Operating Systems
VII. Synchronization

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Outline

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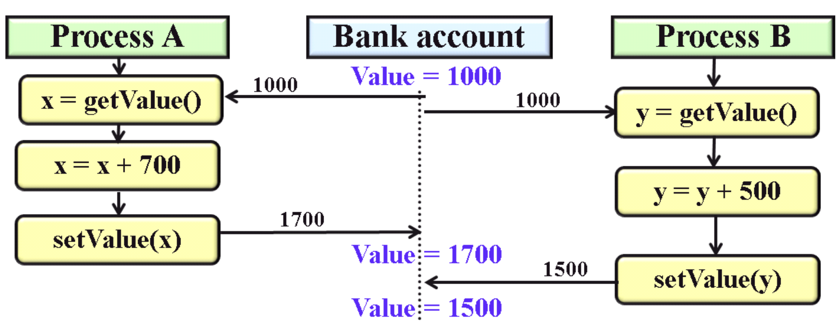
Why is Synchronization Necessary?

- Know for a process / thread at which execution point is another process / thread?
- Ensure shared data consistency

→ Where is my money?!



Critical Section Problem: Definition

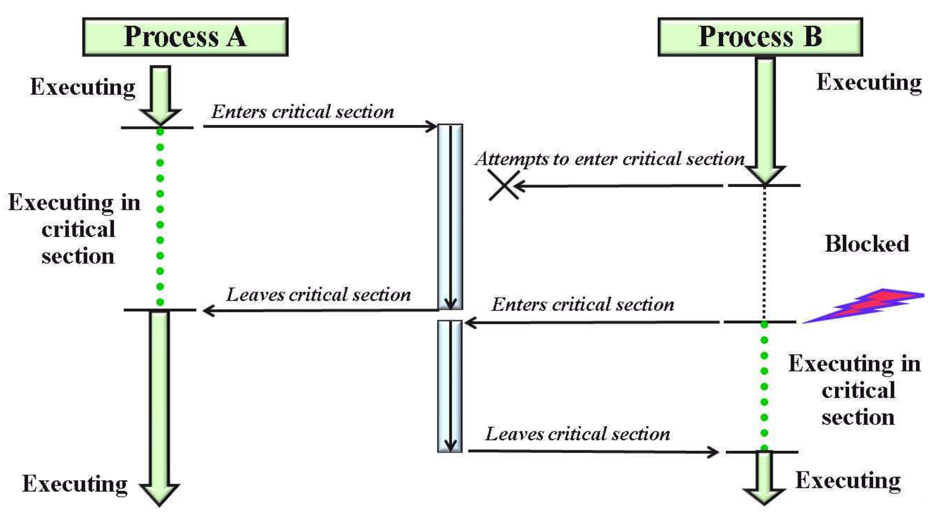
Critical code sections must satisfy the following requirements:

1. **Mutual exclusion (or safety condition)**: At most one process at a time is allowed to execute code inside a critical section of code
2. **Machine independence**: No assumptions should be made about speeds or the number of CPUs
3. **Progress**: Process running outside a critical section may not block other processes
4. **Bounded waiting (or liveness)**: Process should be guaranteed to enter a critical section within a finite time

Critical-sections are:

- Used when resources are shared between different processes
- Supported by many programming mechanisms

Mutual Exclusion Using Critical Sections



The Deadlock Issue

Problematic

- Use of shared resources: request, use, release
- Deadlock = situation in which a process waits for a resource that will never be available

Handling deadlocks: Use a protocol to ensure that the system will never enter a deadlock state

- **Deadlock prevention**: Restraining how requests can be made
- **Deadlock avoidance**: More information from user on the use of resources

The Deadlock Issue (Cont.)

Handling deadlocks: Allow the system to enter a deadlock state and then recover

- **Process termination**
- **Resource preemption**

Ignore the problem (i.e. assume deadlocks never occur in the system)

- **Most OS**, including UNIX

Software Approaches

Disabling Interrupts

- Unwise to empower user processes to turn off interrupts!

Lock variables

- Procedure
  - Reads the value of a shared variable
  - If 0, sets it to 1 and enters the critical section
  - If 1, waits until the variable equals to 0
- Possible scheduling is a major flaw!
  - Can you guess why?

Software Approaches (Cont.)

Strict alternation

- Busy waiting (waste of CPU)
- Violates the progress requirement of critical-sections
  - Can you guess why?

Process 0

```
While(TRUE){
while(turn != 0);
  /*begin critical section */
  ...
  turn = 1;
  /* end critical section */
}
```

Process 1

```
While(TRUE){
while(turn != 1);
  /*begin critical section */
  ...
  turn = 0;
  /* end critical section */
}
```

Software Approaches (Cont.)

Dekker's and Peterson's solution

- 1965, 1981
- Alternation + lock variables

Process 0

```
while(true) {
 flag[0] = true;
 turn = 0;
 while(flag[1] && (turn==0));
 /* Critical section */
 ...
 flag[0] = false;
 /* End critical section */
}
```

Process 1

```
while(true) {
 flag[1] = true;
 turn = 1;
 while(flag[0] && (turn==1));
 /* Critical section */
 ...
 flag[1] = false;
 /* End critical section */
}
```


Hardware Approaches

The Test and Set Lock (TSL) Instruction

- Special assembly instruction which is **atomic**
- TSL Rx, LOCK
  - Reads the content of the memory at address lock and stores it in register Rx

Assembly code to enter / leave critical sections

```
Enter_critical_section:
  TSL register, LOCK        | copy lock to register and set lock to 1
  CMP register, #0          | was lock equal to 0?
  JNE Enter_critical_section     | if != 0 -> lock was set -> loop
  RET                  | return to caller -> ok to enter critical section

Leave_critical_section:
  MOVE LOCK, #0 | Store a 0 in lock
  RET           | return to caller
```

And so...

Limits of Peterson's and TSL solutions

- Busy waiting
- **Priority inversion problem**: If a lower priority process is in critical section and a higher priority process busy waits to enter this critical section, the lower priority process never gains CPU → higher priority processes can never enter critical section

Solution: Sleep and wakeup system calls

- *Sleep()*: Caller is blocked on a given address until another process wakes it up
- *Wakeup()*: Caller wakes up all processes waiting on a given address

Outline

Semaphores

Definition

- A semaphore is a **counter** shared by multiple processes
- Processes can **increment** or **decrement** this counter in an atomic way.
- Mainly used to protect access to shared resources
- But semaphores are quite complex to use

Semaphores: Main functions

Creating Semaphores

```
int semget(key_t key, int nsems, int flag);
```

Modifying the value of a semaphore

```
Struct sembuf {
  ushort sem_num;   /*member # in the set of semaphores */
  short    sem_op;    /* operation: negative (-1), 0, +1, etc.
  short sem_flg;       /* IPC_NOWAIT, SEM_UNDO */
}

int semop(int semid, struct sembuf semoarray[], size_t nops);
```

Using Semaphores to Share Access to a Resource

Initialization

- A semaphore is associated to each resource
- Value of the semaphore is initialized with *semctl*() to the maximum number of processes which can access to this resource at the same time

Using the Semaphore: *semop*()

- Before accessing a given shared resource, a process tries to decrease the value of the semaphore
  - If the value is 0, the process is suspended until the value of the semaphore becomes positive
- To release a resource, a process increments the value of the semaphore

Mutexes

Definition

- <u>Mut</u>ual <u>Ex</u>clusion
- A *mutex* has two states: **locked**, **unlocked**
- Only one thread / process at a time can lock a mutex
- When a mutex is locked, other processes / threads block when they try to lock the same mutex:
  - Locking stops when the mutex is unlocked
  - One of the waiting process / thread succeeds in locking the mutex

Mutexes: Main functions

Initialize a mutex

```
pthread_mutex_t mymutex;
```

Lock the mutex

- Waits for the lock to be released if mutex is already locked

```
pthread_mutex_lock(&mymutex);
```

- Returns immediately if mutex is locked

```
pthread_mutex_trylock(&mymutex);
```

Unlock the mutex

```
pthread_mutex_unlock(&mymutex);
```


Condition Variables

- Used to signal a condition has changed

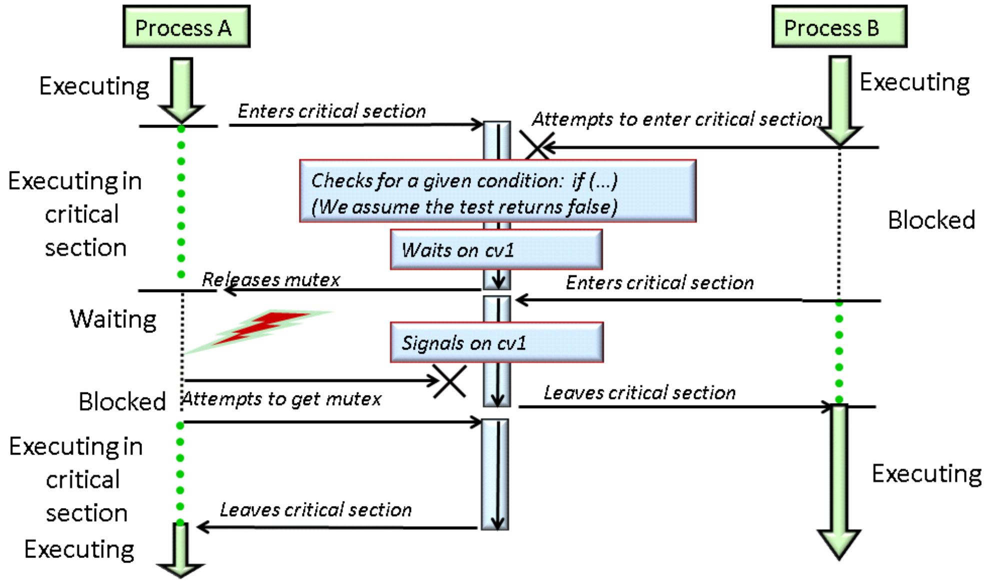
To wait on a condition

- Put lock on mutex
- Wait on that condition → Automatic release of the lock

To signal a change on a condition

- Put lock on mutex
- Signal that condition

Use of Condition Variables



Producer / Consumer Example

```
#include <stdlib.h>
#include <pthread.h>

#define N_THREADS_PROD 3
#define N_THREADS_CONS 4

void *produce(void *); void produceData(int id);
void *consume(void *) ;void consumeData(int id);

int data = 0; int maxData = 5;
pthread_mutex_t myMutex;
pthread_cond_t full, empty;

int main(void) {
  int i;
  pthread_t tid_p[N_THREADS_PROD];
  pthread_t tid_c[N_THREADS_CONS];

  for(i=0; i<N_THREADS_PROD; i++) {pthread_create(&tid_p[i], NULL, produce, (void *)i);
  for(i=0; i<N_THREADS_CONS; i++) {pthread_create(&tid_c[i], NULL, consume, (void *)i);

  for ( i = 0; i < N_THREADS_PROD; i++) {pthread_join(tid_p[i], NULL); }
  for ( i = 0; i < N_THREADS_CONS; i++) {pthread_join(tid_c[i], NULL); }

 return (0);
}
```

Producer / Consumer Example (Cont.)

```c
void *produce(void *arg) {
  int myId = (int)arg;
  while(1) {
    produceData(myId);
    sleep(random() % 5);
  }
}

void *consume(void *arg) {
  int myId = (int)arg;
  printf("I am the consumer #%d\n", myId);
  while(1) {
    consumeData(myId);
    sleep(random() % 5);
  }
}
```


Synchronization issues
Programming with synchronization constraints
Objects for Ensuring Mutual Exclusion
Example: using mutex and condition variables

Producer / Consumer Example (Cont.)

```c
void produceData(int id) {
  pthread_mutex_lock(&myMutex);
  while (data == maxData) {
    printf("#%d is waiting for less data; data = %d\n", id, data);
    pthread_cond_wait(&full, &myMutex);
  }
  data ++;
  printf("#%d is producing data; data = %d\n", id, data);
  pthread_cond_signal(&empty);
  pthread_mutex_unlock(&myMutex);
}

void consumeData(int id){
  pthread_mutex_lock(&myMutex);
  while (data == 0) {
    printf("#%d is waiting for more data; data = %d\n", id, data);
    pthread_cond_wait(&empty, &myMutex);
  }
  data--;
  printf("#%d is consuming data; data = %d\n", id, data);
  pthread_cond_signal(&full);
  pthread_mutex_unlock(&myMutex);
}
```

Why do we use **while** and not **if**?

Producer / Consumer Example: Execution

```
$gcc -lpthread prod prodcons.c
$prod
#3 is waiting for more data; data = 0
#1 is waiting for more data; data = 0
#2 is producing data; data = 1
#2 is producing data; data = 2
#0 is consuming data; data = 1
#2 is consuming data; data = 0
#2 is waiting for more data; data = 0
#3 is waiting for more data; data = 0
#0 is producing data; data = 1
#1 is consuming data; data = 0
#2 is producing data; data = 1
#2 is consuming data; data = 0
#1 is producing data; data = 1
#3 is consuming data; data = 0
#0 is waiting for more data; data = 0
#2 is waiting for more data; data = 0
#0 is producing data; data = 1
#0 is consuming data; data = 0
#0 is waiting for more data; data = 0
#3 is waiting for more data; data = 0
#1 is waiting for more data; data = 0
#2 is producing data; data = 1
#2 is producing data; data = 2
#2 is consuming data; data = 1
#0 is consuming data; data = 0
#1 is producing data; data = 1
```

```
#3 is consuming data; data = 0
#2 is producing data; data = 1
#2 is producing data; data = 2
#1 is consuming data; data = 1
#0 is producing data; data = 2
#0 is producing data; data = 3
#2 is consuming data; data = 2
#2 is producing data; data = 3
#2 is producing data; data = 4
#1 is producing data; data = 5
#0 is consuming data; data = 4
#1 is consuming data; data = 3
#3 is consuming data; data = 2
#1 is producing data; data = 3
#1 is producing data; data = 4
#0 is producing data; data = 5
#0 is waiting for less data; data = 5
#2 is consuming data; data = 4
#0 is producing data; data = 5
#1 is consuming data; data = 4
#2 is producing data; data = 5
#0 is consuming data; data = 4
#1 is producing data; data = 5
#0 is waiting for less data; data = 5
#2 is waiting for less data; data = 5
#3 is consuming data; data = 4
...
```