semaphore mutex = 1; /* controls access to variable rc */

Reader ()
    P(mutex);
    if (rc == 0) P(db);
    rc++;
    V(mutex);

        read database

    P(mutex);
    rc--;
    if (rc == 0) V(db);
    V(mutex);
```

```
Writer( )
{
    P(db);
        write database
    V(db);
}
```

Readers-Writers Problem: Second Attempt

- Semaphore mutex is used for mutual exclusion to update rc
- Semaphore db is used for exclusive database access for writer processes
- Multiple reader processes can access the database concurrently if there is no writer process.

Problem: What happens to a writer if readers keep coming to read the database?

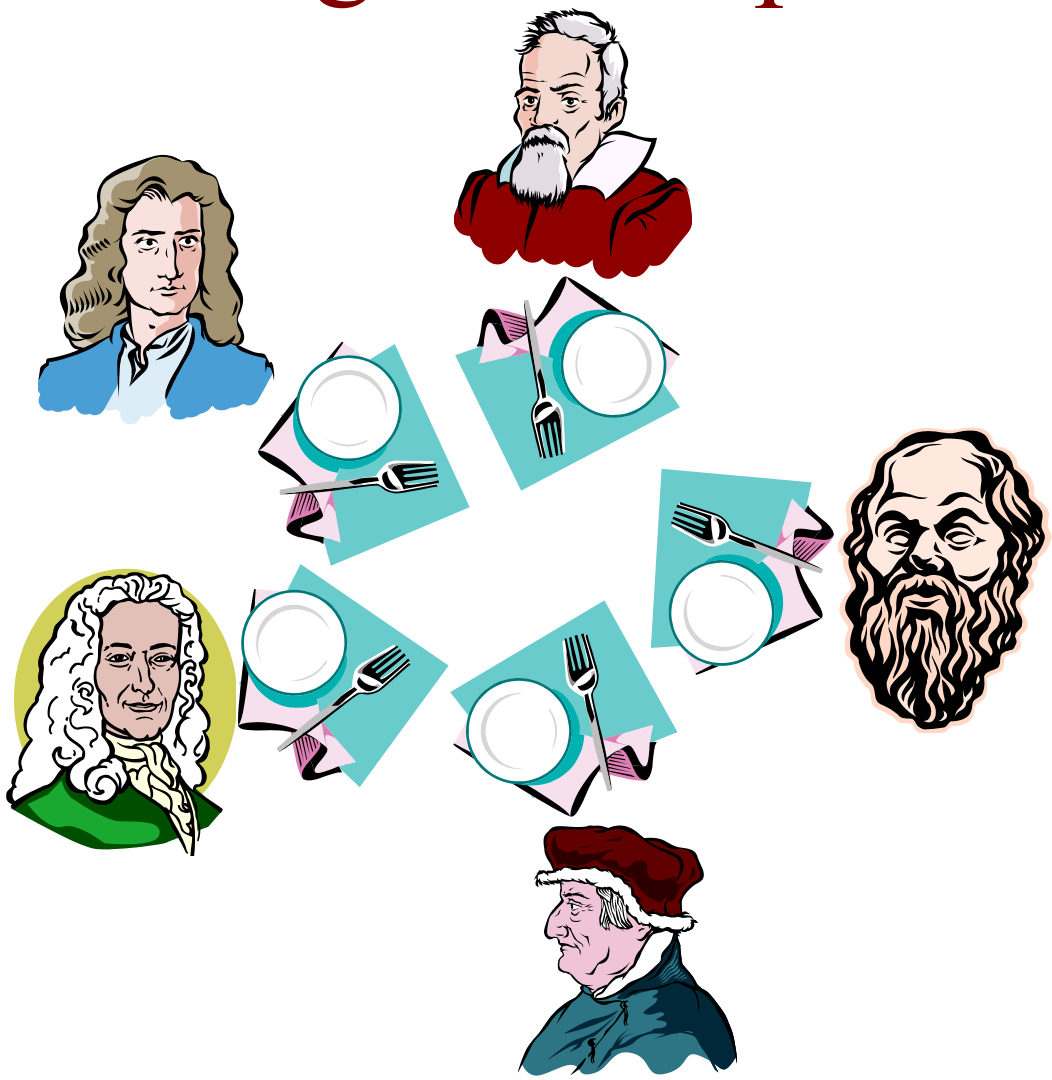
- Writer starvation
- Readers have priority over writers.

- Write a solution that gives preference to writer processes
- Write a solution that is fair to both readers and writers

Dining Philosophers Problem

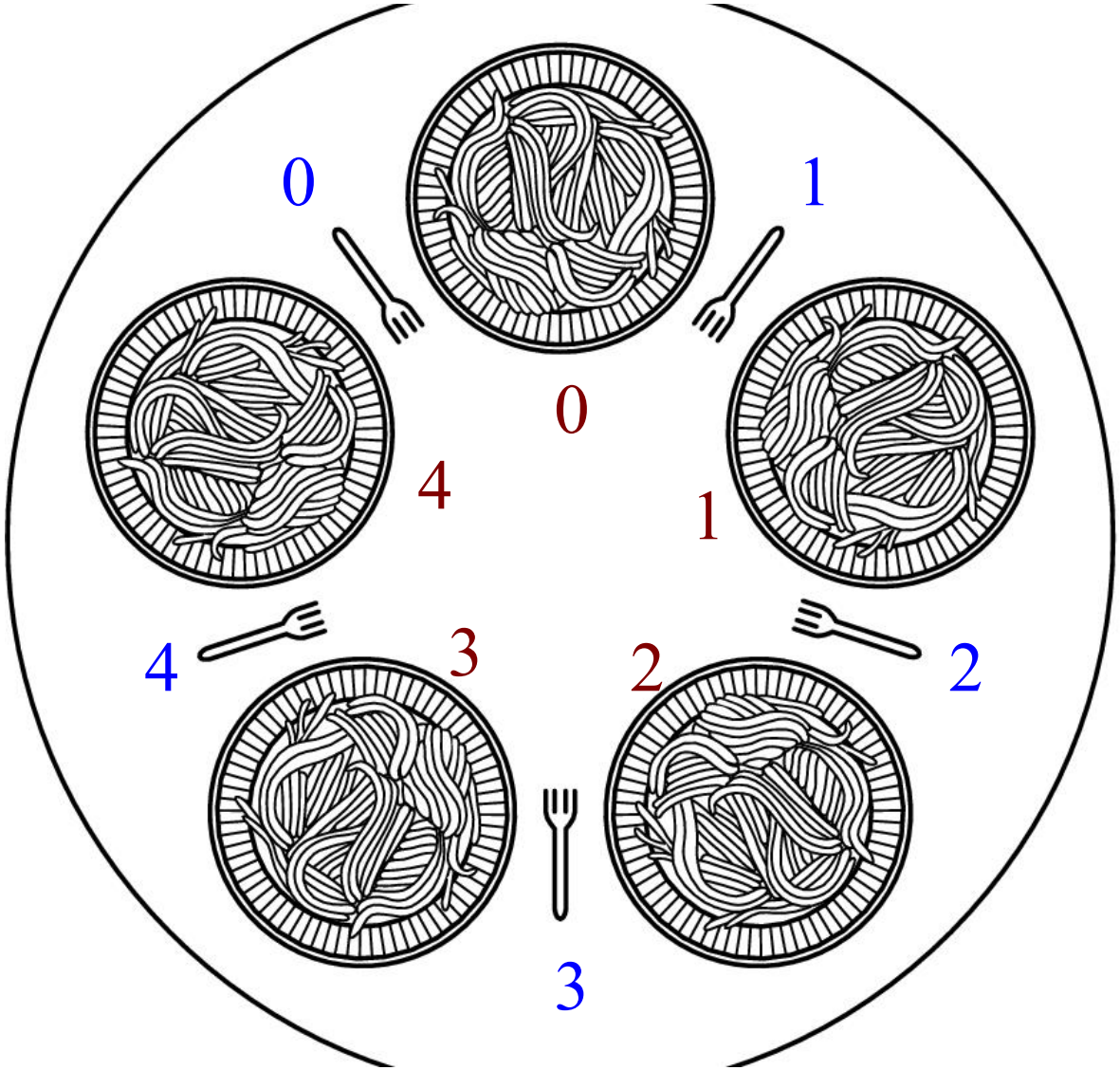
- The most famous synchronization problem.
- Represents a situation that can occur in large community of processes that share a large pool of resources.
- Five philosophers sit around a round dining table. A plate of spaghetti is placed in front of each philosopher, and a fork is placed between any two adjacent plates.
- A philosopher needs two forks to eat spaghetti.
- All philosophers alternate between two activities: thinking and eating.

Dining Philosophers Problem



Write a synchronization program that allows all five philosophers to run their lives

- Deadlock free
- Starvation free


0
1
0
4
1
4
3
2
2
3

Dining Philosophers: First Attempt

```
philosopher(int i) {
  while(TRUE) {
    // Think
    P(fork[i]);
      P(fork[(i+1) mod 5]);
        // EAT
      V(fork[(i+1) mod 5]);
    V(fork[i]);
  }
}
semaphore fork[5] = (1,1,1,1,1);
```

Problem

- On a fateful day, all philosophers decide to eat at the same time.
- All philosophers pick up their right fork.
- All philosophers now wait forever for their left fork to become available, and die of starvation
  - Deadlock.

Dining Philosophers: Second Attempt

```
philosopher(int i) {
  while(TRUE) {
    // Think
    P(mutex);
      P(fork[i]);
      P(fork[(i+1) mod 5]);
    V(mutex);
    // Eat
    V(fork[(i+1) mod 5]);
    V(fork[i]);
  }
}
semaphore fork[5] = (1,1,1,1,1);
semaphore mutex = 1;
```

- This solution doesn't suffer from deadlock
- Problem
  - May not allow two non-adjacent philosophers to eat at the same time

Dining Philosophers: Third Attempt

After picking up a fork, if a philosopher finds that the other fork is not available, she keeps down the fork, waits for some time, and tries again.

- Does this solution work?
- Starvation
- A deadlock-free solution is not necessarily starvation-free

Dining Philosophers: Some possible solutions

- Allow at most 4 philosophers at the same table when there are 5 resources
- Odd philosophers pick first left then right, while even philosophers pick first right then left
- Allow a philosopher to pick up forks *only if both are free.* This requires protection of critical sections to test if both forks are free before grabbing them.
  - we'll see this solution next using monitors
  - Also, there is a construct called an AND semaphore

Higher Level Synchronization Primitives

- Semaphores can result in deadlock due to programming errors
  - forgot to add a P() or V(), or mis-ordered them, or duplicated them
- Relatively simple problems, such as the dining philosophers problem, can be very difficult to solve using low level constructs like semaphores
- Higher level synchronization primitives
  - AND synchronization
  - Events
  - Critical Conditional Regions
  - Monitors: *We will study this*
  - many others…

Monitors

- Abstract data type (similar to C++ classes)
  - Monitors are found in high-level programming languages like Java and C#
- A monitor is a collection of procedures, variables, and data structures
- Processes can access these variables only by calling procedures in the monitor
- Each function in the monitor can only access variables declared locally within the monitor and its parameters
- At most one process may be active at any time in a monitor

- monitor *monitor_name* {
  // shared local variables

  function f1(...) {
  ...
  }
  ...
  function fN(...) {
  ...
  }
  init_code(...) {
  ...
  }
}

Monitors and Condition Variables

- While the above definition of a monitor achieves mutual exclusion (hiding P() and V() from user), it loses the ability that semaphores had to enforce order
  - i.e. P() and V() are used to provide mutual exclusion, but the unique ability for one process to signal another blocked process using V() is lost
- In general, there may be times when one process wishes to signal another process based on a condition, much like semaphores.
  - Thus, augment monitors with *condition variables*.

Monitors and Condition Variables

- Declare a condition variable with pseudo-code

  condition x, y;
- A condition variable *x* in a monitor allows three main operations on itself
  - x.wait()
    - blocks the calling process
    - can have multiple processes suspended on a condition variable, typically released in FIFO order, but textbook describes another variation specifying a priority p, i.e. call x.wait(p)
  - x.signal()
    - resumes exactly 1 suspended process. If none, then *no effect*.
  - x.queue()
    - Returns true if there is at least one process blocked on x

- Note that x.signal() is unlike the semaphore's signaling operation V(), which preserves state in terms of the value of the semaphore.
    - Example: if a process Y calls x.signal() on a condition variable x before process Z calls x.wait(), then Z will wait. The condition variable doesn't remember Y's signal.
    - Comparison: if a process Y calls V(mutex) on a binary semaphore mutex (initialized to 0) before process Z calls P(mutex), then Z will not wait, because the semaphore remembers Y's V() because its value = 1, not 0.

Monitors and Condition Variables

- Within a monitor, if a process P1 calls x.signal(), then normally that would wake another process P2 blocked on x.wait(). But we must avoid having two processes at the same time in the monitor, so need "wake-up" semantics on a x.signal():
  - Hoare semantics, also called signal-and-wait
    - The signaling process P1 either waits for the woken up process P2 to leave the monitor before resuming, or waits on another CV
  - Mesa semantics, also called signal-and-continue
    - The signaled process P2 waits until the signaling process P1 leaves the monitor or waits on another condition

Dining Philosophers: Monitor-based Solution

- Key insight: pick up 2 forks only if both are free
  - Avoids deadlock
  - A philosopher moves to his/her eating state only if both neighbors are not in their eating states
    - Need to define a state for each philosopher
  - If one of my neighbors is eating, and I'm hungry, ask them to signal() me when they're done
    - States of each philosopher: thinking, hungry, eating
    - Need condition variables to signal() waiting hungry philosopher(s)
  - Also, need to Pickup() and Putdown() forks

Dining Philosophers: Monitor-based Solution

```
monitor DiningPhilosophers
{
   enum {Thinking, Hungry, Eating} state[5];
   condition self[5];

   void test(int i) {
      //Called by philosopher i or neighbors of i
      //Check if both neighbors of i are not eating
      //If so, set state[i] to Eating, and signal philosopher i
   }
   void pickup(int i) {
      //Called by philosopher i
      //Set state[i] to Hungry and call test(i)
      //If at least one neighbor is eating, block on self[i];
   }
```

... cond. to the next slide

... cond. from the previous slide

```
    void putdown(int i) {
        //Called by philosopher i after eating
        //change state[i] to Thinking and signal neighbors in
        //case they are waiting to eat
    }

    init( ) {
        for (int i = 0; i < 5; i++)
            state[i] = Thinking;
    }
}
```

```
philosopher (int i)
{
    DiningPhilosophers.pickup(i);
        // pick up forks and eat
    DiningPhilosophers.putdown(i);
}
```

```
void test(int i) {
    if ((state[(i+1)%5] != Eating) &&
       (state[(i-1)%5] != Eating) &&
       (state[i] == Hungry))
    {
       state[i] = eating;
       self[i].signal();
    }
  }
```

```
void pickup(int i) {
   state[i] = hungry;
   test(i);
   if(state[i]!=Eating)
      self[i].wait;
}
```

```
void putdown(int i) {
      state[i] = thinking;
      test((i+1)%5);
      test((i-1)%5);
   }
```

Starvation

- Note that starvation is still possible in the DP monitor solution
  - Suppose P1 arrives first, and start eating, then P2 arrives and sets its state to hungry and blocks
  - Next P3 arrives and starts eating
  - P1 ends, but P2 can't start eating because P3 is eating
  - Now P1 starts eating again before P3 finishes eating
  - P3 ends, but P2 still can't eat
  - P1 and P3 can alternate this way and P2 will never get to eat →starvation