Concurrent Programming
A Review?

Why use processes/threads?

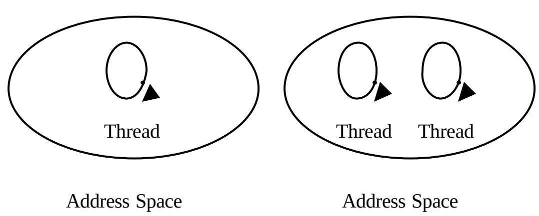
- To capture naturally concurrent activities within the structure of the programmed system.
  - Asynchronous events
- To gain speedup by overlapping activities or exploiting parallel hardware.

Power/energy implications?

Threads and Processes

- Decouple the resource allocation aspect from the control aspect
- Thread abstraction - defines a single sequential instruction stream (PC, stack, register values)
- Process - the resource context serving as a “container” for one or more threads (shared address space)
- Kernel threads - unit of scheduling
  (kernel-supported thread operations –> still slow)

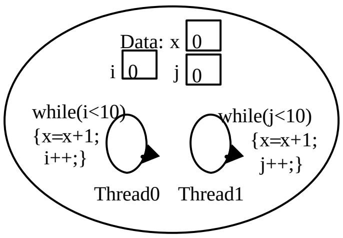
Threads and Processes



User-Level Threads

- To avoid the performance penalty of kernel-supported threads, implement at user level and manage by a run-time system
  - Contained “within” a single kernel entity (process)
  - Invisible to OS (OS schedules their container, not being aware of the threads themselves or their states). Poor scheduling decisions possible.
- User-level thread operations can be 100x faster than kernel thread operations, but need better integration / cooperation with OS.

The Trouble with Threads...



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Nondeterminism

- What unit of work can be performed without interruption? ***Indivisible*** or ***atomic*** operations.
- ***Interleavings*** - possible execution sequences of operations drawn from all threads.
- ***Race condition*** - final results depend on ordering and may not be "correct".

while (i<10) {x=x+1; i++;}

load value of x into reg
yield
add 1 to reg
yield
store reg value at x
yield

Reasoning about Interleavings

- On a uniprocessor, the possible execution sequences depend on when context switches can occur
  - Voluntary context switch - the process or thread explicitly yields the CPU (blocking on a system call it makes, invoking a Yield operation).
  - Interrupts or exceptions occurring - an asynchronous handler activated that disrupts the execution flow.
  - Preemptive scheduling - a timer interrupt may cause an involuntary context switch at any point in the code.
- On multiprocessors, the ordering of operations on shared memory locations is the important factor.

Unprotected Shared Data

```
Thread
  for (i=0; i<20; i++){
      key = rand;
      SortedInsert (key);}
  for (i=0; i<20; i++){
      SortedRemove (*key);
      print (key); }
```

?

Critical Sections

- If a sequence of non-atomic operations must be executed *as if* it were atomic in order to be correct, then we need to provide a way to constrain the possible interleavings in this ***critical section*** of our code.
  - Critical sections are code sequences that contribute to "bad" race conditions.
  - Synchronization needed around such critical sections.
- ***Mutual Exclusion*** - goal is to ensure that critical sections execute atomically w.r.t. related critical sections in other threads or processes.
  - How?

The Critical Section Problem

Each process follows this template:

```
while (1)
{ ...other stuff...   //processes in here shouldn't stop others
  enter_region( );
  critical section
  exit_region( );
}
```

The problem is to define enter_region and exit_region to ensure mutual exclusion with some degree of fairness.

Implementation Options for Mutual Exclusion

- Disable Interrupts
- Busywaiting solutions - spinlocks
  - execute a tight loop if critical section is busy
  - benefits from specialized atomic (read-mod-write) instructions
- Blocking synchronization
  - sleep (enqueued on wait queue) while C.S. is busy

Synchronization primitives (abstractions, such as locks) which are provided by a system may be implemented with some combination of these techniques.

The Critical Section Problem

```
while (1)
{ ...other stuff...

  critical section
  exit_region( );

}
```

Peterson's Alg. for 2 Process Mutual Exclusion

- enter_region:

  needin [me] = true;

  turn = you;

  while (needin [you] && turn == you) {no_op};
- exit_region:

  needin [me] = false;

What about more than 2 processes?

Interleaving of Execution of 2 Threads (blue and green)

enter_region:
  needin [me] = true;
  turn = you;
  while (needin [you] &&
    turn == you) {no_op};
Critical Section
exit_region:
  needin [me] = false;

enter_region:
  needin [me] = true;
  turn = you;
  while (needin [you] &&
    turn == you) {no_op};
Critical Section
exit_region:
  needin [me] = false;

?

needin [blue] = true;

needin [green] = true;

turn = green;

turn = blue;

while (needin [green] && turn == green)

Critical Section

while (needin [blue] && turn == blue){no_op};

while (needin [blue] && turn == blue){no_op};

needin [blue] = false;

while (needin [blue] && turn == blue)

Critical Section

needin [green] = false;

Greedy Version (turn = me)

needin [blue] = true;

needin [green] = true;

turn = blue;

while (needin [green] && turn == green)

Critical Section

turn = green;

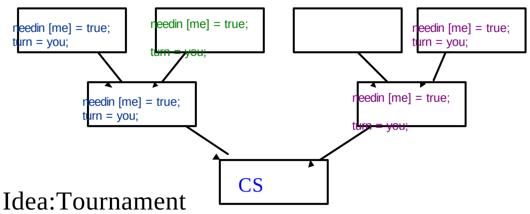
while (needin [blue] && turn == blue)

Critical Section

Oooops!

Can we extend 2-process algorithm to work with n processes?

Can we extend 2-process algorithm to work with n processes?



Idea:Tournament

Details:Bookkeeping (left to the reader)

Hardware Assistance

- 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)
  - *Looks* busy if system is observing behavior

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)

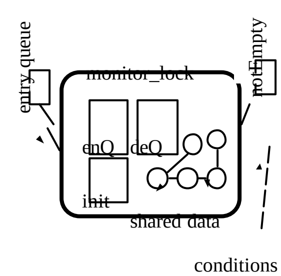
The Critical Section Problem

```
while (1)
{ ...other stuff...
    P(mutex)
  critical section
    V(mutex)
}
```

Semaphore:
mutex initially 1

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.*

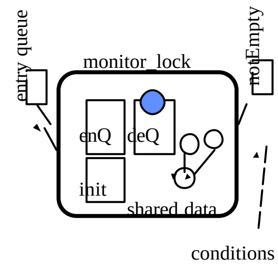


Condition Variables

- 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);}
```



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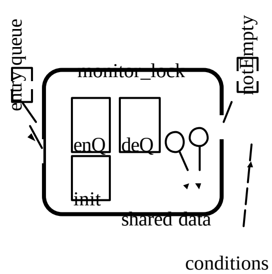

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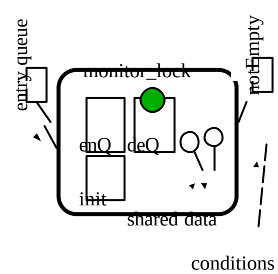

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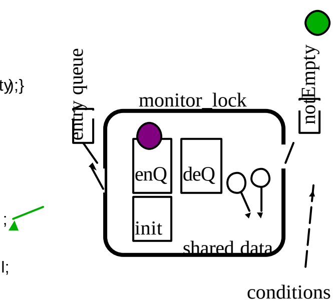
```



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```

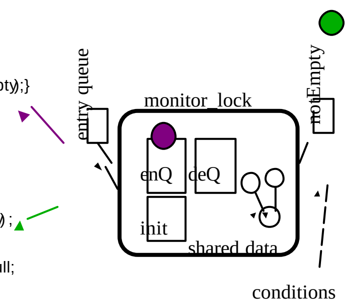

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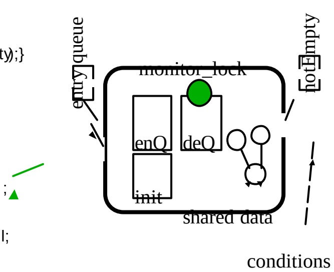


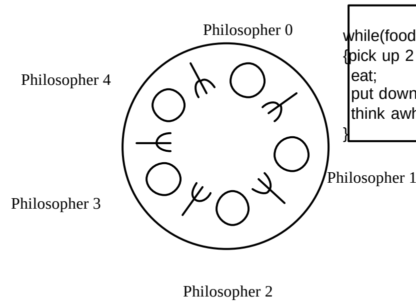
Pitfalls

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

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.

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)
{                          /*pick up forks*/
   P(fork[left(me)]);
   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.