Synchronization: Recap

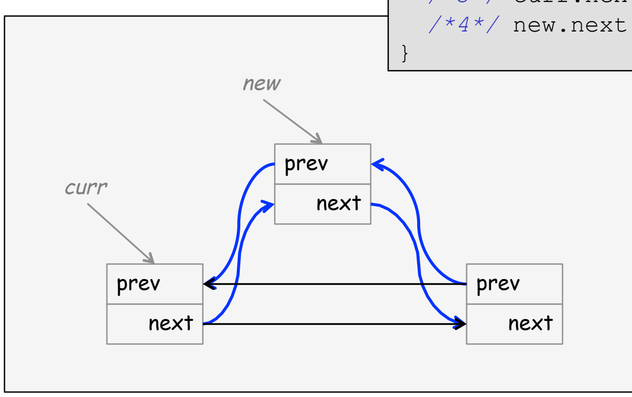
- Why?
  - Example
- The Critical Section Problem (recap!)
- Hardware Support for Synchronization
- Lock-free operations
- Semaphores
- Monitors

- Reading: Silberschatz, Ch. 6

Critical Section Problem: Example

Insertion of an element into a list.

```
void insert(new, curr) {
  /*1*/ new.next = curr.next;
  /*2*/ new.prev = c.next.prev;
  /*3*/ curr.next = new;
  /*4*/ new.next.prev = new;
}
```



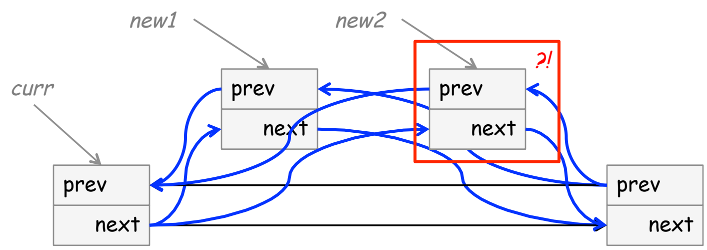
Interleaved Execution causes Errors!

Process 1

```
new1.next = curr.next;
new1.prev = c.next.prev;
…
…
…
…
curr.next = new1;
new1.next.prev = new1;
```

Process 2

```
…
…
new2.next = curr.next;
new2.prev = c.next.prev;
curr.next = new2;
new2.next.prev = new2;
…
…
```



Must guarantee mutually exclusive access to list data structure!

The Critical Section Problem

- Execution of critical section by processes must be mutually exclusive.
- Typically due to manipulation of shared variables.
- Need protocol to enforce mutual exclusion.

```
while (TRUE) {
    enter section;
    critical section;
    exit section;
    remainder section;
}
```

A (Wrong) Solution to the C.S. Problem

- Two processes P_0 and P_1
- `int turn;` /* `turn == i` : P_i is allowed to enter c.s. */

```
Pi: while (TRUE) {
        while (turn != i) no_op;
        critical section;
        turn = j;
        remainder section;
    }
```

Another Wrong Solution

`bool flag[2];` /* initialize to `FALSE` */
/* `flag[i] == TRUE` : P_i intends to enter c.s.*/

```
Pi: while (TRUE) {
        while (flag[j]) no_op;
        flag[i] = TRUE;
        critical section;
        flag[i] = FALSE;
        remainder section;
    }
```

Yet Another Wrong Solution

`bool flag[2];` /* initialize to `FALSE` */
/* `flag[i] == TRUE` : P_i intends to enter c.s.*/

```
Pi: while (TRUE) {
      flag[i] = TRUE;
      while (flag[j]) no_op;

      critical section;

      flag[i] = FALSE;

      remainder section;

    }
```

A Combined Solution (Petersen)

`int turn;`
`bool flag[2];` /* initialize to `FALSE` */

```
Pi: while (TRUE) {
      flag[i] = TRUE;
      turn    = j;
      while (flag[j]) && (turn == j) no_op;

      critical section;

      flag[i] = FALSE;

      remainder section;

    }
```

Hardware Support For Synchronization

- **Disallow interrupts**
  - simplicity
  - widely used
  - problem: interrupt service latency
  - problem: what about multiprocessors?
- **Atomic** operations:
  - Operations that check and modify memory areas in a single step (i.e. operation can not be interrupted)
  - **Test-And-Set**
  - **Fetch-And-Add**
  - **Exchange, Swap, Compare-And-Swap**
  - **Load-Link/Store Conditional**

Hardware Support: Test-And-Set

```
bool TestAndSet(bool & var) {
    bool temp;
    temp = var;
    var  = TRUE;
    return temp;
}
```

atomic!

Mutual Exclusion with **Test-And-Set**

```
bool lock; /* init to FALSE */

while (TRUE) {

  while (TestAndSet(lock)) no_op;

  critical section;

  lock = FALSE;

  remainder section;

}
```

Hardware Support: Exchange (Swap)

```
void Exchange(bool & a, bool & b){
   bool temp;
   temp = a;
   a    = b;
   b    = temp;
}
```

atomic!

Mutual Exclusion with **Exchange**

```
bool lock; /*init to FALSE */

while (TRUE) {

  dummy = TRUE;
  do Exchange(lock, dummy);
  while(dummy);

  critical section;

  lock = FALSE;

  remainder section;
}
```

Hardware Support: Fetch & Add

```
function FetchAndAdd(&location) {
  int value = location;
  location  = value + 1;
  return value;
}
```

```
record locktype {
  int ticketnumber;    int turn;
}
procedure LockInit( locktype * lock ) {
  lock.ticketnumber = 0;
  lock.turn         = 0;
}
procedure Lock( locktype * lock ) {
  int myturn = FetchAndAdd( &lock.ticketnumber );
  while (lock.turn != myturn)
    skip; // spin until lock is acquired
}
procedure UnLock( locktype* lock {
  FetchAndAdd( &lock.turn )
}
```

Hardware Support: Compare-And-Swap

```
bool Compare&Swap(Type * x, Type old, Type new) {
    if *x == old {
      *x = new;
      return TRUE;
      } else {
      return FALSE
      }
}
```

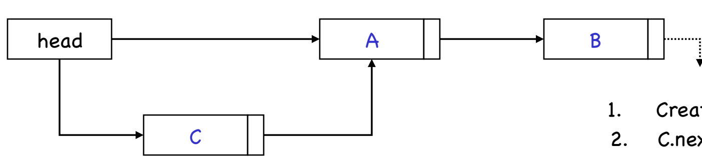
atomic!

```
bool lock; /*init to FALSE */

while (TRUE) {

  while(!C&S(&lock, false, true));

  critical section;

  lock = FALSE;

  remainder section;
}
```

Compare-and-Swap: Example
Lock-Free Concurrent Data Structures

Example: ***Shared Stack***

PUSH element ***C*** onto stack:

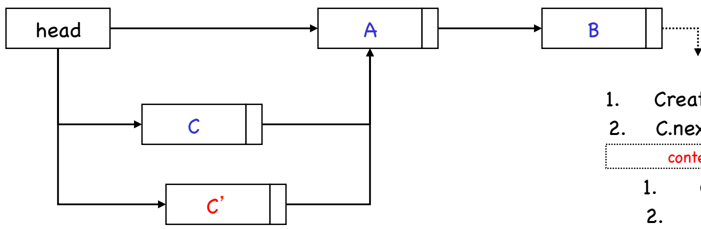


1. Create C
2. C.next = head
3. head = C

Compare-and-Swap: Example
Lock-Free Concurrent Data Structures

Example: **Shared Stack**

PUSH element **C** onto stack: What can go wrong?!



1. Create C
2. C.next = head

context switch!

1. Create C'
2. C'.next = head
3. head = C'

context switch back!

3. head = C

Solution: compare-and-swap(head, C.next, C),
i.e. compare and swap head, new value C, and expected value C.next.
If fails, go back to step 2.

Compare-and-Swap: Example
Lock-Free Concurrent Data Structures

Example: **Shared Stack**

Push Operation:

```
void push(sometype t) {
    Node* node = new Node(t);
    do {
        node->next = head;
    } while (!C&S(&head, node->next, node));
}
```

Compare-and-Swap: Example Lock-Free Concurrent Data Structures

Example: **Shared Stack**

Pop Operation:

```
bool pop(sometype & t) {
    for(;;) {
        Node* ret_ptr = head;
        if (ret_ptr == null) return false;
        Note* next_ptr = ret_ptr->next;
        if(C&S(&head, ret_ptr, next_ptr)) {
            t = current->data;
            return true;
        }
    }
}
```

Compare-And-Swap is "weak": LL/SC

- CSW does not detect updates if old value has been restored! (so-called ABA problem)
- Solution: "strong" pair of instructions:
  - **load-link** (LL): returns current value of memory location
  - subsequent **store-conditional** (SC) stores a new value
    - only if no updates of memory location since LL
    - otherwise SC fails
- Supported on MIPS, PowerPC, Alpha, ARM
- Implementation of LL/SC are often not perfect, e.g.:
  - any exception between LL/SC may cause SC to fail
  - any updates over memory bus may cause SC to fail

Semaphores

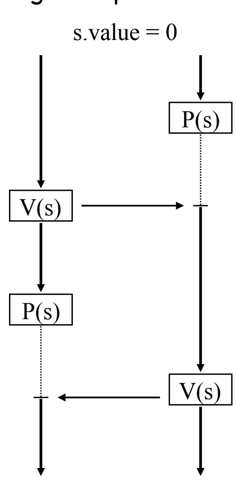
- Problems with solutions above:
  - Although requirements simple (mutual exclusion), addition to programs complex.
  - Based on busy waiting.
- A Semaphore variable has two operations:
  - **V(Semaphore * s);**

    /* Increment value of **s** by 1 in a single indivisible action. If value is not positive, then a process blocked by a **P** is unblocked*/
  - **P(Semaphore * s);**

    /* Decrement value of **s** by 1. If the value becomes negative, the process invoking the **P** operation is blocked. */
- **Binary semaphore**: The value of **s** can be either 1 or 0 (TRUE or FALSE).
- **General semaphore**: The value of **s** can be any integer.

Effect of Semaphores

- **General Synchronization** using semaphores:



- **Mutual exclusion** with semaphores:

```
BinSemaphore * s;
/* init to TRUE*/

while (TRUE) {

  P(s);

  critical section;

  V(s);

  remainder section;
}
```

Implementation (with busy waiting)

- Binary Semaphores:

```
P(BinSemaphore * s) {
  key = FALSE;
  do exchange(s.value, key);
  while (key == FALSE);
}

V(BinSemaphore * s) {
  s.value = TRUE;
}
```

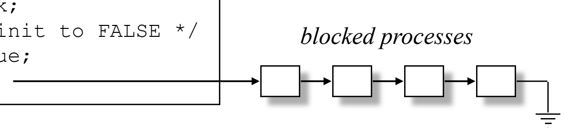
- General Semaphores:

```
BinSemaphore * mutex /*TRUE*/
BinSemaphore * delay /*FALSE*/

P(Semaphore * s) {
 P(mutex);
 s.value = s.value - 1;
 if (s.value < 0)
   { V(mutex); P(delay); }
 else V(mutex);
}
V(Semaphore * s) {
 P(mutex);
 s.value = s.value + 1;
 if (s.value <= 0) V(delay);
 V(mutex);
}
```

Implementation ("without" busy waiting)

Semaphore

```
    bool       lock;
               /* init to FALSE */
    int        value;
    PCBList *  L;
```




```
P(Semaphore * s) {
 while (TestAndSet(lock))
   no_op;
 s.value = s.value - 1;
 if (s.value < 0) {
   append(this_process, s.L);
   lock = FALSE;
   sleep();
 }
 lock = FALSE;
}
```

```
V(Semaphore * s) {
 while (TestAndSet(lock))
   no_op;
 s.value = s.value + 1;
 if (s.value <= 0) {
   PCB * p = remove(s.L);
   wakeup(p);
 }
 lock = FALSE;
}
```

Classical Problems: **Producer-Consumer**

```
Semaphore    * n;     /* initialized to 0    */
BinSemaphore * mutex; /* initialized to TRUE */
```

```
Producer:

while (TRUE) {

  produce item;

  P(mutex);

  deposit item;

  V(mutex);
  V(n);

}
```

```
Consumer:

while (TRUE) {

  P(n);
  P(mutex);

  remove item;

  V(mutex);

  consume item;

}
```

Classical Problems: **Producer-Consumer with Bounded Buffer**

```
Semaphore    * full;  /* initialized to 0    */
Semaphore    * empty; /* initialized to n    */
BinSemaphore * mutex; /* initialized to TRUE */
```

```
Producer:

while (TRUE) {

  produce item;

  P(empty);
  P(mutex);

  deposit item;

  V(mutex);
  V(full);

}
```

```
Consumer:

while (TRUE) {

  P(full);
  P(mutex);

  remove item;

  V(mutex);
  V(empty);

  consume item;

}
```

Classical Problems: Readers/Writers

- Multiple readers can access data element concurrently.
- Writers access data element exclusively.

```
Semaphore * mutex, * wrt;   /* initialized to 1 */
int         nreaders;       /* initialized to 0 */
```

```
Reader:

P(mutex);
  nreaders = nreaders + 1;
  if (nreaders == 1) P(wrt);
V(mutex);

do the reading ....

P(mutex);
  nreaders = nreaders - 1;
  if (nreaders = 0) V(wrt);
V(mutex);
```

```
Writer:

P(wrt);

do the writing ...

V(wrt);
```

Monitors (Hoare / Brinch Hansen, 1973)

- Safe and effective sharing of abstract data types among several processes.
- Monitors can be modules, or objects.
  - local variable accessible only through monitor's procedures
  - process can entrer monitor only by invoking monitor procedure
- Only one process can be active in monitor.
- Additional synchronization through **conditions** (similar to semaphores)

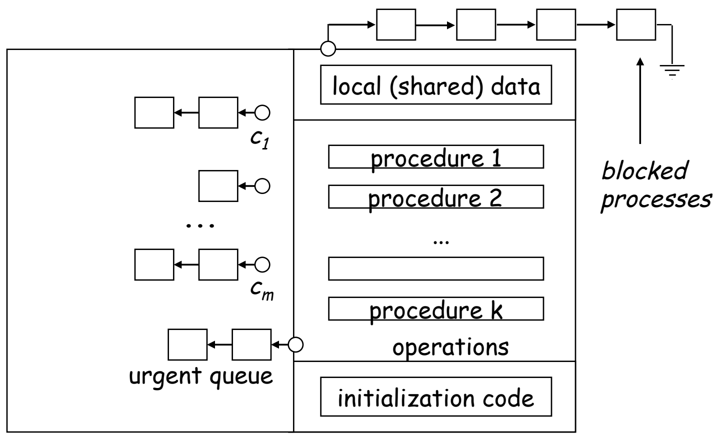
  `Condition c;`

  `c.cwait()` : suspend execution of calling process and enqueue it on condition `c`. The monitor now is available for other processes.

  `c.csignal()` : resume a process enqueued on `c`. If none is enqueued, do nothing.

  - `cwait`/`csignal` different from `P`/`V`: `cwait` always waits, `csignal` does nothing if nobody waits.

Structure of Monitor



Example: Binary Semaphore

```
monitor BinSemaphore {

  bool        locked; /* Initialize to FALSE */
  condition   idle;

  entry  void P() {
      if (locked) idle.cwait();
      locked = TRUE;
  }

  entry void V() {
      locked = FALSE;
      idle.csignal();
  }
}
```

Example: Bounded Buffer Producer/Consumer

```
monitor boundedbuffer {
  Item       buffer[N];    /* buffer has N items   */
  int        nextin;       /* init to 0            */
  int        nextout;      /* init to 0            */
  int        count;        /* init to 0            */
  condition  notfull;      /* for synchronization  */
  condition  notempty;

void deposit(Item x) {
  if (count == N)
    notfull.cwait();
  buffer[nextin] = x;
  nextin = nextin + 1 mod
  N;
  count  = count + 1;
  notempty.csignal();
}

void remove(Item & x) {
  if (count == 0)
    notempty.cwait();
  x = buffer[nextout];
  nextout = nextout + 1 mod N;
  count  = count - 1;
  notfull.csignal();
}
```

Incorrect Implementation of Readers/Writers

```
monitor ReaderWriter{
    int numberOfReaders = 0;
    int numberOfWriters = 0;
    boolean busy = FALSE;

    /* READERS */
    procedure startRead() {
      while (numberOfWriters != 0);
      numberOfReaders = numberOfReaders + 1;
    }
    procedure finishRead() {
      numberOfReaders = numberOfReaders - 1;
    }

    /* WRITERS */
    procedure startWrite() {
      numberOfWriters = numberOfWriters + 1;
      while (busy || (numberOfReaders > 0));
      busy = TRUE;
    };
    procedure finishWrite() {
      numberOfWriters = numberOfWriters - 1;
      busy = FALSE;
    };
  };
```

A Correct Implementation

```
monitor ReaderWriter{
    int numberOfReaders = 0;
    int numberOfWriters = 0;
    boolean busy = FALSE;
    condition okToRead, okToWrite;

    /* READERS */
    procedure startRead() {
      if (busy || (okToWrite.lqueue)) okToRead.wait;
      numberOfReaders = numberOfReaders + 1;
      okToRead.signal;
    }
    procedure finishRead() {
      numberOfReaders = numberOfReaders - 1;
      if (numberOfReaders = 0) okToWrite.signal;
    }

    /* WRITERS */
    procedure startWrite() {
      if (busy || (numberOfReaders > 0)) okToWrite.wait;
      busy = TRUE;
    };
    procedure finishWrite() {
      busy = FALSE;
      if (okToWrite.lqueue) okToWrite.signal;
      else                  okToRead.signal;
    };
  };
```

Synchronization in JAVA

- Critical sections:
  - `synchronized` statement
- Synchronized methods:
  - Only one thread can be in any synchronized method of an object at any given time.
  - Realized by having a single lock (also called monitor) per object.
- Synchronized static methods:
  - One lock per class.
- Synchronized blocks:
  - Finer granularity possible using synchronized blocks
  - Can use lock of any object to define critical section.
- Additional synchronization:
  - `wait()`, `notify()`, `notifyAll()`
  - Realized as methods for all objects

Java Synchronized Methods: vanilla Bounded Buffer Producer/Consumer

```
public class BoundedBuffer {
 Object[] buffer;
 int      nextin, nextout;
 Object   notfull, notempty;
 int      size;
 int      count;
```

```
public BoundedBuffer(int n) {
  size    = n;
  buffer  = new Object[size];
  nextin  = 0;
  nextout = 0;
  count   = 0;
}
```

```
synchronized public deposit(Object x){
  if (count == size) notfull.wait();
  buffer[nextin] = x;
  nextin = (nextin+1) mod size;
  count  = count + 1;
  notempty.notify();
}
```

```
synchronized public Object remove() {
  Object x;
  if (count == 0) notempty.wait();
  x = buffer[nextout];
  nextout = (nextout+1) mod size;
  count   = count - 1;
  notfull.notify();
  return x;
}
```

Example: Synchronized Block

(D. Flanagan, *JAVA in a Nutshell*)

```
public static void SortIntArray(int[] a) {
  // Sort array a.  This is synchronized so that
  // some other thread cannot change elements of
  // the array or traverse the array while we are
  // sorting it.
  // At least no other thread that protect their
  // accesses to the array with synchronized.

  // do some non-critical stuff here...

  synchronized (a) {
     // do the array sort here.
  }

  // do some other non-critical stuff here...

}
```