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Synchronizing Threads and Processes

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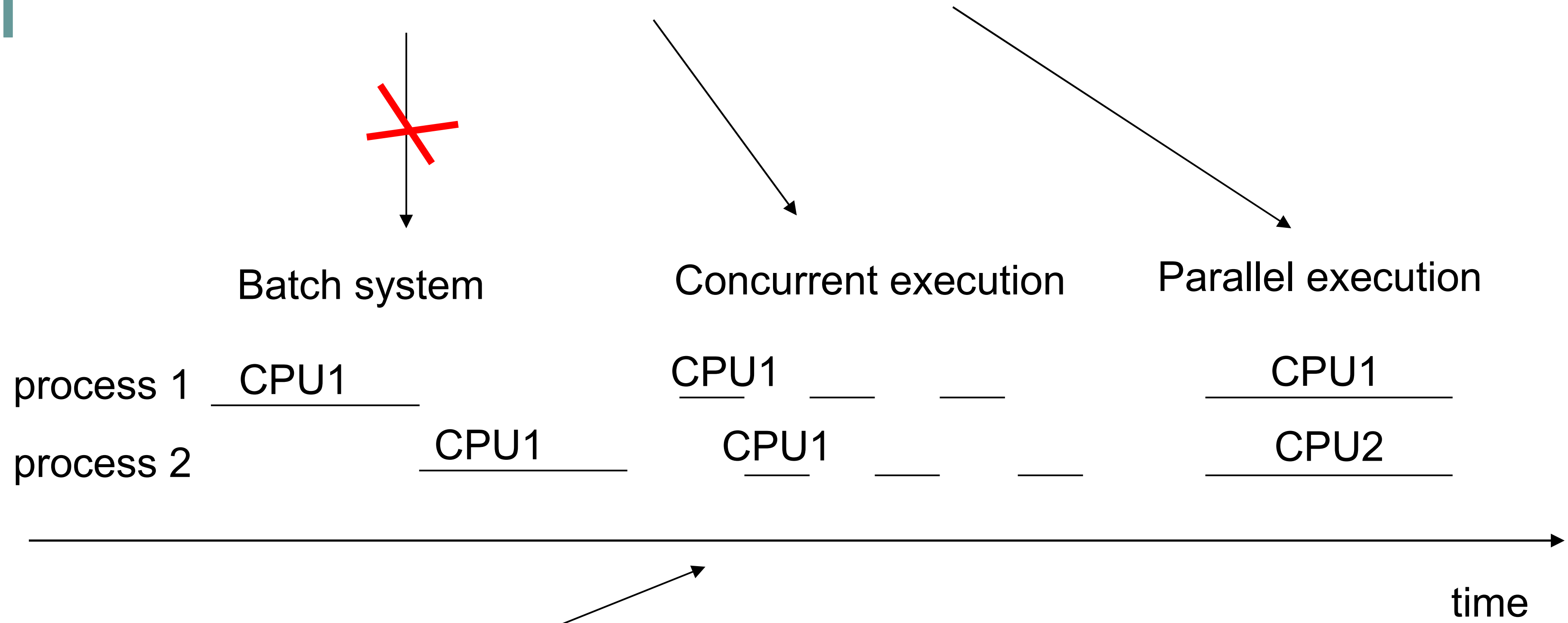
Outline

- **Why to synchronize processes and threads**
- **Means of synchronization**
  - Mutexes
  - Semaphores
  - Monitors
  - Condition variables
- **Threads in Java and C**

Motivation

- **Multiprogramming operating systems**
  - Single CPU may execute several programs (time sharing)
- **Some problems are intrinsically concurrent**
  - e.g. a web server
- **Hyper-threading technology**
  - Single processor executing a couple of threads at the same time
- **Multi-core CPUs emerging**
  - To achieve enough speed all processors have to be used

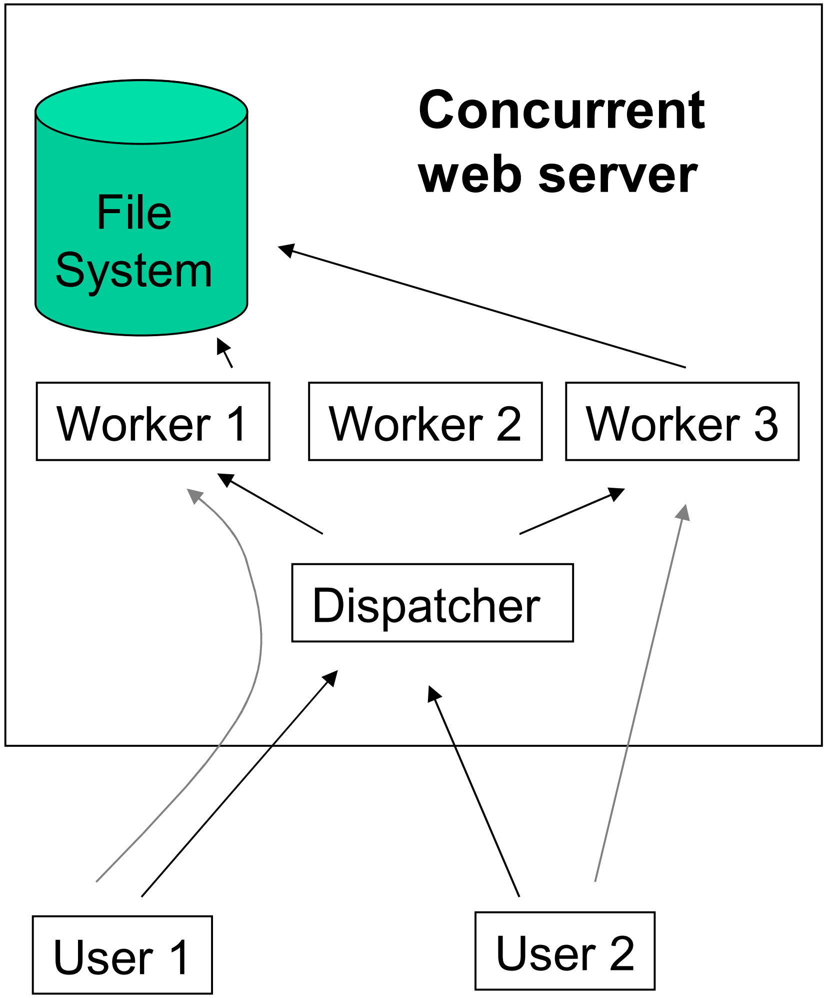
Concurrent programs



- **Time sharing**
  - several programs executed concurrently on a single CPU
  - a processor executes one program for certain time
  - and switches to another one

Example – concurrent web server

- **Before sending a web page the server has to read it from disk**
  - Synchronous IO with a single process would block the whole server
  - Solution:
    - Use asynchronous IO (a bit complicated)
    - Use multiple processes/threads
- **Each process serves one client:**
  - Reads the request from a socket
  - Reads a local file to be send
  - Writes results to the socket



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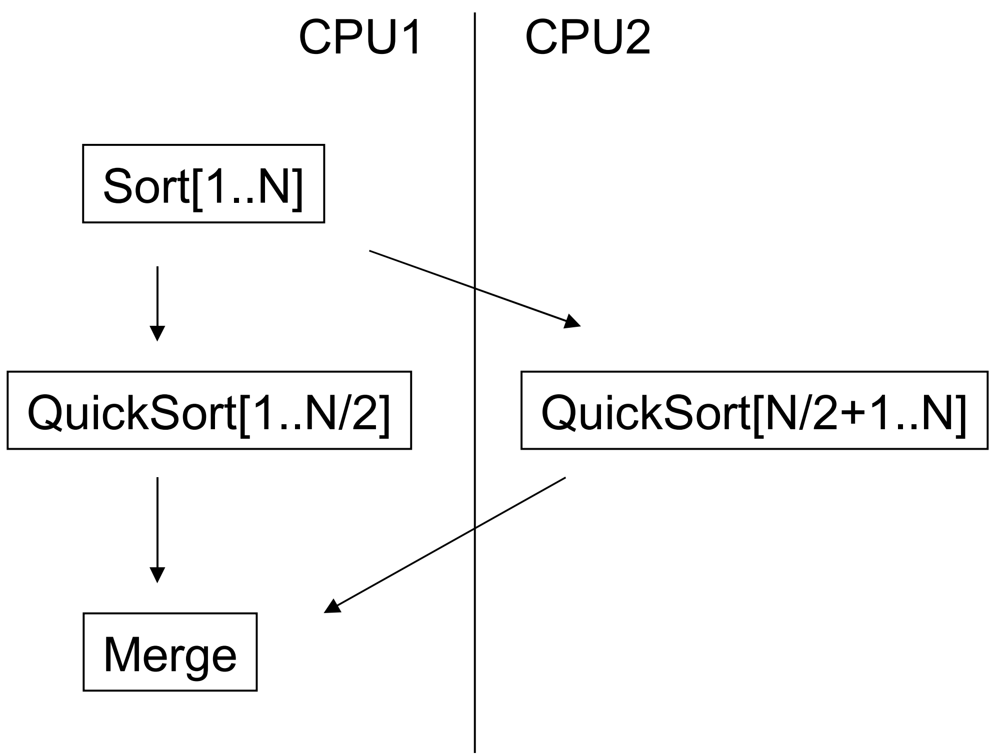
A parallel program

Parallel Sort

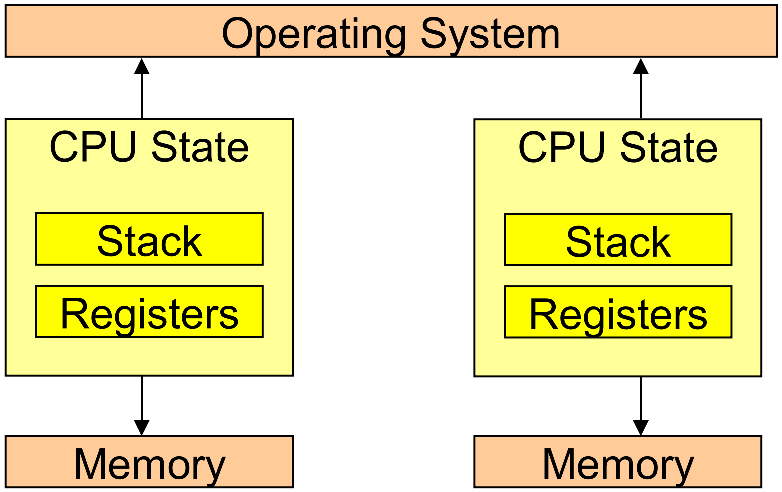


- Problems
  - Start a program on the second CPU
  - Exchange data between CPUs
  - Wait for results

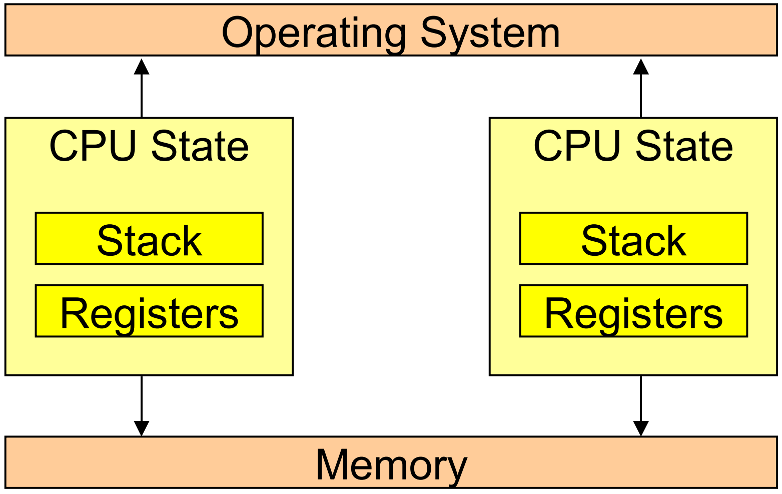
- **With two processors: ~ 2x faster**

Multiprogramming systems

- **Processes**
  - Different CPU state
  - Different memory space
  - Communication via operating system mechanisms
    - Messages, shared memory (allocated using O.S.), Sockets



- **Threads**
  - Exist within a single process
  - Same (global) memory space
  - Different CPU state
  - Communication via memory
  - Faster switching



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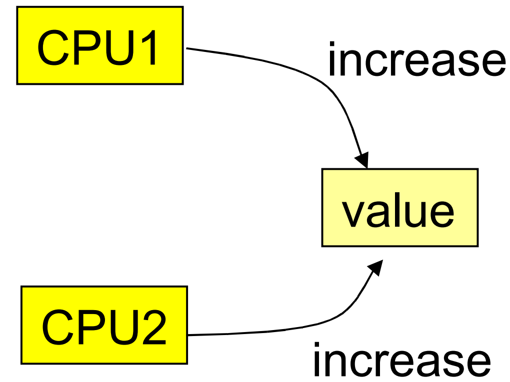
Accessing a memory location

- **Example: Two CPUs execute the same function: add one to a global variable**

```
int value; // global
void increase() {
    int x = value
    x++;
    value = x;
}
```



value == 1

CPU1:		CPU2:	
1. **int** x = value;	// 1		
2.		**int** x = value;	// 1
3.		x++;	// 2
4. x++;	// 2		
5.		value = x;	// 2
6. value = x;	// 2		

value is 2 instead of 3!

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Accessing a memory location

- **The same example. Reading/writing an int (4 bytes) is byte-by-byte**
  - CPU1 reads the value (255: |0|0|0|255|)
  - CPU1 writes the new result: 256 : |0|0|1|0|, first the 3 upper bytes
  - CPU2 reads the value (511: |0|0|1|255|)
  - CPU1 writes the last byte (256: |0|0|1|0|)
  - CPU2 writes the result (512: |0|0|2|0)
- **We get 512 instead of 257!**
- **Luckily most architectures read whole ints at once**

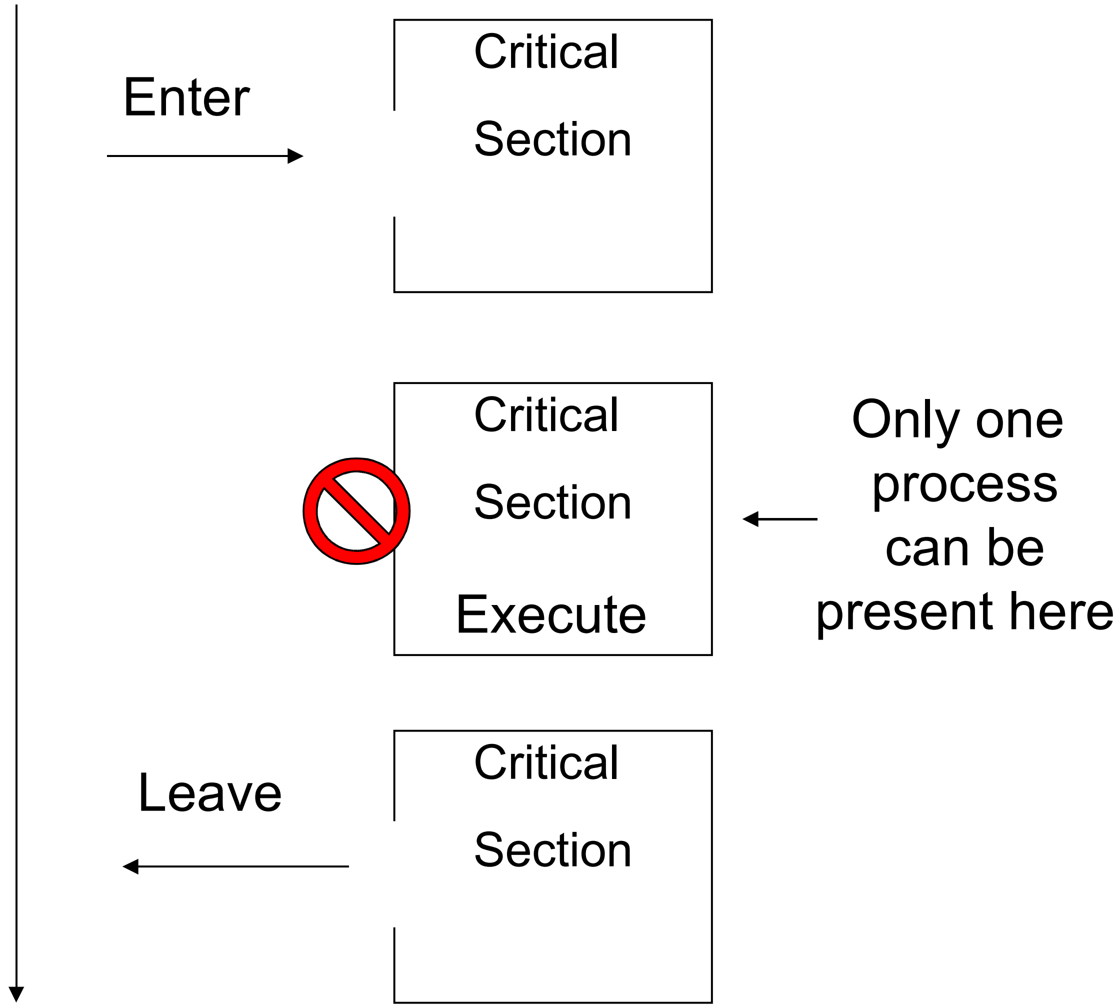
The access to a common variable must be blocked when it is accessed by a processor

Critical section

- **A region of code that can only be executed by one thread or process at a time**
- **Atomic execution (synonym) – execution of code that cannot be interfered with by another process**

```
int value; // global
void increase() {
    int x = value
    x++;
    value = x;
}
```

Critical section



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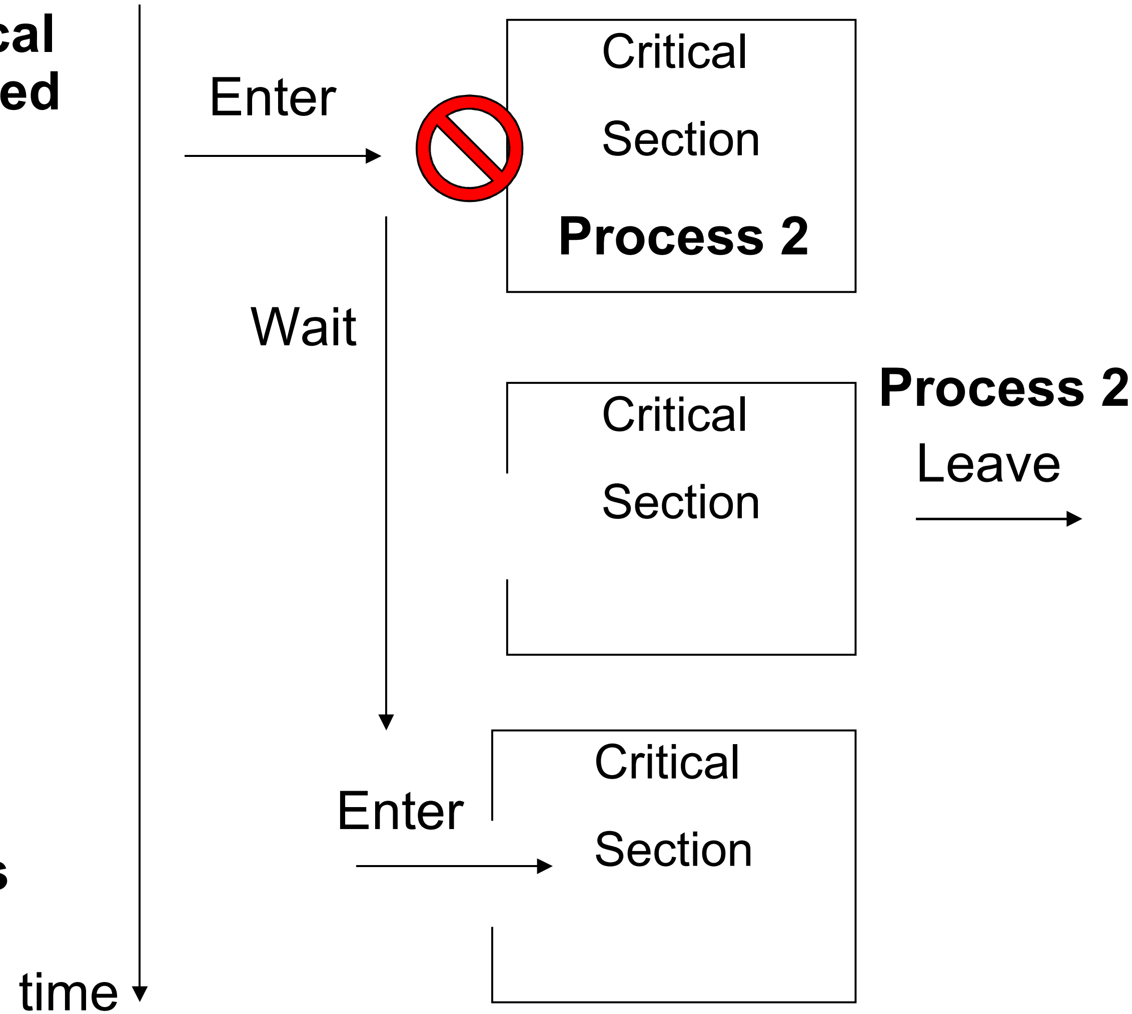
Critical Section 2

- **Process entering a critical section should be blocked until the section is free**
- **How to check if the section is free?**

```
bool lock = false;
while (lock == true)
  ; // empty instruction
lock = true;
  // critical section
lock = false;
```

- **Wrong! – two processes may check lock at the same time and enter**



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Hardware support

- **The test-and-set instruction**
  - Executed atomically

This is sufficient to synchronize processes

```
bool testAndSet(int* lock) {
  // atomic instruction !
  if (*lock == false) {
    *lock = true;
    return false;
  }
  else
    return true;
}
```

Often called SpinLock

```
int value;
int lock = 0;
void increase() {
  while (testAndSet(&lock))
    ;                  // just wait
  int x = value; // now lock == 1
  x++;
  value = x;
  lock = 0;         // release
}
```

Active waiting! – the CPU keeps on testing the variable.
On multiprogramming systems, the CPU should be assigned to another task.
O.S. support is needed.

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Mutexes

Operations:

- **lock()**
  - If the mutex is locked
    - Release the CPU (sleep)
    - Wake up when the mutex is unlocked
  - Lock the mutex and pass over
- **unlock()**
  - Unlock the mutex
  - Wake up one process waiting for the lock (if any)
  - May be executed only by the process that owns the mutex (executed lock())

Atomic once the process is woken up

```
int value;
mutex m;
void increase() {
    m.lock()
    int x = value
    x++;
    value = x;
    m.unlock()
}
```

Critical section

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Bounded buffer

- **Buffer of a fixed size**
- **Processes can read from it and write to it**
  - Readers should be blocked if nothing to read
  - Writers should be blocked if no space to write
- **put/get must be exclusive (critical section)**

```
mutex m;
int buffer[N];
int items = 0;
```

```
void put(int value) {
  m.lock();
  if (items == N)
    wait();     // ????
  buffer[items++] = value;
  m.unlock();
}
```

```
int get() {
  m.lock();
  if (items == 0)
    wait();     // ????
  int rv = buffer[--items];
  m.unlock();
  return rv;
}
```

How can we wait?
- use another mutex (complicated)
- introduce more advanced means of synchronization

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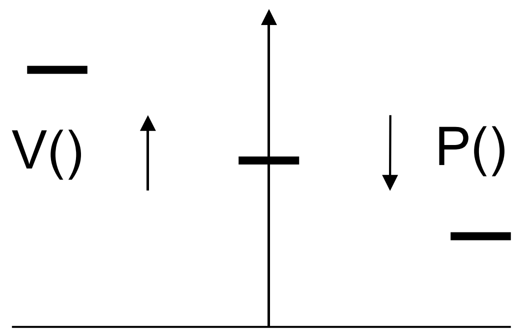
Semaphores

- **An object which holds a value $n \geq 0$**
- **Operations**
  - Init(int v)
    - n := v;
  - V() – atomic
    - n++;
  - P() – atomic once *n*>0 is detected
    - await n > 0;
    - n--;
- **Semaphores are considered nonstructural, obsolete, error-prone**
  - But they are useful



Bounded Buffer

```
semaphore empty(N);
semaphore full(0);
mutex m;
int buffer[N];
int items = 0;
```

```
void put(int value) {
  empty.P();
  m.lock();
  buffer[items++] = value;
  m.unlock();
  full.V();
}
```

```
int get(int value) {
  full.P();
  m.lock();
  int rv = buffer[--items];
  m.unlock();
  empty.V();
  return rv;
}
```

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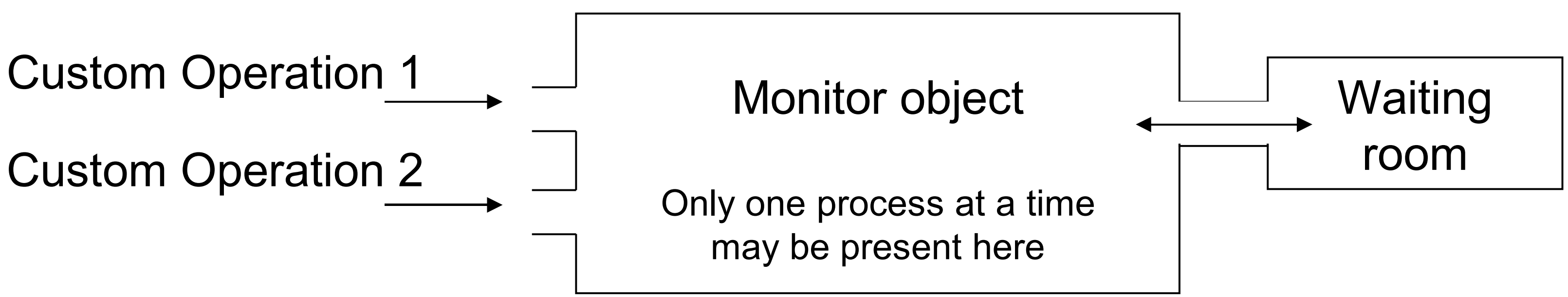
Monitor Objects

- **Previous example was rather complicated**
  - We'd prefer to use the lock-wait strategy as in the first trial with mutexes
- **Monitors – higher level synchronization**
- **Operations:**
  - Custom operations (fully synchronized)
  - Wait() – release the monitor and wait
  - Notify() – wake up one of the waiting processes
  - NotifyAll() – wake up all the waiting processes

```
void put(int value) {
  m.lock();
  if (items == N)
    wait();     // ????
  buffer[items++] = value;
  m.unlock();
}
```



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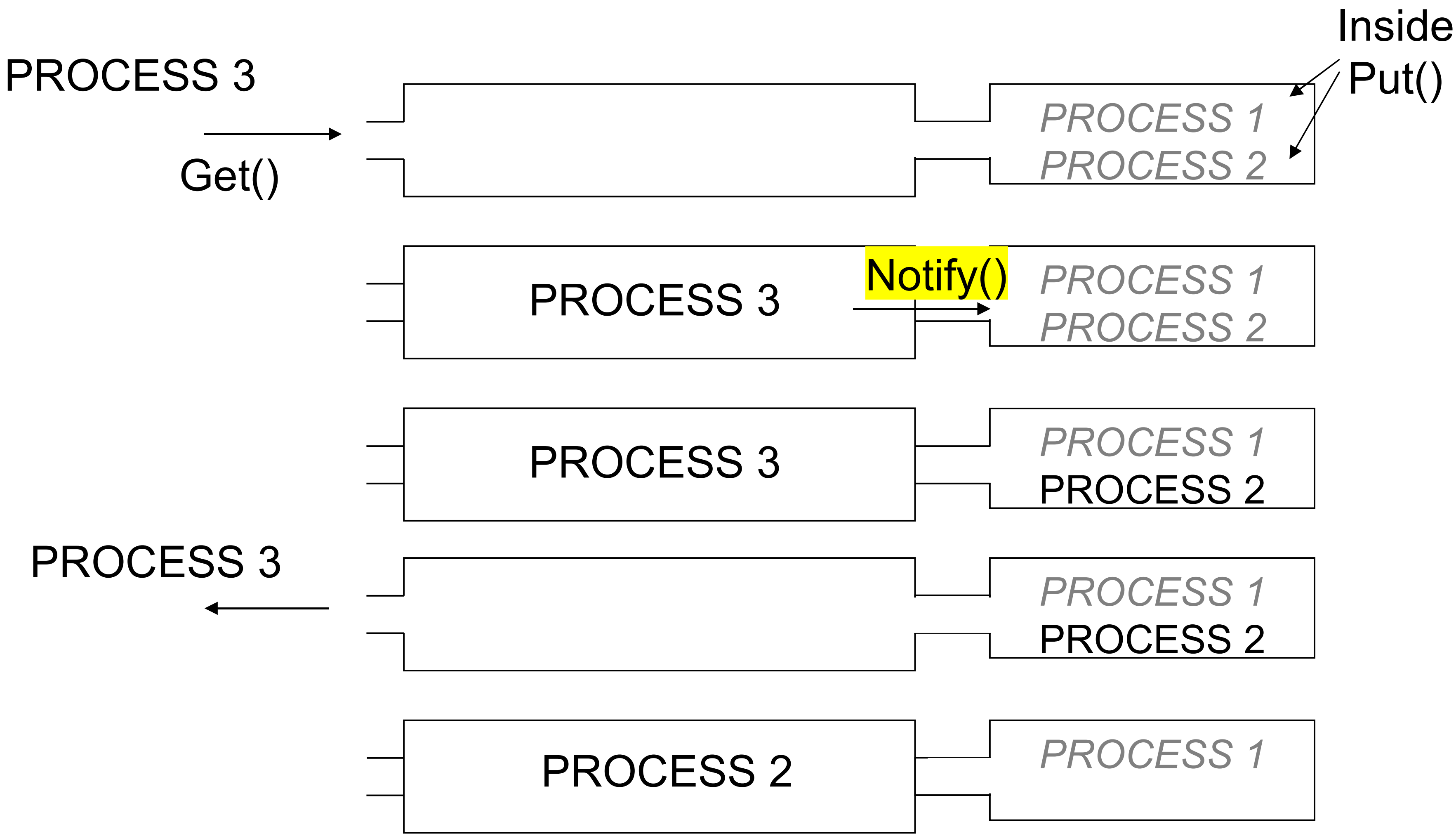
Monitor Objects – Notify()



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Java monitors

- **Exactly this kind of monitors has been implemented in Java**

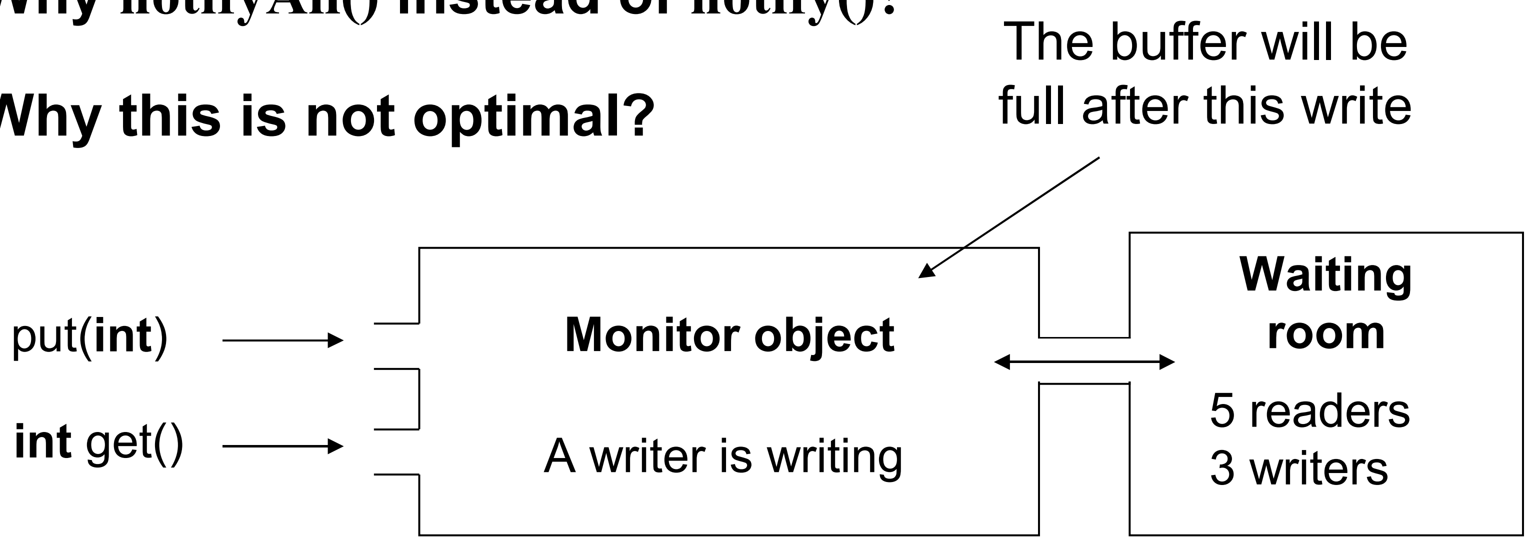
```
public class BoundedBuffer {
  int A[], N; // buffer and its size
  int  k = 0;  // filled elements

  public BoundedBuffer(int size) {
    N = size;
    A = new int[N];
  }
  // custom operations
  public synchronized void put(int r) {…}
  public synchronized int get() { … }
}
```

```
public synchronized void put(int r)
      throws InterruptedException {
  while (k == N)
    wait();             // full buffer
  A[k++] = r;
  notifyAll();
}
```

```
public synchronized int get()
      throws InterruptedException {
  while (k == 0)
    wait();             // empty buffer
  notifyAll();
  return A[--k];
}
```

Java monitors cont.

- **Why notifyAll() instead of notify()?**
- **Why this is not optimal?**



Notify() would wake up just one process. Writer => deadlock!

NotifyAll() wakes up everybody in the waiting room

But only readers can continue!

We would prefer to have separate waiting rooms for readers and writers.

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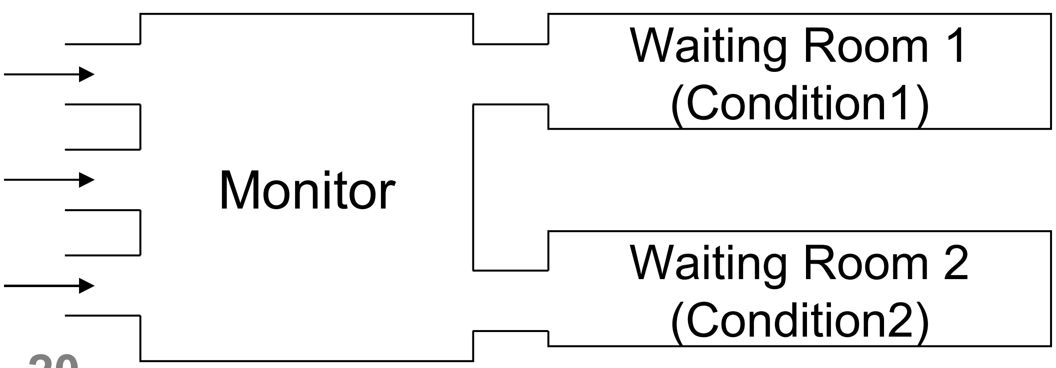
Condition Variables

- **A monitor objects holds several *condition variables* – waiting rooms**
- **When waiting, a condition should be specified**
- **When notifying, a condition should be specified**
  - Wakes up only processes waiting on that condition



Pseudo–java code:

```
Condition readers, writers;
```

```
put(int r) {
  while (k == N)
    writers.wait();   // full buffer
  A[k++] = r;
  readers.notify();
}
```

```
int get() {
  while (k == 0)
    readers.wait();   // empty buffer
  writers.notify();
  return A[--k];
}
```

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Bounded buffer with conditions

- **Real Java code:**
  - Monitor’s lock must be managed explicitly (synchronized keyword doesn’t work)
  - Condition variables are associated with that lock. In the wait method:
    - Lock is released when waiting
    - Lock is reacquired when waking up
  - Operation names: await(), signal() and signalAll()

```
import java.util.concurrent.locks.Condition;
import java.util.concurrent.locks.ReentrantLock;

public class BoundedBuffer {
  int N, A[], k = 0;
  private ReentrantLock lock = new ReentrantLock();
  Condition readers, writers;   // ...
}
```

The constructor:

```
public BoundedBuffer(int size) {
  N = size;
  A = new int[N];
  readers = lock.newCondition();
  writers = lock.newCondition();
}
```

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Bounded buffer with conditions 2

- **Methods code**
  - Note: there is no **synchronized** statement (explicit locking)

```
public int get()
        throws InterruptedException {
   lock.lock();
   try {
      while (k == 0)
         readers.await();
      writers.signal();
      return A[--k];
   } finally {
      lock.unlock();
   }
}
```

lock must be locked when calling signal!

```
public void put(int r)
        throws InterruptedException {
   lock.lock();
   try {
      while (k == N)
         writers.await();
      A[k++] = r;
      readers.signal();
   } finally {
      lock.unlock();
   }
}
```

Java: how to create a thread

- **Create your thread's class:**
  - Inherit from the Thead class
  - Implement the run() method
- **Create such an object and call start()**
  - Calling start() will create a new thread which starts in the run() method
- **Use the constructor to pass initial data to the thread**
  - E.g. in the BoundedBuffer example all readers and writers have to know the buffer object

```
public class MyThread extends Thread {
  // local thread's data
  public MyThread(/* Parameters */) {
    // use constructor parameters to pass
    // initial data to the thread
    // e.g. global data structures
  }
  public void run() {
    // thread's own code
  }
}
```

```
myThread = new MyThread(globalData);
myThread.start();
```

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Java: Complete Example

```java
public class Producer extends Thread {
  BoundedBuffer buff;
  public Producer(BoundedBuffer b) {
    buff = b;
  }
  public void run() {
    try {
      for (int i = 0; i < 100; i++)
        buff.put(i);
    } catch (InterruptedException e) {}
  }
}
```

```java
public class Consumer extends Thread {
  BoundedBuffer buff;
  public Consumer(BoundedBuffer b) {
    buff = b;
  }
  public void run() {
    try {
      for (int i = 0; i < 100; i++)
        System.out.println( buff.get() );
    } catch (InterruptedException e) {}
  }
}
```

```java
public class TestBounderBuffer {
  public static void main(String[] args) {
    BoundedBuffer b = new BoundedBuffer(10);
    Producer p = new Producer(b);          Consumer c = new Consumer(b);
    p.start();                             c.start();
  }
}
```

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C language threads

- **Pthreads – POSIX threads standard**
  - Just API specification
  - Implementations available for various systems (windows, linux, other unixes)
- **Synchronization:**
  - mutexes
  - condition variables
- **Same semantics as in Java (almost)**

Datatypes:

```
pthread_t
pthread_cond_t
pthread_mutex_t
```

```
void* start_routine(void*);
```

Thread functions:

```
pthread_create(&thread,
        attr, start_routine, arg)
pthread_exit(ret_val)
pthread_join(thread_id);
```

Mutex functions:

```
pthread_mutex_init(mutex, attr);
pthread_mutex_destroy(mutex);
pthread_mutex_lock(mutex);
pthread_mutex_unlock(mutex);
```

Condition functions:

```
pthread_cond_init(condition, 0);
pthread_cond_destroy(condition);
pthread_cond_wait(condition, mutex);
pthread_cond_signal(condition);
pthread_cond_broadcast(condition);
```

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New concurrent Java API

- **From Java 1.5 – new concurrent API: java.util.concurrent**
- **Atomic datatypes: java.util.concurrent.atomic**
  - AtomicBoolean
  - AtomicInteger
  - AtomicReference<E>
  - AtomicIntegerArray
  - Operations: get, set, getAndSet, compareAndSet, incrementAndGet
- **New means of synchronization:**
  - Semaphores
  - Condition, Lock
  - ReadWriteLock (allow many readers but writing is exclusive)
- **Synchronized datastructures**
  - BlockingQueue<E> – more or less our BoundedBuffer)
  - ConcurrentMap<K, V> – additional synchronized methods: putIfAbsent(), remove(), replace()

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Interprocess communication in UNIX

- **Pipes**
  - Two file descriptors connected to each other
  - Created before forking the second process
- **Fifos**
  - Special file in a file system.
  - One process opens it for reading and the other for writing
- **Message queues**
  - Structured messages
- **Shared memory**
  - Processes can locate shared memory segments using *keys*
- **Signals**
  - One process may send a signal to another one
  - Breaks the normal execution of a sequential program to execute the signal handler
  - Very primitive way of communication

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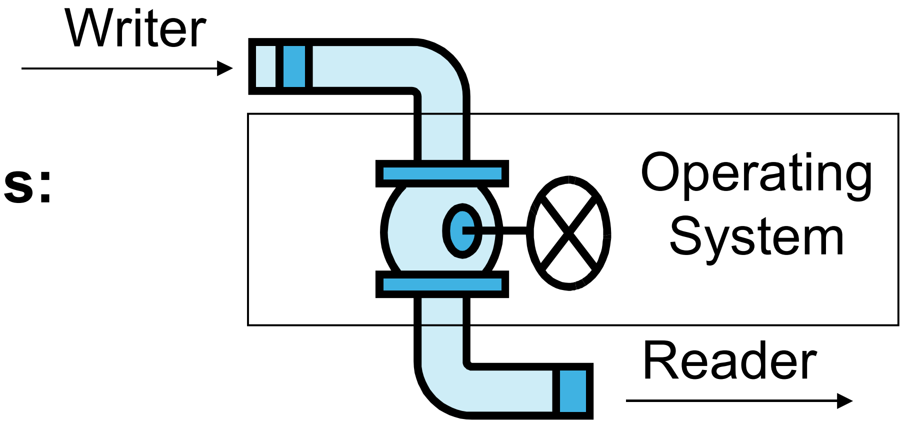
Pipes, FIFOs

- **„Virtual" file in memory**
  - One process writes data
  - The other reads data
- **Standard file access functions:**
  - read(), write()
  - fprintf(), fscanf()
- **Pipes**
  - Only for related processes (parent-child)
- **FIFOs**
  - For any processes
  - Can be found via the file system (special file)



Message queues, shared memory

- **Both reside within the kernel**
  - Can be found using O.S. calls
  - ID of the queue/shmem has to be known to the processes
- **Message queues:**
  - msgsnd()
  - msgrcv()

- **Shared memory**
  - Just read/write data as with threads
  - Don't forget about synchronization (semaphores, mutexes, etc.)!

Difficulties

- **Testing is not enough**
  - Problems with synchronization may occur very rarely. E.g. the famous AT&T crash ('90)
- **Deadlocks**
  - Two processes waiting for each other
- **Starvation**
  - Some processes may never be allowed to enter a critical section

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Summary

- Concurrent programs are inevitable for efficient usage of a multiprocessor system
- Threads and processes within a concurrent application have to be synchronized
- There are typical means of synchronization: mutexes, semaphores, monitors
- Other interprocess communication mechanisms are based on messages
- Writing and testing a concurrent application is much more difficult than a sequential one

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Further reading and materials used

- ***Concurrent Programming*** **course at Warsaw University**
- **Stevens – *UNIX Network Programming, Volume 2: Interprocess Communication***
- **Wikipedia**
- **Contact: mbiskup@mimuw.edu.pl**