Background

- Processes can execute concurrently
  - May be interrupted at any time, partially completing execution
- Concurrent access to shared data may result in data inconsistency
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes
- Illustration of the problem:
  - Suppose that we wanted to provide a solution to the consumer-producer problem that fills ***all*** the buffers.
  - We can do so by having an integer **`counter`** that keeps track of the number of full buffers. Initially, **`counter`** is set to 0. It is incremented by the producer after it produces a new buffer and is decremented by the consumer after it consumes a buffer.

Producer

```
while (true) {
     /* produce an item in next produced */

     while (counter == BUFFER_SIZE) ;
          /* do nothing */
     buffer[in] = next_produced;
     in = (in + 1) % BUFFER_SIZE;
     counter++;
}
```

in

out

empty full

0 N

Consumer

```
while (true) {
      while (counter == 0)
            ; /* do nothing */
      next_consumed = buffer[out];
      out = (out + 1) % BUFFER_SIZE;
      counter--;
      /* consume the item in next consumed */
}
```

Race Condition

- **`counter++`** could be implemented as

```
1 register1 = counter
2 register1 = register1 + 1
3 counter = register1
```

- **`counter--`** could be implemented as

```
4 register2 = counter
5 register2 = register2 - 1
6 counter = register2
```

5
++ 1 2 3
6
4 5
-- 6
5

- Consider this execution interleaving with "count = 5" initially:

S0: producer execute `register1 = counter` {register1 = 5}
S1: producer execute `register1 = register1 + 1` {register1 = 6}
S2: consumer execute `register2 = counter` {register2 = 5}
S3: consumer execute `register2 = register2 - 1` {register2 = 4}
S4: producer execute `counter = register1` {counter = 6 }
S5: consumer execute `counter = register2` {counter = 4}

5 ++ -- 5

Counter ++

```
mov 0x8049a1c , %eax
add $0x1 , %eax
mov %eax , 0x8049a1c
```

Counter = 50

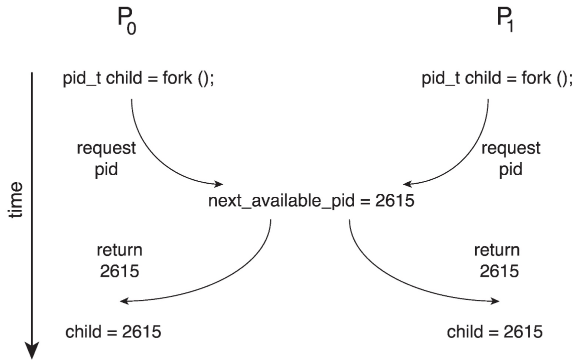
OS	Thread 1	Thread 2	%eax	Counter
			0	50
	`mov 0x8049a1c, %eax`		50	50
	`add $0x1, %eax`		51	50
interrupt save T1's state restore T2's state			0	50
		`mov 0x8049a1c, %eax`	50	50
		`add $0x1, %eax`	51	50
		`mov %eax, 0x8049a1c`	51	51
interrupt save T2's state restore T1's state			51	51
	`mov %eax, 0x8049a1c`		51	51

Race Condition (cont.)

- Where multiple processes are writing or reading some shared data and the final result depends on who runs precisely when, are called race conditions

Race Condition (cont.)

- Processes P_0 and P_1 are creating child processes using the `fork()` system call
- Race condition on kernel variable `next_available_pid` which represents the next available process identifier (pid)



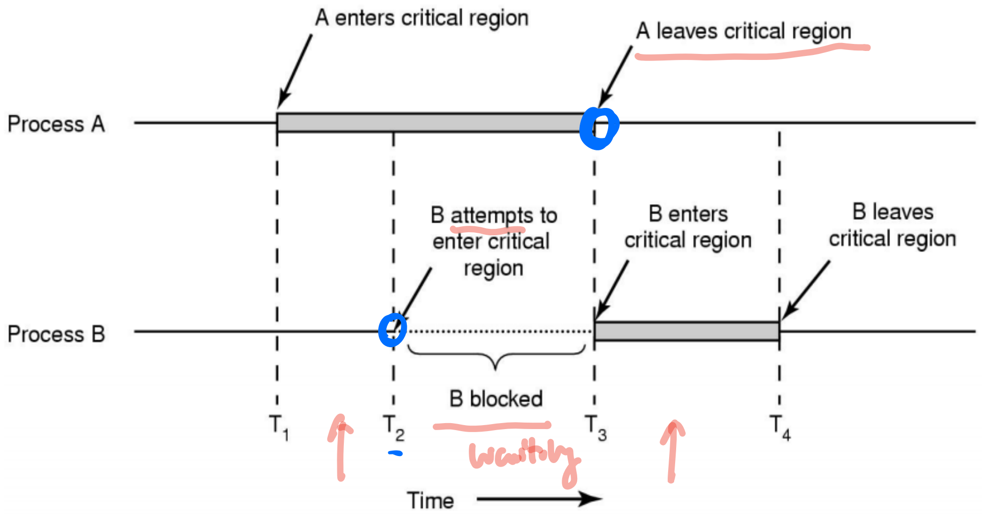
- Unless there is mutual exclusion, the same pid could be assigned to two different processes!

Critical Section & Mutual Exclusion

- Critical Section
  - A section of code in which the process accesses and modifies ***shared variables***
- Mutual Exclusion
  - A method for ensuring that one (or a specified number) of processes are in a critical section

n

Mutual Exclusion



Critical Section Problem

- Consider system of *n* processes $\{p_0, p_1, \ldots p_{n-1}\}$
- Each process has critical section segment of code
  - Process may be changing common variables, updating table, writing file, etc.
  - When one process in critical section, no other may be in its critical section
- *Critical section problem* is to design protocol to solve this
- Each process must ask permission to enter critical section in entry section, may follow critical section with exit section, then remainder section

Critical Section

- General structure of process $\boldsymbol{P_i}$

```
do {
    entry section
        critical section
    exit section
        remainder section
} while (true);
```

Algorithm for Process P_i

entry →

```
do {
    while (turn == i);
        critical section
    turn = j;
        remainder section
} while (true);
```

exit →

turn = i ;

P_j

```
do {
    while (turn==j)
        CS
    turn = i;
} while (true);
```

Solution to Critical-Section Problem

n+1 th

up to n

1. Mutual Exclusion - If process P_i is executing in its critical section, then no other processes can be executing in their critical sections
2. Progress - If no process is executing in its critical section and there exist some processes that wish to enter their critical section, then the selection of the processes that will enter the critical section next cannot be postponed indefinitely
3. Bounded Waiting - A bound must exist on the number of times that other processes are allowed to enter their critical sections after a process has made a request to enter its critical section and before that request is granted
   - Assume that each process executes at a non-zero speed
   - No assumption concerning relative speed of the *n* processes

Critical-Section Handling in OS

Two approaches depending on if kernel is preemptive or non-preemptive

- Preemptive – allows preemption of process when running in kernel mode
- Non-preemptive – runs until exits kernel mode, blocks, or voluntarily yields CPU
  - Essentially free of race conditions in kernel mode

How to Implement Mutual Exclusion

XOR

- Three possibilities
  - SW Application: programmer builds some method into the program
  - Hardware: special h/w instructions provided to implement ME
  - OS: provides some services that can be used by programmer
- All schemes rely on some code for
  - enter_critical_section, and
  - exit_critical_section

Application Mutual Exclusion

- Application Mutual Exclusion is
  - Implemented by the programmer
  - Hard to get correct, and very inefficient
- All rely on some form of busy waiting (process tests a condition, set a flag, and loops while the condition remains the same)

polling — busy waiting

interrupt

lock=0 (unlocked)

Example

- Producer

```
produce
if lock = 1 loop until lock = 0
lock = 1
put in buffer
lock = 0
```

locked

unlocked

entry

exit

busy waiting

produce
while (lock==0)
lock =1
put) CS
lock=0

- Consumer

```
if lock = 1 loop until lock = 0
lock = 1
get from buffer
lock = 0
consume
```

entry

exit

busy waiting

while (lock ==0)
lock = 1
fetch) CS
lock=0
Consume

lock = 0

	Producer				Consumer		
1		produce					
2	entry	while (lock == 0)	interrupt		while (lock == 0)	entry	1
3		lock = 1			lock = 1		2
4	cs	(put	interrupt		fetch)	cs	3
5	exit	lock = 0			lock = 0	exit	4
					consume		5

mutual exclusion violated

Locks

- A lock is a variable
- Two states
  - Available or free
  - Locked or held

- `lock()` : tries to acquire the lock
- `unlock()` : releases the lock which has been acquired by caller

Disabling Interrupts

non-preemptive

- One solution supported by hardware may be to use interrupt capability

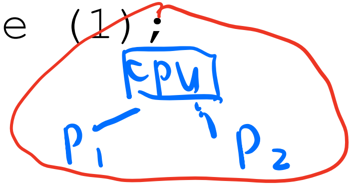
```
do {
      lock();
      critical section
      unlock();
      remainder section
} while (1);
```

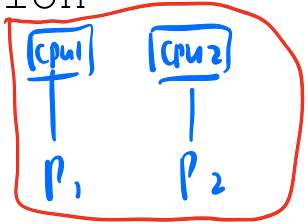
```
void lock(){
        DisableInterrupts();
}
void unlock(){
        EnableInterrupts();
}
```

⊕ Simple

⊖ - interrupt lost

- Privileged instruction
- Multi-processor
- inefficient & slow





Disabling Interrupts (cont.)

- On a single CPU only one process is executed
- Concurrency is achieved by interleaving execution (usually done using interrupts)
- If you disable interrupts then you can be sure only one process will ever execute
- One process can lock a system or degrade performance greatly

Synchronization Hardware

all or nothing

- Many machines provide special hardware instructions to help achieve mutual exclusion
- The Test-And-Set (TAS) instruction tests and modifies the content of a memory word atomically
- TAS returns old value pointed to by old_ptr and updates said value to new

```
Int TestAndSet(int *old_ptr, int new) {
      int old = *old_ptr;      //fetch old value at old_ptr
      *old_ptr = new;          //store 'new' into old_ptr
      return old;              // return the old value
}
```

as a single unit

Mutual Exclusion with TAS

- Initially, lock's flag set to 0

```
typedef struct __lock_t {
        int flag;
} lock_t;
void init(lock_t *lock) {
        // 0 indicates that lock is available, 1 that it is held
        lock->flag = 0;
}
void lock(lock_t *lock) {
        while (TestAndSet(&lock->flag, 1) == 1)
                ; // spin-wait (do nothing)
}
void unlock (lock_t *lock) {
        lock->flag = 0;
}
```

① unlocked (lock=0)

P_1 invokes lock()

↳ invokes TAS

↳ return 0

lock = 1

atomically

② locked (lock=1)

P_2 invokes lock()

↳ invokes TAS

↳ return 1

lock = 1

atomically

busy waiting

Busy Waiting and Spin Locks

- This approach is based on busy waiting
  - If the critical section is being used, waiting processes loop continuously at the entry point
- A binary "lock" variable that uses busy waiting is called a spin lock
  - Processes that find the lock unavailable "spin" at the entry
- It actually works (mutual exclusion)
- Disadvantages?
  - Fairness?
  - Performance?

Another HW Approach: Compare-And-Swap

- Test whether the value at the address specified by `ptr` is equal to `expected`
- If so, update the memory location pointed to by `ptr` with the new value. If not, do nothing.

```
int CompareAndSwap(int *ptr, int
expected, int new) {
        int actual = *ptr;
        if (actual == expected)
                *ptr = new;
        return actual;
}
```

old

old

old

atomically

```
void lock(lock_t *lock) {
        while (CompareAndSwap(&lock->flag,
0, 1) == 1)
                ; // spin
}
```

Hardware ME Characteristics

- Advantages
  - Can be used by a single or multiple processes (with shared memory)
  - Simple and therefore easy to verify
  - Can support multiple critical sections
- Disadvantages
  - Busy waiting is used
  - Starvation is possible
  - Deadlock is possible (especially with priorities)

Mutual Exclusion Through OS

- Semaphores
- Message passing IPC

Mutex Locks

mutual exclusion

- 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

lock

unlock

acquire() and release()

- ```
  acquire() {
     while (!available)
        ; /* busy wait */
     available = false;;
  }
  ```
- ```
  release() {
     available = true;
  }
  ```
- ```
  do {
  acquire lock
     critical section
  release lock
    remainder section
  } while (true);
  ```
  ```

Semaphores

- Introduced by Edsger Dijkstra
- Motivation: Avoid busy waiting by blocking a process execution until some condition is satisfied
- Major advance incorporated into many modern operating systems (Unix, OS/2)
- A semaphore is
  - a non-negative integer
  - that has two valid operations

Semaphore Operations

- Wait(s):

```
If s > 0 then s:= s - 1
     s=0 else block this process   sleep
```

- Signal(s):

```
If there is a blocked process on this semaphore
then wake it up
           else s:= s + 1
```

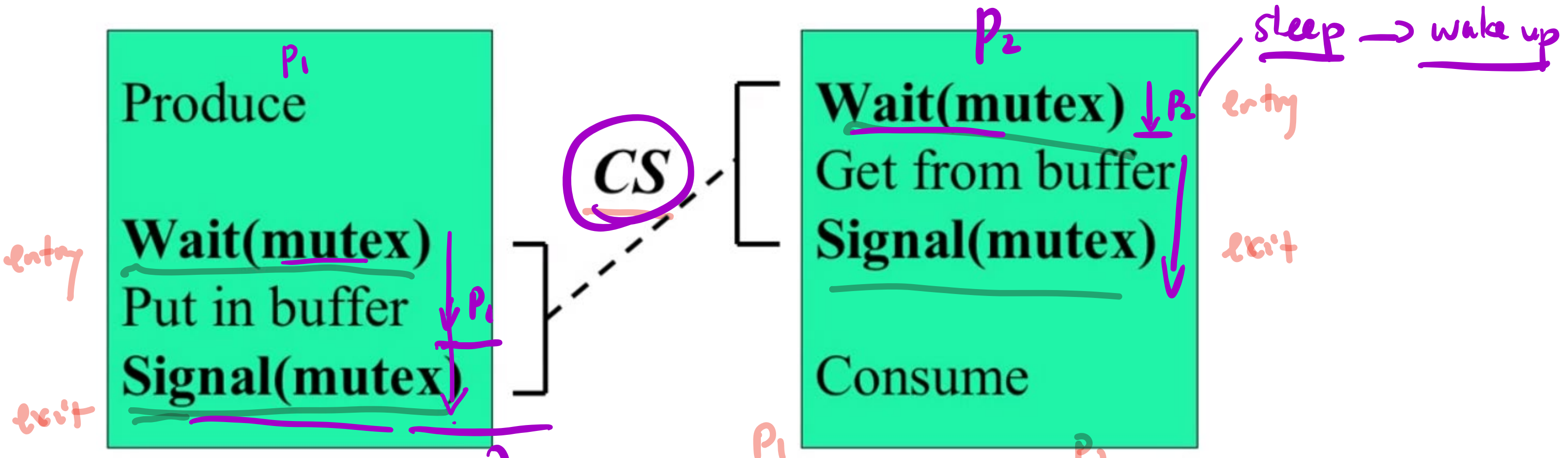
- Wait() and Signal() originally called P() and V()
  - prolaag: “probeer” in Dutch means “try”, and “verlaag” means “decrease” wait
  - verhoog: Dutch for “increase” signal

More on Semaphores

- Two types of semaphores
  - Binary semaphores can only be 0 or 1
    - Same as a mutex lock
  - Counting semaphores can be any non-negative integer
- Semaphores are an OS service implemented using one of the methods shown already
  - Usually by disabling interrupts for a very short time

Producer – Consumer Problem: Solution by Semaphores

mutex = 1 → 0



- Initially semaphore ***mutex*** is 1

binary semaphore

P1 wait(mutex) → 0

P2 wait(mutex) → P2 blocked

P1 signal(mutex)

wake up

Another Example

How many possible outputs?

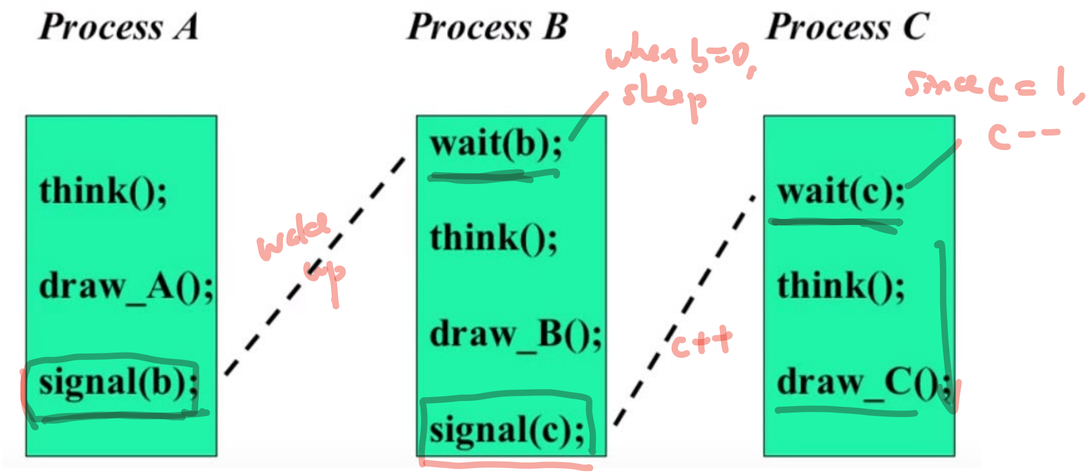
3!

ABC
ACB
BAC
BCA
CAB
CBA

- Three processes all share a resource on which
  - one draw an A
  - one draw a B
  - one draw a C
- Implement a form of synchronization so that the output appears ABC

Process A	*Process B*	*Process C*
think();	think();	think();
draw_A();	draw_B();	draw_C();

- Semaphore b = 0, c = 0;



Problem - Consumer

Bounded-Buffer Problem

- We need 3 semaphores:

binary semaphore

1. We need a semaphore **mutex** to have mutual exclusion on buffer access

ensure mutual exclusion

2. We need a semaphore **full** to synchronize producer and consumer on the number of consumable items

notify consumers how many items are there

3. We need a semaphore **empty** to synchronize producer and consumer on the number of empty spaces

notify producers how many empty slots are there

Counting semaphores

Avoid underflow ; Avoid overflow

Bounded-Buffer - Semaphores

- Shared data

```
semaphore full, empty, mutex;
```

Initially:

```
full = 0, empty = n, mutex = 1
```

unlocked

no item to consume

all slots are available

Bounded-Buffer – Producer Process

wait(mutex);
wait(empty);

```
do {
…
produce an item in nextp
…
wait(empty);    if there is an empty slot to insert
wait(mutex);    if there is any process accessing the buffer now
…
add nextp to buffer
…
signal(mutex);
signal(full);
} while (1);
```

x

Bounded-Buffer – Consumer Process

```
do {
wait(full);        if there is any item to consume
wait(mutex);       if there is any process accessing the buffer now
…
remove item from buffer to nextc
…
signal(mutex);
signal(empty);     has no effect
…
consume the item in nextc
…
} while (1);
```

x

Notes on Bounded-Buffer Solution

- Remarks (from consumer point of view)
  - Putting signal(empty) inside the CS of the consumer (instead of outside) has no effect since the producer must always wait for both semaphores before proceeding
  - The consumer must perform wait(full) before wait(mutex), otherwise deadlock occurs if consumer enters CS while the buffer is empty
- Conclusion: using semaphores is a difficult art

Mutual Exclusion Problem: Starvation

- Definition
  - Indefinitely delaying the scheduling of a process in favor of other processes
- Cause
  - Usually a bias in a system scheduling policies
- Solution
  - Implement some form of aging

Another Problem: Deadlocks

- Two (or more) processes are blocked waiting for an event that will never occur
- Generally, A waits for B to do something and B is waiting for A
- Both are not doing anything so both events never occur

Classical IPC Problems

producer r, w
Consumer r, w

reader r
writer w

Producer - Consumer problem

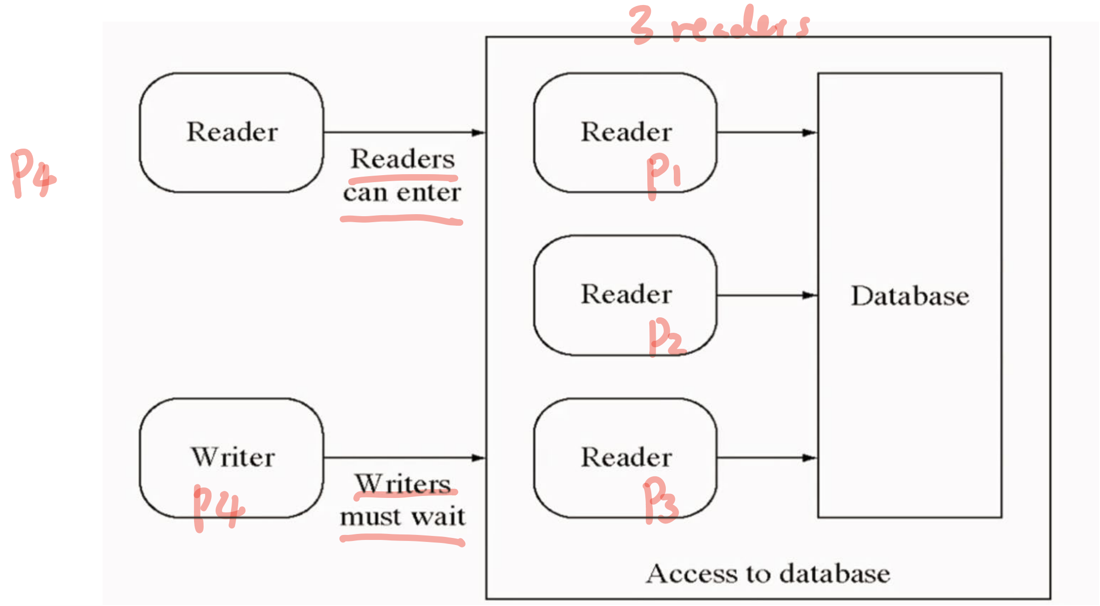
- Bounded-buffer problem
- Readers and writers problem
  - Models access to a database (both read and write)
- Dining philosophers problem
  - Models processes competing for exclusive access to a limited number of resources such as I/O devices

Readers-Writers Problem

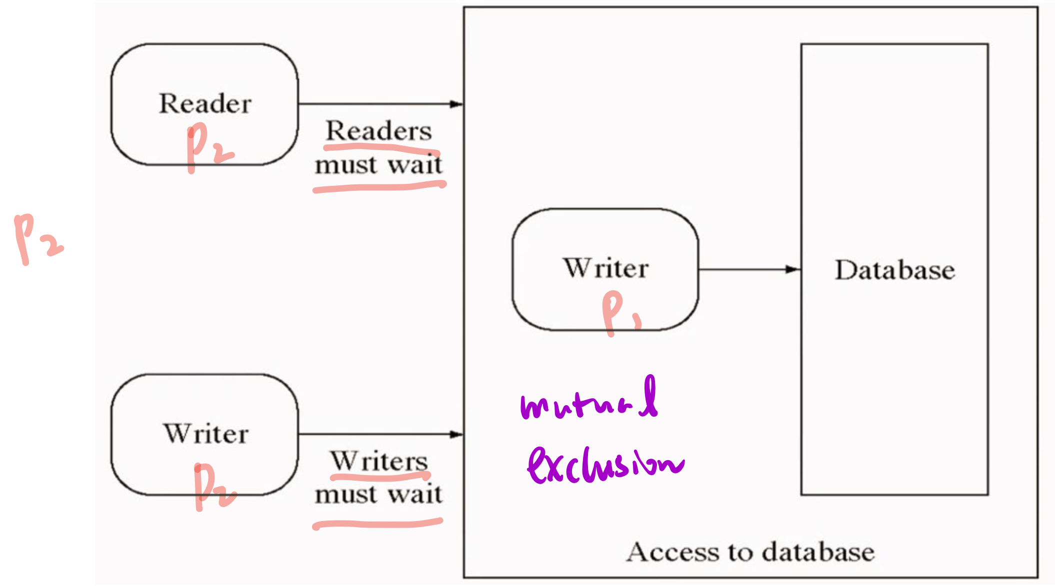
- Any number of reader activities and writer activities are running
- At any time, a reader activity may wish to read data
- At any time, a writer activity may want to modify the data
- Any number of readers may access the data simultaneously
- During the time a writer is writing, no other reader or writer may access the shared data

mutual exclusion for writers

Readers-Writers with active readers



Readers-Writers with an active writer

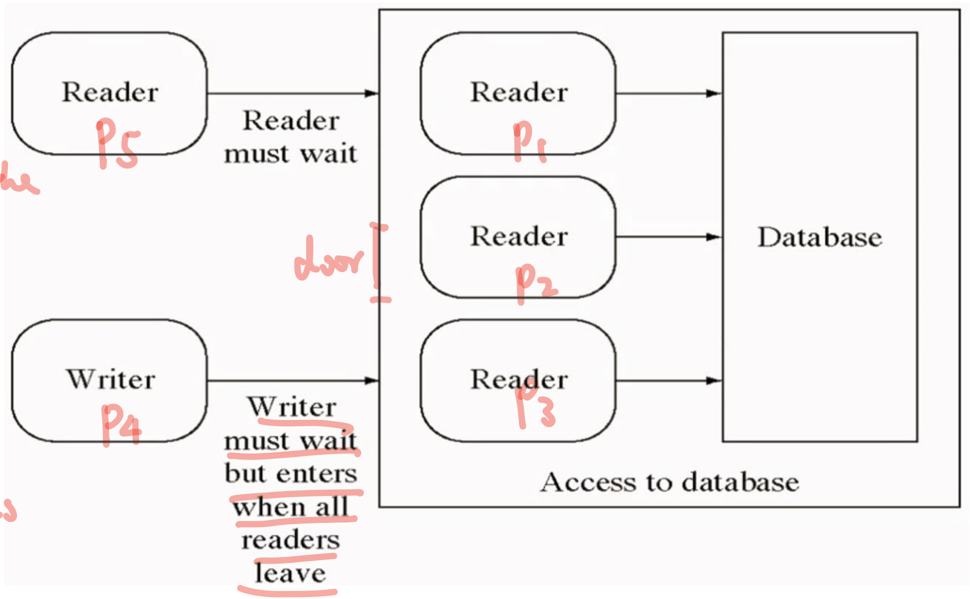


Should readers wait for waiting writer?

3 active readers

Case 1:

P5 may skip the line, enter



Case 2:

P5 must wait until P4 leaves

Readers-Writers problem

give priority to readers

1. The first readers-writers problem, requires that no reader will be kept waiting unless a writer has obtained access to the shared data
2. The second readers-writers problem, requires that once a writer is ready, no new readers may start reading

give priority to writers

3. In a solution to the first case writers may starve; In a solution to the second case readers may starve.

First Readers-Writers Solution

- **readcount** counter keeps track of how many processes are currently reading
- **mutex** semaphore provides mutual exclusion for updating **readcount**
- **wrt** semaphore provides mutual exclusion for the writers; it is also used by the first or last reader that enters or exits the CS

lock wrt when first reader enters — no writer can enter

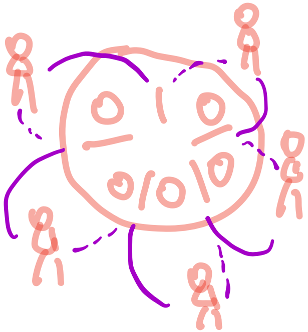
unlock wrt when last reader leaves — writers can enter

no readers inside

Solution to Second RW problem requires five variables

Dining Philosophers Problem

- Five philosophers are seated around a circular table
- In front of each one is a bowl of rice
- Between each pair of people there is a chopstick (fork), so there are five chopsticks
- It takes two chopsticks to eat rice, so while n is eating neither n+1 or n-1 can be eating



5 ppl x 2 chopstick = 10

Dining Philosophers Problem

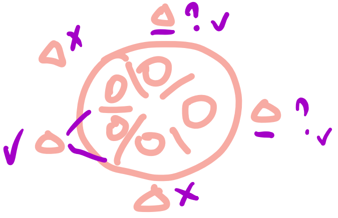
- Each one thinks for a while, gets the chopsticks needed, eats, and puts the chopsticks down again, in an endless cycle
- Illustrates the difficulty of allocating resources among processes without deadlock and starvation
- The challenge is to grant requests for chopsticks while avoiding deadlock and starvation
- Deadlock can occur if everyone tries to get their chopsticks at once. Each gets a left chopstick, and is stuck, because each right chopstick is someone else's left chopstick

Dining Philosophers Solution

6 ← 5 ppl

5 chopsticks

2 ppl can eat at the same time.



- Each philosopher is a process
- One semaphore per fork
  - fork: array[0..4] of semaphores
  - Initialization:

    fork[i].count := 1

    for i := 0..4

```
Process Pi:
repeat
   think;
   wait(fork[i]);          — left
   wait(fork[i+1 mod 5]);  — right
   eat;
   signal(fork[i+1 mod 5]); — right
   signal(fork[i]);        — left
forever
```

4 ppl

5 chopsticks

⇓

at least one person can get two sticks and eat

First attempt: deadlock if each philosopher starts by picking up his left fork (chopstick)!

Dining Philosophers Solution

- Possible solutions to avoid deadlock:
  - Allow at most four philosophers to be sitting at the table at same time
  - Odd numbered philosopher picks up left fork first, even one picks up right fork

Weakness of the Semaphore

- The user is expected to write wait and signal in the right order
- The user must remember to execute signal for each exit
- Calls may be spread throughout the program
- The logic may demand that a process must check and signal his peers

- There have been a wide number of alternatives proposed
- Monitors are one common approach

Summary

- We have seen two problems
  - Critical Sections – cannot both be modifying variable
  - Synchronization – must define ordering
- Often, our problems are a combination of the two
  - Readers/writers share storage, and readers should wait if there are writers waiting
- It is difficult to use semaphores correctly
- While there has been language support for Monitors for some time, standard UNIX still only supports semaphores (man sem_open)

Exit Slips

- Take 1-2 minutes to reflect on this lecture
- On a sheet of paper write:
  - One thing you learned in this lecture
  - One thing you didn’t understand