Process Synchronization

- Background
- The Critical-Section Problem
- Synchronization Hardware
- Semaphores
- Classical Problems of Synchronization

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 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.

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 $(a_0,\ldots, a_{n-1})$ is a number, k, such that $k \geq a_i$ for i - 0, $\ldots, n - 1$
- 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;
    tqrget = 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
}
```

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
$wait(S);$	$wait(Q);$
$wait(Q);$	$wait(S);$
$\vdots$	$\vdots$
$signal(S);$	$signal(Q);$
$signal(Q)$	$signal(S);$

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

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);
```

Readers-Writers Problem

- Shared data

  semaphore mutex, wrt;

  Initially

  mutex = 1, wrt = 1, readcount = 0

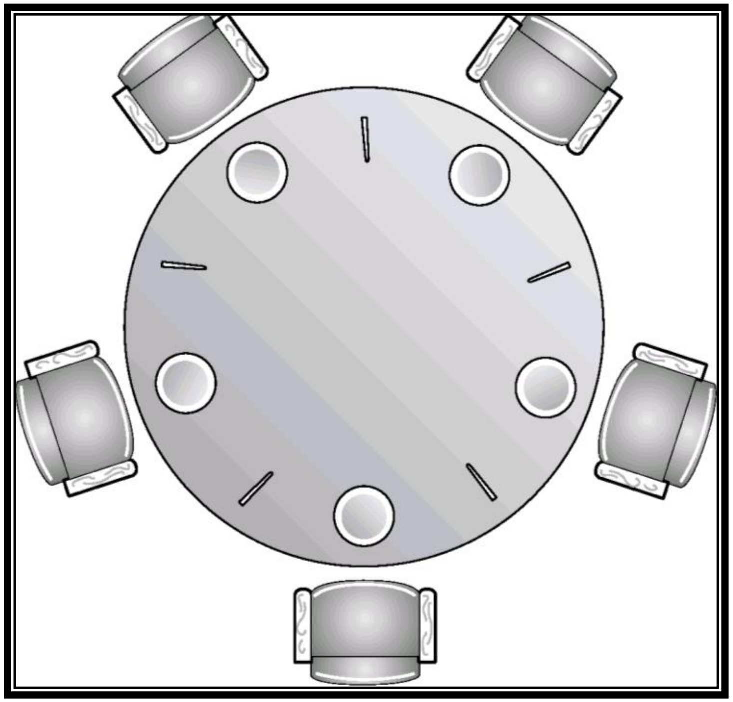
Readers-Writers Problem Writer Process

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

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):
```

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);
```

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

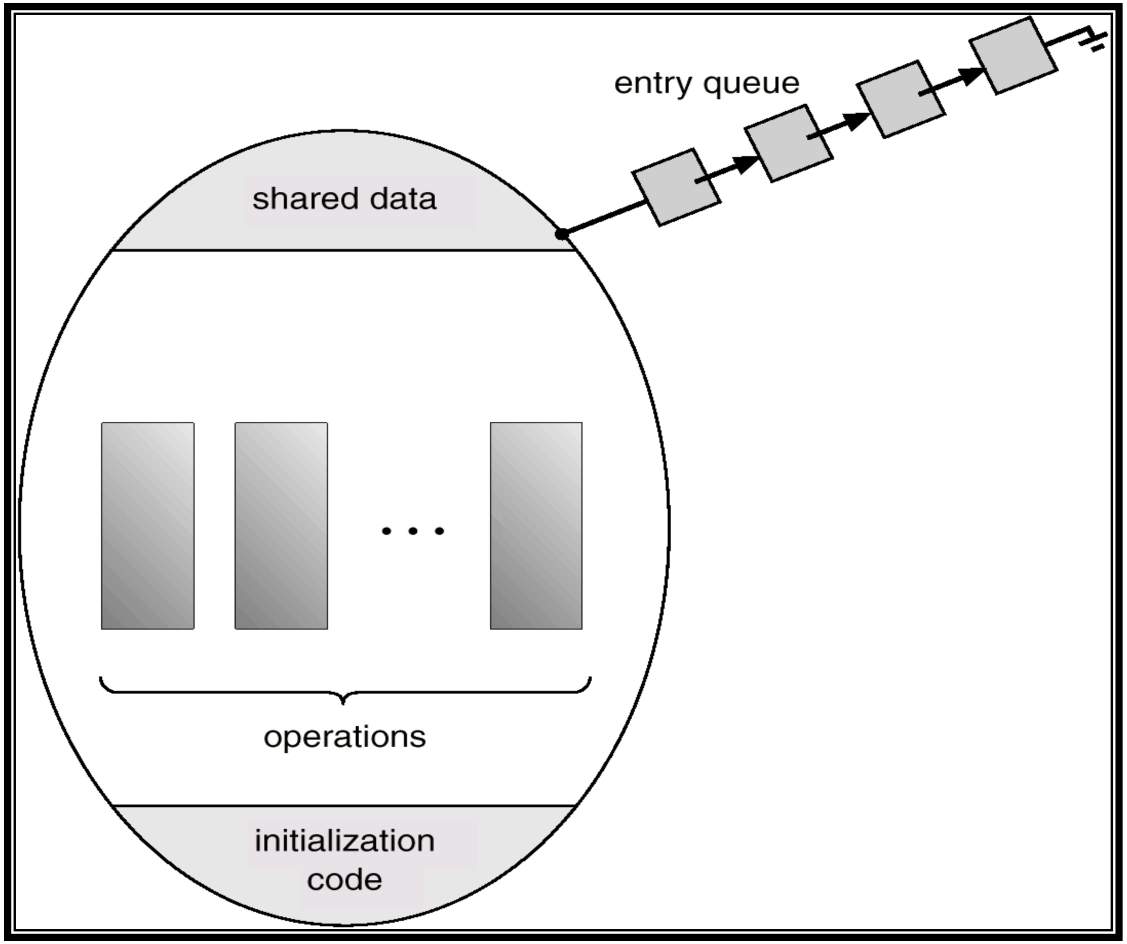
    x.wait();

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

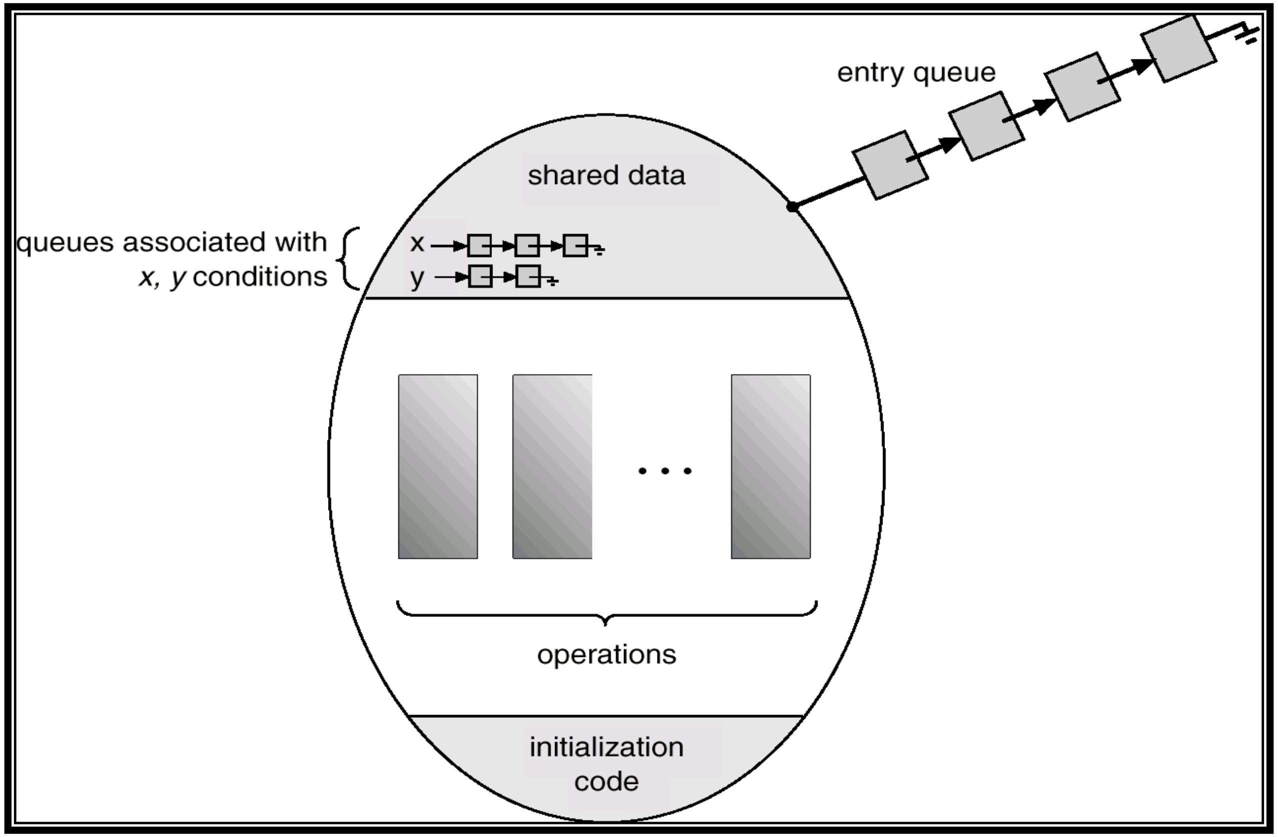
    x.signal();

  - 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--;
}
```