CSC 4103 - Operating Systems
Fall 2009

# LECTURE - IX
# PROCESS SYNCHRONIZATION - II

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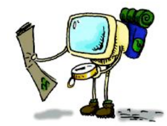
## Roadmap

- Solutions for Critical-Section Problem
- Semaphores
- Classic Problems of Synchronization
  - Bounded Buffer
  - Readers-Writers
  - Dining Philosophers
  - Sleeping Barber



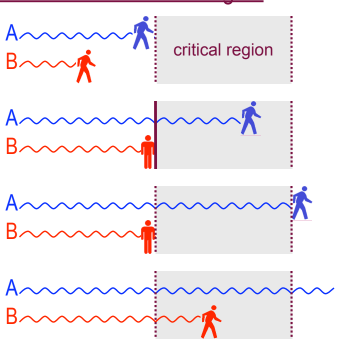


## Mutual Exclusion

➢ Desired effect: mutual exclusion from the critical region

HOW is this achieved??

1. thread A reaches the gate to the critical region (CR) before B
2. thread A enters CR first, preventing B from entering (B is waiting or is blocked)
3. thread A exits CR; thread B can now enter
4. thread B enters CR

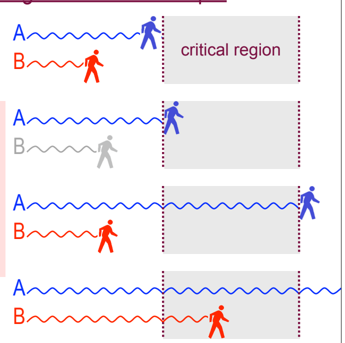





## Mutual Exclusion

➢ **Implementation 1** — disabling hardware interrupts

1. thread A reaches the gate to the critical region (CR) before B
2. as soon as A enters CR, it disables all interrupts, thus B cannot be scheduled
3. as soon as A exits CR, it enables interrupts; B can be scheduled again
4. thread B enters CR






## Mutual Exclusion

➢ **Implementation 1** — disabling hardware interrupts

- ✓ it works, but not reasonable!
- ✓ what guarantees that the user process is going to ever exit the critical region?
- ✓ meanwhile, the CPU cannot interleave any other task, even unrelated to this race condition
- ✓ the critical region becomes one *physically* indivisible block, not logically
- ✓ also, this is not working in multi-processors

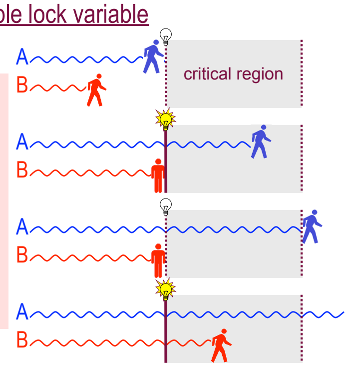
```
void echo()
{
   char chin, chout;
   do {
      disable hardware interrupts
      chin = getchar();
      chout = chin;
      putchar(chout);
      enable hardware interrupts
   }
   while (...);
}
```



## Mutual Exclusion

➢ **Implementation 2** — simple lock variable

1. thread A reaches CR and finds a lock at 0, which means that A can enter
2. thread A sets the lock to 1 and enters CR, which prevents B from entering
3. thread A exits CR and resets lock to 0; thread B can now enter
4. thread B sets the lock to 1 and enters CR



## Mutual Exclusion

- **Implementation 2** — simple lock variable
  - ✓ the "lock" is a shared variable
  - ✓ entering the critical region means testing and then setting the lock
  - ✓ exiting means resetting the lock

```
while (lock);
   /* do nothing: loop */
lock = TRUE;

lock = FALSE;
```

```
bool lock = FALSE;

void echo()
{
   char chin, chout;
   do {
      test lock, then set lock
      chin = getchar();
      chout = chin;
      putchar(chout);
      reset lock
   }
   while (...);
}
```



## Mutual Exclusion

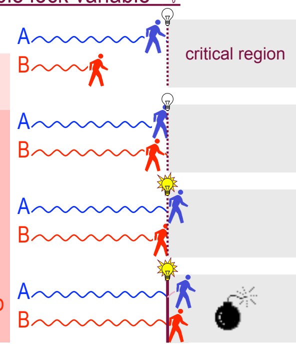
- **Implementation 2** — simple lock variable

1. thread A reaches CR and finds a lock at 0, which means that A can enter

1.1 but before A can set the lock to 1, B reaches CR and finds the lock is 0, too

1.2 A sets the lock to 1 and enters CR but cannot prevent the fact that . . .

1.3 . . . B is going to set the lock to 1 and enter CR, too






## Mutual Exclusion

- **Implementation 2** — simple lock variable
  - ✓ suffers from the very flaw we want to avoid: a race condition
  - ✓ the problem comes from the small gap between testing that the lock is off and setting the lock

```
while (lock);   lock = TRUE;
```

  - ✓ it may happen that the other thread gets scheduled exactly in between these two actions (falls in the gap)
  - ✓ so they both find the lock off and then they both set it and enter

```
bool lock = FALSE;

void echo()
{
   char chin, chout;
   do {
      test lock, then set lock
      chin = getchar();
      chout = chin;
      putchar(chout);
      reset lock
   }
   while (...);
}
```



## Mutual Exclusion

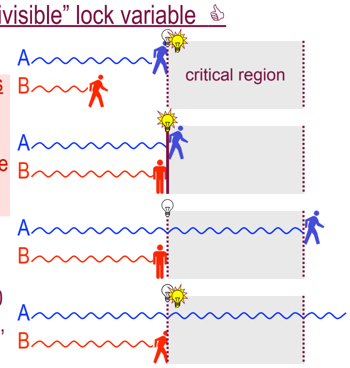
- **Implementation 3** — "indivisible" lock variable

1. thread A reaches CR and finds the lock at 0 *and* sets it in one shot, then enters

1.1' even if B comes right behind A, it will find that the lock is already at 1

2. thread A exits CR, then resets lock to 0

3. thread B finds the lock at 0 and sets it to 1 in one shot, just before entering CR






## Mutual Exclusion

- **Implementation 3** — "indivisible" lock variable
  - ✓ the indivisibility of the "test-lock-and-set-lock" operation can be implemented with the hardware instruction **TSL**

```
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
```

```
void echo()
{
   char chin, chout;
   do {
      test-and-set-lock
      chin = getchar();
      chout = chin;
      putchar(chout);
      set lock off
   }
   while (...);
}
```

Tanenbaum, A. S. (2001)
*Modern Operating Systems (2nd Edition).*



## Mutual Exclusion

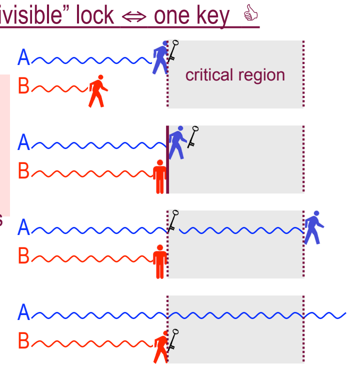
- **Implementation 3** — "indivisible" lock ⇔ one key

1. thread A reaches CR and finds a key *and* takes it

1.1' even if B comes right behind A, it will not find a key

2. thread A exits CR and puts the key back in place

3. thread B finds the key and takes it, just before entering CR



## Mutual Exclusion

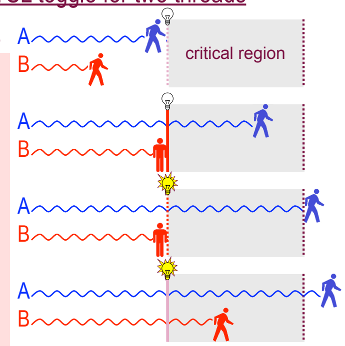
- **Implementation 3** — "indivisible" lock ⇔ one key ☝
  - ✓ "holding" a unique object, like a key, is an equivalent metaphor for "test-and-set"
  - ✓ this is similar to the "speaker's baton" in some assemblies: only one person can hold it at a time
  - ✓ holding is an indivisible action: you see it and grab it in one shot
  - ✓ after you are done, you release the object, so another process can hold on to it

```
void echo()
{
    char chin, chout;
    do {
      take key and run
        chin = getchar();
        chout = chin;
        putchar(chout);
      return key
    }
    while (...);
}
```



## Mutual Exclusion

- **Implementation 4** — no-TSL toggle for two threads
  1. thread A reaches CR, finds a lock at 0, and enters without changing the lock
  2. however, the lock has an opposite meaning for B: "off" means do not enter
  3. only when A exits CR does it change the lock to 1; thread B can now enter
  4. thread B sets the lock to 1 and enters CR: it will reset it to 0 for A after exiting






## Mutual Exclusion

- **Implementation 4** — no-TSL toggle for two threads
  - ✓ the "toggle lock" is a shared variable used for strict alternation
  - ✓ here, entering the critical region means only testing the toggle: it must be at 0 for A, and 1 for B
  - ✓ exiting means switching the toggle: A sets it to 1, and B to 0

| A's code | B's code |
|---|---|
| `while (toggle); /* loop */` | `while (!toggle); /* loop */` |
| `toggle = TRUE;` | `toggle = FALSE;` |

```
bool toggle = FALSE;

void echo()
{
    char chin, chout;
    do {
      test toggle
        chin = getchar();
        chout = chin;
        putchar(chout);
      switch toggle
    }
    while (...);
}
```



## Mutual Exclusion

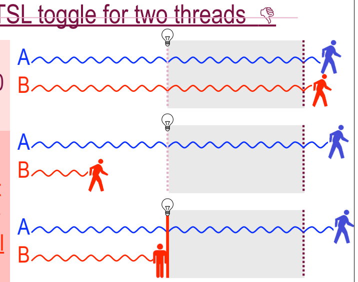
- **Implementation 4** — no-TSL toggle for two threads ☟

5. thread B exits CR and switches the lock back to 0 to allow A to enter next

5.1 but scheduling happens to make B faster than A and come back to the gate first

5.2 as long as A is still busy or interrupted in its noncritical region, B is barred access to its CR

® *this violates item 2. of the chart of mutual exclusion*

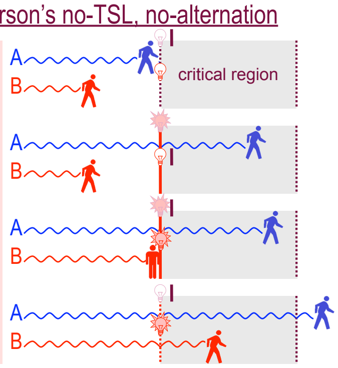



® *this implementation avoids TSL by splitting test & set and putting them in enter & exit; nice try... but flawed!*



## Mutual Exclusion

- **Implementation 5** — Peterson's no-TSL, no-alternation
  1. A and B each have their own lock; an extra toggle is also masking either lock
  2. A arrives first, sets its lock, pushes the mask to the other lock and may enter
  3. then, B also sets its lock & pushes the mask, but must wait until A's lock is reset
  4. A exits the CR and resets its lock; B may now enter






## Mutual Exclusion

- **Implementation 5** — Peterson's no-TSL, no-alternation
  - ✓ the mask & two locks are shared
  - ✓ entering means: setting one's lock, pushing the mask and tetsing the other's combination
  - ✓ exiting means resetting the lock

| A's code | B's code |
|---|---|
| `lock[A] = TRUE; mask = B; while (lock[B] && mask == B); /* loop */` | `lock[B] = TRUE; mask = A; while (lock[A] && mask == A); /* loop */` |
| `lock[A] = FALSE;` | `lock[B] = FALSE;` |

```
bool lock[2];
int mask;
int A = 0, B = 1;
void echo()
{
    char chin, chout;
    do {
      set lock, push mask, and test
        chin = getchar();
        chout = chin;
        putchar(chout);
      reset lock
    }
    while (...);
}
```

## Mutual Exclusion

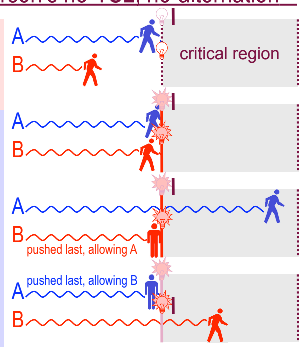
- **Implementation 5** — Peterson's no-TSL, no-alternation

1. A and B each have their own lock; an extra toggle is also masking either lock

2.1 A is interrupted between setting the lock & pushing the mask; B sets its lock

2.2 now, both A and B race to push the mask: whoever does it last will allow the other one inside CR

® *mutual exclusion holds!! (no bad race condition)*






## Mutual Exclusion

- Summary of these implementations of mutual exclusion
  - ✓ **Impl. 1 — disabling hardware interrupts**
    - NO: race condition avoided, but can crash the system!
  - ✓ **Impl. 2 — simple lock variable (unprotected)**
    - NO: still suffers from race condition
  - ✓ **Impl. 3 — indivisible lock variable (TSL)**
    - YES: works, but requires hardware

    *this will be the basis for "mutexes"*
  - ✓ **Impl. 4 — no-TSL toggle for two threads**
    - NO: race condition avoided inside, but lockup outside
  - ✓ **Impl. 5 — Peterson's no-TSL, no-alternation**
    - YES: works in software, but processing overhead



## Mutual Exclusion

- Problem: all implementations (2-5) rely on busy waiting
  - ✓ "busy waiting" means that the process/thread continuously executes a tight loop until some condition changes
  - ✓ busy waiting is bad:
    - **waste of CPU time** — the busy process is not doing anything useful, yet remains "Ready" instead of "Blocked"
    - **paradox of inversed priority** — by looping indefinitely, a higher-priority process B may starve a lower-priority process A, thus preventing A from exiting CR and . . . liberating B! (B is working against its own interest)
  - ® *we need for the waiting process to block, not keep idling*



## Synchronization Hardware

- Many systems provide hardware support for critical section code
- Uniprocessors – could disable interrupts
  - Currently running code would execute without preemption
  - Generally too inefficient on multiprocessor systems
    - Operating systems using this not broadly scalable
- Modern machines provide special atomic hardware instructions
  - Atomic = non-interruptable
  - Either test memory word and set value
  - Or swap contents of two memory words



## Semaphore

- Semaphore *S* – integer variable
- Two standard operations modify wait() and signal()
  - Originally called P() and V()

```
- wait (S) {
        while S <= 0
                ; // no-op
            S--;
    }

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

- Less complicated
- Can only be accessed via two indivisible (atomic) operations



## Semaphores as Synchronization Tool

- Counting semaphore – integer value can range over an unrestricted domain
- Binary semaphore – integer value can range only between 0 and 1; can be simpler to implement
  - Also known as mutex locks

- Provides mutual exclusion

```
- Semaphore S;    //  initialized to 1
- wait (S);
        Critical Section
  signal (S);
```

## 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); |

- Starvation – indefinite blocking. A process may never be removed from the semaphore queue in which it is suspended.



## Classical Problems of Synchronization

- Bounded-Buffer Problem
- Readers and Writers Problem
- Dining-Philosophers Problem
- Sleeping Barber Problem



## Bounded-Buffer Problem

- *N* buffers, each can hold one item
- Semaphore mutex for access to the buffer, initialized to 1
- Semaphore full (number of full buffers) initialized to 0
- Semaphore empty (number of empty buffers) initialized to N



## Bounded Buffer Problem (Cont.)

- The structure of the producer process

```
do {

      //   produce an item

    wait (empty);
    wait (mutex);

      //  add the item to the  buffer

    signal (mutex);
    signal (full);
```



## Bounded Buffer Problem (Cont.)

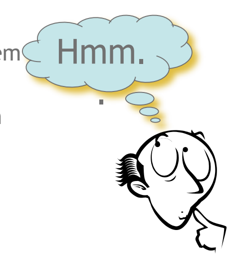
- The structure of the consumer process

```
do {
    wait (full);
    wait (mutex);

      //  remove an item from  buffer

    signal (mutex);
    signal (empty);

      //  consume the removed item
```



## Summary

- Solutions for Critical-Section Problem
- Semaphores
- Classic Problems of Synchronization
  - Bounded Buffer
  - Readers-Writers
  - Dining Philosophers
  - Sleeping Barber




- Next Lecture: Deadlocks - I
- Reading Assignment: Chapter 6 from Silberschatz.

## Acknowledgements

- “Operating Systems Concepts” book and supplementary material by A. Silberschatz, P. Galvin and G. Gagne
- “Operating Systems: Internals and Design Principles” book and supplementary material by W. Stallings
- “Modern Operating Systems” book and supplementary material by A. Tanenbaum
- R. Doursat and M. Yuksel from UNR