Synchronization

Weeks 4 - 6

Announcements & Comments

- Read the whole Synchronization Chapter in the book; it contains important material for the second assignment
- My slides go beyond the chapter on synchronization, read them carefully, **<u>especially with regards to the second assignment (read forward, i.e., beyond the material covered in the lecture) !!</u>**
- I may not cover the slides in the exact sequence presented

Announcements & Comments

- About the assignment's **locks** see these slides
- About the assignment's **condition variables** see these slides and read monitor section in book
- For **pet synchronization** read classical synchronization section in the book
- Pet synchronization solution *et al.* should be **generic**

…

- You can execute your synchronization mechanisms and your solution to the pet problem via the kernel's boot menu (see handout)
- Design **a generic solution** to the pet problem (we will test for that)
- We will compare all submitted assignments to identify cheaters …
- Do NOT change the **boot menu** or the **test code** that it invokes (we plan to add additional test code, beyond the one in your distribution)

…

- *Only* fill in **the blanks (function stubs)** in the respective files (do not worry about how these functions are invoked)
- Start Assignment 1 **from a new and clean distribution** (make sure you do not unpack it over your old distribution, since certain files may or may not be overwritten)
  - **Start from scratch with a new distribution**
  - **If you wish, keep your debugging statements**
  - **You will build on the synchronization primitives you develop**
- **You may have to modify all kinds of OS/161 code, not just the pieces we explicitly point you to**
- **Localized understanding is essential;** understanding the whole kernel is not required to solve the assignment

Before We Start

- OS/161 processes are single threaded
- OS/161 processes are realized via the “threads structure” (see earlier slides), but **<u>are NOT threads in the sense introduced in my lecture</u>**

- Nothing prevents you from making them multi-threaded – we wont ask you to do that

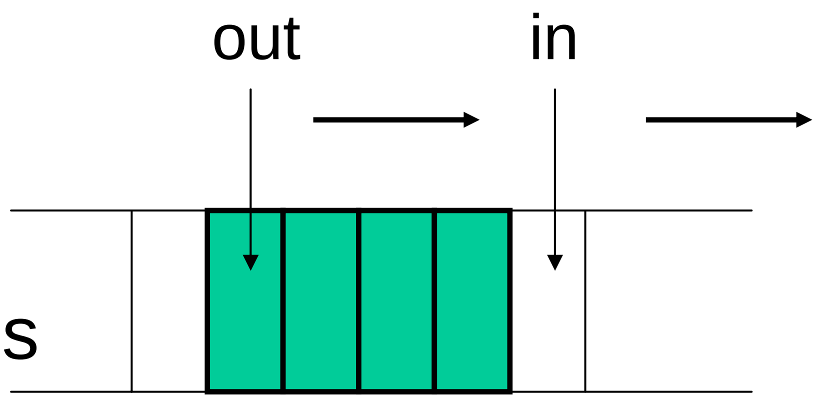
Motivation

- Processes may want to **pass on information**, e.g., UNIX pipe "`ls –l | grep *.c`".
- Process A may **require to wait for output** of process B, e.g., printer spooler waits for files to print.
- **Coordinate critical activities** e.g., memory allocation.
- **Share and access** data elements
- Keep track of the **number of times an activity is execution**, e.g., the number of writing transactions in a DBMS

Bounded Buffer

Examples

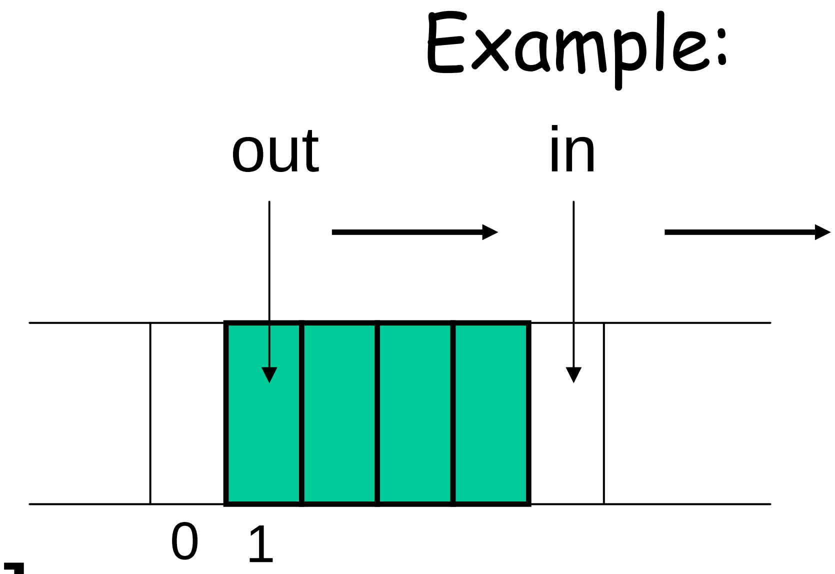
- Printer queues
- Device buffers
- Shared buffers or queues
  to pass information between
  processes



The following discussion applies equally to process and to threads.

Shared Data for Bounded-Buffer

```
//shared data
#define BUFFER_SIZE 10
typedef struct {
. . .
} item;
item buffer[BUFFER_SIZE];
//initial values
int in = 0;
int out = 0;
int counter = 0;
```



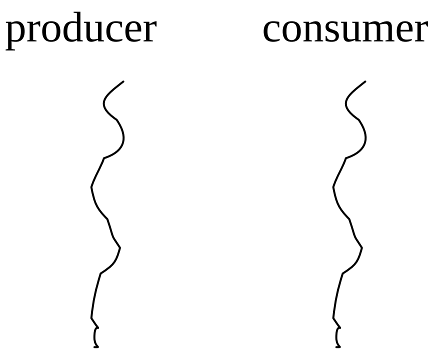
out = 1
in = 5
counter = 4

Bounded Buffer: Producer

```
item nextProduced;
while (TRUE) {
    while (counter == BUFFER_SIZE)
            ; /* FULL - do nothing */
    buffer[in] = nextProduced;
    in = (in + 1) % BUFFER_SIZE;
    counter++;
}
```

Bounded Buffer: Consumer

```
item nextConsumed;
while (TRUE) {
    while (counter == 0)
            ; /* EMPTY - do nothing */
    nextConsumed = buffer[out];
    out = (out + 1) % BUFFER_SIZE;
    counter--;
}
```



Machine-level Implementation

- Implementation of "counter++"

$register_1$ = counter
$register_1$ = $register_1$ + 1
counter = $register_1$

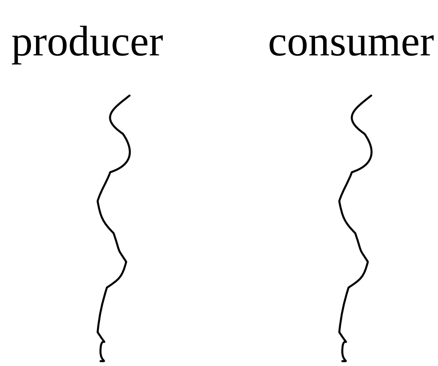
- Implementation of "counter—"

$register_2$ = counter
$register_2$ = $register_2$ – 1
counter = $register_2$

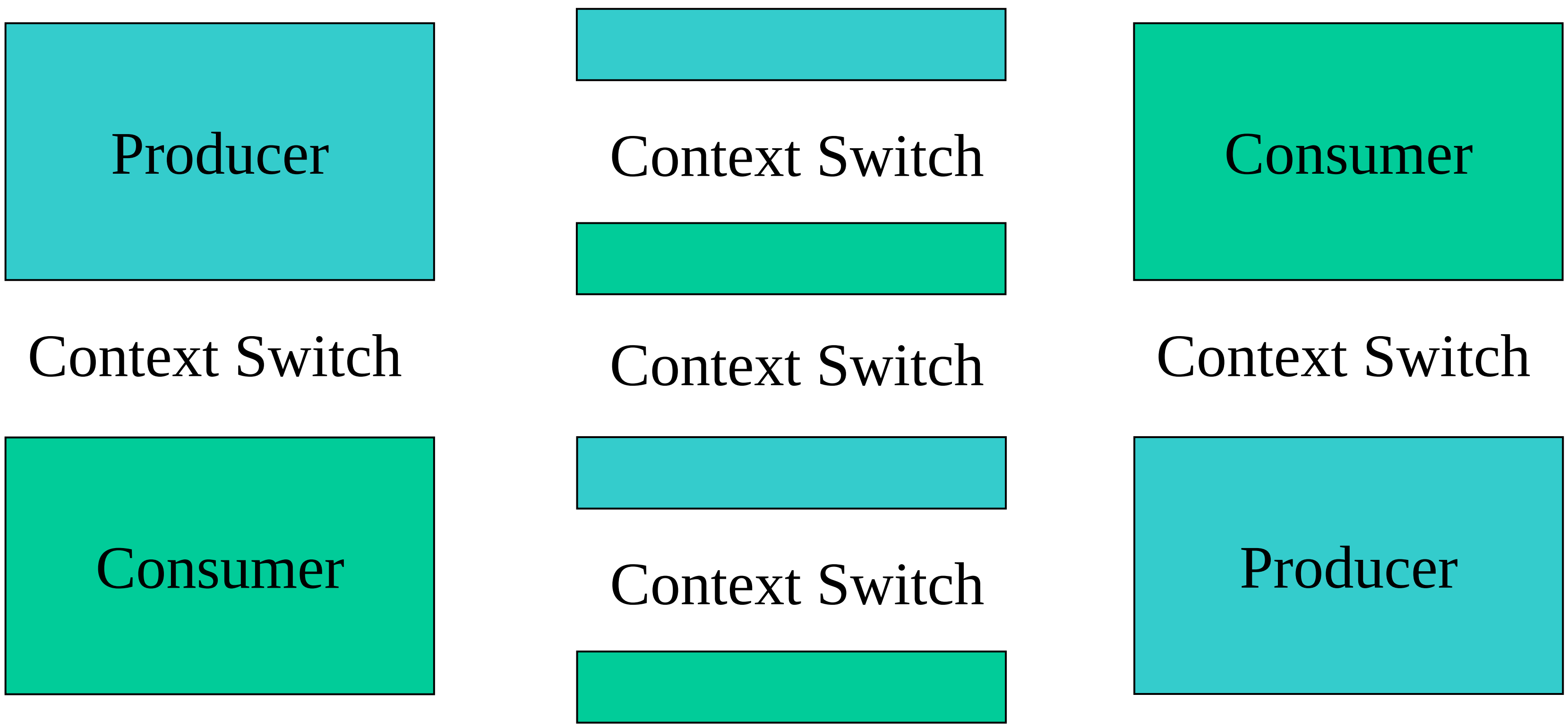
Bounded Buffer

- If both the producer and consumer attempt to update the buffer **concurrently**, the assembly language statements may get **interleaved**.

- Interleaving **depends** upon how the producer and consumer are **scheduled**.



Possible Execution Patterns



Interleaved Execution

- Assume **counter** is 5 and one interleaved execution of producer and consumer code (i.e., **counter++** and **counter--**):

P: **r1**	**= counter**	(*register*$_1$ *= 5*)
P: **r1**	**= r1 + 1**	(*register1 = 6*)
C: **r2**	**= counter**	(*register*$_2$ *= 5*)
C: **r2**	**= r2 – 1**	(*register*$_2$ *= 4*)
P: **counter**	**= r1**	(*counter = 6*)
C: **counter**	**= r2**	(***counter = 4***)

context switch

- The value of **counter** may be either 4 or 6, where <u>the correct result should be 5.</u>

Race Condition

- **Race condition**: The situation where **several** processes or threads **access** and **manipulate shared data concurrently**, while the **final value** of the shared data **depends** upon which process finishes last.
- In our example for P last, result would be 6, and for C last, result would be 4.
- To prevent race conditions, concurrent processes must be **synchronized**.

The Moral of this Story

- The statements
  counter++;
  counter--;
  must be performed ***atomically***.
- Atomic operation means an operation that **completes in its entirety without interruption**.
- This is achieved through **synchronization primitives** (semaphores, locks, condition variables, monitors …).

Synchronization: Overview

- More formal definition of problem (the critical section problem)
- Simple solutions to this problem
- Software solutions to this problem (defer till later)
- Hardware support for synchronization (defer till later)
- Locking, semaphores, condition variables
- Higher-level synchronization primitives
- Common synchronization problems

The Critical-Section Problem

- ***n*** processes all competing to **use some shared data.**
- Each process has a code segment, called ***critical section***, in which the shared data is accessed.
- **Problem**: ensure that when one process is executing in its critical section, no other process is allowed to execute in its critical section.
- Sometimes also called critical region – *don't confuse this with our book's critical region construct.*

A Simple Solution: Disabling of Interrupts

- Context switches come about through **interrupts** (e.g., clock or other interrupts)
- So how about **disabling interrupts** while `counter++` is executed?
  - Should user really be allowed to do that?
  - What does that mean in a multi-CPU context?
- Inside kernel code this may be acceptable
- This is the mechanism employed by OS/161 to achieve atomicity in the kernel – for short pieces of code
- Your mission – should you accept it ☺ - is to **implement higher-level synchronization mechanisms** in OS/161 (locks and condition variables)

Meta Comment

- We will skip a number of sections in the book at this point and come back to them later
- We are skipping *software-based solutions* to the critical section problem for now (read them)
- We are skipping *hardware features* in support of critical section
- These solutions are based on mechanisms that **require busy waiting**

Semaphores

- Higher-level synchronization mechanism
- Higher than disabling interrupts
  - Fine for short sequences of code in kernel
  - Not fine for application-level use

Semaphores

- **Semaphore *S***, integer variable
- can only be accessed via two **indivisible** (atomic) operations

1. *wait* (*S*): // historically a.k.a. P(S)

while do ***nothing***;

atomic for S > 0

atomic

e.g., by disabling interrupts

busy waiting loop

2. *signal* (*S*): // historically a.k.a. V(S)

wait(S)

EI – enable interrupt

DI – disable interrupt

critical section for S <= 0

critical section for S > 0

```
loop:     DI
          if  S < = 0 then {
                 EI;
                 goto loop
          }
          else {
                 S—;
                 EI;
          }
```

Critical Section of ***n*** Processes

- **Shared data**:

  semaphore mutex; *//* initially *mutex* = 1

- Process *Pi:*

do {

    wait(mutex);

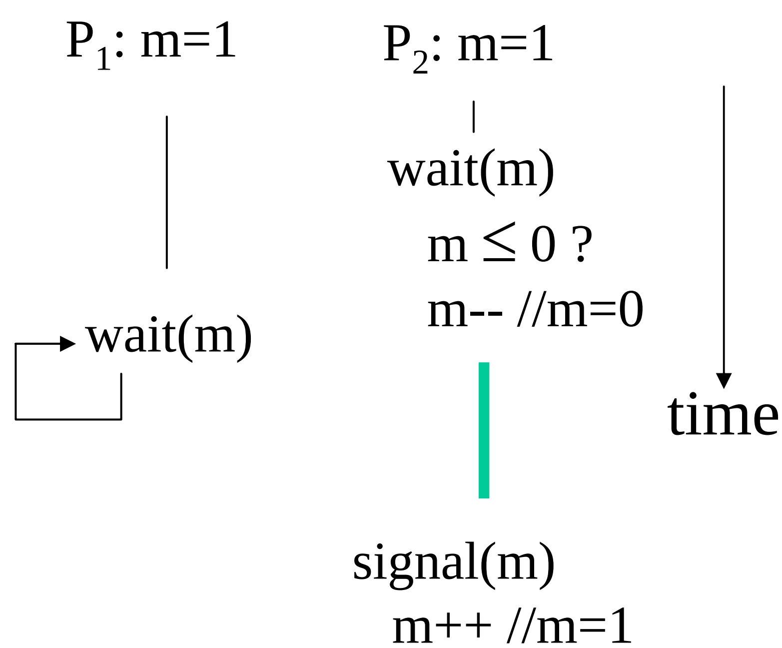
        critical section

    signal(mutex);

        remainder section

} while (TRUE);

Timeline:



semaphore m=1

P_1: m=1

wait(m)
m ≤ 0 ?

P_2: m=1

wait(m)
m ≤ 0 ?

P_3: m=1

wait(m)
m ≤ 0 ?
m-- //m=0

signal(m)
m++ //m=1

P_4: m=1

wait(m)
m ≤ 0 ?

wait (*S*):

while **do *nothing*;**

semaphore m=3

P_1: m=3

2 wait(m)

m ≤ 0 ?

m-- //m=1

P_2: m=3

4 wait(m)

m ≤ 0 ?

P_3: m=3

1 wait(m)

m ≤ 0 ?

m-- //m=2

signal(m)

m++ //m=1

P_4: m=3

3 wait(m)

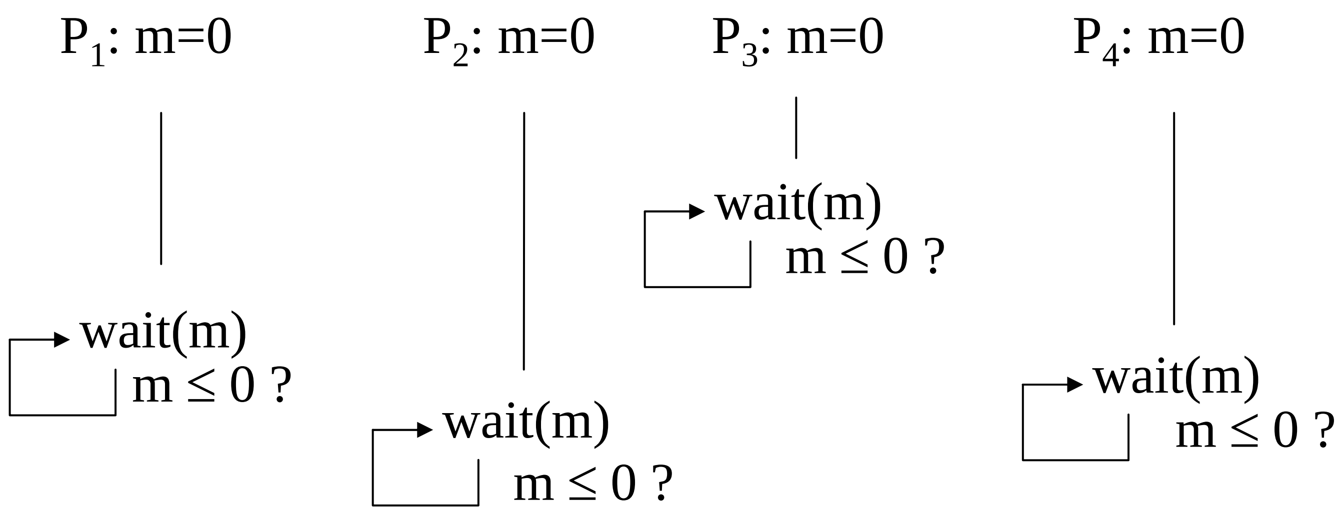
m ≤ 0 ?

m-- //m=0

wait (*S*):

while **do *nothing*;**

semaphore m=0



Rien ne va plus!

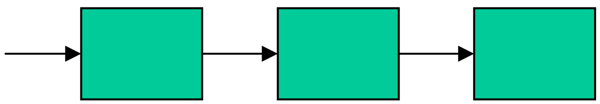
wait (*S*):

while **do *nothing*;**

Semaphore Implementation

- Variant that avoids busy waiting
- Define a semaphore as a record (**shared data**)

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



- Assume two simple operations:
  - **block()** suspends the process that invokes it.
  - **wakeup(*P*)** resumes the execution of a blocked process **P**.

Implementation Alternative

wait(*S*):

atomic

signal(*S*):

atomic

Example (expressed as timeline)

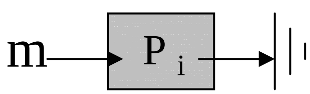
Semaphore m;
m=1; // shared data

P_i	P_j	P_k	time ↓

P_j:
wait(m)
  m.v-- **//m.v= 0**
  m.v < 0 ?

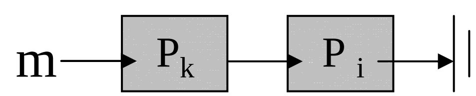
(1)

P_i:
wait(m)
  m.v-- //**m.v= -1**
  m.v < 0 ?
    enqueue + block



(2)

P_k:
wait(m)
  m.v-- //**m.v= -2**
  m.v < 0 ?
    enqueue + block



(3)

P_j:
signal(m)
  m.v++ //**m.v= -1**
  m.v ≤ 0 ?
  dequeue + wakeup

Semaphore m;
do {   \\ P_i
wait(m);
critical section
signal(m);
remainder section
} while (TRUE);

Semaphores in OS/161

- Defined in `src/kern/thread/synch.c` and `src/kern/include/synch.h`
- Based on Dijkstra semantic with P/V (*proberen* (try) / *verhogen* (increase)) operations instead of wait/signal

Semaphore Implementation in OS/161

```
void P(struct semaphore *sem)
{
	int spl;
	assert(sem != NULL);
	spl = splhigh();
	while (sem->count==0) {
		thread_sleep(sem);
	}
	assert(sem->count>0);
	sem->count--;
	splx(spl);
}
```

Puts thread to sleep and … (?)

Why is there a while loop?

Is like our wait(sem).

Semaphore Implementation in OS/161

```
void V(struct semaphore *sem)
{
    int spl;
    assert(sem != NULL);
    spl = splhigh();
    sem->count++;
    assert(sem->count>0);
    thread_wakeup(sem);
    splx(spl);
}
```

Wakes up all threads waiting on sem

Is like our signal(sem).

Semaphore as Synchronization Tool

- Execute *B* in P_j only after *A* executed in P_i
- Use semaphore ***flag*** **initialized to 0**
- Code:

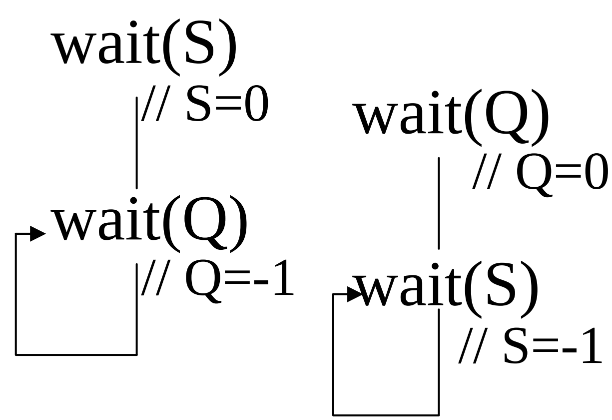
P_i	P_j
A	*wait*(*flag*)
signal(*flag*)	*B*

Careful: 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*);
M	M
signal(*S*);	*signal*(*Q*);
signal(*Q*)	*signal*(*S*);

Timeline:



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

Bounded Buffer with Semaphores

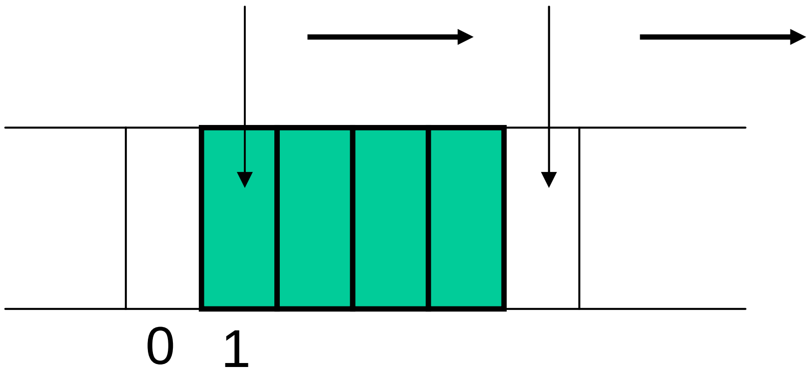
- Shared data:

  `semaphore mutex = 1;` // exclusive access

  `semaphore empty = N;` // number of empty slots

  `semaphore full = 0;` // number of full slots

- Semaphores initialized to 1 and used to *serialize* access to a critical section are sometimes called **binary semaphores** ≠ **locks**



Bounded Buffer: Producer

```
item nextProduced;
while (TRUE) {
  wait (empty);
  wait (mutex);
  insert(nextProduced);
  signal (mutex);
  signal (full);
}
```

```
item nextConsumed;
while (TRUE) {
  wait (full);
  wait (mutex);
  nextConsumed = remove();
  signal (mutex);
  signal (empty);
}
```

- Buffer implemented as a linked list

Bounded Buffer: Producer (broken)

```
item nextProduced;
while (TRUE) {
    while (counter == BUFFER_SIZE)
            ; /* FULL - do nothing */
    buffer[in] = nextProduced;
    in = (in + 1) % BUFFER_SIZE;
    counter++;
}
```

Semaphores & Locks

Semaphores, Locks & Mutexes

- **Counting** semaphores vs. **binary** semaphores
  – semaphore integer takes on various values
  – semaphore integer takes on values 0 and 1
  – *Can a counting semaphore be implemented based on a binary semaphore?*
- **A binary semaphore is not a lock**
  – But maybe used just like a lock (other use patterns also possible)

Semaphores, Locks & Mutexes

- **Mutex** often refers to *a locking mechanism* available in user-space (user-level threads)
  - Various different kinds …
- Term **lock** is used to also refer to a ***locking mechanism*** (*remember presentation of semaphores in class – lock/unlock – wait/signal*)
  - However, wait/signal can be used by two different processes
  - Lock/corresponding unlock **must be called from same process**

Mutex – Mutual Exclusion

(What the assignment calls a lock.)

- A semaphore that allows **only one process** inside the critical section is often called a **mutex**
- Semaphores' **ability to count not required** in the application semantic
- Mutexes are **used exclusively to manage mutual exclusion** of critical section (i.e., lock and unlock)
- **Easy and efficient to implement** (therefore attractive for user-level thread packages)
- Mutex **knows one of two states**, 0 or 1 – ***unlocked, locked***
- If **TSE** instruction available, mutexes can be **easily implemented in user space** (discussed later)

Semaphores in OS/161

- For implementing locks/CVs it maybe helpful to study the semaphore implementation in OS/161
- Defined in `src/kern/thread/synch.c` and `src/kern/include/synch.h`
- Based on Dijkstra semantic with P/V (*proberen* (try) / *verhogen* (increase)) operations instead of wait/signal

Desirable & Undesirable Properties of Lock Implementations

- Improper use of locks
  - **Locking a non-initialised mutex** (lock)
  - **Locking a mutex** that you **already own**
  - **Unlocking a mutex** that you **don't own**
- As always in this context, it's **the user's responsibility** to prevent this from happening
- Some **thread implementations do check for these conditions** and signal the problem
- Note, that **for semaphore** (binary semaphores) **the above properties are not meant** to be enforced

Mutexes/Locks in OS/161

```
struct lock{
  char * name;
  struct thread *holder;
};
struct lock *
       lock_create          (const char *name);
void   lock_acquire         (struct lock *);
void   lock_release         (struct lock *);
int    lock_do_i_hold       (struct lock *);
void   lock_release         (struct lock *);
```

Towards Higher-level Synchronization Constructs

- Getting the wait/signals correct is not easy
- Higher-level languages help programmer synchronize the applications, e.g.,
  - Java's synchronize (single threaded access of methods of class guaranteed)
  - 1975 introduction of **monitor** by Hoar *et al*.
  - See also "**critical region construct"** in our text book

Monitor

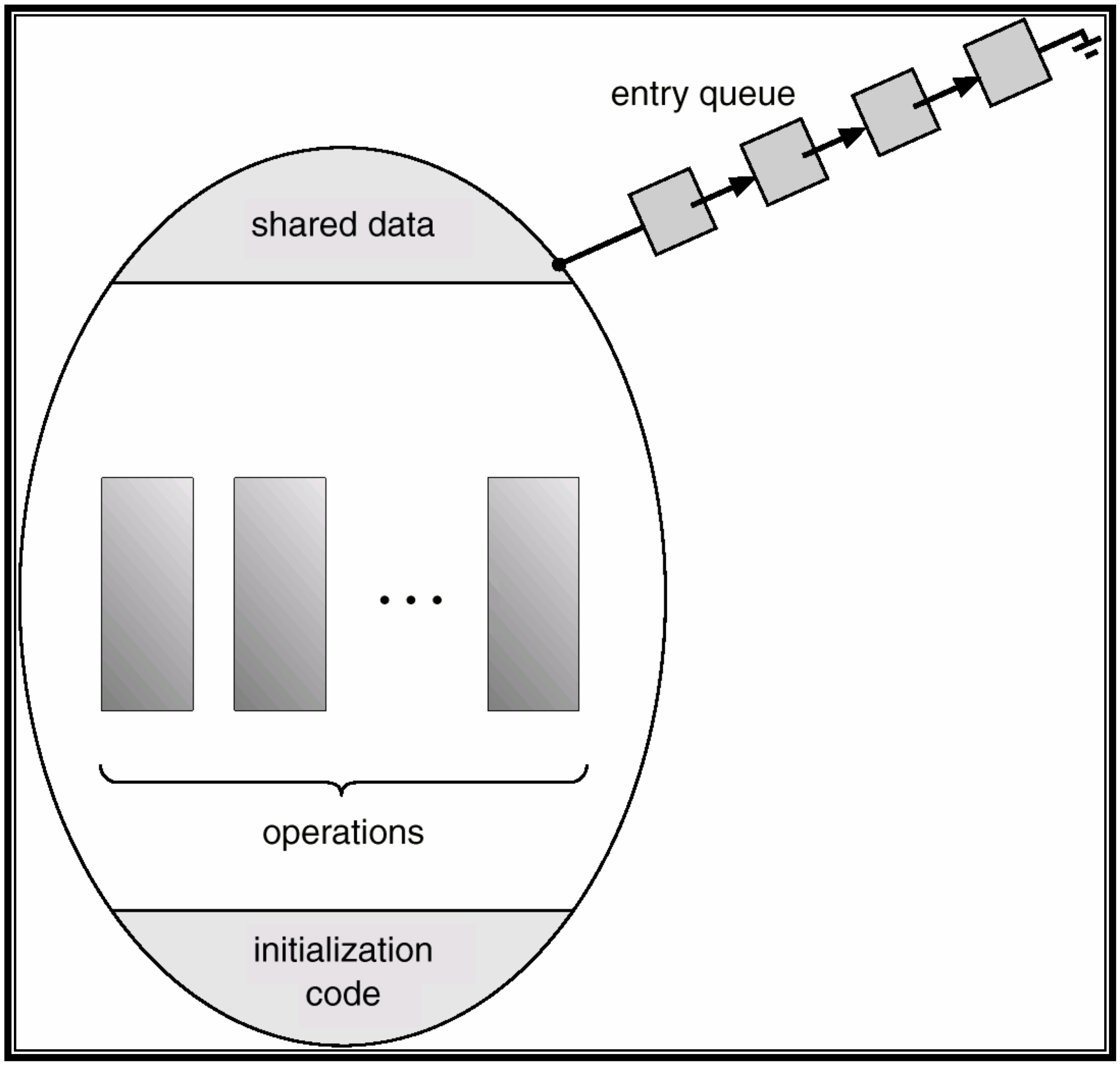
- **High-level synchronization** construct that allows the **safe sharing** of an abstract data type among concurrent processes.

```
monitor monitor-name {
    shared variable declarations
    procedure body P1 (…) { . . . }
          …
    procedure body P2 (…) {. . . }
    procedure body Pn (…) { . . .}

       { initialization code }
}
```

- Access to monitor code is **mutually exclusive** for caller

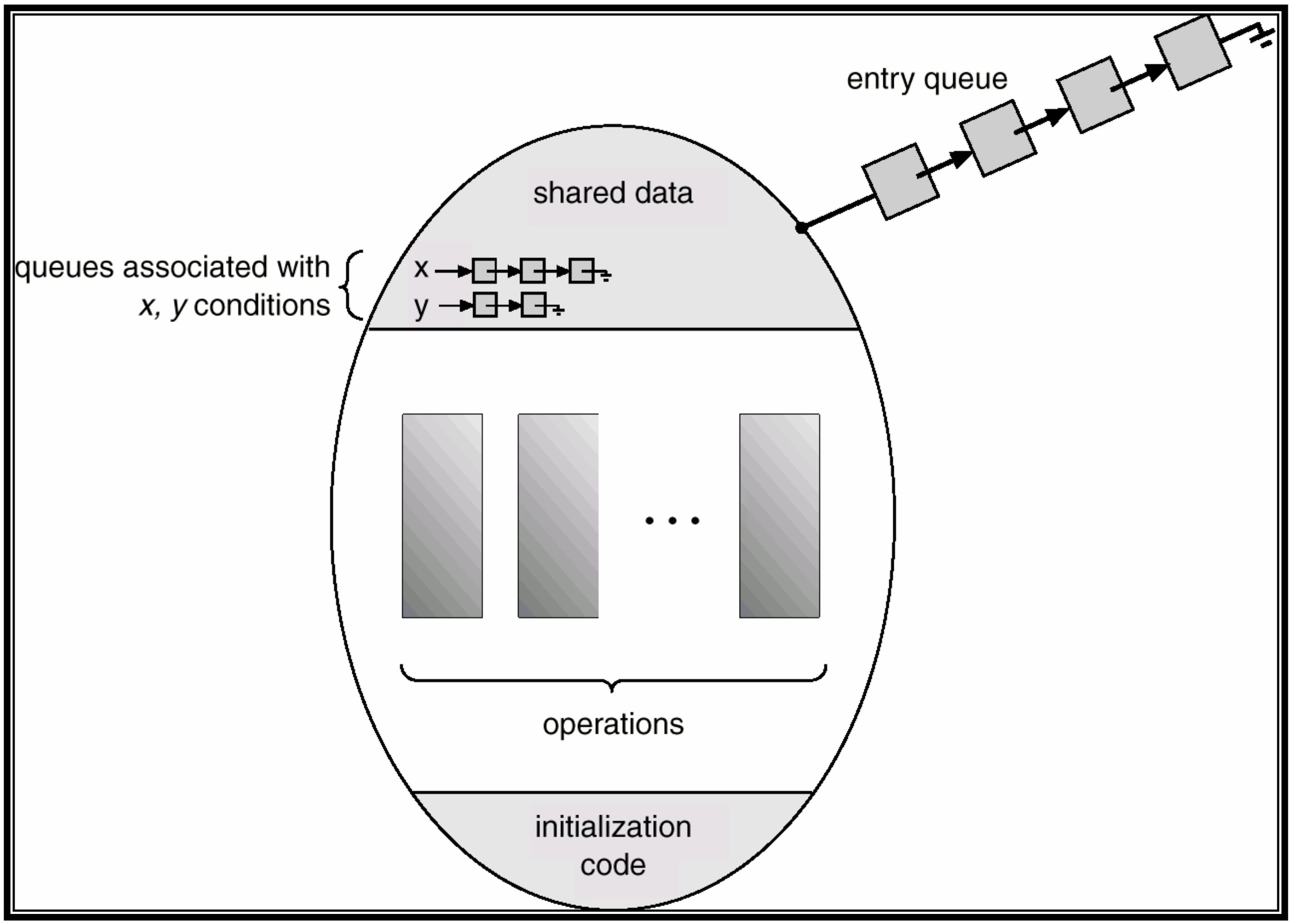
Schematic View of a Monitor



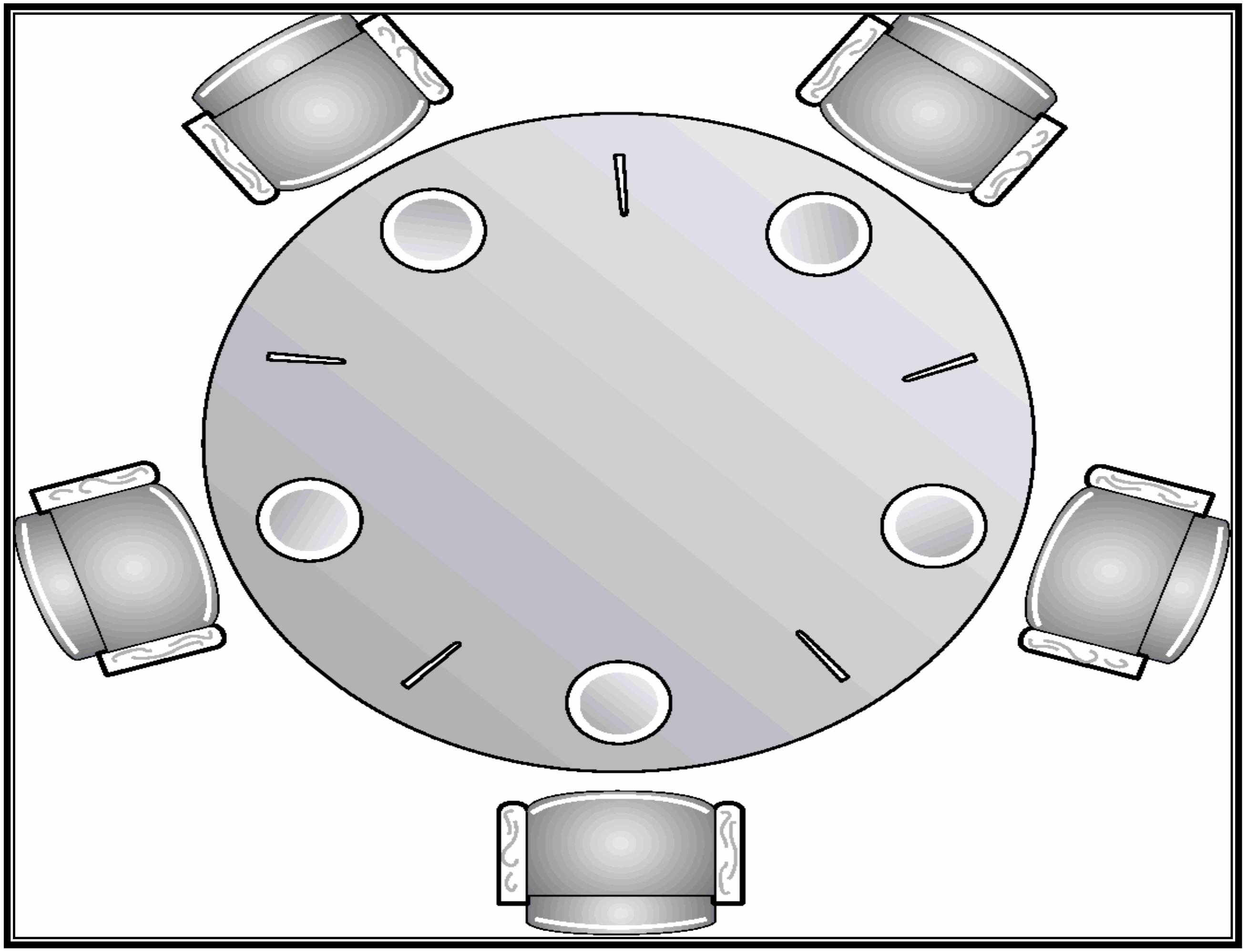
Condition Variables

- To allow a process to wait within the monitor, a **condition variable** must be declared, as **condition x, y;**
- Condition variables can only be used with the operations **wait** and **signal**.
  - **x.wait()** means that the process invoking this operation is suspended until another process invokes **x.signal();**
  - **x.signal** resumes **exactly one** suspended process. If no process is waiting, then the **signal** operation has **no** effect (**unlike a semaphore's signal**(…).)

Monitor With Condition Variables



Dining-Philosophers Problem



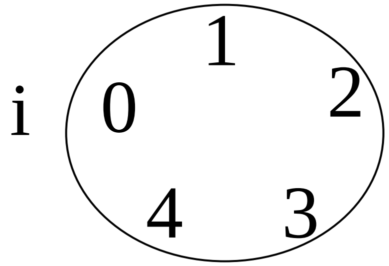
Dining Philosophers Example

```
monitor dp {
 enum {thinking, hungry, eating} state[5];
 condition self[5];
 void pickup(int i)
 void putdown(int i)
 void test(int i)
 void init() {
   for (int i = 0; i < 5; i++)
        state[i] = thinking;
 }
}
```

Dining Philosophers

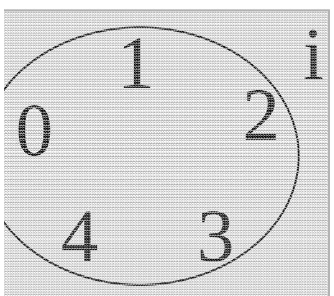
```
void pickup(int i) {
   state[i] = hungry;
   test[i];
   if (state[i] !=  eating)
        self[i].wait();
   }
}
```

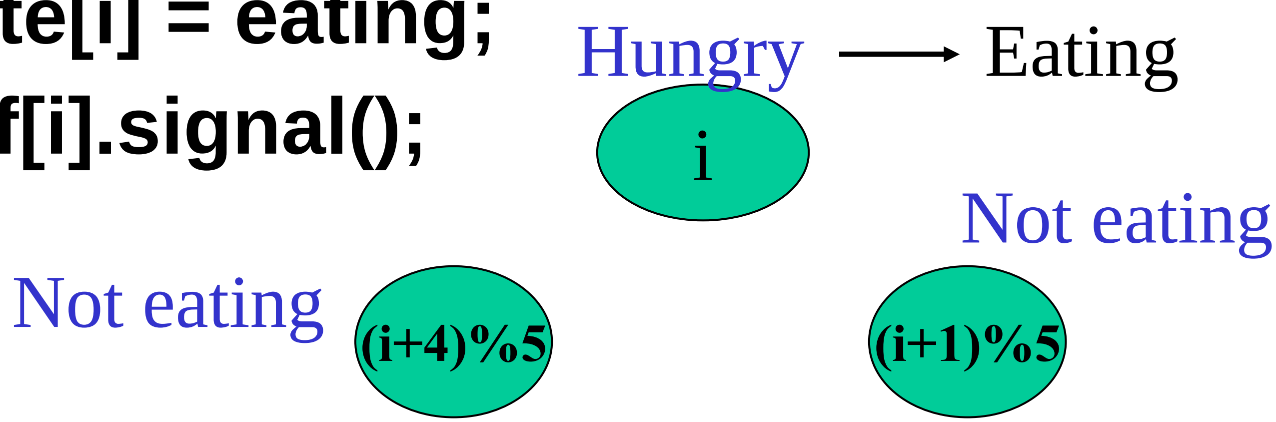
```
void putdown(int i) {
        state[i] = thinking;
        test( (i+4) % 5 );
        test( (i+1) % 5 );
   }
```



Dining Philosophers

```
void test(int i) {
    if ( (state[(i + 4) % 5] != eating) &&      //left neighbour
         (state[i] == hungry) &&                 //I am hungry
         (state[(i + 1) % 5] != eating) )        //right neighbour
    {
         state[i] = eating;
         self[i].signal();
    }
}
```





Example: Putdown

```
void putdown(int i) {
        state[i] = thinking;
        test((i+4) % 5);
        test((i+1) % 5);
  }
```

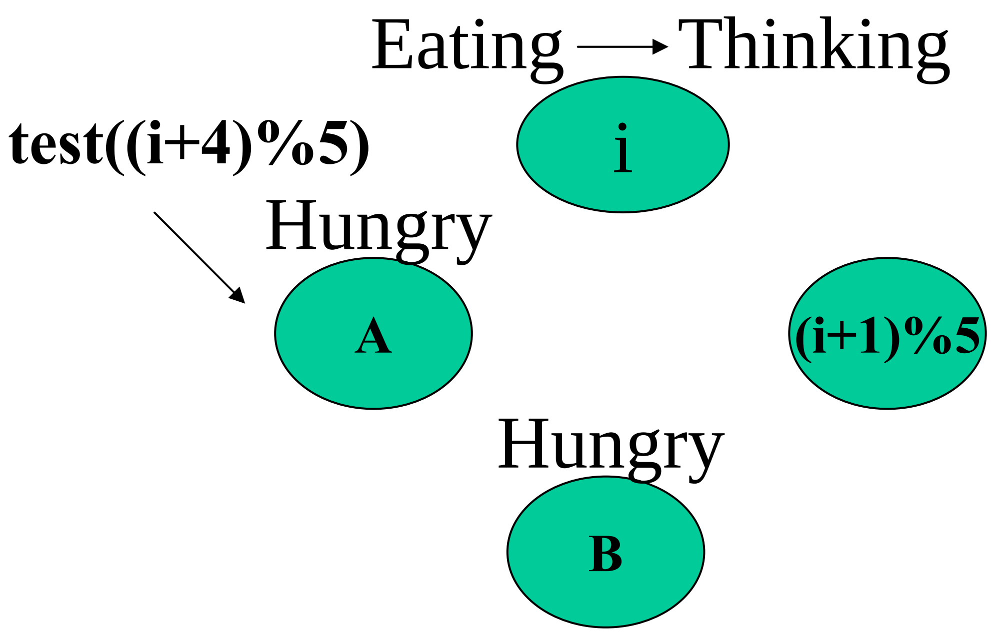
(2): putdown(i)

test(A) …

test(A):

If left ng. not eating **and**
“A” is hungry **and**
right ng. not eating **then**
set “A” to eat
signal(A) // wakeup A

putdown(i)



(1): pickup(A)

- **A** tried picking up a ch.stick
- Failed and put itself to sleep

NB: OS/161 CVs

- The notion of CVs in the context of monitors correspond to the notion of CVs asked from you in this current assignment (i.e., in OS/161)
- The **difference** between a monitor CV and an OS/161 CV is
  - For a **monitor the lock** that protects the monitor data structure (i.e., realizes mutual exclusion) **is implicit** – by virtue of the construct being a monitor
  - For the OS/161 / **second assignment CV the lock is explicit** and is passed as argument to the CV API / function calls you have to implement

Condition Variables

- Monitor's signal & wait are **condition variables**
- CVs also exist outside monitors, e.g., in Pthreads and in OS/161, *at least, hopefully soon …*
- CVs are a way for threads to notify each other (a notification system for threads)
- Instead of CVs threads could poll variables (I.e., lock, query, unlock, which is not efficient)
- Read the specification in `synch.h,` which tells you how to implement CVs

CV Example

```
#include <stdio.h>
#include <pthread.h>
#define NUM_THREADS  3
#define TCOUNT 10
#define COUNT_THRES 12

int     count = 0;
int     thread_ids[3] = {0,1,2};
pthread_mutex_t
   count_lock=PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t
   count_hit_threshold=PTHREAD_COND_INITIALIZER;
```

- This is an example based on pthreads.
- Here the “monitor” lock is made explicit
- This is not a monitor
- This is very similar to the OS/161 API of CVs

CV Example

```
main(void) {
  int       i;
  pthread_t threads[3];

  pthread_create(&threads[0], NULL, inc_count, (void
    *)&thread_ids[0]);
  pthread_create(&threads[1], NULL, inc_count, (void
    *)&thread_ids[1]);
  pthread_create(&threads[2], NULL, watch_count, (void
    *)&thread_ids[2]);

  for (i = 0; i < NUM_THREADS; i++) {
    pthread_join(threads[i], NULL);
  }
  return 0;
}
```

CV Example

```
void *inc_count(void *idp) {
  int i=0, save_state, save_type;
  int *my_id = idp;
  for (i=0; i<TCOUNT; i++) {
    pthread_mutex_lock(&count_lock);
    count++;
    printf(" … ");
    if (count == COUNT_THRES) {
      printf(" … ");
      pthread_cond_signal(&count_hit_threshold);  } // ends if
    pthread_mutex_unlock(&count_lock);  } // ends for
 return(NULL); } // ends inc_count procedure
```

However, if predictable scheduling behavior is required, then that **mutex** should be locked by the thread calling pthread_cond_signal().

CV Example

```
void *watch_count(void *idp) {
 int i=0, save_state, save_type;
 int *my_id = idp;
 printf("watch_count(): thread %d\n", *my_id);
 pthread_mutex_lock(&count_lock);
 while (count < COUNT_THRES) {
  pthread_cond_wait(&count_hit_threshold,
  &count_lock);
  printf(“ … “);
 }
 pthread_mutex_unlock(&count_lock);
 return(NULL);  // ends watch_count  }
```

Synchronization

Recap on Semaphores/Locks and CVS

Synchronization Mechanisms: Overview

- Semaphores (binary, counting)
  - Enforce **mutually exclusive** use of resources
  - Enforce **arbitrary execution patterns** (e.g., **sequential** or **ordering** constraints)
  - Enforce **synchronization constraints** (e.g., full, empty, ..)
- Locks and mutexes
  - Enforce **mutually exclusive** use of resources, **exclusively**
- Condition variables
  - Enforce **waiting for events and conditions** (e.g., value of data)
- Monitors (& critical region construct)
  - **Higher-level** synchronization primitives
  - **Condition variables** introduced in this context

Common Use-patterns of the Above

```
wait(mutex);
  … critical section
signal(mutex);
```

A	signal(flag)
wait(flag)	B

```
wait (empty);
wait (mutex);
  insert(…);
signal (mutex);
signal (full);
```

```
lock(l)
  … critical section
unlock(l);
```

Classical Problems of Synchronization

- (Bounded-Buffer Problem)
  - Already covered based on semaphores
- Readers and Writers Problem
- Dining-Philosophers Problem

Readers-Writers Problem

- The problem
  - Many readers may access critical section concurrently
  - Writer requires exclusive access to critical section
    - *If readers are in CS and a writer comes along, CS is drained*
    - If readers are in CS and a writer comes along, writer waits until there are no further readers
- Shared data
  semaphore mutex, wrt;
- Initially
  mutex = 1, wrt = 1;
  int readcount = 0;

Readers-Writers Problem **Writer Process**

- Exclusive access to critical section must be enforced via the semaphore, **wrt**

```
wait(wrt);   //write lock
             ...
        writing is performed
             ...
signal(wrt);
```

Readers-Writers Problem **Reader Process**

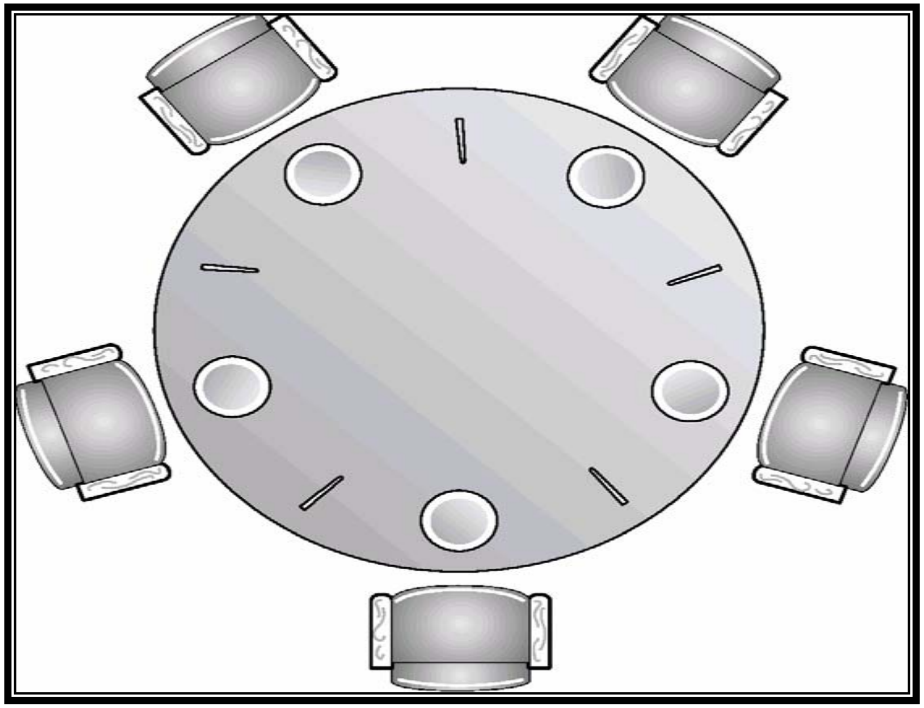
```
wait(mutex);
readcount++;
if (readcount == 1)
   wait(wrt);
signal(mutex);
    …
reading is performed
    …
wait(mutex);
readcount--;
if (readcount == 0)
   signal(wrt);
signal(mutex);
```

- Concurrent access by other readers
- Counts the number of readers in CS

For **1st reader**:
- If CS is not locked, enter and read
- …otherwise, wait on writer exiting, i.e., lock writer lock (wrt)

For **last reader** exciting CS:
- unlock writer lock

Dining-Philosophers Problem



- Shared data

  semaphore chopstick[5];
- Initially all values are 1

Dining-Philosophers Problem

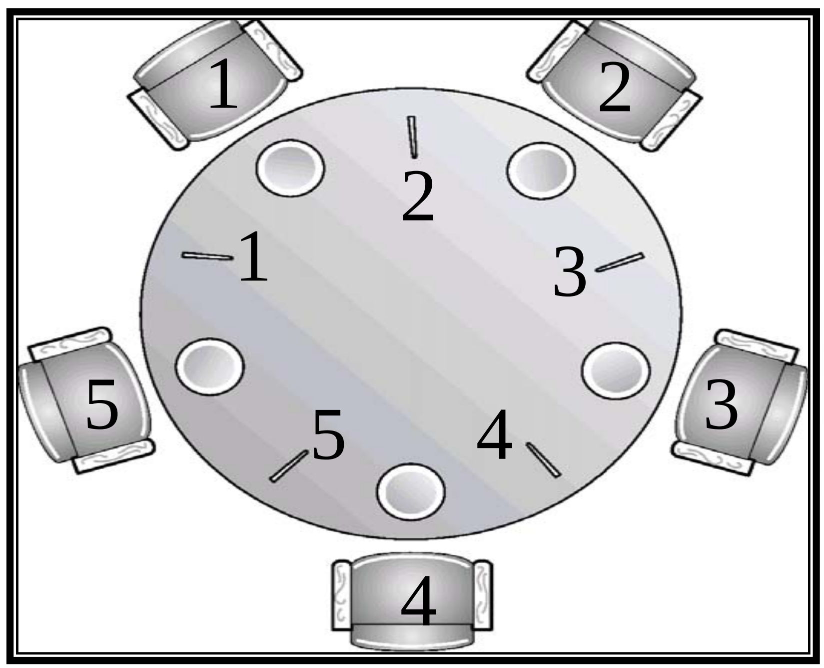
```
do {                              // Philosopher  i
   wait(chopstick[i])
   wait(chopstick[(i+1) % 5])
                  …
   eat
                  …
   signal(chopstick[i]);
   signal(chopstick[(i+1) % 5]);
                    …
    think
                       …
} while (TRUE);
```

Example Execution

wait(1)
wait(2)

wait(2)
wait(3)

wait(5)
wait(1)



Example Execution: Problem Case

1

wait(1)

wait(5) … ➘ wait(2) **2**

signal(5) … ***signal(2)***

signal(1) wait(4) ***signal(3)***

wait(3)

Hardware-based Solutions for Synchronization

Atomicity

Semaphore Implementation in OS/161

```
void P(struct semaphore *sem)
{
        int spl;
        assert(sem != NULL);
        spl = splhigh();
        while (sem->count==0) {
                thread_sleep(sem);
        }
        assert(sem->count>0);
        sem->count--;
        splx(spl);
}
```

Puts thread to sleep and … (?)

Why is there a while loop?

Is like our wait(sem).

Semaphores

- **Semaphore *S***, integer variable
- can only be accessed via two **indivisible** (atomic) operations

1. *wait* (*S*): // historically a.k.a. P(S)

while [ ] **do *nothing*;**

atomic

e.g., by disabling interrupts

busy waiting loop

2. *signal* (*S*): // historically a.k.a. V(S)

Implementation Alternative

wait(*S*):

atomic

signal(*S*):

atomic

Our Atomicity Assumption in Semaphores

- Our assumption was not obvious and not fully true
- Now, with a little help from the hardware
  - **TSE RX, Lock**   // Atomic test-and-set
  - Read ***Lock*** into register, *RX*
  - Store a non-zero value into memory location ***Lock***

  } —— Atomicity **guaranteed** by hardware !

  - i.e., no other process can access memory location until the operation has completed
  - CPU executing TSE, locks the memory bus to prevent access of memory from other CPUs (if multi CPU sys.)
- Supported by many hardware platforms (not by MIPS-1, ☺; but there we have splhigh/splx)

Synchronization Hardware

- TSE modifies the content of a word atomically
- As pseudo code below
- Implemented by one hardware instruction, **TSE**

```
Boolean TestAndSet(Boolean &target) {
    Boolean rv = target;
    target = true;
    return rv;
}
```

Atomicity **guaranteed** by hardware !

User-level Implementation

```
Lock:                        //enter_section
    TSE R, MUTEX             //cpy M. to R and set M to 1
    CMP R, #0                //was mutex 0?
    JZE ok                   //if 0, M. unlocked, jmp to ok
    CALL thread_yield        //M. busy, invoke scheduler
    JMP Lock                 //try again later
ok  RET

UN_Lock:                     //exit_section
   MV MUTEX,#0               //store 0 in mutex, i.e., unlock
   RET                       //return to caller
```

Applies to threads discussion only.

Mutual Exclusion with Test-and-Set

- **Shared data**:
  Boolean lock = false;
- Process P_i

do {

while (TestAndSet(lock)) ;

critical section

lock = false;

remainder section

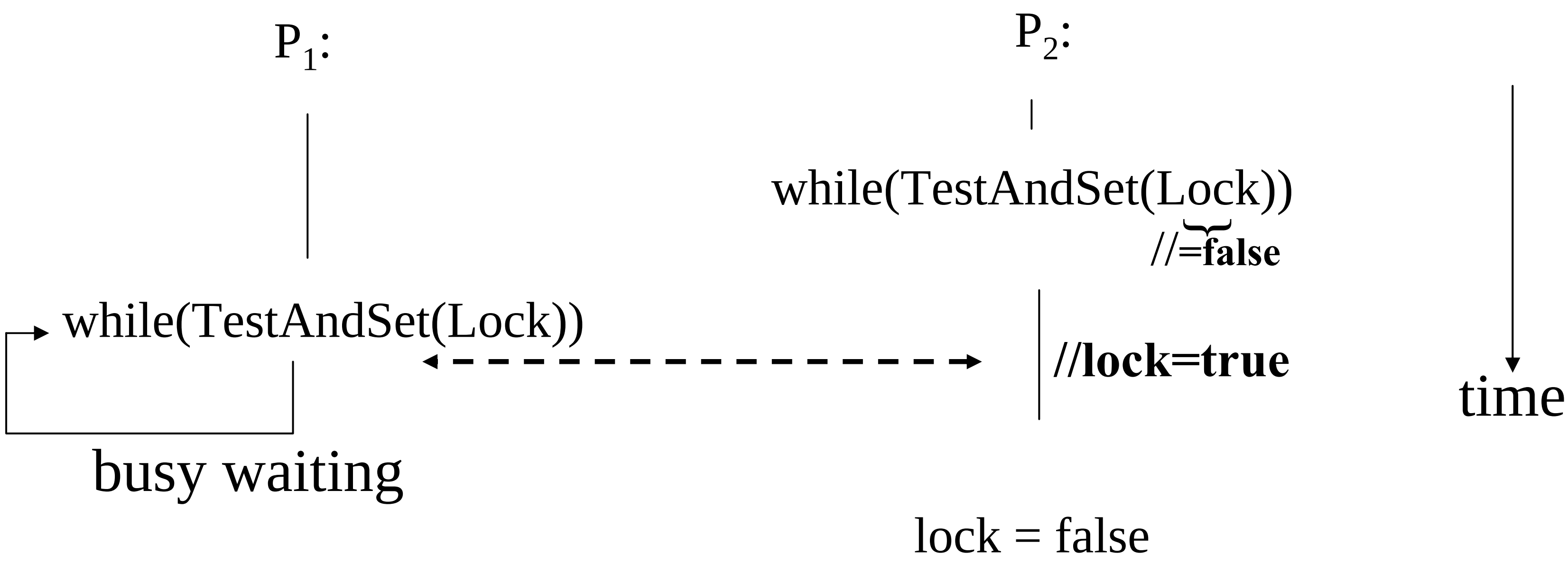
}

Busy waiting

```
enter_section:
        TSE R, Lock
        CMP R, #0
        JNE enter_section
        RET
leave_section:
        MOVE Lock, #0
        RET
```

Example: Timeline

Shared data: **lock = false;**



Atomicity Requirement Revisited

- Our assumption should now be clear; it was correct
- TSE could be used to enforce atomicity for semaphore implementation
- Disabling of interrupts could be used to enforce atomicity for semaphore implementation
- *How are semaphores implemented in OS/161?*
- *Is the semaphore implementation based on block() & wakeup() always busy waiting free?*

Software-based Solutions for Synchronization

Implementation Alternatives

- Disabling of interrupts
- Atomic instructions (e.g., TSE, SWAP, …)
- If neither of the above is available, *can the critical section problem still be solved?*
- This comes down to solving the critical section problem in software, i.e., algorithmically.

Model Process to Study Problem

- Our model process for looking at this problem
- 2 processes, P_0 and P_1
- General structure of process P_i (other process P_j)

do {

entry section

critical section

exit section

remainder section

} **while (TRUE)**;

Requirements for Solutions

1. **Mutual Exclusion**
2. **Progress**
3. **Bounded Waiting**

- Assume that each process executes at a non-zero speed
- No assumption concerning relative speed of the *n* processes.
- For the following algorithms 1 to 3, we assume two processes P_0 and P_1

Algorithm 1

Shared variables:

int turn; **turn = 0;** **// initialization**

turn == i $\Rightarrow P_i$ may enter CS

$P_{i:}$

```
do {          busy wait loop
    while (turn != i) ;          Entry section
      critical section
    turn = 1 - i;          Exit section
      remainder section
  } while (TRUE);
```

Algorithm 1

Shared variables:

- **int turn**; **turn = 0; // initialization**
- **turn - i** $\Rightarrow P_i$ may enter CS

$P_{i:}$

busy wait loop

do {

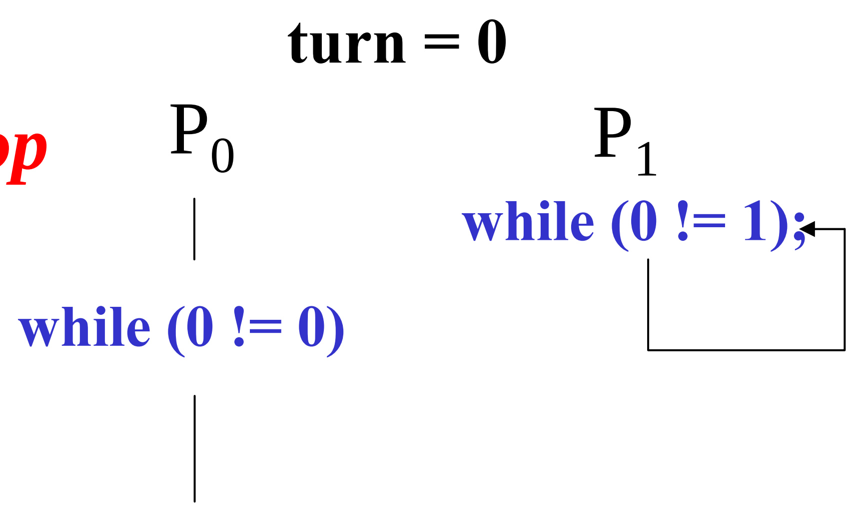
while (turn != i) ;

critical section

turn = j;

reminder section

} **while (TRUE)**;



turn = 0

P$_0$ P$_1$

while (0 != 1);

while (0 != 0)

Critical section

turn = 1

Critical section

while (1 != 0)

turn = 1 – 1 // =0

Critical section

Remainder section

turn = 1

while (1 != 0)

```
do {
    while (turn != i) ;
        critical section
    turn = j;
        reminder section
} while (TRUE);
```

Algorithm 1

- Enforces a **strictly alternating pattern** between both processes
  - P0, P1, P0, P1, P0
  - P0, P1, P1 is not possible
- That is **mutual exclusion** is guaranteed
- Progress is not (see previous case)

Algorithm 2

Shared variables

- **Boolean flag[2]**;
- **flag [0] = flag [1] = false**
- **flag [i] = true** $\Rightarrow$ P_i ready to enter its critical section

P_i

```
do {
  flag[i] = true;          Entry section
  while (flag[1 - i]) ;
    critical section
  flag [i] = false;        Exit section
    remainder section
} while (TRUE);
```

flag[0] = false   flag[1] = false

P_0   *P_1*

flag[1] = true
while(flag[0]);

flag[0] = true
while(flag[1]);

flag[1] = false

flag[0] = false   flag[1] = false

P_0	P_1
	flag[1] = true
flag[0] = true	
	while(flag[0]);
while(flag[1]);	

- Lacks progress requirement

Algorithm 3

- Combined shared variables of algorithms 1 and 2.
- Process P_i

do { // P0's perspective

flag [i]:= true; **//** **"I want to enter CS"**

turn = 1 - i; **//** **"Let P1 go ahead"**

while (flag [1-i] and turn == 1 – i) ;

critical section

flag [i] = false;

remainder section

} **while (TRUE);**

P_0

flag [0]:= true; turn = 1;

while (flag [1] and turn = 1) ;

flag[0] = false   flag[1] = false

P$_0$ *P*$_1$

flag[1] = true

turn = 0

flag[0] = true

turn = 1

turn = 0

while(flag[1] && turn == 1);

Depending on scheduling

Decision turn is either 1 or 0

Bakery Algorithm

(synchronization of n processes)

- Before entering its critical section, **process receives a number**.
- Holder of the **smallest number** enters the critical section **first** (*Bakery analogy*).
- If processes P_i and P_j receive **the same number** ("*due to scheduling accident* ☺")
  - if $i < j$, then P_i is served first
  - else P_j is served first (based on unique PIDs)
- The numbering scheme always generates numbers in **increasing order of enumeration**; i.e., 1,2,3,3,3,3,4,5...

Bakery Algorithm

- Notation < corresponds to lexicographical order
  - *(a,b)* is *(ticket #, process id)*
  - (a,b) < (c,d) if $a < c$ or if $a = c$ and $b < d$
  - max ($a_0, \ldots, a_{n-1}$) is a number, k, such that $k \geq a_i$ for $i = 0, \ldots, n - 1$
- Shared data // initialization

boolean choosing[n]; // all false

int nr [n]; // all 0

High-level Description of Algorithm

- Indicate that you are choosing a number
- Choose a number
  – This may occur concurrently and therefore result in two chosen numbers being equal (i.e., kind of race condition)
- Indicate that you have completed choosing a number
- Select the process with the smallest number to proceed into the critical section

Bakery Algorithm: Process P_i

```
do {
   choosing[i] = true;   // indicate choosing a number
   nr[i] = max( nr[0], nr[1], …, nr[n – 1] ) + 1;
   choosing[i] = false;   // has chosen a number
   for (j = 0; j < n; j++) { // process with smallest nr.
        while (choosing[j]) ; // wait if Pj chooses a nr
        while (  (nr[j] != 0) && ((nr[j], j) < (nr[i],i))  );
   }
    critical section
   nr[i] = 0;
    remainder section
} while (TRUE);
```

If P_j has a number, check it out

Is it smaller than my own nr.?

Why May Two Numbers Be Equal?

If this happens concurrently both numbers may be equal

Nr[0] = max(0, …0)

→ Nr[k] = max(0, …0)

+ 1

←

→ + 1

= 1 Context switch = 1

Both are equal to 1 at this point.

Bakery Algorithm (without choosing)

```
do {
   nr[i] = max( nr[0], nr[1], …, nr[n – 1] ) + 1;
   for (j = 0; j < n; j++) {
     while (  (nr[j] != 0) && ( (nr[j], j ) < ( nr[i],i) )  ) ;
   }
        critical section
   nr[i] = 0;
        remainder section
} while (TRUE);
```

Problem Case

nr[0] = max(0, …0) …

nr[1] = max(0, …0) +1
= 1

nr[0]=0!

Context switch

Critical section

= 1

Does P_1 have a smaller number? Both are 1.

Well, break ties by looking at PID (0 & 1, here),

(nr[1],1) < (nr[0],0) // (1,1) < 1,0) - false

therefore enter CS (violation of mutual exclusion)

Critical section

Context switch

Critical section

Adding choosing[i] back in

choosing[0] = true
nr[0] = max(0, …0) …

choosing[1] = true
nr[1] = max(0, …0) +1
= 1

Here, we would have waited for P_0 to choose a number.

for (…)
while (choosing[i]);

Then we would have let P_0 proceed into its CS first

```
while (  …
   ( (nr[0], 0 ) < ( nr[1],1) )  ) ;
//     (1,0)        <  (1,1)  - true
// therefore busy wait
```

Binary Semaphore

Two Types of Semaphores

- ***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.
- Is a binary semaphore the same as a lock?
- **Can we implement a counting semaphore *S* as a binary semaphore**?

Implementing ***S*** as a Binary Semaphore

- Data structures:

  binary-semaphore S1, S2;

  int C:

- Initialization:

  S1 = 1

  S2 = 0

  C = initial value of semaphore **S**

Implementing ***S***

Wait(C) operation:

```
wait(S1);
C--;
if (C < 0) {
        signal(S1);
        wait(S2);        }
signal(S1);
```

Signal(C) operation:

```
wait(S1);
C ++;
if (C <= 0)
    signal(S2);
else
    signal(S1);
```

Synchronization Mechanisms Summary

- Race conditions
- Semaphores (binary, counting)
  - Enforce **mutually exclusive** use of resources
  - Enforce **arbitrary execution patterns** (e.g., **sequential** or **ordering** constraints)
  - Enforce **synchronization constraints** (e.g., full, empty, readers/writers constraint)
- Locks and mutexes
  - Enforce **mutually exclusive** use of resources, **exclusively**
- Condition variables
  - Enforce **waiting for events and conditions** (e.g., value of data)

Synchronization Mechanisms Summary

- Monitors (& critical region construct)
  – **Higher-level** synchronization primitives
  – **Condition variables** introduced in this context
- Disabling of interrupts to enforce atomicity
- Test-and-Set Instruction
- Classical problems
  – Bounded buffer problem
  – Dining Philosophers problem
  – Reader Writers problem (reader priority)

Outlook

- Inter-process communication
- OS Architecture
- Scheduling
- Memory management
- …

Critical Region Construct

Critical Region Construct

- High-level synchronization construct
- A shared variable ***v*** of type ***T***, is declared as:

  v: shared T
- Variable ***v*** accessed only inside statement

  region v when B do S

  where ***B*** is a Boolean expression.
- While statement ***S*** is being executed, no other process can access variable ***v***.

Critical Regions

- Regions referring to the same shared variable exclude each other in time.
- When a process tries to execute the region statement, the Boolean expression *B* is evaluated.
  - If *B* is true, statement *S* is executed.
  - If it is false, the process is delayed until *B* becomes true and no other process is in the region associated with *v*.

Example – Bounded Buffer

- Shared data:

```
struct buffer {
    int pool[n];
    int count, in, out;
}
```

Bounded Buffer Producer Process

- Producer process inserts **nextp** into the shared buffer

```
region buffer when( count < n) {
        pool[in] = nextp;
        in:= (in+1) % n;
        count++;
}
```

Bounded Buffer Consumer Process

- Consumer process removes an item from the shared buffer and puts it in **nextc**

```
region buffer when (count > 0) {
    nextc = pool[out];
    out = (out+1) % n;
    count--;
}
```