"Programming with Threads" Birrell

- Multiprocessors
- Waiting for slow devices
- Human users
- Shared network servers multiplexing among client (each client served by its own thread)
- Maintenance tasks

Hardware Assistance for Synchronization

- Most modern architectures provide some support for building synchronization: atomic ***read-modify-write*** instructions.
- Example: ***test-and-set (loc, reg)***

  [sets bit to 1 in the new value of loc; returns old value of loc in reg]

  [ ] notation means atomic
- Other examples:

  compare-and-swap, fetch-and-op

Busywaiting with Test-and-Set

- Declare a shared memory location to represent a *busyflag* on the critical section we are trying to protect.
- enter_region (or *acquiring* the "lock"):

  waitloop: tsl busyflag, R0 // R0 = busyflag; busyflag = 1

  bnz R0, waitloop // was it already set?
- exit region (or *releasing* the "lock"):

  busyflag = 0

?

Pros and Cons of Busywaiting

- Key characteristic - the "waiting" process is actively executing instructions in the CPU and using memory cycles.
- Appropriate when:
  - High likelihood of finding the critical section unoccupied (don't take context switch just to find that out) or estimated wait time is very short
- Disadvantages:
  - Wastes resources (CPU, memory, bus bandwidth)
    - Cache-miss heavy
  - *Looks* busy if system is observing behavior

Better Implementations from Multiprocessor Domain

- Dealing with *contention* of Test&Set spinlocks:
  - Don't execute test&set so much
  - Spin without generating bus traffic
- Test&Set with Backoff
  - Insert delay between test&set operations (not too long)
  - Exponential seems good (k*ci)
  - Not fair
- Test-and-Test&Set
  - Spin (test) on local cached copy *until it gets invalidated*, then issue test&set
  - Intuition: No point in trying to set the location until we know that it's not set, which we can detect when it get invalidated...
  - Still contention after invalidate
  - Still not fair
- Analogies for Energy?

Blocking Synchronization

- OS implementation involving changing the state of the "waiting" process from running to blocked.
- Need some synchronization abstraction known to OS - provided by system calls.
  - mutex locks with operations acquire and release
  - semaphores with operations P and V (down, up)
  - condition variables with wait and signal

Template for Implementing Blocking Synchronization

- Associated with the lock is a memory location (busy) and a queue for waiting threads/processes.
- Acquire syscall:
  while (busy) {enqueue caller on lock's queue}
  /*upon waking to nonbusy lock*/ busy = true;
- Release syscall:
  busy = false;
  /* wakup */ move any waiting threads to Ready queue

Pros and Cons of Blocking

- Waiting processes/threads don't consume resources
- Appropriate: when the cost of a system call is justified by expected waiting time
  - High likelihood of contention for lock
  - Long critical sections
- Disadvantage: OS involvement
  –> overhead

Semaphores

- Well-known synchronization abstraction
- Defined as a non-negative integer with two atomic operations

  P(s) - [wait until s > 0; s--]

  V(s) - [s++]
- The atomicity and the waiting can be implemented by either busywaiting or blocking solutions.

Semaphore Usage

- Binary semaphores can provide mutual exclusion (solution of critical section problem)
- Counting semaphores can represent a resource with multiple instances (e.g. solving producer/consumer problem)
- Signalling events (persistant events that stay relevant even if nobody listening right now)

The Critical Section Problem

while (1)

{ *...other stuff...*

P(mutex)

critical section

V(mutex)

}

Semaphore:
mutex initially 1

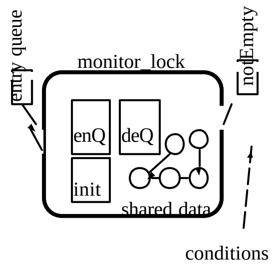
Knowing shared from private…

SRC Thread Primitives

- SRC thread primitives
  - Thread = Fork (procedure, args)
  - result = Join (thread)
  - LOCK mutex DO critical section END
  - Wait (mutex, condition)
  - Signal (condition)
  - Broadcast (condition)
  - Acquire (mutex), Release (mutex) //more dangerous

Monitor Abstraction

- Encapsulates shared data and operations with mutual exclusive use of the object (an associated *lock*).
- Associated *Condition Variables* with operations of *Wait* and *Signal.*

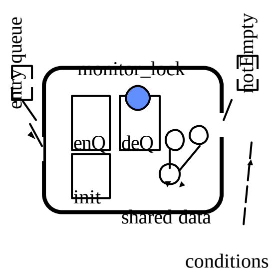


Condition Variables

- We build the monitor abstraction out of a lock (for the mutual exclusion) and a set of associated condition variables.
- *Wait on condition*: releases lock held by caller, caller goes to sleep on condition's queue. When awakened, it must reacquire lock.
- *Signal condition*: wakes up one waiting thread.
- *Broadcast*: wakes up all threads waiting on this condition.

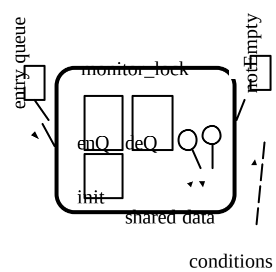
Monitor Abstraction

```
EnQ:{aquire (lock);
    if (head == null)
        {head = item;
        signal (lock, notEmpty);}
    else tail->next = item;
    tail = item;
    release(lock);}
deQ:{acquire (lock);
    if (head == null)
        wait (lock, notEmpty);
     item = head;
     if (tail == head) tail = null;
     head=item->next;
    release(lock);}
```



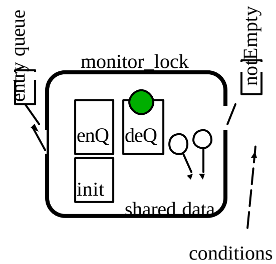
Monitor Abstraction

```
EnQ:{aquire (lock);
    if (head == null)
        {head = item;
        signal (lock, notEmpty);}
    else tail->next = item;
    tail = item;
    release(lock);}
deQ:{acquire (lock);
    if (head == null)
        wait (lock, notEmpty);
     item = head;
     if (tail == head) tail = null;
     head=item->next;
    release(lock);}
```



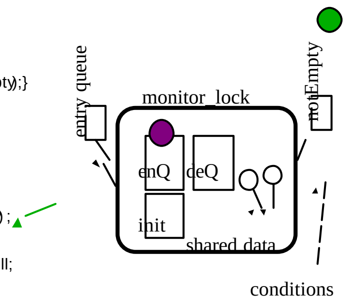
Monitor Abstraction

```
EnQ:{aquire (lock);
    if (head == null)
        {head = item;
        signal (lock, notEmpty);}
    else tail->next = item;
    tail = item;
    release(lock);}
deQ:{acquire (lock);
    if (head == null)
        wait (lock, notEmpty);
     item = head;
     if (tail == head) tail = null;
     head=item->next;
    release(lock);}
```



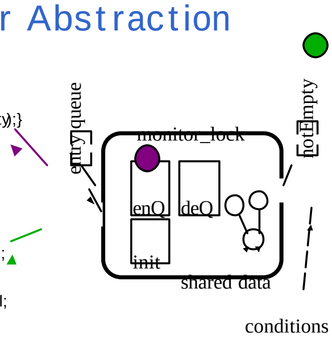
Monitor Abstraction

```
EnQ:{aquire (lock);
    if (head == null)
        {head = item;
        signal (lock, notEmpty);}
    else tail->next = item;
    tail = item;
    release(lock);}
deQ:{acquire (lock);
    if (head == null)
        wait (lock, notEmpty);
     item = head;
     if (tail == head) tail = null;
     head=item->next;
    release(lock);}
```



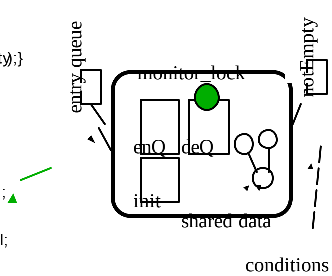
Monitor Abstraction

```
EnQ:{aquire (lock);
    if (head == null)
        {head = item;
        signal (lock, notEmpty);}
    else tail->next = item;
    tail = item;
    release(lock);}
deQ:{acquire (lock);
    if (head == null)
        wait (lock, notEmpty);
     item = head;
     if (tail == head) tail = null;
     head=item->next;
    release(lock);}
```



Monitor Abstraction

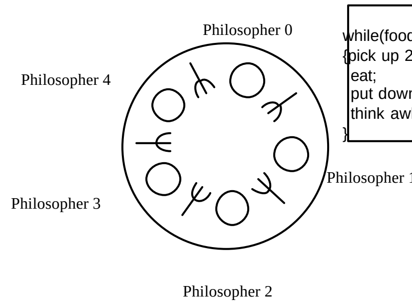
```
EnQ:{aquire (lock);
    if (head == null)
        {head = item;
        signal (lock, notEmpty);}
    else tail->next = item;
    tail = item;
    release(lock);}
deQ:{acquire (lock);
    while (head == null)
        wait (lock, notEmpty);
     item = head;
     if (tail == head) tail = null;
     head=item->next;
    release(lock);}
```



Pitfalls

- ✓ Race conditions, failure to implement mutual exclusion within critical sections of code.
- ➢ Deadlock
- ➢ Starvation
- ➢ Priority inversion
- ✓ Performance Issues (including energy implications)
  - Difficulty of detecting idleness with busywaiting synchronization
  - Lock granularity issues

5 Dining Philosophers




```
while(food available)
{pick up 2 adj. forks;
 eat;
 put down forks;
 think awhile;
}
```

Template for Philosopher

```
while (food available)
{        [          ]  /*pick up forks*/

   eat;  [          ]  /*put down forks*/

   think awhile;
}
```

Naive Solution

```
while (food available)
{
   P(fork[left(me)]);       /*pick up forks*/
   P(fork[right(me)]);
   eat;
   V(fork[left(me)]);       /*put down forks*/
   V(fork[right(me)]);
   think awhile;
}
```

Philosophy 101
(or why 5DP is interesting)

- How to eat with your Fellows without causing ***Deadlock.***
  - Circular arguments (the circular wait condition)
  - Not giving up on firmly held things (no preemption)
  - Infinite patience with Half-baked schemes (hold some & wait for more)
- Why ***Starvation*** exists and what we can do about it.

Circular Wait Condition

```
while (food available)
{   if (me == 0) {P(fork[left(me)]); P(fork[right(me)]);}
    else {(P(fork[right(me)]); P(fork[left(me)]); }
    eat;
    V(fork[left(me)]); V(fork[right(me)]);

    think awhile;
}
```

Ordered resources

Hold and Wait Condition

```
while (food available)
{   P(mutex);
    while (forks [me] != 2)
          {blocking[me] = true; V(mutex); P(sleepy[me]); P(mutex);}
    forks [leftneighbor(me)] --;  forks [rightneighbor(me)]--;
    V(mutex):
    eat;
    P(mutex); forks [leftneighbor(me)] ++;  forks [rightneighbor(me)]++;
    if (blocking[leftneighbor(me)]) V(sleepy[leftneighbor(me)]);
    if (blocking[rightneighbor(me)]) V(sleepy[rightneighbor(me)]);
    V(mutex);
    think awhile;
}
```

Starvation

The difference between deadlock and starvation is subtle:

- Once a set of processes are deadlocked, there is no future execution sequence that can get them out of it.
- In starvation, there does exist some execution sequence that is favorable to the starving process although there is no guarantee it will ever occur.
- Rollback and Retry solutions are prone to starvation.
- Continuous arrival of higher priority processes is another common starvation situation.

Issues

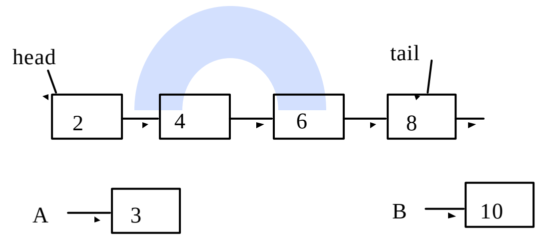
- Locking overhead (granularity)
- Broadcast vs. Signal and other causes of spurious wakeups
- Nested lock/condition variable problem

Unseen in call

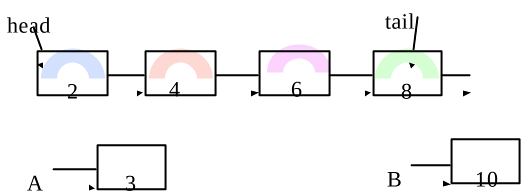
```
LOCK a DO
    LOCK b DO
        while (not_ready) wait (b, c) //releases b not a
    END
END
```

- Priority inversions

Lock Granularity



Lock Granularity



Spurious Wakeups

while (! required_conditions) wait (m, c);

- Why we use "while" not "if" – invariant not guaranteed
- Why use broadcast – using one condition queue for many reasons. Waking threads have to sort it out. Possibly better to separate into multiple conditions (more complexity to code)

Mars Pathfinder Example

- In July 1997 Pathfinder's computer reset itself several times during data collection and transmission from Mars.
  - One of its processes failed to complete by a deadline, triggering the reset
- Priority Inversion Problem
  - A low priority process held a mutual exclusion semaphore on a shared data structure but was preempted to let higher priority processes run
  - The high priority process that failed to complete on time was blocked on this semaphore and priority inheritance was not enabled.
  - Meanwhile a bunch of medium priority processes ran, until finally the deadline ran out. The low priority semaphore-holding process never got the chance to fun again in that time to the point of releasing the mutex.

Tricks (mixed syntax)

```
if (some_condition) // as a hint
{
  LOCK m DO
     if (some_condition) //the truth
     {stuff}
  END
}
```

Cheap to get info but must check for correctness; always a slow way

More Tricks

General pattern:

while (! required_conditions) wait (m, c);

Broadcast works because waking up too many is OK (correctness-wise) although a performance impact.

```
LOCK m DO
    ...
    deferred_signal = true;
END
if (deferred_signal) signal (c);
```

Spurious lock conflicts caused by signals inside critical section and threads waking up to test mutex before it gets released.

Alerts

Thread state contains flag, alert-pending

Exception alerted

Alert (thread)
- alert-pending to true, wakeup a waiting thread

AlertWait (mutex, condition)
- if alert-pending set to false and raise exception
- else wait as usual

Boolean b = TestAlert()
- tests and clear alert-pending

```
TRY
  while (empty)
    AlertWait (m, nonempty); return (nextchar());
EXCEPT
  Thread.Alerted:
      return (eof);
```

Using Alerts

```
sibling = Fork (proc, arg);
while (!done)
{ done = longComp();
  if (done) Alert (sibling);
  else done = TestAlert();
}
```

Wisdom

Do s

- Reserve using alerts for when you don't know what is going on
- Only use if you forked the thread
- Impose an ordering on lock acquisition
- Write down invariants that should be true when locks aren't being held

Don't s

- Call into a different abstraction level while holding a lock
- Move the "last" signal beyond scope of Lock
- Acquire lock, fork, and let child release lock
- Expect priority inheritance since few implementations
- Pack data and expect fine grain locking to work