Chapter 7: Process Synchronization

- Background
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- Semaphores
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Background

- Concurrent access to shared data may result in data inconsistency.
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes.
- Shared-memory solution to bounded-butter problem (Chapter 4) allows at most $n - 1$ items in buffer at the same time. A solution, where all N buffers are used is not simple.
  - Suppose that we modify the producer-consumer code by adding a variable *counter*, initialized to 0 and incremented each time a new item is added to the buffer

Bounded-Buffer

- Shared data

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


Bounded-Buffer

- Producer process

```
item nextProduced;

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

Bounded-Buffer

- Consumer process

```
item nextConsumed;

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


Bounded Buffer

- The statements

  counter++;
  counter--;

  must be performed *atomically*.

- Atomic operation means an operation that completes in its entirety without interruption.

Bounded Buffer

- The statement "**count++**" may be implemented in machine language as:

  register1 = counter
  register1 = register1 + 1
  counter = register1

- The statement "**count--**" may be implemented as:

  register2 = counter
  register2 = register2 – 1
  counter = register2

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 processes are scheduled.

Bounded Buffer

- Assume **counter** is initially 5. One interleaving of statements is:

  producer: **register1 = counter** (*register1 = 5*)
  producer: **register1 = register1 + 1** (*register1 = 6*)
  consumer: **register2 = counter** (*register2 = 5*)
  consumer: **register2 = register2 – 1** (*register2 = 4*)
  producer: **counter = register1** (*counter = 6*)
  consumer: **counter = register2** (*counter = 4*)

- The value of **count** may be either 4 or 6, where the correct result should be 5.

Race Condition

- **Race condition**: The situation where several processes access – and manipulate shared data concurrently. The final value of the shared data depends upon which process finishes last.
- To prevent race conditions, concurrent processes must be **synchronized**.

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.

Solution to Critical-Section Problem

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 nonzero speed
   - No assumption concerning relative speed of the *n* processes.

Initial Attempts to Solve Problem

- Only 2 processes, P_0 and P_1
- General structure of process P_i (other process P_j)

```
do {
    entry section
        critical section
    exit section
        reminder section
} while (1);
```

- Processes may share some common variables to synchronize their actions.

Algorithm 1

- Shared variables:
  - **int turn**;
    initially **turn = 0**
  - **turn - i** $\Rightarrow P_i$ can enter its critical section
- Process P_i

```
do {
    while (turn != i) ;
        critical section
    turn = j;
        reminder section
} while (1);
```

- Satisfies mutual exclusion, but not progress

Algorithm 2

- Shared variables
  - **boolean flag[2]**;
    initially **flag [0] = flag [1] = false.**
  - **flag [i] = true** ⇒ P_i ready to enter its critical section
- Process P_i

```
do {
    flag[i] := true;
    while (flag[j]) ;
        critical section
    flag [i] = false;
        remainder section
} while (1);
```

- Satisfies mutual exclusion, but not progress requirement.

Algorithm 3

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

```
do {
    flag [i]:= true;
    turn = j;
    while (flag [j] and turn = j) ;
        critical section
    flag [i] = false;
        remainder section
} while (1);
```

- Meets all three requirements; solves the critical-section problem for two processes.
- Exercise: Read and understand the proof.

Bakery Algorithm

Critical section for n processes

- Before entering its critical section, process receives a number. Holder of the smallest number enters the critical section.
- If processes P_i and P_j receive the same number, if $i < j$, then P_i is served first; else P_j is served first.
- The numbering scheme always generates numbers in increasing order of enumeration; i.e., 1,2,3,3,3,3,4,5...

Bakery Algorithm

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

```
boolean choosing[n];
int number[n];
```

Data structures are initialized to **false** and **0** respectively

Bakery Algorithm

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


Synchronization Hardware

- Test and modify the content of a word atomically

  .

```
boolean TestAndSet(boolean &target) {
    boolean rv = target;
    target = true;

    return rv;
}
```

Mutual Exclusion with Test-and-Set

- Shared data:

  boolean lock = false;

- Process P_i

```
do {
   while (TestAndSet(lock)) ;
      critical section
   lock = false;
      remainder section
}
```


Synchronization Hardware

- Atomically swap two variables.

```
void Swap(boolean &a, boolean &b) {
   boolean temp = a;
   a = b;
   b = temp;
}
```

Mutual Exclusion with Swap

- Shared data (initialized to **false**):
  boolean lock;
  boolean waiting[n];
- Process P_i

```
do {
    key = true;
    while (key == true)
              Swap(lock,key);
        critical section
    lock = false;
        remainder section
}
```


Semaphores

- Semaphores were invented by Dijkstra in 1965, and can be thought of as a generalized locking mechanism
  - A semaphore supports two **atomic** operations, **P / wait** and **V / signal**
    - For critical section, the semaphore initialized to 1
    - Before entering the critical section, a thread calls "**P(semaphore)**", or sometimes "**wait(semaphore)**"
    - After leaving the critical section, a thread calls "**V(semaphore)**", or sometimes "**signal(semaphore)**"

Semaphores

- Semaphore “s” is initially 1
- Before entering the critical section, a thread calls “**P(s)**” or “**wait(s)**”
  - wait (s):
    - s = s – 1
    - if (s < 0)

      block the thread that called wait(s) on a queue associated with semaphore s
    - otherwise

      let the thread that called wait(s) continue into the critical section
- After leaving the critical section, a thread calls “**V(s)**” or “**signal(s)**”
  - signal (s):
    - s = s + 1
    - if (s ≤ 0), then

      wake up one of the threads that called wait(s), and run it so that it can continue into the critical section

Critical Section of *n* Processes

- Shared data:

  semaphore mutex; // initially *mutex* = 1
- Process *Pi:*

```
do {
   wait(mutex);
      critical section
   signal(mutex);
      remainder section
} while (1);
```

Semaphores – Operation & Values

- Semaphores (simplified slightly):

wait (s):	signal (s):
s = s – 1	s = s + 1
if (s < 0) block the thread that called wait(s)	if (s ≤ 0) wake up & run one of the waiting threads
otherwise continue into CS	

- Semaphore values:
  - Positive semaphore = number of (additional) threads that can be allowed into the critical section
  - Negative semaphore = number of threads blocked (note — there's also one in CS)
  - *Binary semaphore* has an initial value of 1
  - *Counting semaphore* has an initial value greater than 1

Semaphore Variants

- Semaphores from last time (simplified):

wait (s):	signal (s):
s = s – 1	s = s + 1
if (s < 0) block the thread that called wait(s)	if (s ≤ 0) wake up one of the waiting threads
otherwise continue into CS	

- "Classical" version of semaphores:

wait (s):	signal (s):
if (s ≤ 0) block the thread that called wait(s)	if (a thread is waiting) wake up one of the waiting threads
s = s – 1	s = s + 1
continue into CS	

- Do both work? What is the difference??

Semaphore Implementation 1

- Implementing semaphores using *busy-waiting*:

wait (s):
```
while (s ≤ 0)
   do nothing;
s = s – 1
```

signal (s):
```
s = s + 1
```

- Evaluation:
  - Doesn't support queue of blocked threads waiting on the semaphore
  - Waiting threads wastes time *busy-waiting* (doing nothing useful, wasting CPU time)
  - The code inside wait(s) and signal(s) is a critical section also, and it's not protected

Semaphore Implementation 2

- Implementing semaphores (not fully) by *disabling interrupts*:

wait (s):
```
disable interrupts
while (s ≤ 0)
   do nothing;
s = s – 1
enable interrupts
```

signal (s):
```
disable interrupts
s = s + 1
enable interrupts
```

- Evaluation:
  - Doesn't support queue of blocked threads waiting on the semaphore
  - Waiting threads wastes time *busy-waiting* (doing nothing useful, wasting CPU time)
  - Doesn't work on multiprocessors
  - Can interfere with timer, which might be needed by other applications
  - OK for OS to do this, but users aren't allowed to disable interrupts! (Why not?)

Semaphore Implementation 3

- Implementing semaphores (not fully) using a *test&set instruction*:

wait (s):	signal (s):
while (test&set(lk)!=0)	while (test&set(lk)!=0)
do nothing;	do nothing;
while (s ≤ 0)	s = s + 1
do nothing;	
s = s – 1	
lk = 0	lk = 0

- Operation:
  - Lock "lk" has an initial value of 0
  - If "lk" is free (lk=0), test&set atomically:
    - reads 0, sets value to 1, and returns 0
    - loop test fails, meaning lock is now busy
  - If "lk" is busy (lk=1), test&set atomically:
    - reads 1, sets value to 1, and returns 1
    - loop test is true, so loop continues until someone releases the lock

Semaphore Implementation

- Define a semaphore as a record

```
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

- Semaphore operations now defined as

void *wait*(semaphore *S*):

```
        S.value--;
        if (S.value < 0) {
                add this process to S.L;
                block;
        }
```

void *signal*(semaphore *S*):

```
        S.value++;
        if (S.value <= 0) {
                remove a process P from S.L;
                wakeup(P);
        }
```


Semaphore as a General 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*

Deadlock and Starvation

- **Deadlock** – two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes.
- Let *S* and *Q* be two semaphores initialized to 1

P_0	P_1
wait(*S*);	*wait*(*Q*);
wait(*Q*);	*wait*(*S*);
⋮	⋮
signal(*S*);	*signal*(*Q*);
signal(*Q*)	*signal*(*S*);

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

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.
- Can 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* operation

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

- *signal* operation

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

Classical Problems of Synchronization

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

Bounded-Buffer Problem

- Shared data

  semaphore full, empty, mutex;

  Initially:

  full = 0, empty = n, mutex = 1

Bounded-Buffer Problem Producer Process

```
do {
        …
    produce an item in nextp
        …
    wait(empty);
    wait(mutex);
        …
    add nextp to buffer
        …
    signal(mutex);
    signal(full);
} while (1);
```


Bounded-Buffer Problem Consumer Process

```
do {
    wait(full)
    wait(mutex);
        …
    remove an item from buffer to nextc
        …
    signal(mutex);
    signal(empty);
        …
    consume the item in nextc
        …
} while (1);
```

First Readers-Writers Problem

- No reader is kept waiting unless a writer has already received permission to write
- Shared data

  semaphore mutex, wrt;

  Initially

  mutex = 1, wrt = 1, readcount = 0

Readers-Writers Problem Reader Process

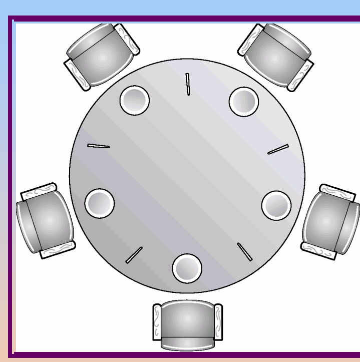
```
wait(mutex);
readcount++;
if (readcount == 1)
        wait(rt);
signal(mutex);
         …
   reading is performed
         …
wait(mutex);
readcount--;
if (readcount == 0)
   signal(wrt);
signal(mutex):
```

Readers-Writers Problem Writer Process

```
wait(wrt);
        …
    writing is performed
        …
signal(wrt);
```

- Q: Could there be starvation?
- Other variations on problem:
  - 2nd Reader-Writer problem: any ready writer performs write as soon as possible i.e. no new readers are admitted.

Dining-Philosophers Problem



- Shared data

semaphore chopstick[5];

Initially all values are 1

Dining-Philosophers Problem

- Philosopher *i*:

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

- **Possibility of deadlock**
- **Exercise: Read about possible solutions and work out how to do them.**

Semaphores in Nachos

- The class Semaphore is defined in **threads/ synch.h** and **synch.cc**
  - The classes Lock and Condition are also defined , but their member functions are empty (implementation left as exercise)
- Interesting functions:
  - Semaphores:
    - Semaphore::Semaphore( ) — creates a semaphore with specified name & value
    - Semaphore::P( ) — semaphore wait
    - Semaphore::V( ) — semaphore signal
  - Locks:
    - Lock::Acquire( )
    - Lock::Release( )
  - Condition variables:
    - Condition::Wait( )
    - Condition::Signal( )

Semaphores in Nachos – P()

```
void
Semaphore::P()
{
   IntStatus oldLevel = interrupt->
                     SetLevel(IntOff);              // disable interrupts

   while (value == 0) {                            // sema not avail
                     queue->
                                  // so go to sleep
                                              Append((void *)currentThread);
                     currentThread->Sleep();
   }

   value--;                                                             //
     semaphore available,

                                              // consume its value

     (void) interrupt->                      // re-enable interrupts
                     SetLevel(oldLevel);
}
```


Semaphores in Nachos – V()

```
void
Semaphore::V()
{
   Thread *thread;

   IntStatus oldLevel = interrupt->
                     SetLevel(IntOff);

   thread = (Thread *)queue->Remove();
   if (thread != NULL)        // make thread ready,
                                                       // consuming
     the V immediately
                     scheduler->ReadyToRun(thread);

   value++;

   (void) interrupt->SetLevel(oldLevel);
}
```

Critical Regions

- 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--;
}
```


Implementation region *x* when *B* do *S*

- Associate with the shared variable *x*, the following variables:

  semaphore mutex, first-delay, second-delay;
  int first-count, second-count;

- Mutually exclusive access to the critical section is provided by **mutex**.
- If a process cannot enter the critical section because the Boolean expression **B** is false, it initially waits on the **first-delay** semaphore; moved to the **second-delay** semaphore before it is allowed to reevaluate *B*.

Implementation

- Keep track of the number of processes waiting on **first-delay** and **second-delay**, with **first-count** and **second-count** respectively.
- The algorithm assumes a FIFO ordering in the queuing of processes for a semaphore.
- For an arbitrary queuing discipline, a more complicated implementation is required.

Monitors

- 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
        }
}
```

Monitors

- To allow a process to wait within the monitor, a **condition** variable must be declared, as

  condition x, y;

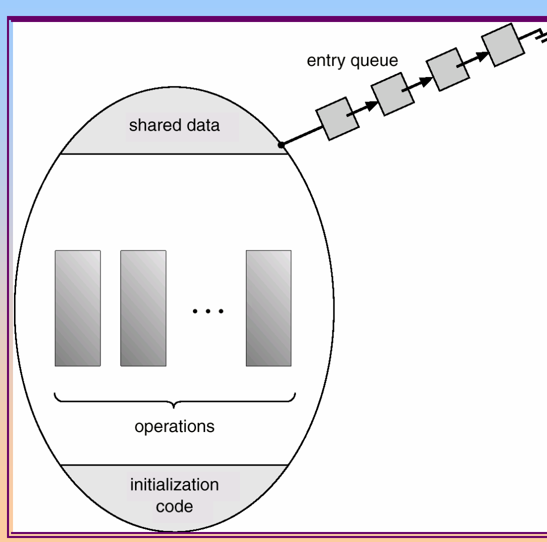
- Condition variable can only be used with the operations **wait** and **signal**.
  - The operation

    x.wait();

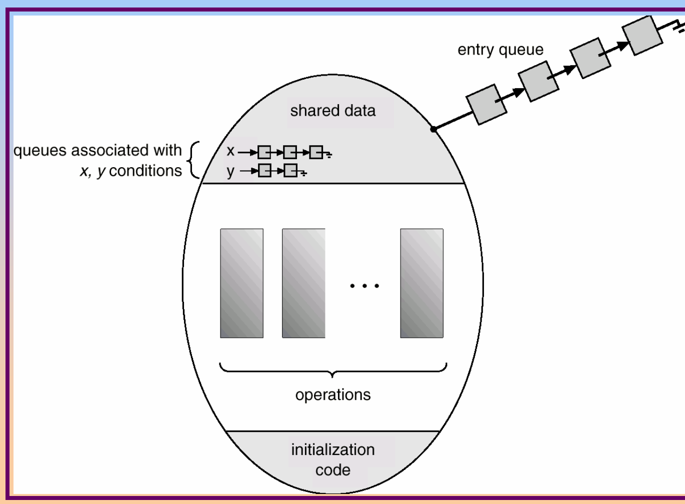
    means that the process invoking this operation is suspended until another process invokes

    x.signal();
  - The **x.signal** operation resumes exactly one suspended process. If no process is suspended, then the **signal** operation has no effect.

Schematic View of a Monitor



Monitor With Condition Variables



Dining Philosophers Example

```
monitor dp
{
  enum {thinking, hungry, eating} state[5];
  condition self[5];
  void pickup(int i)          // following slides
  void putdown(int i)         // following slides
  void test(int i)            // following slides
  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 left and right neighbors
        test((i+4) % 5);
        test((i+1) % 5);
}
```


Dining Philosophers

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

Monitor Implementation Using Semaphores

- Variables

```
semaphore mutex;  // (initially  = 1)
semaphore next;     // (initially  = 0)
int next-count = 0;
```

- Each external procedure ***F*** will be replaced by

```
wait(mutex);
   …
 body of F;
   …
if (next-count > 0)
  signal(next)
else
  signal(mutex);
```

- Mutual exclusion within a monitor is ensured.

Monitor Implementation

- For each condition variable ***x***, we have:

```
semaphore x-sem; // (initially  = 0)
int x-count = 0;
```

- The operation **x.wait** can be implemented as:

```
x-count++;
if (next-count > 0)
     signal(next);
else
     signal(mutex);
wait(x-sem);
x-count--;
```

Monitor Implementation

- The operation **x.signal** can be implemented as:

```
if (x-count > 0) {
    next-count++;
    signal(x-sem);
    wait(next);
    next-count--;
}
```


Monitor Implementation

- *Conditional-wait* construct: **x.wait(c);**
  - **c** – integer expression evaluated when the **wait** operation is executed.
  - value of **c** (a *priority number*) stored with the name of the process that is suspended.
  - when **x.signal** is executed, process with smallest associated priority number is resumed next.
- Check two conditions to establish correctness of system:
  - User processes must always make their calls on the monitor in a correct sequence.
  - Must ensure that an uncooperative process does not ignore the mutual-exclusion gateway provided by the monitor, and try to access the shared resource directly, without using the access protocols.

Solaris 2 Synchronization

- Implements a variety of locks to support multitasking, multithreading (including real-time threads), and multiprocessing.
- Uses *adaptive mutexes* for efficiency when protecting data from short code segments.
- Uses *condition variables* and *readers-writers* locks when longer sections of code need access to data.
- Uses *turnstiles* to order the list of threads waiting to acquire either an adaptive mutex or reader-writer lock.

Windows 2000 Synchronization

- Uses interrupt masks to protect access to global resources on uniprocessor systems.
- Uses *spinlocks* on multiprocessor systems.
- Also provides *dispatcher objects* which may act as wither mutexes and semaphores.
- Dispatcher objects may also provide *events*. An event acts much like a condition variable.