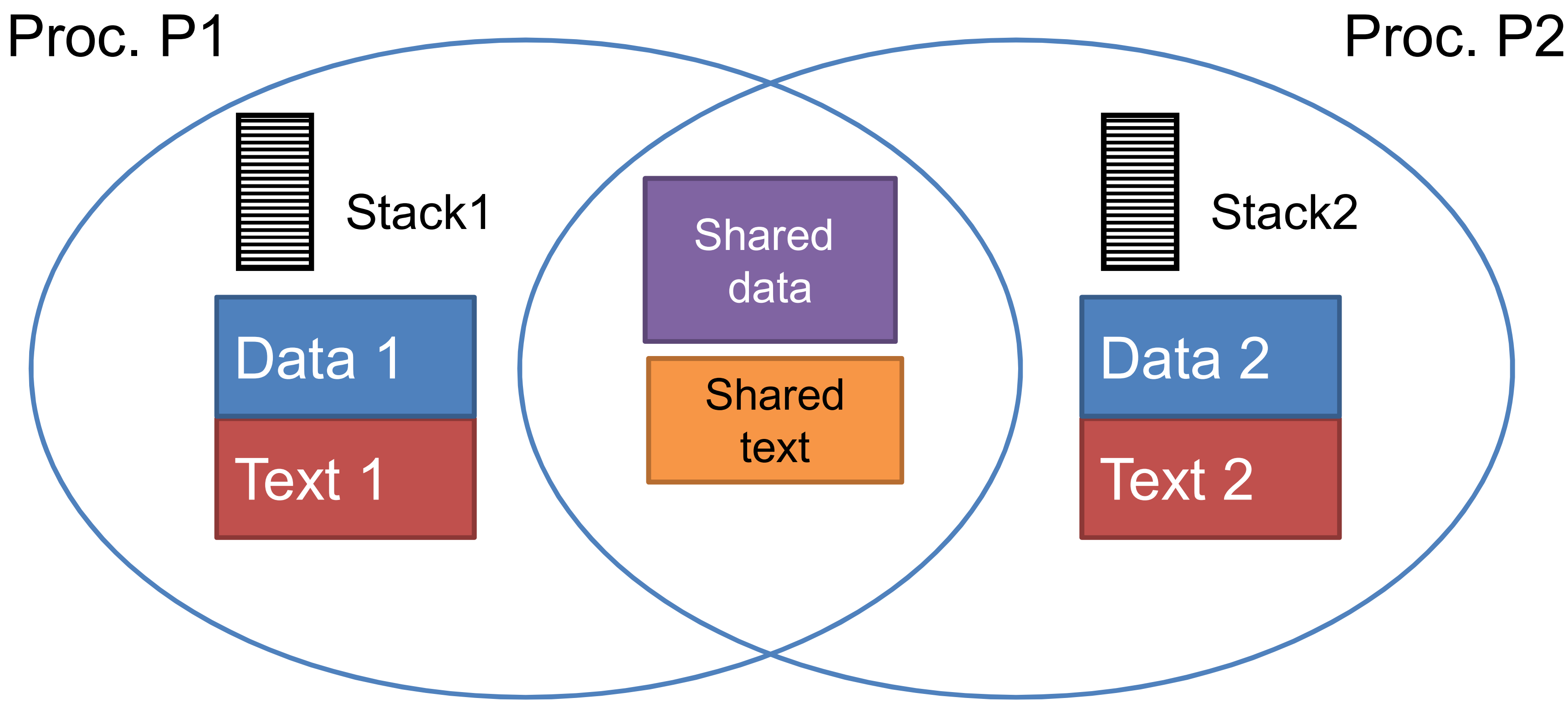
Cooperation models

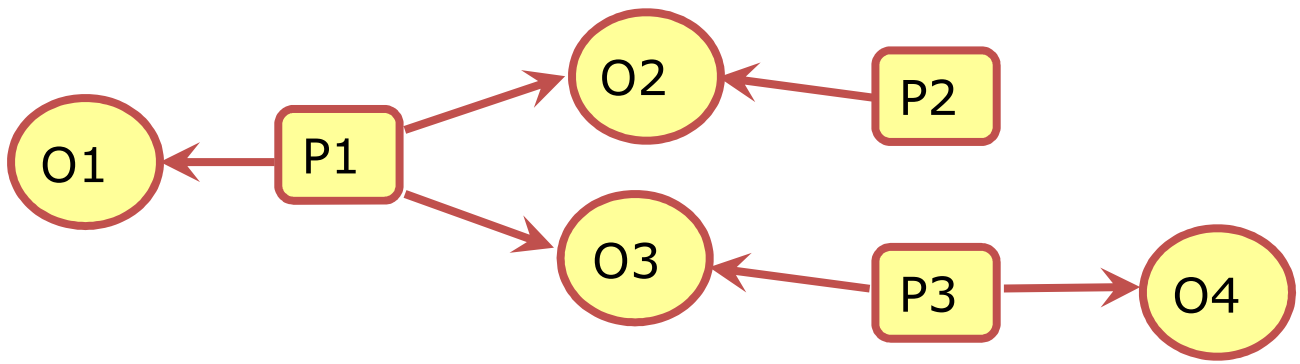
Global vs. local model

- Global environment
  - Processes (threads) can share data
  - Shared memory
- Local environment
  - processes/ do not share data
  - No shared memory

Global environment

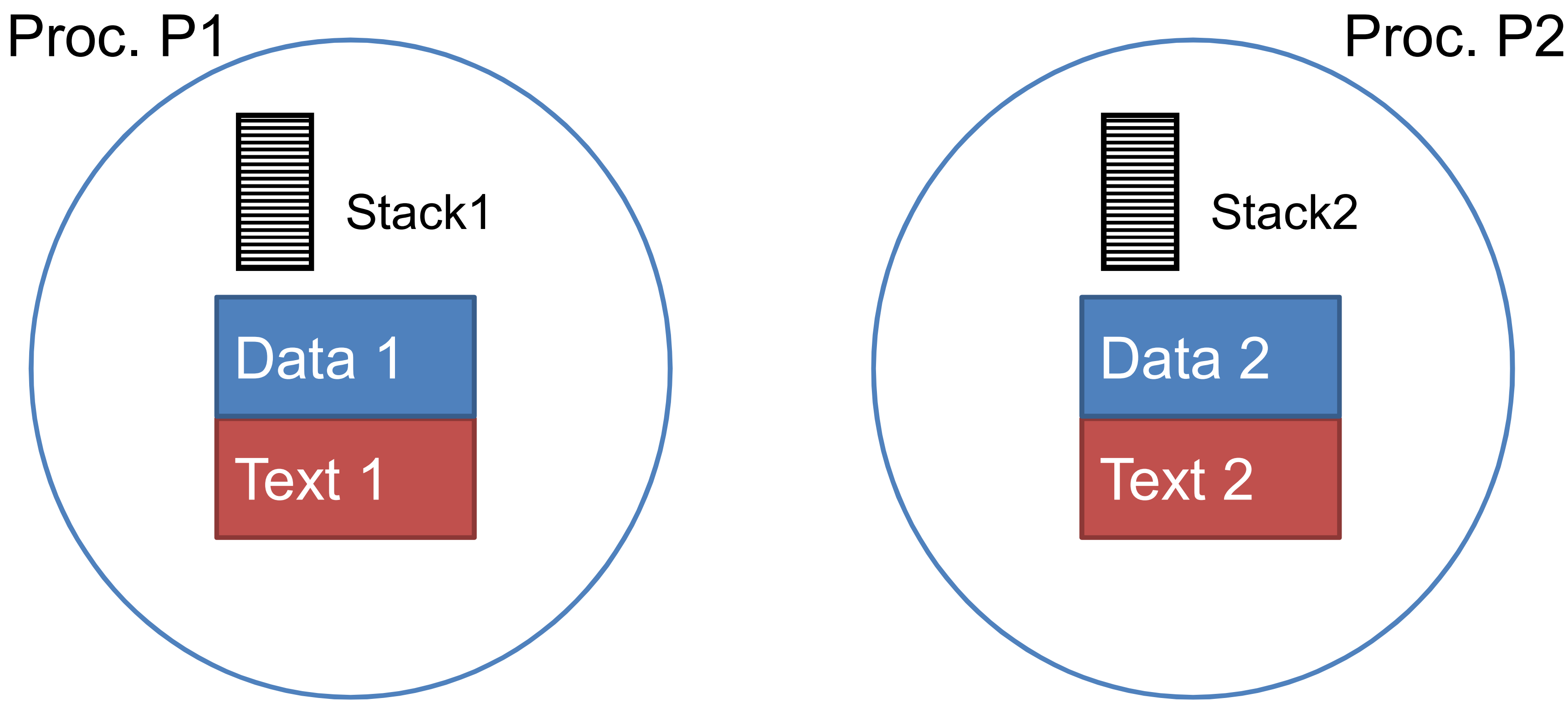


Global environment

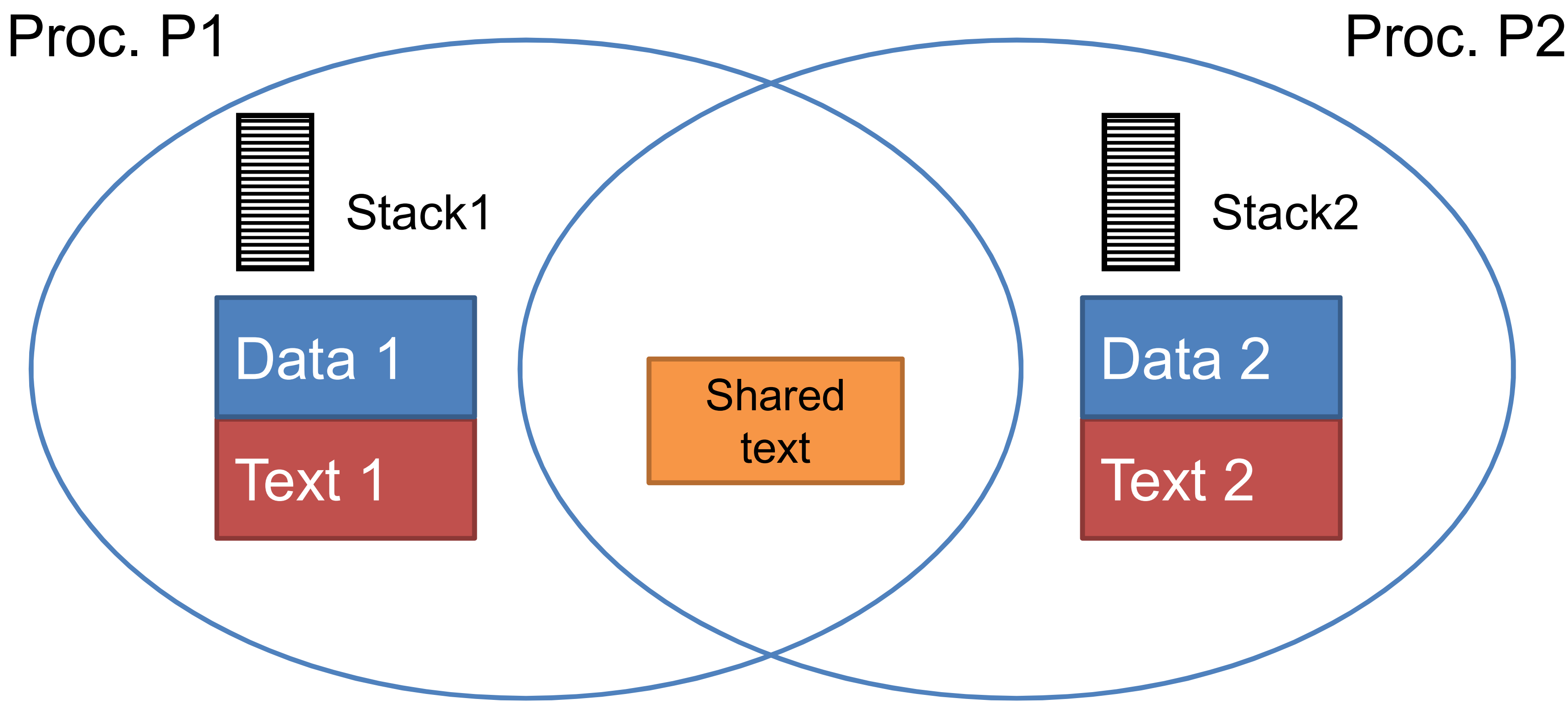


O1, O4 private objects
O2, O3 shared objects
• competition, cooperation

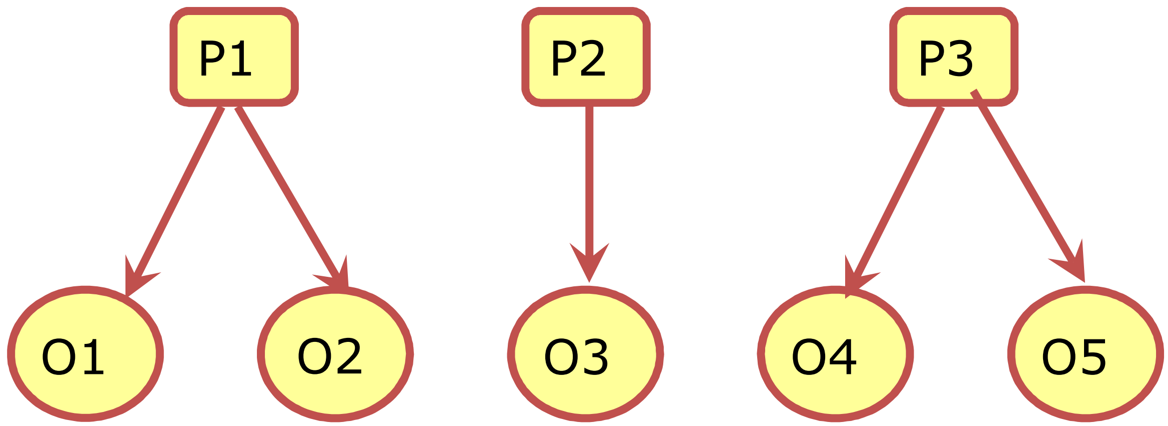
Local environment



Local environment

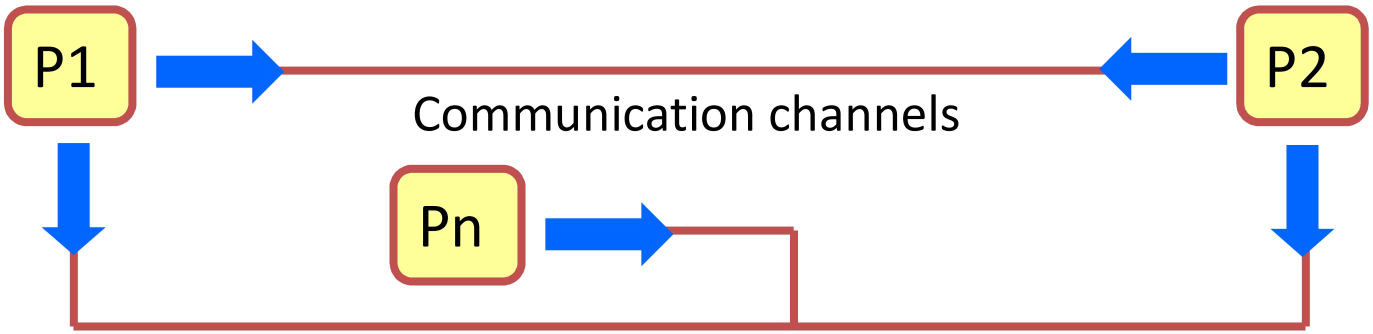


Local environment



O1-O5 are private objects
Competition through server processes
Cooperation through communication

Local environment



Cooperation (communication, synchronization) by means of message passing

Synchronization

Global environment

Synchronization Motivation

Thread 1

```
p = someFn();
isInitialized = true;
```

Thread 2

```
while (! isInitialized ) ;
q = aFn(p);

if q != aFn(someFn())
   panic
```

Too Much Milk Example

	Person A	Person B
12:30	Look in fridge. Out of milk.	
12:35	Leave for store.	
12:40	Arrive at store.	Look in fridge. Out of milk.
12:45	Buy milk.	Leave for store.
12:50	Arrive home, put milk away.	Arrive at store.
12:55		Buy milk.
1:00		Arrive home, put milk away. Oh no!

Definitions

- **Race condition (corsa critica):** output of a concurrent program depends on the order of operations between threads
- **Mutual exclusion (mutual esclusione):** only one thread does a particular thing at a time
- **Critical section (sezione critica):** piece of code that only one thread can execute at once
- **Lock:** prevent someone from doing something
  - Lock before entering critical section, before accessing shared data
  - unlock when leaving, after done accessing shared data
  - wait if locked (all synch involves waiting!)

Too Much Milk, Try #1

- Correctness property
  - Someone buys if needed (**liveness**)
  - At most one person buys (**safety**)
- Try #1: leave a note

```
if !note
   if !milk {
      leave note
      buy milk
      remove note
   }
```

Too Much Milk, Try #1

Thread A

```
if (!note) {
  if (!milk)
    leave note
    buy milk
    remove note
  }
```

Thread B

```
if (!note){
  if (!milk)
    leave note
    buy milk
    remove note
  }
```

Too Much Milk, Try #2

Thread A

```
leave note A
if (!note B) {
  if (!milk)
    buy milk
  }
remove note A
```

Thread B

```
leave note B
if (!noteA){
  if (!milk)
    buy milk
  }
remove note B
```

Too Much Milk, Try #3

Thread A

```
leave note A
while (note B) // X
  do nothing;
if (!milk)
  buy milk;
remove note A
```

Thread B

```
leave note B
if (!noteA){   // Y
  if (!milk)
    buy milk
  }
remove note B
```

Can guarantee at X and Y that either:

(i) Safe for me to buy

(ii) Other will buy, ok to quit

Lessons

- Solution is complicated
  - “obvious” code often has bugs
- Modern compilers/architectures reorder instructions
  - Making reasoning even more difficult
- Generalizing to many threads/processors
  - Peterson’s algorithm: even more complex

Another example: a stack

- Two threads interact by means of a stack, with push and pop operations
- Expected behaviour:

T_1

……………

```
Top--
Stack[top]=y
```

……………

T_2

……………

```
Z=Stack[top]
Top++
```

……………

Critical sections

Another example: a stack

- Here the operations of T_1 are interrupted by a pop executed by T_2
- Possible behaviour:

T_1

```
……………
Top--
Stack[top]=y
……………
```

T_2

```
……………
Z=Stack[top]
Top++
……………
```

Interference!

Exercise:

- Show a concrete case (with numbers in the stack) in which the stack becomes inconsistent and/or the processes read wrong data from the stack

Locks

- lock_acquire
  - wait until lock is free, then take it
- lock_release
  - release lock, waking up anyone waiting for it

1. At most one lock holder at a time (safety)
2. If no one holding, acquire gets lock (progress)
3. If all lock holders finish and no higher priority waiters, waiter eventually gets lock (progress)

Too Much Milk, #4

Locks allow concurrent code to be much simpler:

```
lock_acquire()
if (!milk) buy milk
lock_release()
```

- How do we implement locks? (Later)
  - Hardware support for read/modify/write instructions

Lock Example: Malloc/Free

```
char *malloc (n) {
  lock_acquire(Mlock);
  p = allocate memory
  lock_release(Mlock);
  return p;
}
```

```
void free(char *p) {
  lock_acquire(Mlock);
  put p back on free list
  lock_release(Mlock);
}
```

Rules for Using Locks

- Lock is initially free
- Always acquire before accessing shared data structure
  - Beginning of procedure!
- Always release after finishing with shared data
  - End of procedure!
  - DO NOT throw lock for someone else to release
- Never access shared data without lock
  - Danger!

Will this code work?

```
[…]
if (p == NULL) {
  lock_acquire(lock);
  if (p == NULL) {
    p = newP();
  }
  release_lock(lock);
}
use p->field1
```

```
newP() {
  p = malloc(sizeof(p));
  p->field1 = …
  p->field2 = …
  return p;
}
```

Lock example: Bounded Buffer

```
tryget() {
  item = NULL;
  lock.acquire();
  if (nelem>0) {
        item = buf[front];
        front = (front++)%size;
        nelem – –;
  }
  lock.release();
  return item;
}
```

```
tryput(item) {
  lock.acquire();
  if (nelem < size) {
        buf[last] = item;
        last = (last ++)%size;
        nelem ++;
  }
  lock.release();
}
```

Initially: nelem = front = last = 0; lock = FREE;
size is buffer capacity

Condition Variables

- Called only when holding a lock

- Wait: atomically release lock and relinquish processor until signaled
- Signal: wake up a waiter, if any
- Broadcast: wake up all waiters, if any

Example: Producer/Consumer

Definition:

- One (or more) producer (s) deposits messages in a shared buffer
- One (or more) consumer (s) extracts messages from the buffer

Requirements:

- Each message that is produced must be consumed exactly once.

Example: Bounded Buffer

```
get() {
  lock.acquire();
  while (nelem == 0)
        empty.wait(lock);
  item = buf[front];
  front=  (front++) % size;
  nelem – –;
  full.signal(lock);
  lock.release();
  return item;
}
```

```
put(item) {
  lock.acquire();
  while (nelem == size)
        full.wait(lock);
  buf[last] = item;
  last = (last ++) % size;
  nelem ++;
  empty.signal(lock);
  lock.release();
}
```

Initially: nelem = front = last = 0; size is buffer capacity

empty/full are condition variables

Pre/Post Conditions

- What is state of the bounded buffer at lock acquire?
  - nelem>=0 (and front <= last, without considering the modulal operation)
  - nelem<=size (and front + size >= last, without considering the modular operations)
  - (also true on return from wait)
- Also true at lock release!
- Allows for proof of correctness

Condition Variables

- ALWAYS hold lock when calling wait, signal, broadcast
  - Condition variables provide synchronization FOR shared state
  - ALWAYS hold lock when accessing shared state
- Condition variable is memoryless
  - If signal when no one is waiting, no op
  - If wait before signal, waiter wakes up
- Wait atomically releases lock
  - What if wait, then release?
  - What if release, then wait?

Condition Variables, cont'd

- When a thread is woken up from wait, it may not run immediately
  - Signal/broadcast put thread on ready list
  - When lock is released, anyone might acquire it
- Wait MUST be in a loop

```
while (needToWait())
    condition.Wait(lock);
```

- Simplifies implementation
  - Of condition variables and locks
  - Of code that uses condition variables and locks

Java Manual

When waiting upon a Condition, a “spurious wakeup” is permitted to occur, in general, as a concession to the underlying platform semantics. This has little practical impact on most application programs as a Condition should always be waited upon in a loop, testing the state predicate that is being waited for.

Structured Synchronization

- Identify objects or data structures that can be accessed by multiple threads concurrently
- Add locks to object/module
  - Grab lock on start to every method/procedure
  - Release lock on finish
- If need to wait
  - while(needToWait()) condition.Wait(lock);
  - Do not assume, when you wake up, that signaller just ran
- If do something that might wake someone up
  - Signal or Broadcast
- Always leave shared state variables in a consistent state
  - When lock is released, or when waiting

Mesa vs. Hoare semantics

- Mesa (in textbook, Hansen)
  - Signal puts waiter on ready list
  - Signaller keeps lock and processor
- Hoare
  - Signal gives processor and lock to waiter
  - When waiter finishes, processor/lock given back to signaller
  - Nested signals possible!

Mesa & Hoare semantics

- The producer/consumer solution works well with both Mesa & Hoare semantics
- However it does not make any assumption on the order in which:
  - The producers that are waiting are waked up and deposit their messages
  - The consumers that are waiting are waked up

FIFO Bounded Buffer (Hoare semantics)

```
get() {
  lock.acquire();
  while (nelem == 0)
        empty.wait(lock);
  item = buf[front];
  front=  (front++) % size;
  nelem ––;
  full.signal(lock);
  lock.release();
  return item;
}
```

```
put(item) {
  lock.acquire();
  while (nelem == size)
        full.wait(lock);
  buf[last] = item;
  last = (last ++) % size;
  nelem ++;
  empty.signal(lock);
  // CAREFUL: someone else ran
  lock.release();
}
```

Initially: nelem = front = last = 0; size is buffer capacity

empty/full are condition variables

FIFO Bounded Buffer (Mesa semantics)

- Create a condition variable for every waiter
- Queue condition variables (in FIFO order)
- Signal picks the front of the queue to wake up
- CAREFUL if spurious wakeups!

- Easily extends to case where queue is LIFO, priority, priority donation, …
  - With Hoare semantics, not as easy

FIFO Bounded Buffer (Mesa semantics, put() is similar)

```
get() {
 lock.acquire();
 if (  nelem == 0 ||
      !nextGet.empty() ) {
    self = new Condition;
    nextGet.Append(self);
    while (nelem == 0)
      self.wait(lock);
    nextGet.Remove(self);
    delete self;
  }
  item = buf[front];
  front=  (front++) % size;
  nelem – –;
  if (!nextPut.empty())
    nextPut.first()->signal(lock);
  lock.release();
  return item;
}
```

Initially: nelem = front = last = 0; size is buffer capacity

nextGet, nextPut are queues of Condition Variables

Implementing Synchronization

Concurrent Applications

Semaphores | Locks | Condition Variables

Interrupt Disable | Atomic Read/Modify/Write Instructions

Multiple Processors | Hardware Interrupts

Implementing Synchronization

Take 1: using memory load/store

– See “too much milk” solution / Peterson’s algorithm

Take 2:

lock.acquire() { disable interrupts }

lock.release() { enable interrupts }

Lock Implementation, Uniprocessor

```
LockAcquire() {
  disableInterrupts ();
  if (value == BUSY) {
     waiting.add(current TCB);
     suspend(); *
  } else {
     value = BUSY;
  }
  enableInterrupts ();
}
```

* Invokes the scheduler, context switch & enable interrupts

```
LockRelease() {
  disableInterrupts ();
  if (!waiting.Empty()){
    thread = waiting.Remove();
    readyList.Append(thread);
  } else {
    value = FREE;
  }
  enableInterrupts ();
}
```

Multiprocessor

- Read-modify-write instructions
  - Atomically read a value from memory, operate on it, and then write it back to memory
  - Intervening instructions prevented in hardware
- Examples
  - Test and set
  - Intel: xchgb, lock prefix
  - Compare and swap
- Does it matter which type of RMW instruction we use?
  - Not for implementing locks and condition variables!

Spinlocks

Lock where the processor waits in a loop for the lock to become free

- Assumes lock will be held for a short time
- Used to protect ready list to implement locks

```
SpinlockAcquire() {
  while (testAndSet(&spinLockValue) == BUSY)
    ;
}
SpinlockRelease() {
  spinLockValue = FREE;
}
```

Spinlocks: a low-level implementation

```
// &spinLockValue is a memory cell containing a binary value: Free (0) or BUSY (1)

// TSL R, &spinLockValue :
     writes the content of &spinLockValue in R and writes BUSY (1) in &LockValue

SpinlockAcquire&Lockvalue) {
       Loop:         TSL R, & spinLockValue
                     CMP R, BUSY
                     JEQ Loop:
                     RET  // at this point &lockValue == BUSY!!!!
}

SpinlockRelease() {
     MOV #FREE, &spinLockValue      // this unlocks a thread in the loop, if any
}
```

Lock Implementation, Multiprocessor

```
LockAcquire(){
   spinLock.Acquire();
   if (value == BUSY){
     waiting.add(current TCB);
     sched.suspend(&spinLock); *
   } else {
      value = BUSY;
      spinLock.Release();
}
```

* scheduler: marks thread as waiting; release spinlock; schedules next thread;

```
LockRelease() {
   spinLock.Acquire();
   if (!waiting.Empty()){
     thread = waiting.Remove();
     sched.makeReady (thread,
   &spinLock); *
   } else {
     value = FREE;
   }
   spinLock.Release();
}
```

* scheduler: marks thread as ready, put it in the ready list.

Lock Implementation, Linux

- Fast path
  - If lock is FREE, and no one is waiting, test&set
- Slow path
  - If lock is BUSY or someone is waiting, see previous slide

- User-level locks
  - Fast path: acquire lock using test&set
  - Slow path: system call to kernel, to use kernel lock

Semaphores

- Semaphore has a non-negative integer value
  - P() atomically waits for value to become > 0, then decrements
  - V() atomically increments value (if no waiter is present); else it wakes up one waiter
- Semaphores are like integers except:
  - Only operations are P and V
  - Operations are atomic
    - If value is 1, two P's will result in value 0 and one waiter
- Semaphores are useful for
  - Unlocked wait: interrupt handler, fork/join

P&V Implementation, Multiprocessor

```
P(sem){
  spinLock.Acquire();
  disableInterrupts ();
  if (sem.value == 0){
    waiting.add(current TCB);
    suspend(&spinLock); *
} else {
     sem.value --;
     spinLock.Release();
     enableInterrupts ();
}
```

* suspends, invokes scheduler, context switch & enable interrupts

```
V(sem) {
  spinLock.Acquire();
  disableInterrupts ();
  if (!waiting.Empty()){
     thread = waiting.Remove();
     readyList.Append(thread);
  } else {
     sem.value ++;
  }
  spinLock.Release();
  enableInterrupts ();
}
```

Semaphore Bounded Buffer

```
get() {
  empty.P();
  mutex.P();
  item = buf[front]
  front= (front+1) % size;
  mutex.V();
  full.V();
  return item;
}
```

```
put(item) {
  full.P();
  mutex.P();
  buf[last] = item;
  last = (last +1) % size;
  mutex.V();
  empty.V();
}
```

Initially: front = last = 0; size is buffer capacity

empty/full are semaphores (initialized to 0 and size)

Mutex is a semaphore initialized to 1

Implementing Condition Variables using Semaphores (Take 1)

```
wait(lock) {
  lock.release();
  sem.P();
  lock.acquire();
}
signal() {
  sem.V();
}
```

Implementing Condition Variables using Semaphores (Take 2)

```
wait(lock) {
  lock.release();
  sem.P();
  lock.acquire();
}
signal() {
  if semaphore is not empty
     sem.V();
}
```

Implementing Condition Variables using Semaphores (Take 3)

```
wait(lock) {
  sem = new Semaphore;
  queue.Append(sem);   // queue of waiting threads
  lock.release();
  sem.P();
  lock.acquire();
}
signal() {
  if !queue.Empty() {
     sem = queue.Remove();
     sem.V();           // wake up waiter
  }
}
```

Synchronization Summary

- Use consistent structure
- Always use locks and condition variables
- Always acquire lock at beginning of procedure, release at end
- Always hold lock when using a condition variable
- Always wait in while loop
- Never spin in sleep()