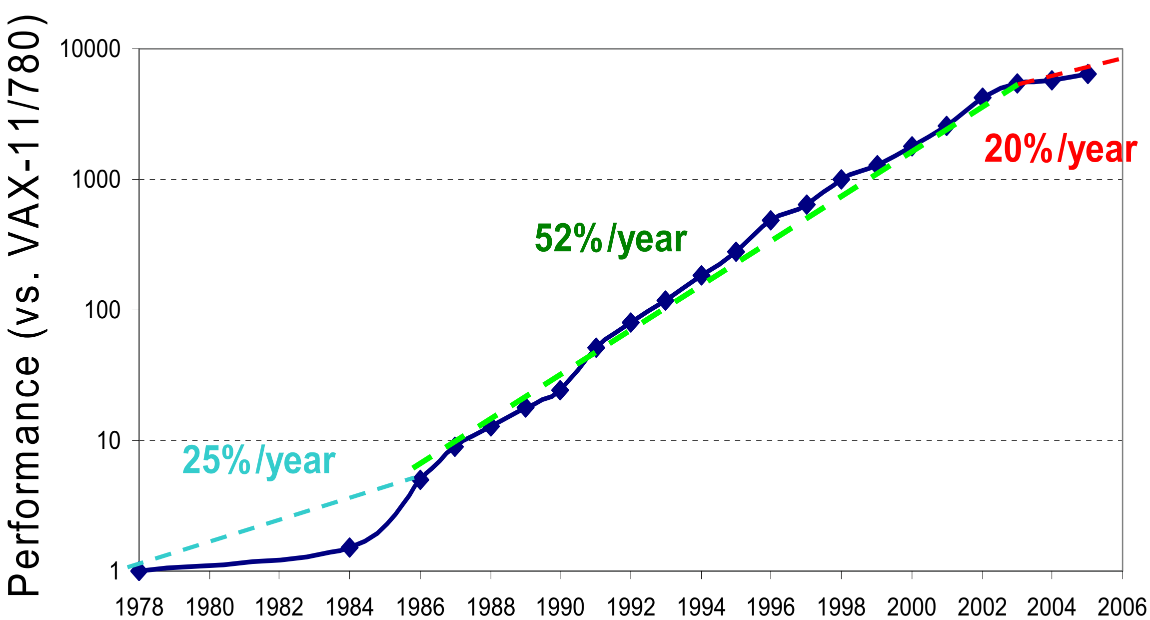
Concurrent Programing: Motivation, Theory, Practice

Emmett Witchel
First Bytes Teacher Conference
July 2008

Uniprocessor Performance Not Scaling

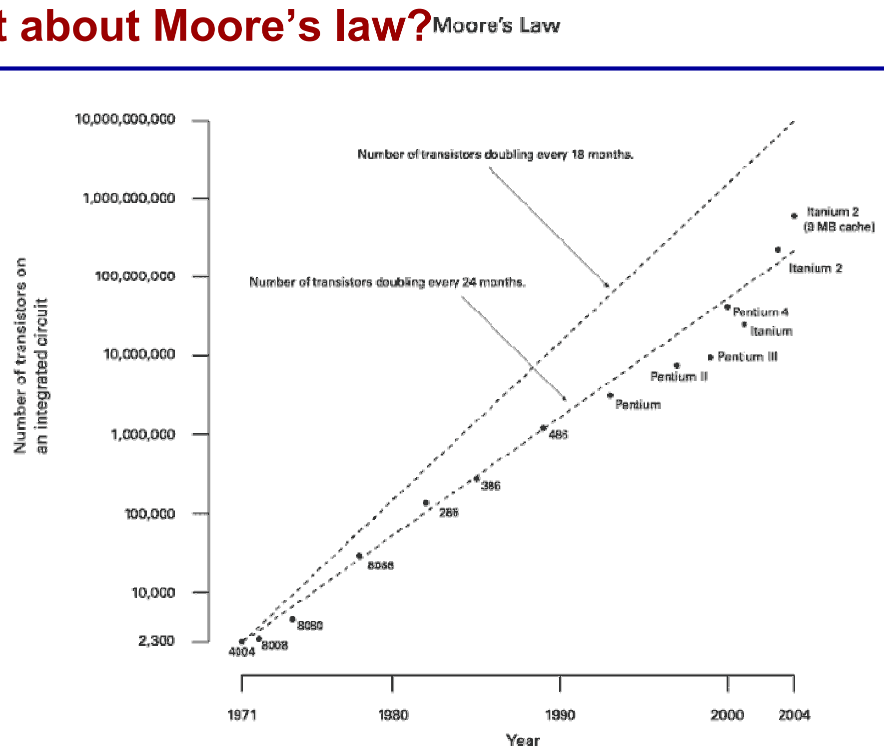


Graph by Dave Patterson

Power and heat lay waste to processor makers

- Intel P4 (2000-2007)
  - 1.3GHz to 3.8GHz, 31 stage pipeline
  - "Prescott" in 02/04 was too hot. Needed 5.2GHz to beat 2.6GHz Athalon
  - Too much power
- Intel Pentium Core, (2006-)
  - 1.06GHz to 3GHz, 14 stage pipeline
  - Based on mobile (Pentium M) micro-architecture
    - Power efficient
  - Designed by small team in Israel
- 2% of electricity in the U.S. feeds computers
  - Doubled in last 5 years

What about Moore's law?



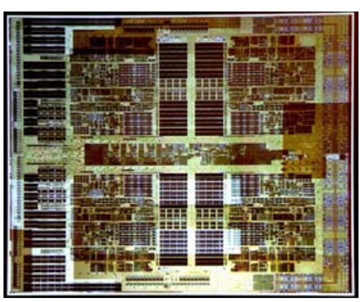
- Number of transistors double every 24 months
  - Not performance!

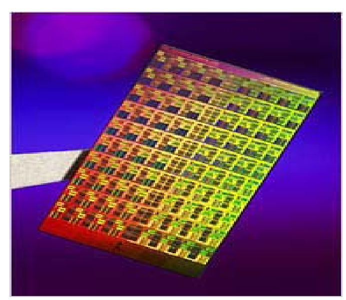
Architectural trends that favor multicore

- Power is a first class design constraint
  - Performance per watt the important metric
- Leakage power significant with small transisitors
  - Chip dissipates power even when idle!
- Small transistors fail more frequently
  - Lower yield, or CPUs that fail?
- Wires are slow
  - Light in vacuum can travel ~1m in 1 cycle at 3GHz
- Quantum effects
- Motivates multicore designs (simpler, lower-power cores)

Multicores are here, and coming fast!

4 cores in 2008 | 16 cores in 2009 | 80 cores in 20??





AMD Quad Core | Sun Rock | Intel TeraFLOP

"[AMD] quad-core processors … are just the beginning…."
http://www.amd.com

"Intel has more than 15 multi-core related projects underway"
http://www.intel.com

Houston, We have a problem!

- Running multiple programs only goes so far
- How does one application take advantage of multiple cores?
  - Parallel programming is a hard problem
- Even systems programmers find it challenging

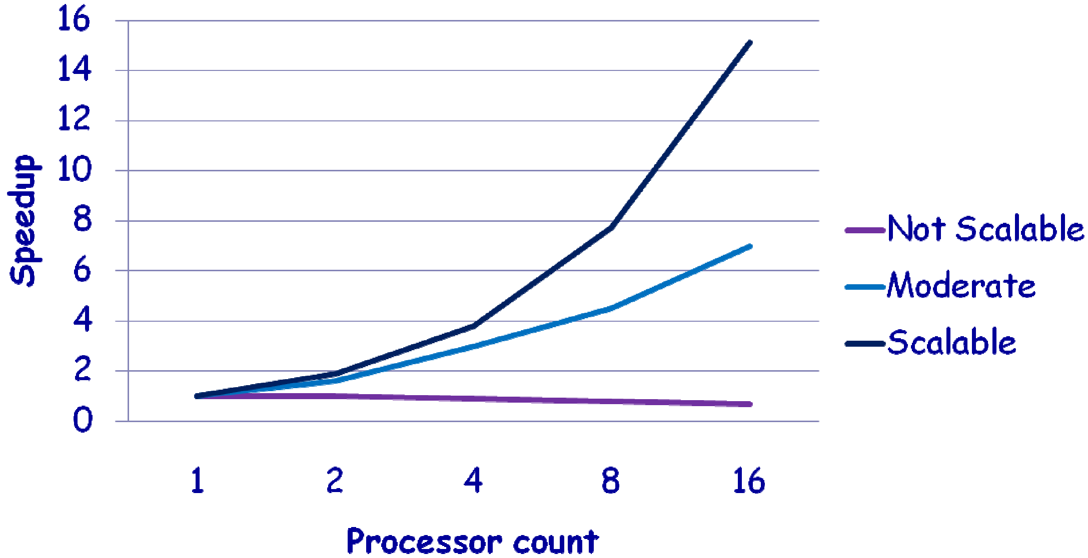
  "Blocking on a mutex is a surprisingly delicate dance"
  —OpenSolaris, mutex.c
- What about Visual Basic programmers?

  "The distant threat has come to pass.....parallel computers are the inexorable next step in the evolution of computers."
  — James Larus, Microsoft Research
  In *Transactional Memory*,
  Morgan & Claypool Publishers, 2007

What's hard about parallel programming?

- Answer #1: Little experience
  - Most application programmers have never written or substantially modified a significant parallel program
- Answer #2: Poor programming models
  - Primitive synchronization mechanisms
  - Haven't changed significantly in 50 years
- Answer #3: People think sequentially
  - Programming models approximate sequential execution

Application performance with more processors



- Not scalable: Most current programs
- Moderate: The hope for the future
- Scalable: Scientific codes, some graphics, server workloads

Processes
Process Management

What is a Process?

- A process is a program during execution.
  - Program = static executable file (image)
  - Process = executing program = program + execution state.
- A process is the basic unit of execution in an operating system
- Different processes may run several instances of the same program
- At a minimum, process execution requires following resources:
  - Memory to contain the program code and data
  - A set of CPU registers to support execution

Program to Process

- We write a program in e.g., Java.
- A compiler turns that program into an instruction list.
- The CPU interprets the instruction list (which is more a graph of basic blocks).

```
void X (int b) {
    if(b == 1) {
…
int main() {
   int a = 2;
   X(a);
}
```

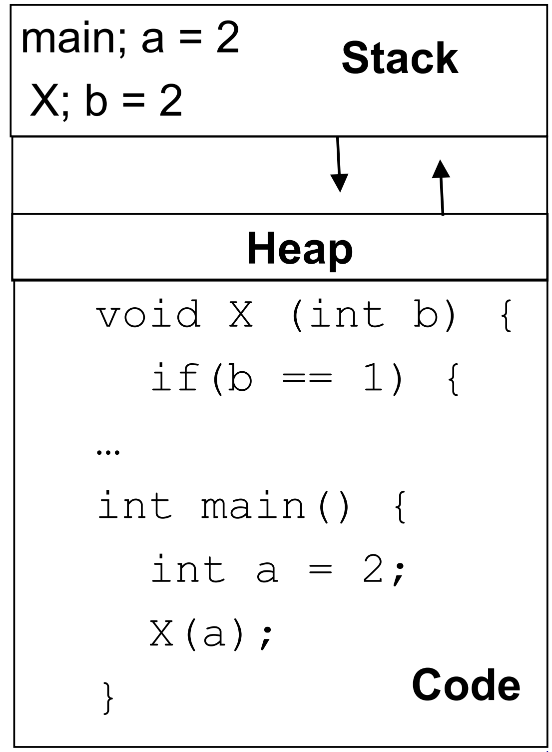
Process in Memory

- Program to process.
  - What you wrote

```
void X (int b) {
  if(b == 1) {
…
int main() {
  int a = 2;
  X(a);
}
```

  - What must the OS track for a process?

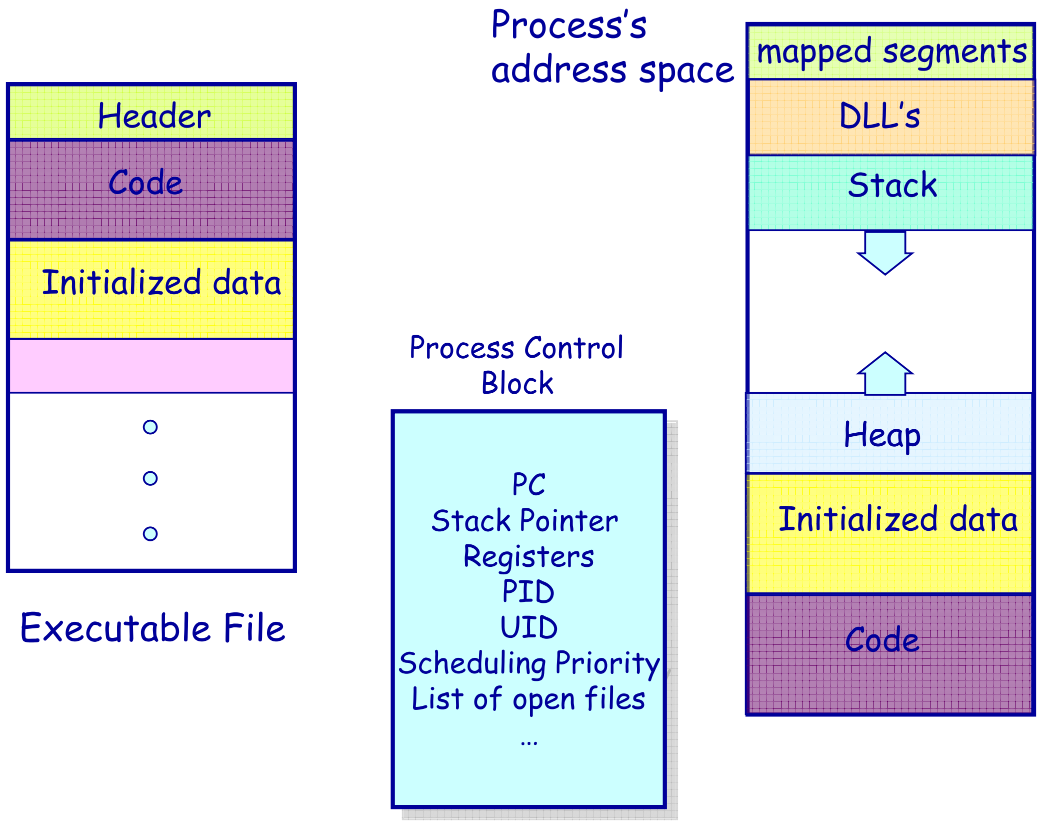
- What is in memory.



Keeping track of a process

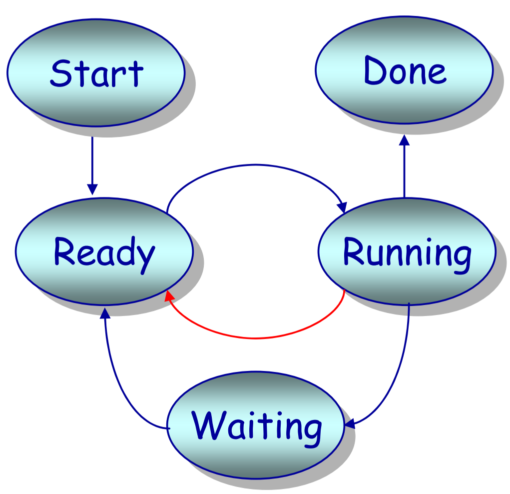
- A process has code.
  - OS must track program counter (code location).
- A process has a stack.
  - OS must track stack pointer.
- OS stores state of processes' computation in a process control block (PCB).
  - E.g., each process has an identifier (process identifier, or PID)
- Data (program instructions, stack & heap) resides in memory, metadata is in PCB.

Anatomy of a Process



Process Life Cycle

- Processes are always either *executing, waiting to execute* or *waiting for an event* to occur



- A preemptive scheduler will force a transition from running to ready. A non-preemptive scheduler waits.

From Processes to Threads

Processes, Threads and Processors

- Hardware can interpret N instruction streams at once
  - Uniprocessor, N==1
  - Dual-core, N==2
  - Sun's Niagra 2 (2008) N == 64, but 8 groups of 8
- An OS can run 1 process on each processor at the same time
  - Concurrent execution increases throughput
- An OS can run 1 thread on each processor at the same time
  - Do multiple threads reduce latency for a given application?

Processes and Threads

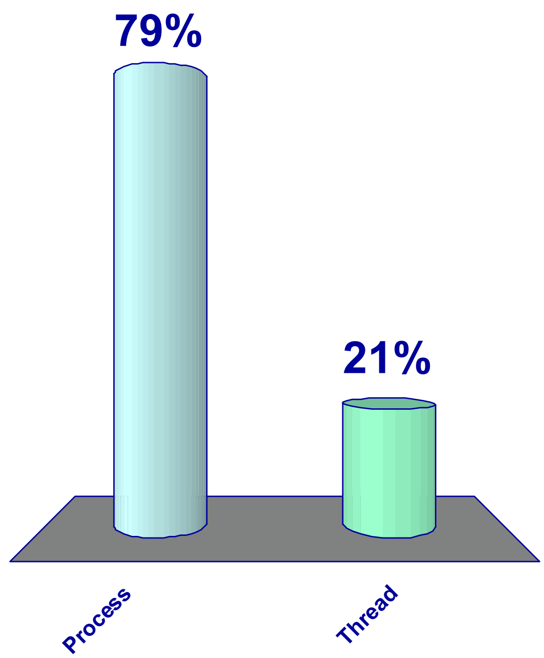
- Process abstraction combines two concepts
  - Concurrency
    - Each process is a sequential execution stream of instructions
  - Protection
    - Each process defines an address space
    - Address space identifies all addresses that can be touched by the program
- Threads
  - Key idea: separate the concepts of concurrency from protection
  - A thread is a sequential execution stream of instructions
  - A process defines the address space that may be shared by multiple threads

Introducing Threads

- A thread represents an abstract entity that executes a sequence of instructions
  - It has its own set of CPU registers
  - It has its own stack
  - There is no thread-specific heap or data segment (unlike process)
- Threads are lightweight
  - Creating a thread more efficient than creating a process.
  - Communication between threads easier than btw. processes.
  - Context switching between threads requires fewer CPU cycles and memory references than switching processes.
  - Threads only track a subset of process state (share list of open files, mapped memory segments …)
- Examples:
  - OS-level: Windows threads, Sun's LWP, POSIX's threads
  - User-level: Some JVMs
  - Language-supported: Modula-3, Java

Context switch time for which entity is greater?

1. Process
2. Thread



Programmer's View

```
void fn1(int arg0, int arg1, …) {…}

main() {
    …
    tid = CreateThread(fn1, arg0, arg1, …);
    …
}
```

At the point CreateThread is called, execution continues in parent thread in main function, and execution starts at fn1 in the child thread, *both in parallel (concurrently)*

Threads vs. Processes

Threads

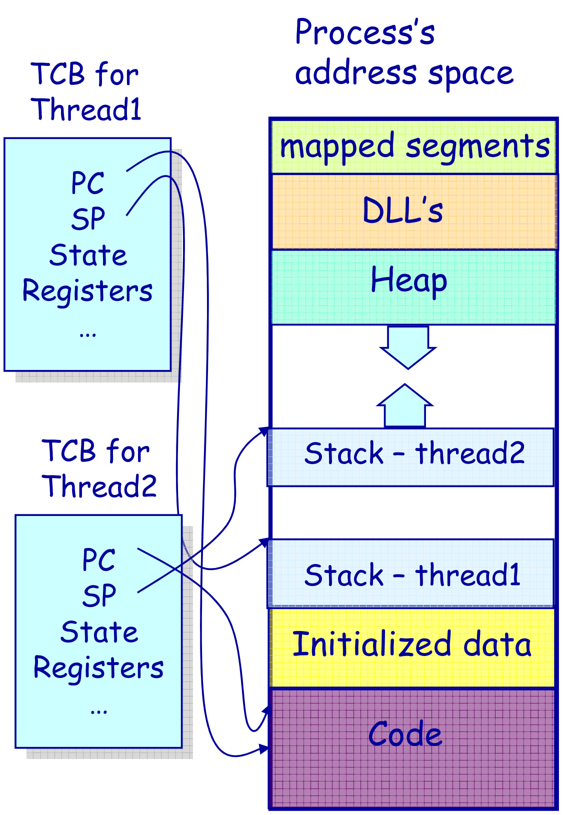
- A thread has no data segment or heap
- A thread cannot live on its own, it must live within a process
- There can be more than one thread in a process, the first thread calls main & has the process's stack
- Inexpensive creation
- Inexpensive context switching
- If a thread dies, its stack is reclaimed
- Inter-thread communication via memory.

Processes

- A process has code/data/heap & other segments
- There must be at least one thread in a process
- Threads within a process share code/data/heap, share I/O, but each has its own stack & registers
- Expensive creation
- Expensive context switching
- If a process dies, its resources are reclaimed & all threads die
- Inter-process communication via OS and data copying.

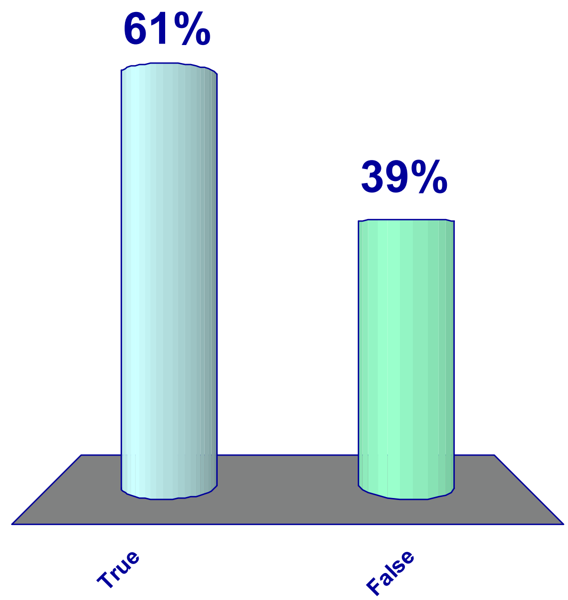
Implementing Threads

- Processes define an address space; threads share the address space
- Process Control Block (PCB) contains process-specific information
  - Owner, PID, heap pointer, priority, active thread, and pointers to thread information
- Thread Control Block (TCB) contains thread-specific information
  - Stack pointer, PC, thread state (running, …), register values, a pointer to PCB, …



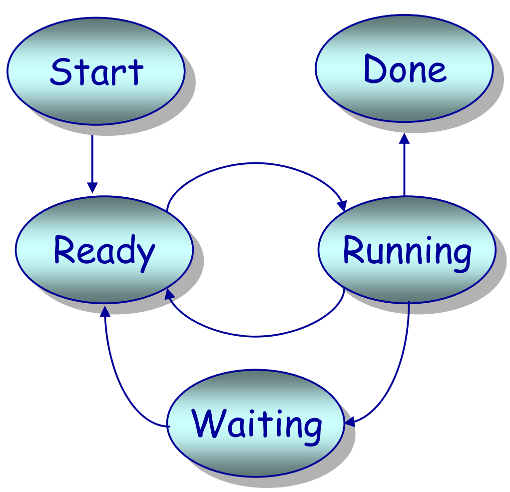
Threads have the same scheduling states as processes

1. True
2. False



Threads' Life Cycle

- Threads (just like processes) go through a sequence of *start*, *ready*, *running*, *waiting*, and *done* states



How Can it Help?

- How can this code take advantage of 2 threads?

```
for(k = 0; k < n; k++)
    a[k] = b[k] * c[k] + d[k] * e[k];
```

- Rewrite this code fragment as:

```
do_mult(l, m) {
    for(k = l; k < m; k++)
      a[k] = b[k] * c[k] + d[k] * e[k];
}
main() {
   CreateThread(do_mult, 0, n/2);
   CreateThread(do_mult, n/2, n);
```

- What did we gain?

How Can it Help?

- Consider a Web server

  Create a number of threads, and for each thread do

  - get network message (URL) from client
  - get URL data from disk
  - send data over network

- Why does creating multiple threads help?

Overlapping Requests (Concurrency)

Request 1 Thread 1	Request 2 Thread 2
❖ get network message (URL) from client	
❖ get URL data from disk	
	❖ get network message (URL) from client
(disk access latency)	❖ get URL data from disk
	(disk access latency)
❖ send data over network	
	❖ send data over network

Time

- Total time is less than request 1 + request 2

Latency and Throughput

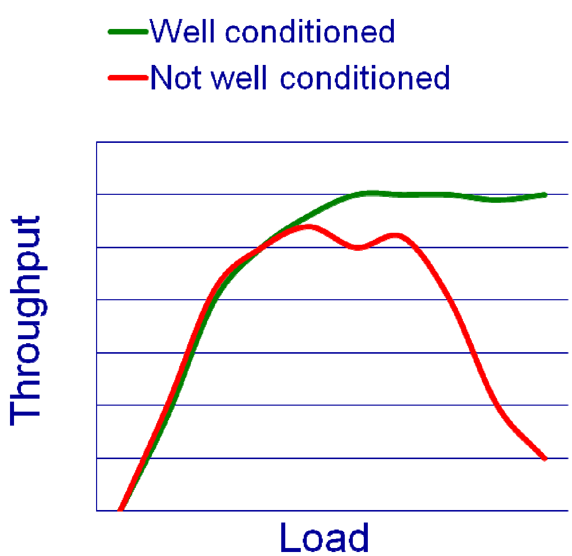
- Latency: time to complete an operation
- Throughput: work completed per unit time
- Multiplying vector example: reduced latency
- Web server example: increased throughput
- Consider plumbing
  - Low latency: turn on faucet and water comes out
  - High bandwidth: lots of water (e.g., to fill a pool)
- What is "High speed Internet?"
  - Low latency: needed to interactive gaming
  - High bandwidth: needed for downloading large files
  - Marketing departments like to conflate latency and bandwidth…

Relationship between Latency and Throughput

- Latency and bandwidth only loosely coupled
  - Henry Ford: assembly lines increase bandwidth without reducing latency
- Latency reduction is difficult
- Often, one can buy bandwidth
  - E.g., more memory chips, more disks, more computers
  - Big server farms (e.g., google) are high bandwidth

Thread or Process Pool

- Creating a thread or process for each unit of work (e.g., user request) is dangerous
  - High overhead to create & delete thread/process
  - Can exhaust CPU & memory resource
- Thread/process pool controls resource use
  - Allows service to be well conditioned.



Thread Synchronization: Too Much Milk

Concurrency Problems, Real Life Example

- Imagine multiple chefs in the same kitchen
  - Each chef follows a different recipe
- Chef 1
  - Grab butter, grab salt, do other stuff
- Chef 2
  - Grab salt, grab butter, do other stuff
- What if Chef 1 grabs the butter and Chef 2 grabs the salt?
  - Yell at each other (not a computer science solution)
  - Chef 1 grabs salt from Chef 2 (preempt resource)
  - Chefs all grab ingredients in the same order
    - Current best solution, but difficult as recipes get complex
    - Ingredient like cheese might be sans refrigeration for a while

The Need For Mutual Exclusion

- Running multiple processes/threads in parallel increases performance
- Some computer resources cannot be accessed by multiple threads at the same time
  - E.g., a printer can't print two documents at once
- Mutual exclusion is the term to indicate that some resource can only be used by one thread at a time
  - Active thread excludes its peers
- For shared memory architectures, data structures are often mutually exclusive
  - Two threads adding to a linked list can corrupt the list

Sharing among threads increases performance…

```
int a = 1, b = 2;
main() {
    CreateThread(fn1, 4);
    CreateThread(fn2, 5);
}
fn1(int arg1) {
    if(a) b++;
}
fn2(int arg1) {
    a = arg1;
}
```

What are the value of a & b at the end of execution?

… But it can lead to problems!!

```
int a = 1, b = 2;
main() {
    CreateThread(fn1, 4);
    CreateThread(fn2, 5);
}
fn1(int arg1) {
    if(a) b++;
}
fn2(int arg1) {
    a = 0;
}
```

What are the values of a & b at the end of execution?

Some More Examples

- What are the possible values of x in these cases?

```
Thread1: x = 1;                    Thread2: x = 2;
```

```
Initially y = 10;
Thread1: x = y + 1;                Thread2: y = y * 2;
```

```
Initially x = 0;
Thread1: x = x + 1;                Thread2: x = x + 2;
```

Concurrency Problem

- Order of thread execution is non-deterministic
  - Multiprocessing
    - A system may contain multiple processors ➔ cooperating threads/processes can execute simultaneously
  - Multi-programming
    - Thread/process execution can be interleaved because of time-slicing
- Operations are often not "atomic"
  - Example: x = x + 1 is not atomic!
    - read x from memory into a register
    - increment register
    - store register back to memory
- Goal:
  - Ensure that your concurrent program works under ALL possible interleaving

The Fundamental Issue

- In all these cases, what we thought to be an *atomic* operation is not done atomically by the machine
- An atomic operation is all or nothing:
  - Either it executes to completion, or
  - it did not execute at all, and
  - partial progress is not visible to the rest of the system

Are these operations usually atomic?

- Writing an 8-bit byte to memory
  - True (is atomic)
  - False
- Creating a file
  - True
  - False
- Writing a disk 512-byte disk sector
  - True
  - False

Critical Sections

- A critical section is an abstraction that
  - consists of a number of consecutive program instructions
  - all code within the section executes atomically
- Critical sections are used frequently in an OS to protect data structures (e.g., queues, shared variables, lists, …)
- A critical section implementation must be:
  - Correct: for a given k, only k threads can execute in the critical section at any given time (usually, k = 1)
  - Efficient: getting into and out of critical section must be fast. Critical sections should be as short as possible.
  - Concurrency control: a good implementation allows maximum concurrency while preserving correctness
  - Flexible: a good implementation must have as few restrictions as practically possible

Safety and Liveness

- *Safety property* : "nothing bad happens"
  - holds in every finite execution prefix
    - Windows™ never crashes
    - a program never produces a wrong answer
- *Liveness property*: "something good eventually happens"
  - no partial execution is irremediable
    - Windows™ always reboots
    - a program eventually terminates
- Every property is a combination of a safety property and a liveness property - (Alpern and Schneider)

Safety and liveness for critical sections

- At most k threads are concurrently in the critical section
  - A. Safety
  - B. Liveness
  - C. Both
- A thread that wants to enter the critical section, will eventually succeed
  - A. Safety
  - B. Liveness
  - C. Both
- Bounded waiting: If a thread *i* is in entry section, then there is a bound on the number of times that other threads are allowed to enter the critical section before thread *i*'s request is granted
  - A. Safety B. Liveness C. Both

Critical Section: Implementation

- Basic idea:
  - Restrict programming model
  - Permit access to shared variables only within a critical section
- General program structure
  - Entry section
    - "Lock" before entering critical section
    - Wait if already locked
    - Key point: synchronization may involve wait
  - Critical section code
  - Exit section
    - "Unlock" when leaving the critical section
- Object-oriented programming style
  - Associate a lock with each shared object
  - Methods that access shared object are critical sections
  - Acquire/release locks when entering/exiting a method that defines a critical section

Thread Coordination

Too much milk!

Jack

- Look in the fridge; out of milk
- Leave for store
- Arrive at store
- Buy milk
- Arrive home; put milk away

Jill

- Look in fridge; out of milk
- Leave for store
- Arrive at store
- Buy milk
- Arrive home; put milk away
- Oh, no!

Fridge and milk are shared data structures

Formalizing "Too Much Milk"

- Shared variables
  - "Look in the fridge for milk" – check a variable
  - "Put milk away" – update a variable
- Safety property
  - At most one person buys milk
- Liveness
  - Someone buys milk when needed
- How can we solve this problem?

Introducing Locks

- Locks – an API with two methods
  - Lock::Acquire() – wait until lock is free, then grab it
  - Lock::Release() – release the lock, waking up a waiter, if any
- With locks, too much milk problem is very easy!

```
Lock→Acquire();
if (noMilk) {
        buy milk;
}
Lock→Release();
```

How can we implement locks?

Atomic Read-Modify-Write (ARMW)

- For uni- and multi-processor architectures: implement locks using atomic read-modify-write instructions
  - Atomically
    1. read a memory location into a register, and
    2. write a new value to the location
  - Implementing ARMW is tricky in multi-processors

    Requires cache coherence hardware. Caches snoop the memory bus.

- Examples:
  - Test&set instructions (most architectures)

    Reads a value from memory

    Write "1" back to memory location
  - Compare & swap (68000), exchange (x86), …

    Test the value against some constant

    If the test returns true, set value in memory to different value

    Report the result of the test in a flag

    if [addr] == r1 then [addr] = r2;

Using Locks Correctly

- Make sure to release your locks along every possible execution path.

```
unsigned long flags;
local_irq_save( flags );  // Disable & save
  …
  if(somethingBad) {
     local_irq_restore( flags );
     return ERROR_BAD_THING;
  }
  …
local_irq_restore( flags ); // Reenable
return 0;
```

Using Locks Correctly

- Java provides convenient mechanism.

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

aLock.lock();
try {
   …
} finally {
   aLock.unlock();
}
return 0;
```


Implementing Locks: Summary

- Locks are higher-level programming abstraction
  - Mutual exclusion can be implemented using locks
- Lock implementation generally requires some level of hardware support
  - Atomic read-modify-write instructions

    Uni- and multi-processor architectures
- Locks are good for mutual exclusion but weak for coordination, e.g., producer/consumer patterns.

Why Locks are Hard

- Coarse-grain locks
  - Simple to develop
  - Easy to avoid deadlock
  - Few data races
  - Limited concurrency
- Fine-grain locks
  - Greater concurrency
  - Greater code complexity
  - Potential deadlocks
    - Not composable
  - Potential data races
    - Which lock to lock?

```
// WITH FINE-GRAIN LOCKS
void move(T s, T d, Obj key){
  LOCK(s);
  LOCK(d);
  tmp = s.remove(key);
  d.insert(key, tmp);
  UNLOCK(d);
  UNLOCK(s);
}
```

Thread 0	Thread 1
`move(a, b, key1);`	
	`move(b, a, key2);`

DEADLOCK!

Monitors & Condition Variables

- Three operations
  - Wait()
    - Release lock
    - Go to sleep
    - Reacquire lock upon return
  - Notify() (historically called Signal())
    - Wake up a waiter, if any
  - NotifyAll() (historically called Broadcast())
    - Wake up all the waiters
- Implementation
  - Requires a per-condition variable queue to be maintained
  - Threads waiting for the condition wait for a notify()
- Butler Lampson and David Redell, "Experience with Processes and Monitors in Mesa."

Summary

- Non-deterministic order of thread execution ➔ concurrency problems
  - Multiprocessing
    - A system may contain multiple processors ➔ cooperating threads/processes can execute simultaneously
  - Multi-programming
    - Thread/process execution can be interleaved because of time-slicing
- Goal: Ensure that your concurrent program works under ALL possible interleaving
- Define synchronization constructs and programming style for developing concurrent programs
    - Locks → provide mutual exclusion
    - Condition variables → provide conditional synchronization

More Resources

- Sun's Java documentation
  - http://java.sun.com/javase/6/docs/api/
  - http://java.sun.com/docs/books/tutorial/essential/concurrency/
- Modern Operating Systems (3rd Edition) by Andrew Tanenbaum (ISBN-10: 0136006639)
- Operating System Concepts with Java by Abraham Silberschatz, Peter Baer Galvin, Greg Gagne (ISBN-10: 047176907X)
- *Concurrent Programming in Java: Design Principles and Patterns* by Doug Lea (ISBN-10: 0201310090)