CS370 Operating Systems

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Synchronization

Slides based on
- Text by Silberschatz, Galvin, Gagne
- Various sources

FAQ

- What are the shared “resources”? Memory, shared variables, ..
- Two processes do not share any resources, do they need critical sections? No
- What does a process do in a critical section? Access a shared resource.
- It is unlikely that two processes will try to access a resources at the same time. Do they need a critical section? Probably not.
- I want to know more about queuing theory. Videos and on-line books.

FAQ

- Peterson's solution
  - Two processes, i and j, may want to enter their critical sections around the same time.
  - Why does Pi do this:

```
turn = j;
```

  - You can go ahead if you want to (if not, I will go ahead)

```
while (flag[j] && turn == j);  /*Wait*/
```

- Synchronization examples:
  - remember multiple processes are *interacting*, even though code for just one is usually given.

Synchronization: Hardware Support

- Most modern processors provide hardware support (*ISA*) for implementing the critical section code. FAQ
- All solutions below based on idea of **locking**
  - Protecting critical regions via locks
- Modern machines provide special atomic hardware instructions
    - **Atomic** = non-interruptible
  - test memory word and set value
  - swap contents of two memory words
  - others

Solution 1: using test_and_set()

- Shared Boolean variable lock, initialized to FALSE
- Solution:

```
do {
    while (test_and_set(&lock)) ; /* do nothing */

            /* critical section */
     ….. .
    lock = false;
            /* remainder section */
  …   ..
} while (true);
```

To break out:
Return value of TestAndSet should be
FALSE

test_and_set(&lock) returns the lock value and then sets it to True .

Lock TRUE: locked, Lock FALSE: not locked.
If two TestAndSet() are attempted *simultaneously*, they will be executed *sequentially* in some arbitrary order

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Using Swap (concurrently executed by both)

```
do {
    key = TRUE;
    while (key == TRUE) {
        Swap(&lock, &key)
        }

    critical section

    lock = FALSE;

    remainder section
} while (TRUE);
```

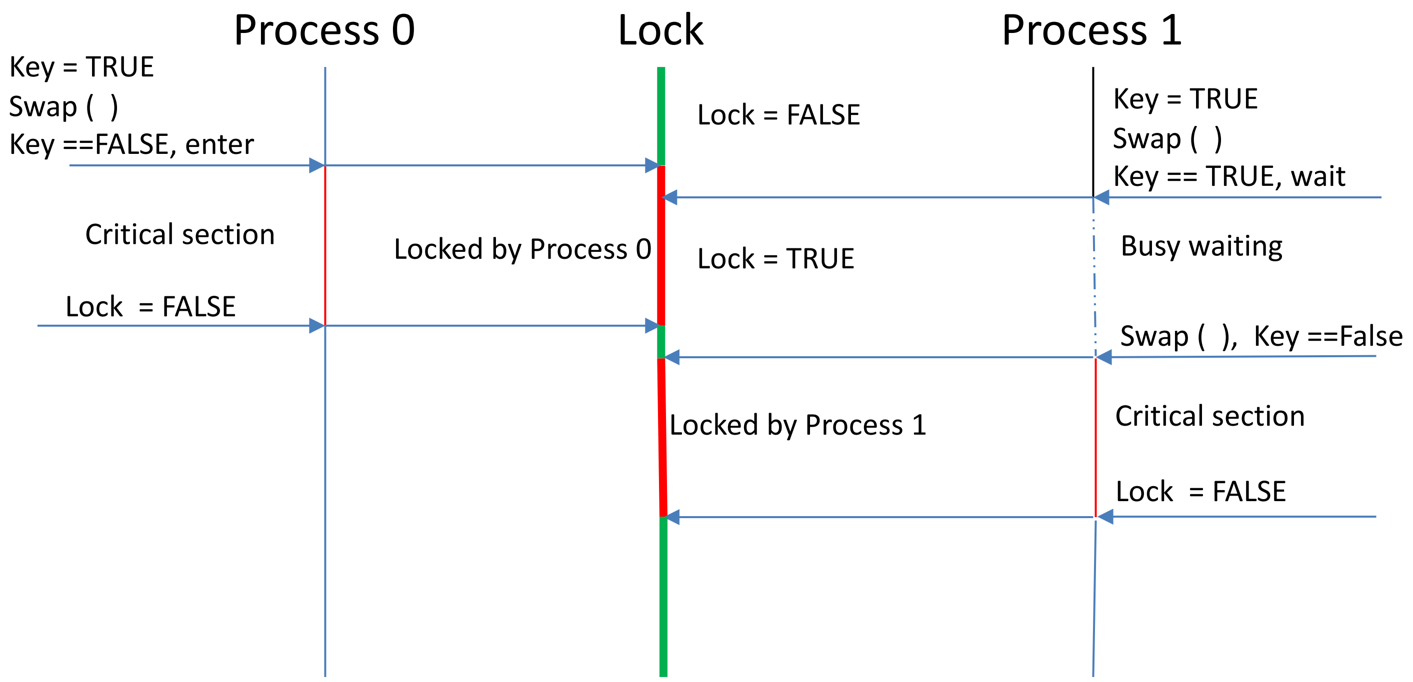
Lock is a SHARED variable.
Key is a variable local to the process.

Lock == false when no process is in critical section.

Cannot enter critical section UNLESS lock == FALSE *by other process or initially*

If two Swap() are executed simultaneously, they will be executed sequentially in some arbitrary order

Swap()



Note: I created this to visualize the mechanism. It is not in the book. - Yashwant

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Bounded-waiting Mutual Exclusion with test_and_set

For process i:

```
do {
   waiting[i] = true;
   key = true;
   while (waiting[i] && key)
      key = test_and_set(&lock);
   waiting[i] = false;
   /* critical section */
   j = (i + 1) % n;
   while ((j != i) && !waiting[j])
      j = (j + 1) % n;
   if (j == i)
      lock = false;
   else
      waiting[j] = false;
   /* remainder section */
} while (true);
```

Shared Data structures initialized to FALSE

- `boolean waiting[n];` Pr n wants to enter
- `boolean lock;`

The entry section for process i :

- First process to execute TestAndSet will find key == false ; ENTER critical section,
- EVERYONE else must wait

The exit section for process i:

Attempts to finding a suitable waiting process j (while loop) and enable it,

or if there is no suitable process, make lock FALSE.

Bounded-waiting Mutual Exclusion with test_and_set

The previous algorithm satisfies the three requirements

- **Mutual Exclusion**: The first process to execute TestAndSet(lock) when lock is false, will set lock to true so no other process can enter the CS.
- **Progress**: When a process i exits the CS, it either sets lock to false, or waiting[i] to false (allowing j to get in) , allowing the next process to proceed.
- **Bounded Waiting**: When a process exits the CS, it examines all the other processes in the waiting array in a circular order. Any process waiting for CS will have to wait at most n-1 turns

Mutex Locks

- Previous solutions are complicated and generally inaccessible to application programmers
- OS designers build software tools to solve critical section problem
- Simplest is mutex lock
- Protect a critical section by first `acquire()` a lock then `release()` the lock
  - Boolean variable indicating if lock is available or not
- Calls to `acquire()` and `release()` must be atomic
  - Usually implemented via hardware atomic instructions
- But this solution requires **busy waiting**
  - This lock therefore called a **spinlock**

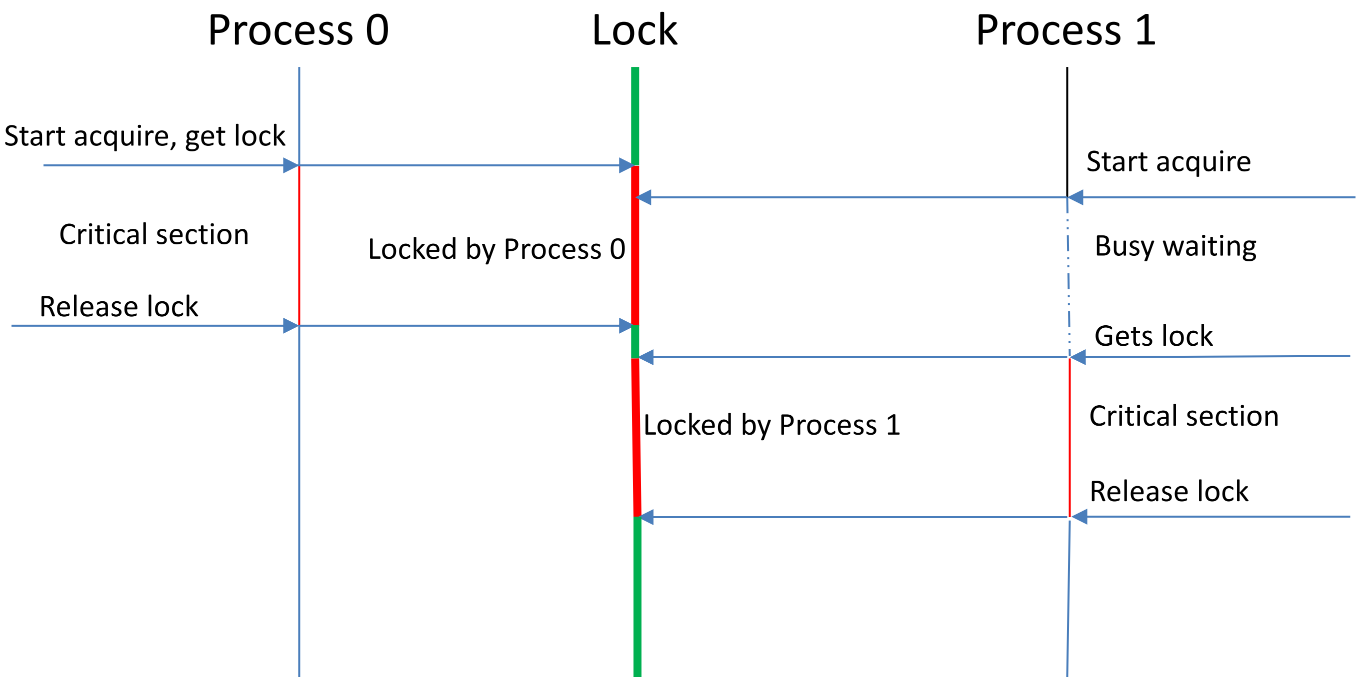
acquire() and release()

`acquire() {`
`      while (!available)`
`        ; /* busy wait */`
	`release() {`
	`      available = true;`
	`   }`

•Usage

```
do {
    acquire lock
        critical section
    release lock
        remainder section
} while (true);
```

acquire() and release()



How are locks supported by hardware?

- Atomic read-modify-write
- Atomic instructions in x86
  - LOCK instruction prefix, which applies to an instruction does a read-modify-write on memory (INC, XCHG, CMPXCHG etc)
  - Ex: lock cmpxchg <dest>, <source>
- In RISK processors? Instruction-pairs
  - LL (Load Linked Word), SC (Store Conditional Word) instructions in MIPS
  - LDREX, STREX in ARM
  - Creates an atomic sequence

Semaphores by Dijkstra

- Synchronization tool that provides more sophisticated ways (than Mutex locks) for process to synchronize their activities.
- Semaphore ***S*** – integer variable
- Can only be accessed via two **indivisible (atomic)** operations
  - **`wait()`** and **`signal()`**
    - Originally called **`P()`** and **`V()`** **`based on Dutch words`**
- Definition of the **`wait() operation`**

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

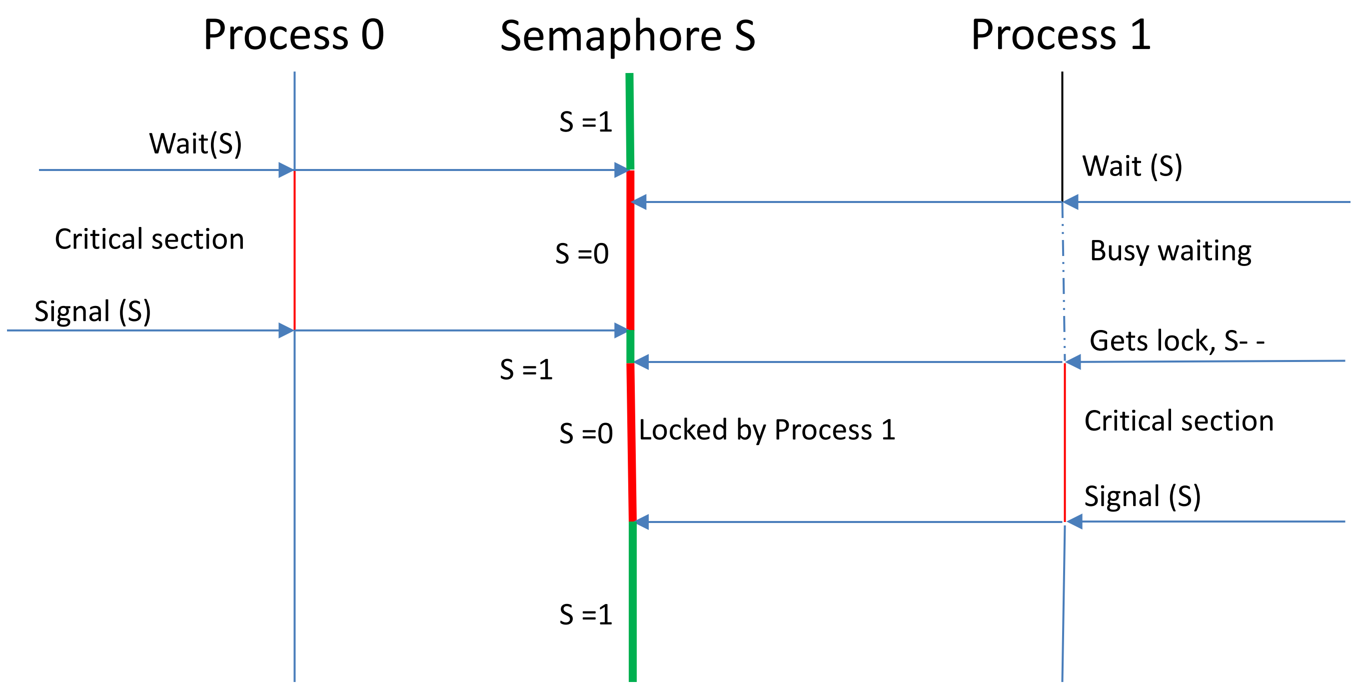
- Definition of the **`signal() operation`**

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

Waits until another process makes S=1

Binary semaphore: When s is 0 or 1, it is a mutex lock

Wait(S) and Signal (S)



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Semaphores

I was hoping the distance learning service might use more up-to-date technology

Semaphore Usage

- **Counting semaphore** – integer value can range over an unrestricted domain
- **Binary semaphore** – integer value can range only between 0 and 1
  - Practically same as a **mutex lock**
- Can solve various synchronization problems
- Ex: Consider P_1 and P_2 that requires event S_1 to happen before S_2

  Create a semaphore "**synch**" initialized to 0 i.e not available

P1: S_1; **signal(synch);**	**P2:** **wait(synch);** S_2;

- Can implement a counting semaphore ***S*** as a binary semaphore

The counting semaphore

- **Controls access to a finite set of resources**
- Initialized to the number of resources
- Usage:
  - Wait (S): to use a resource
  - Signal (S): to release a resource
- When all resources are being used: S == 0
  - Block until S > 0 to use the resource

Semaphore Implementation

- Must guarantee that no two processes can execute the **`wait()`** and **`signal()`** on the same semaphore at the same time
- Thus, the implementation becomes the critical section problem where the **`wait`** and **`signal`** code are placed in the critical section
  - Could now have **busy waiting** in critical section implementation
    - But implementation code is short
    - Little busy waiting if critical section rarely occupied
- Note that applications may spend lots of time in critical sections and therefore this is not a good solution
- Alternative: block and wakeup (next slide)

Semaphore Implementation with no Busy waiting

- With each semaphore there is an associated waiting queue
- Each entry in a waiting queue has two data items:
  - value (of type integer)
  - pointer to next record in the list
- Two operations:
  - **block** – place the process invoking the operation on the appropriate waiting queue
  - **wakeup** – remove one of processes in the waiting queue and place it in the ready queue

-
```
typedef struct{
 int value;
 struct process *list;
 } semaphore;
```

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Implementation with no Busy waiting (Cont.)

```
wait(semaphore *S) {
    S->value--;
    if (S->value < 0) {
        add this process to S->list;
        block();
    }
}

signal(semaphore *S) {
    S->value++;
    if (S->value <= 0) {
        remove a process P from S->list;
        wakeup(P);
    }
}
```

If value < 0
abs(value) is the number
of waiting processes

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

Deadlock and Starvation

- **Deadlock** – two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes
- Let *S* and *Q* be two semaphores initialized to 1

P_0	P_1
`wait(S);`	`wait(Q);`
`wait(Q);`	`wait(S);`
`...`	`...`
`signal(S);`	`signal(Q);`
`signal(Q);`	`signal(S);`

  - P0 executes wait(s), P1 executes wait(Q)
  - P0 must wait till P1 executes signal(Q)
  - P1 must wait till P0 executes signal(S)   Deadlock!

Priority Inversion

- **Priority Inversion** – Scheduling problem when lower-priority process P_L holds a lock needed by higher-priority process P_H.
  - The low priority task may be preempted by a medium priority task P_M which does not use the lock, causing P_H to wait because of P_M.

Mars pathfinder
Mission problem 1997

- Solved via **priority-inheritance protocol**
  - Process accessing resource needed by higher priority process Inherits higher priority till it finishes resource use
  - Once done, process reverts to lower priority

Classical Problems of Synchronization

- Classical problems used to test newly-proposed synchronization schemes
  - Bounded-Buffer Problem
  - Readers and Writers Problem
  - Dining-Philosophers Problem
- Monitors

Bounded-Buffer Problem

- *n* buffers, each can hold one item
- Binary semaphore (mutex)
  - Provides mutual exclusion for accesses to buffer pool
  - Initialized to 1
- Counting semaphores
  - empty: Number of empty slots available
    - Initialized to n
  - full: Number of filled slots available n
    - Initialized to 0

3 semaphores needed,
1 binary, 2 counting

Bounded-Buffer : Note

- Producer and consumer must be ready before they attempt to enter critical section
- Producer readiness?
  - When a slot is available to add produced item
    - wait(empty)
      - empty is initialized to n
- Consumer readiness?
  - When a producer has added new item to the
    - wait(full)
      - full initialized to 0

empty: Number of empty slots available
wait(empty) wait until at least 1 empty

full: Number of filled slots available
wait(full) wait until at least 1 full

Bounded Buffer Problem (Cont.)

The structure of the producer process

```
do {
      ...
      /* produce an item in next_produced */
      ...
   wait(empty);          wait till slot available
   wait(mutex);          Allow producer OR consumer to (re)enter critical section
      ...
      /* add next produced to the buffer */
      ...
   signal(mutex);        Allow producer OR consumer to (re)enter critical section
   signal(full);         signal consumer that a slot is available
} while (true);
```

Bounded Buffer Problem (Cont.)

The structure of the consumer process

```
Do {
    wait(full);  wait till slot available for consumption
    wait(mutex);  Only producer OR consumer can be in critical section
        ...
    /* remove an item from buffer to next_consumed */
        ...
    signal(mutex);  Allow producer OR consumer to (re)enter critical section
    signal(empty);  signal producer that a slot is available to add
        ...
    /* consume the item in next consumed */
        ...
 } while (true);
```

Readers-Writers Problem

- A data set is shared among a number of concurrent processes
  - Readers – only read the data set; they do ***not*** perform any updates
  - Writers – can both read and write
- Problem
  - allow multiple readers to read at the same time
  - Only one single writer can access the shared data at the same time. No readers permitted when writer is accessing the data.
- Several variations of how readers and writers are considered – all involve some form of priorities

Readers-Writers Problem

- Shared Data
  - Data set
  - Semaphore **rw_mutex** initialized to 1 (mutual exclusion for writer)
  - Semaphore **mutex** initialized to 1 (mutual exclusion for read_count)
  - Integer **read_count** initialized to 0 (how many readers?)

Readers-Writers Problem (Cont.)

- The structure of a writer process

```
do {
        wait(rw_mutex);
             ...
      /* writing is performed */
             ...
        signal(rw_mutex);
} while (true);
```

When: writer in critical section
and if n readers waiting:
- 1 reader is queued on rw_mutex
- (n-1) readers queued on mutex

Readers-Writers Problem (Cont.)

- The structure of a reader process

```
do {
    wait(mutex);
      read_count++;
      if (read_count == 1)
         wait(rw_mutex);
    signal(mutex);
       ...
      /* reading is performed */
       ...
    wait(mutex);
      read count--;
      if (read_count == 0)
         signal(rw_mutex);
    signal(mutex);
} while (true);
```

mutex for mutual exclusion to read_count

Cannot read if writer is writing

When:
writer in critical section and if n readers waiting
1 is queued on rw_mutex
(n-1) queued on mutex

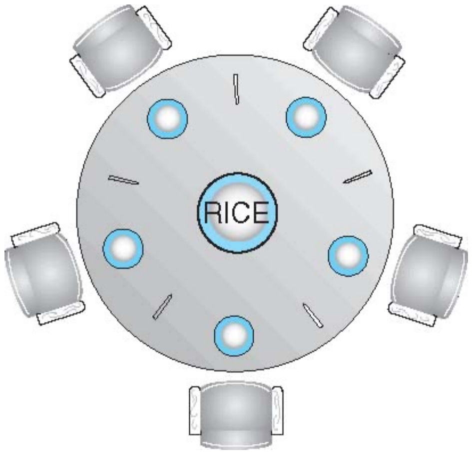
First reader needs to wait for the writer to finish.
If other readers are already reading, a new reader
Process just goes in.

Readers-Writers Problem Variations

- ***First*** variation – no reader kept waiting unless writer has already obtained permission to use shared object
- ***Second*** variation – once writer is ready, it performs the write ASAP, i.e. if a writer is waiting, no new readers may start.
- Both may have starvation leading to even more variations
- Problem is solved on some systems by kernel providing reader-writer locks

Dining-Philosophers Problem

- Philosophers spend their lives alternating thinking and eating
- Don’t interact with their neighbors, occasionally try to pick up 2 chopsticks (one at a time) to eat from bowl
  - Need both to eat,
  - then release both when done
- Each chopstick is a semaphore
  - Grab by executing wait ( )
  - Release by executing signal ( )
- Shared data
  - Bowl of rice (data set)
  - Semaphore chopstick [5] initialized to 1



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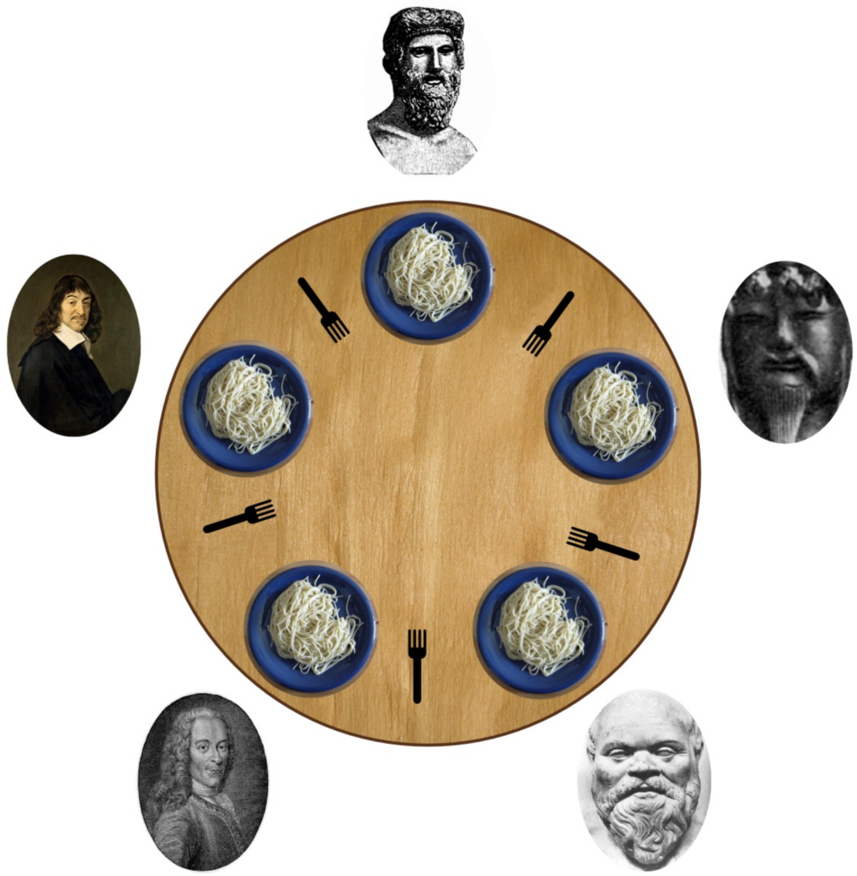
Dining-Philosophers Problem



Plato, Confucius, Socrates, Voltaire and Descartes

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Dining-Philosophers Problem Algorithm: Simple solution?

- The structure of Philosopher *i*:

```
do {
     wait (chopstick[i] );
      wait (chopStick[ (i + 1) % 5] );

                    //  eat

      signal (chopstick[i] );
      signal (chopstick[ (i + 1) % 5] );

                    //  think

} while (TRUE);
```

- What is the problem with this algorithm?
  - If all of them pick up the the left chopstick first - Deadlock

Dining-Philosophers Problem Algorithm (Cont.)

- Deadlock handling
  - Allow at most 4 philosophers to be sitting simultaneously at the table (with the same 5 forks).
  - Allow a philosopher to pick up the forks only if both are available (picking must be done in a critical section.
  - Use an asymmetric solution -- an odd-numbered philosopher picks up first the left chopstick and then the right chopstick. Even-numbered philosopher picks up first the right chopstick and then the left chopstick.

Related classes

- Classes that follow CS370
  - CS455 Distributed Systems Spring
  - CS457 Networks Fall
  - CS470 Computer Architecture Spring
  - CS475 Parallel Programming Fall
  - CS435: Introduction to Big Data Spring

Problems with Semaphores

- Incorrect use of semaphore operations:
  - Omitting of wait (mutex)
    - Violation of mutual exclusion
  - or signal (mutex)
    - Deadlock!
- Solution: Monitors