Operating System Principles

操作系统原理

Inter-Process Communication

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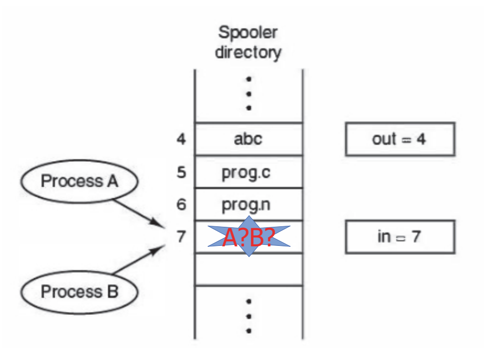
Objectives

- race condition
- mutual exclusion
- synchronization
- communication

Race Condition

- race condition 竞态



Murphy's law

If something can go wrong, it will

Race Conditions 竞态

two or more processes are reading or writing some shared data and the final result depends on who runs precisely

Processes Relations

- Resource sharing
- Co-operation
- …

Critical Regions

- Critical Resource 临界资源
  - File, memory, semaphore, ...
- Critical Regions 临界区
  - Sometimes a process has to access shared memory or files, or do other critical things that can lead to races
  - That part of the program where the shared memory is accessed is called the critical region or critical section

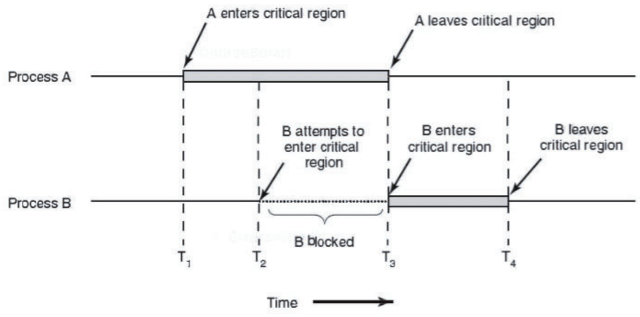
Four Prerequisites 前提

for avoiding race conditions

- **1. No two processes may be simultaneously inside their critical regions.**
- **2. No assumptions may be made about speeds or the number of CPUs.**
- **3. No process running outside its critical region may block other processes.**
- **4. No process should have to wait forever to enter its critical region.**

Mutual Exclusion

- 互斥访问



Mutual Exclusion

- How to access critical resource

Repeat

entry section

Critical sections;

exit section

Remainder section;

Until false

Solutions of Mutual Exclusion

- Disabling Interrupts
  - With interrupts disabled, no clock interrupts can occur.
  - The CPU is only switched from process to process as a result of clock or other interrupts, after all, and with interrupts turned off the CPU will not be switched to an other process.
    - Thus, once a process has disabled interrupts, it can examine and update the shared memory without fear that any other process will intervene.

Solutions of Mutual Exclusion

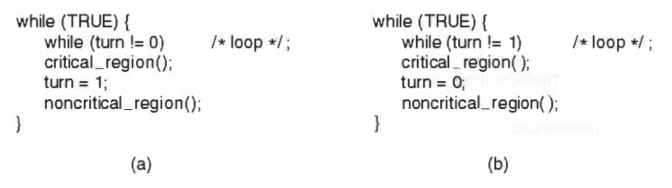
- Lock Variables

?Race Condition

  - a software solution
  - Consider having a single, shared (lock) variable, initially 0.
  - When a process wants to enter its critical region, it first tests the lock. If the lock is 0, the process sets it to 1 and enters the critical region. If the lock is already 1, the process just waits until it becomes 0.
  - Thus, a 0 means that no process is in its critical region, and a 1 means that some process is in its critical region.

Solutions of Mutual Exclusion

- Strict alternation 严格轮换法
  - the integer variable turn, initially 0, keeps track of whose turn it is to enter the critical region and examine or update the shared memory



```
while (TRUE) {
    while (turn != 0)        /* loop */ ;
    critical_region();
    turn = 1;
    noncritical_region();
}
```

(a)

```
while (TRUE) {
    while (turn != 1)        /* loop */ ;
    critical_region( );
    turn = 0;
    noncritical_region( );
}
```

(b)

Strict alternation (cont.,)

- Problem 1
  - busy waiting

    Continuously testing a variable until some value appears
- Problem 2
  - running speed does not match
- Problem 3
  - process 0 is being blocked by a process not in its critical region
- Case: spinlock 自旋锁

Solutions of Mutual Exclusion

- Peterson's Solution

```
#define FALSE 0
#define TRUE  1
#define N       2    /*number of processes*/
shared int turn;                /*whose turn is it?*/
shared int interested[N];  /*all values initially 0*/
void enter_region(int process)
{
    int other;
    other=1-process;
    interested[process]=TRUE;
     turn=process;
?while(turn!=process && interested[other]==TRUE);   Is ok?
}
void leave_region(int process)
{
     interested[process]=FALSE;
}
```

Solutions of Mutual Exclusion

- TSL Instruction
  - test and set lock   TSL REGISTER,LOCK

```
enter_region:
    TSL REGISTER,LOCK1
   CMP  REGISTER,#0
   JNE   enter_region
   RET

leave_region:
    MOVE LOCK1,#0
    RET
```

Solutions of Mutual Exclusion

- TSL Instruction
  - test and set lock   TSL REGISTER,LOCK
  - It reads the contents of the memory word lock into register RX and then stores a nonzero value at the memory address lock.
  - The operations of reading the word and storing into it are guaranteed to be indivisible-no other processor can access the memory word until the instruction is finished.

Solutions of Mutual Exclusion

- Swap Instruction
  - XCHG

```
Procedure Swap(var a,b:boolean)
Var temp:boolean;
Begin
  temp:=a;
  a:=b;
  b:=temp;
End;
```

Solutions of Mutual Exclusion

- Summary
  - busy waiting
    - Spinning
      - a process repeatedly checks to see if a condition is true
- priority inversion problem
  - a high priority task is indirectly preempted by a medium priority task effectively "inverting" the relative priorities of the two tasks
    - The higher priority task: enough time, but no critical resource
    - The lower priority task: using critical resource, but no time

New Solution of Mutual Exclusion

- Semaphore
  - 1965, E. W. Dijkstra (EWD 迪科斯彻)
  - A semaphore, as defined in the dictionary, is a mechanical signaling device or a means of doing visual signaling
  - The analogy typically used is the railroad mechanism of signaling trains,
    - where **mechanical arms** would swing **down** to block a train from a section of track that another train was currently using.
    - When the track was free, the arm would swing up, and the waiting train could then proceed.

New Solution of Mutual Exclusion

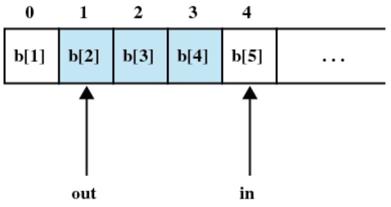
- Semaphore
  - A variable
  - Has two atomic operations: Primitive 原语
    - Down, Up
    - P (Proberen), V (Verhagen); Wait(), Signal()
  - Down()
    - If so, it decrements the value and just continues.
    - If the value is 0, the process is put to sleep without completing the down for the moment.
  - Up()
    - The up operation increments the value of the semaphore addressed. If one or more processes were sleeping on that semaphore, unable to complete an earlier down operation, one of them is chosen by the system and is al lowed to complete its down

IPC Primitives 原语

- inter-process communication primitives
  - block in stead of wasting CPU time when they are not allowed to enter their critical regions
- example
  - sleep
  - wakeup

The Producer-Consumer Problem

- The Producer-Consumer Problem(PCP)
  - the bounded-buffer problem
  - multi-processes share a common, fixed-size buffer



First Solution: The Producer-Consumer Problem

```
#define  N 100
/*number of slots in the buffer*/
int count=0;
/*number of items in the buffer*/
void producer(void){
  int item;
  while(TRUE){
    produce_item(&item);
    if (count==N) sleep();
    enter_item(item);
    count=count+1;
    if (count==1)
       wakeup(consumer);
  }
}
```

? Race Condition

Add:
wakeup waiting bit

```
void comsumer(void){
  int item;
  while(TRUE){
    if(count==0) sleep();
    remove_item(&item);
    count=count-1;
    if (count==N-1)
       wakeup(producer);
    consume_item(item);
  }
}
```

PCP using Semaphore

```
#define  N 100    /*number of slots in the buffer*/
typedef int semaphore;
semaphore mutex=1;
semaphore empty=N;
semaphore full=0;
void producer(void){
   int item;
   while(TRUE){
   produce_item(&item);
   down(&empty);
   down(&mutex);
   enter_item(item);
   up(&mutex);
   up(&full);
   }
}
```

```
void consumer(void){
     int item;
     while(TRUE){
               down(&full);
               down(&mutex);
                remove_item(&item);
               up(&mutex);
               up(&empty);
               consume_item(item);
     }
```

? exchange two lines

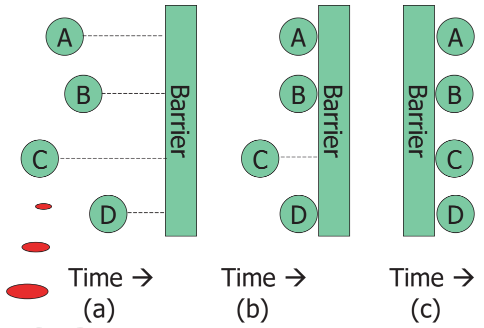
down(&mutex);

down(&empty);

Semaphore Scenarios

- mutual exclusion
  - semaphore mutex=1;
- synchronization
  - semaphore empty=N;
  - semaphore full=0;

Barrier(屏障)



?How to Implement

Implement of mutex

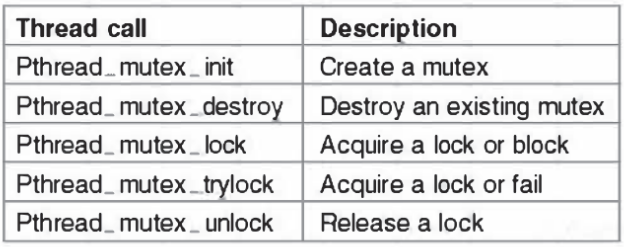
- Mutex
  - Value: 0,1

```
mutex_lock:
          TSL REGISTER,MUTEX
          CMP REGISTER,#0
          JZE  ok
          CALL thread_yield                 ;schedule another thread
          JMP mutex_lock
ok: RET

mutex_unlock:
          MOVE MUTEX,#0
          RET
```

No busy waiting

Pthread Calls: Semaphores



Thread call	Description
Pthread_mutex_init	Create a mutex
Pthread_mutex_destroy	Destroy an existing mutex
Pthread_mutex_lock	Acquire a lock or block
Pthread_mutex_trylock	Acquire a lock or fail
Pthread_mutex_unlock	Release a lock

Semaphore Set

- Why

```
Process A:                    Process B:
   wait(mutex1);                 wait(mutex2);
   wait(mutex2);                 wait(mutex1);
```

- Semaphore Set

  Swait(S1,S2,…,Sn)

  Ssignal(S1,S2,…,Sn)

Condition Variables

- Condition Variable
  - typedef   boolean cond;
    - true,false
    - Using semaphore
- Functions

condition_init(cond)

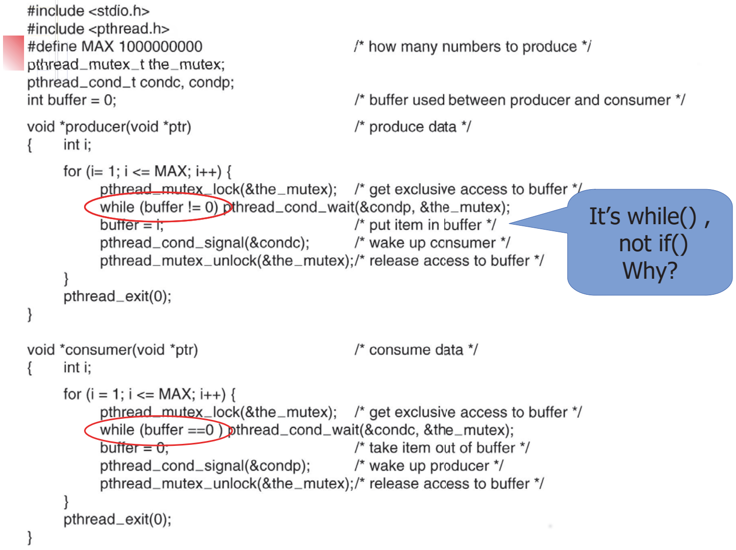
condition_wait(cond,mutex)

condition_signal(cond)

condition_broadcast(cond)

Example: condition variables

```
int main(int argc, char **argv)
{
        pthread_t pro, con;
        pthread_mutex_init(&the_mutex, 0);
        pthread_cond_init(&condc, 0);
        pthread_cond_init(&condp, 0);
        pthread_create(&con, 0, consumer, 0);
        pthread_create(&pro, 0, producer, 0);
        pthread_join(pro, 0);
        pthread_join(con, 0);
        pthread_cond_destroy(&condc);
        pthread_cond_destroy(&condp);
        pthread_mutex_destroy(&the_mutex);
}
```



```
#include <stdio.h>
#include <pthread.h>
#define MAX 1000000000                          /* how many numbers to produce */
pthread_mutex_t the_mutex;
pthread_cond_t condc, condp;
int buffer = 0;                                 /* buffer used between producer and consumer */

void *producer(void *ptr)                       /* produce data */
{       int i;

        for (i= 1; i <= MAX; i++) {
                pthread_mutex_lock(&the_mutex);     /* get exclusive access to buffer */
                while (buffer != 0) pthread_cond_wait(&condp, &the_mutex);
                buffer = i;                         /* put item in buffer */
                pthread_cond_signal(&condc);        /* wake up ccnsumer */
                pthread_mutex_unlock(&the_mutex);/* release access to buffer */
        }
        pthread_exit(0);
}

void *consumer(void *ptr)                       /* consume data */
{       int i;

        for (i = 1; i <= MAX; i++) {
                pthread_mutex_lock(&the_mutex);     /* get exclusive access to buffer */
                while (buffer ==0 ) pthread_cond_wait(&condc, &the_mutex);
                buffer = 0;                         /* take item out of buffer */
                pthread_cond_signal(&condp);        /* wake up producer */
                pthread_mutex_unlock(&the_mutex);/* release access to buffer */
        }
        pthread_exit(0);
}
```

It's while() , not if() Why?

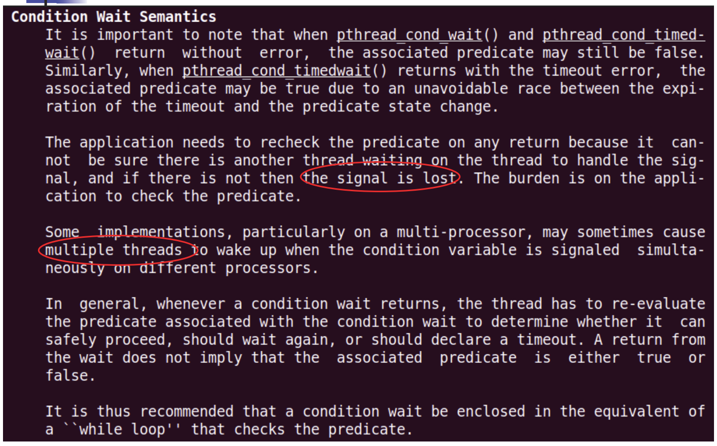
How to Imp Condition Wait

- pthread_mutex_t the_mutex;
- pthread_cond_t condc, condp;
- /*the_mutex:1 */
- /*the_mutex:1->0*/
- pthread_mutex_lock(&the_mutex);
- /*the_mutex:0->1*/
- /*cond:waiting*/
- /*the_mutex:1->0*/
- while(buffer!=0) pthread_cond_wait(&condp,&the_mutex);
- /*the_mutex:0 */
- XXXXX /*execute to critical section*/
- pthread_cond_signal(&condc);
- /*the_mutex:0 */
- /*the_mutex:0->1 */
- pthread_mutex_unlock(&the_mutex);
- /*the_mutex:1 */

How to Imp Condition Wait

```
int pthread_cond_wait(&condp,&the_mutex){
    pthread_unlock_mutex(&the_mutex);
    while( 循环 spin 时间 ){
    判断是否有 signal 来，若有则 goto done;
    }
    while(1){
    futex_wait_cancelable(cond,private);
    判断是否有 signal 来，若有则 goto done;
    }
    done:
    __condvar_confirm_wakeup(cond,private);
    pthread_lock_mutex(&the_mutex);
}
```

Condition Wait Semantics



```
Condition Wait Semantics
    It is important to note that when pthread_cond_wait() and pthread_cond_timed-
    wait()  return  without  error,  the associated predicate may still be false.
    Similarly, when pthread_cond_timedwait() returns with the timeout error,  the
    associated predicate may be true due to an unavoidable race between the expi-
    ration of the timeout and the predicate state change.

    The application needs to recheck the predicate on any return because it  can-
    not  be sure there is another thread waiting on the thread to handle the sig-
    nal, and if there is not then the signal is lost. The burden is on the appli-
    cation to check the predicate.

    Some  implementations, particularly on a multi-processor, may sometimes cause
    multiple threads to wake up when the condition variable is signaled  simulta-
    neously on different processors.

    In  general, whenever a condition wait returns, the thread has to re-evaluate
    the predicate associated with the condition wait to determine whether it  can
    safely proceed, should wait again, or should declare a timeout. A return from
    the wait does not imply that the  associated  predicate  is  either  true  or
    false.

    It is thus recommended that a condition wait be enclosed in the equivalent of
    a ``while loop'' that checks the predicate.
```

Get Help and the Source Code

```
• sudo apt update
• sudo apt install man-db manpages-posix
• sudo apt install manpages-dev manpages-posix-dev
• man ls
• man pthread_cond_wait
• sudo apt source glibc
```

Condition Variables: POSIX

```
▪ #include <pthread.h>
▪ int pthread_cond_init(pthread_cond_t *restrict cond,
          const pthread_condattr_t *restrict attr);
     pthread_cond_t cond = PTHREAD_COND_INITIALIZER;
▪ int pthread_cond_destroy(pthread_cond_t *cond);
▪ int pthread_cond_timedwait(pthread_cond_t *restrict cond,
          pthread_mutex_t *restrict mutex,
          const struct timespec *restrict abstime);
▪ int pthread_cond_wait(pthread_cond_t *restrict cond,
          pthread_mutex_t *restrict mutex);
▪ int pthread_cond_signal(pthread_cond_t *cond);
▪ int pthread_cond_broadcast(pthread_cond_t *cond);
```

Event Counter

- Reed and Kanodia,1979
- Three operations
  - Read(E)
  - Advance(E)
    - E=E+1 (atomic)
  - Await(E,v)
    - Wait until E>=v

PCP:Event Counter

```
#define  N 100
typedef int event_counter;
event_counter in =0;
event_counter out =0;
void producer(void){
   int item,sequence=0;
   while(TRUE){
     produce_item(&item);
     sequence=sequence+1;
     await(out,sequence-N);
     enter_item(item);
     advance(&in);
   }
}
```

```
void consumer(void){
          int item,sequence=0;
          while(TRUE){
            sequence=sequence+1;
            await(in,sequence);
            remove_item(&item);
            advance(&out);
            consume_item(item);
          }
}
```

Monitor

- Some errors with using semaphore
  - Error 1:

signal(mutex)
critical section
wait(mutex)

  - Error 2:

wait(mutex)
critical section
wait(mutex)

  - Error 3:

ignore wait(mutex)

  - Error 4:

ignore signal(mutex)

Monitor 管程

Hoare(1974),Brinch Hansen(1975)

```
monitor example
        integer i;
        condition c;

        procedure producer( );
        .
        .
        .
        end;

        procedure consumer( );
        .        .        .
        end;
end monitor;
```

PCP: Monitor

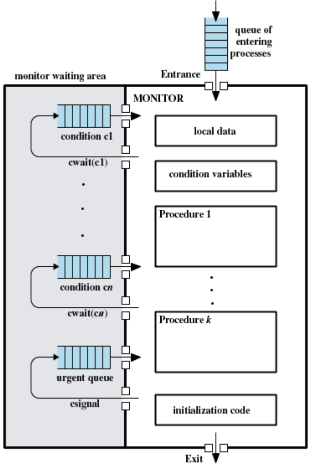
```
monitor ProducerConsumer
    condition full,empty;
    integer count;
    procedure insert(item:integer);
    begin
    if count=N then wait(full);
    insert_item(item);
    count:=count+1;
    if count=1 then signal(empty);
    end;
    function remove:integer;
    begin
    if count=0 then wait(empty);
    remove=remove_item;
    count:=count-1;
    if count=N-1 then signal(full);
    end;
    count:=0;
end monitor;
```

```
procedure producer;
begin
  while true do
     begin
       item=produce_item;
       ProducerConsumer.insert(item);
     end
end;
procedure consumer;
begin
  while true do
  begin
     item=ProducerConsumer.remove;
     consume_item(item);
  end
end;
```

Implement of Monitor

```
type monitor-name=monitor
  variable declarations
procedure entryP1(…);
begin
   …
end;
procedure entryP2(…);
begin  …   end;
…
procedure entryPn(…);
begin  …   end;

begin
   initialization code
end
```



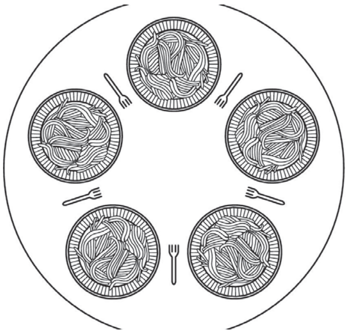
Classical IPC Problems

- The Dining Philosophers Problem(DPP)*
- The Readers and Writers problem(RWP)*
- The Sleeping Barber Problem(SBP)*

The Dining Philosophers Problem

1965, Dijkstra

- Philosophers eat/think
- Eating needs 2 forks
- Pick one fork at a time
- How to prevent deadlock



The Dining Philosophers Problem

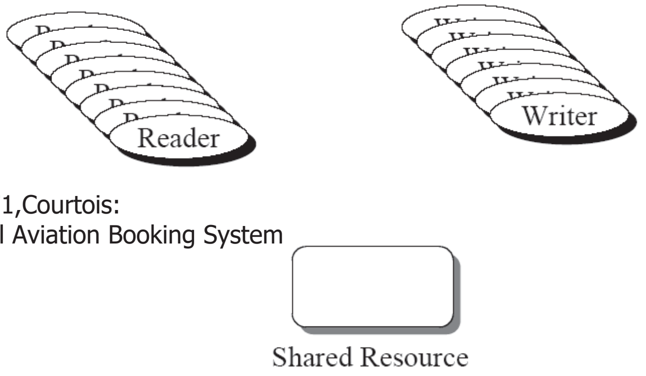
```
#define N  5
void philosopher(int i){
  while(TRUE){
      think();
      take_fork(i);
      take_fork((i+1)%N);
      eat();
      put_fork(i);
      put_fork((i+1)%N);
  }
}
```

The Dining Philosophers Problem

```
#define N 5
#define LEFT (i+N-1)%N
#define RIGHT (i+1)%N
#define THINKING  0
#define  HUNGRY  1
#define  EATING    2
typedef int semaphore;
int state[N];
semaphore mutex=1;
semaphore s[N];
void philosopher(int){
  while(TRUE){
     think();
       take_forks(i);
     eat();
         put_forks(i);
  }
}
```

```
void take_forks(int i){
  down(&mutex);
  state[i]=HUNGRY;     test(i);
  up(&mutex);
  down(&s[i]);
}
void put_forks(int i){
  down(&mutex);
  state[i]=THINKING;
  test(LEFT);     test(RIGHT);
  up(&mutex);
}
void test(int i){
  if(state[i]==HUNGRY && state[LEFT]!=EATING
     && state[RIGHT]!=EATING){
     state[i]=EATING;
     up(&s[i]);
  }
}
```

The Readers and Writers problem



1971,Courtois:
Civil Aviation Booking System

RWP: Solution 1

```
typedef int semaphore;
semaphore  mutex=1;
semaphore  db=1;
int rc=0;
void  reader(void){
   while(TRUE){
      down(&mutex);
      rc=rc+1;
      if(rc==1) down(&db);
      up(&mutex);
      read_data_base();
       down(&mutex);
      rc=rc-1;
      if (rc==0) up(&db);
      up(&mutex);
      use_data_read();
}}
```

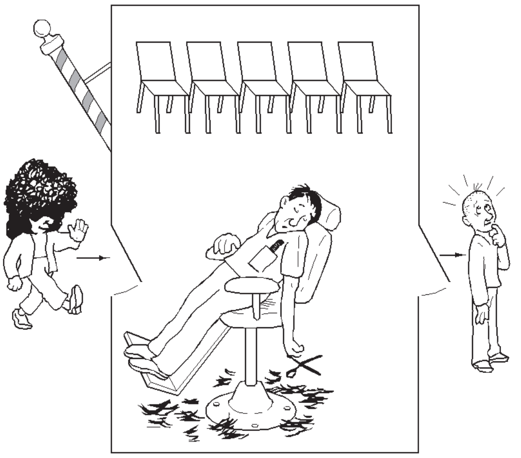
```
void  writer(void){
   while(TRUE){
       think_up_data();
       down(&db);
       write_data_base();
       up(&db);
   }
}
```

```
program readersandwriters;
var readcount,writecount:integer;
x,y,z,wsem,rsem:semaphore(:=1);
procedure reader;
begin
     repeat
     wait(z);
     wait(rsem);
     wait(x);
     readcount:= readcount+1;
     if readcount=1 then wait(wsem);
     signal(x);
     signal(rsem);
     signal(z);
     READUNIT;
     wait(x);
     readcount:= readcount-1;
     if readcount=0 then signal(wsem);
     signal(x);
     forever
end;
```

z 是否必须？

```
procedure writer;
begin     repeat
     wait(y);
     writecount:= writecount+1;
     if writecount=1 then wait(rsem);
     signal(y);
     wait(wsem);
     WRITEUNIT;
     signal(wsem);
     wait(y);
     writecount:= writecount-1;
     if writecount=0 then signal(rsem);
     signal(y);
     forever
end;
begin     readcount,writecount:=0;
     parbegin
     reader;writer;
     parend
end.
```

The Sleeping Barber Problem



The Sleeping Barber Problem

```
#define CHAIRS  5
typedef int semaphore;
semaphore customers=0;
semaphore barbers=0;
semaphore mutex=1;
int waiting =0;
void barber(void){
    while(TRUE){
        down(&customers);
   down(&mutex);
   waiting=waiting-1;
   up(&barbers);
   up(&mutex);
   cut_hair();
   }
}
```

```
void  customer(void){
  down(&mutex);
  if(waiting<CHAIRS){
    waiting=waiting+1;
    up(&customers);
    up(&mutex);
    down(&barbers);
    get_haircut();
  }else{
     up(&mutex);
  }
}
```

Synchronization Approaches: Summary

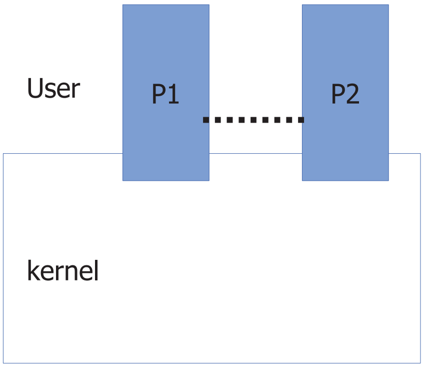
- Mutex
- Semaphore
- Semaphore Set
- Condition Variable
- Event Counter
- Monitor
- Message Passing

All are equivalent!

Alternative Synchronization Approaches

- Transactional Memory
- Functional Programming Languages
- …

Inter-Process Data Communication

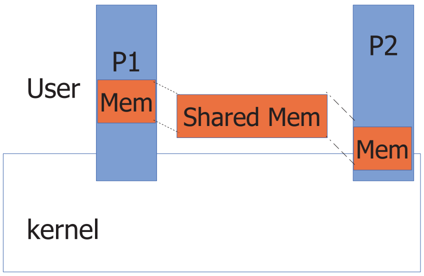


Inter-Process Data Communication

- Shared-Memory System
- Message passing System
- Pipeline System
- Remote Procedure Call

Shared-Memory System

- memory that may be simultaneously accessed by multiple programs with an intent to provide communication among them or avoid redundant copies



Message passing System

- Send(destination, &message)
- Receive(source, &message)

Synchronization
- Send
  - blocking
  - nonblocking
- Receive
  - blocking
  - nonblocking
  - test for arrival

Addressing
- Direct
  - send
  - receive
    - explicit
    - implicit
- Indirect
  - static
  - dynamic
  - ownership

Format
- Content
- Length
  - fixed
  - variable

Queuing Discipline
- FIFO
- Priority

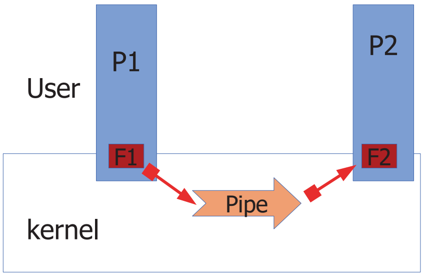
PCP: Message Passing

```
#define  N  100
void producer(void){
   int item;
   message m;
   while(TRUE){
      item=produce_item();
      receive(consumer,&m);
      build_message(&m,item);
      send(consumer,&m);
   }
}
```

```
void consumer(void){
  int item,i;
  message m;
  for(i=0;i<N;i++)
    send(producer,&m);
  while(TRUE){
     receive(producer,&m);
    item=extract_item(&m);
    send(producer,&m);
    consume_item(item);
   }
}
```

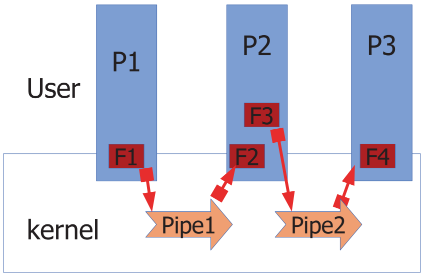
Pipe System

- a set of data processing elements connected in series, where the output of one element is the input of the next one

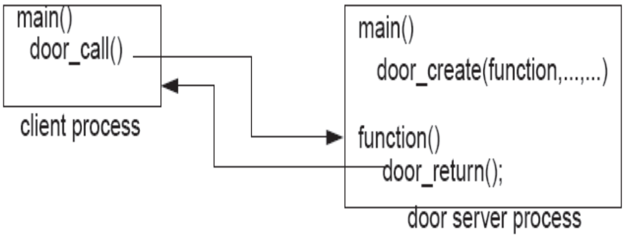


Pipeline System

cat file1 file2 file3 | grep “root” | wc -l



Remote Procedure Call



```
main()
  door_call()
```

client process

```
main()
  door_create(function,...,...)

function()
  door_return();
```

door server process

Summary

- race condition
- mutual exclusion
- synchronization
- Communication
- Classical IPC Problems

Q&A?