Concurrent Programming with Threads: Why you should care deeply

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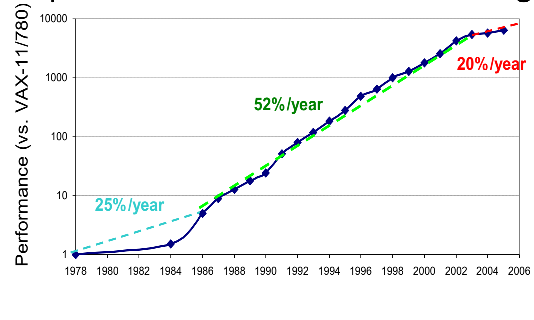
Portions courtesy Emmett Witchel

Uniprocessor Performance Not Scaling

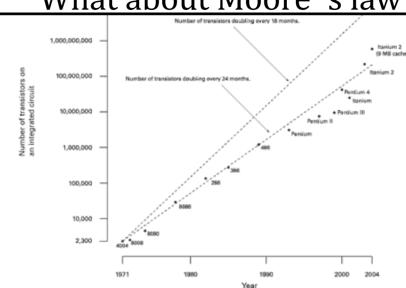


Graph by Dave Patterson

Power and Heat Lay Waste to CPU 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
- Intel Pentium Core, (2006-)
  - 1.06GHz to 3GHz, 14 stage pipeline
  - Based on mobile (Pentium M) micro-architecture
    - Power efficient
- 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!

Transistor Budget

- We have an increasing glut of transistors
  - (at least for a few more years)
- But we can't use them to make things faster
  - Techniques that worked in the 90s blew up heat faster than we can dissipate it
- What to do?
  - Use the increasing transistor budget to make more cores!

Multi-Core is Here: Plain and Simple

- Raise your hand if your laptop is single core?
- Your phone?
- That's what I thought

Multi-Core Programming == Essential Skill

- Hardware manufacturers betting big on multicore
- Software developers are needed
- Writing concurrent programs is not easy
- You will learn how to do it in this class

Still treated like a bonus: Don't graduate without it!

Threads: OS Abstraction for Concurrency

- 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
  - Threads can execute on different cores on a multicore CPU (parallelism for performance) and can communicate with other threads by updating memory

Practical Difference

- With processes, you coordinate through nice abstractions (relatively speaking – e.g., lab 1)
  - Pipes, signals, etc.
- With threads, you communicate through data structures in your process virtual address space
  - Just read/write variables and pointers

Programmer's View

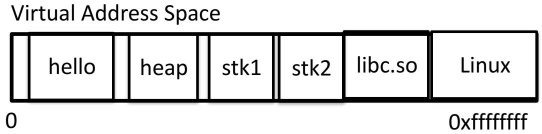
```
void fn1(int arg0, int arg1, …) {…}

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)*

Implementing Threads: Example Redux

Virtual Address Space



- 2 threads requires 2 stacks in the process
- No problem!
- Kernel can schedule each thread separately
  - Possibly on 2 CPUs
  - Requires some extra bookkeeping

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 Threads Help?

- Consider a Web server
  Create a number of threads, and for each thread do
    - get network message from client
    - get URL data from disk
    - send data over network
- What did we gain?

Overlapping I/O and Computation

Request 1
Thread 1
- get network message (URL) from client
- get URL data from disk

(disk access latency)

- send data over network

Request 2
Thread 2
- get network message (URL) from client
- get URL data from disk

(disk access latency)

- send data over network

Time

- Total time is less than request 1 + request 2

Why threads? (summary)

- Computation that can be divided into concurrent chunks
  - Execute on multiple cores: reduce wall-clock exec. time
  - Harder to identify parallelism in more complex cases
- Overlapping blocking I/O with computation
  - If my web server blocks on I/O for one client, why not work on another client's request in a separate thread?
  - Other abstractions we won't cover (e.g., events)

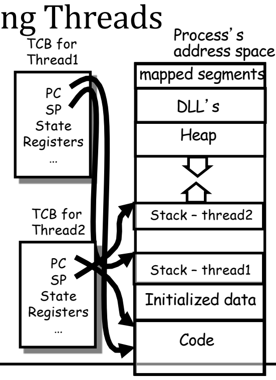
Threads vs. Processes

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
- If a thread dies, its stack is reclaimed
- Inter-thread communication via memory.
- Each thread can run on a different physical processor
- Inexpensive creation and context switch

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
- If a process dies, its resources are reclaimed & all threads die
- Inter-process communication via OS and data copying.
- Each process can run on a different physical processor
- Expensive creation and context switch

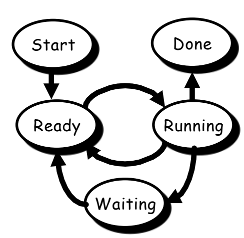
Implementing Threads

- 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, …



Thread Life Cycle

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



Threads have their own…?

1. CPU
2. Address space
3. PCB
4. Stack ☺
5. Registers ☺

Threads have the same scheduling states as processes

1. True☺
2. False

- In fact, OSes generally schedule *threads* to CPUs, not processes

Yes, yes, another white lie in this course

Lecture Outline

- What are threads?
- Small digression: Performance Analysis
  - There will be a few more of these in upcoming lectures
- Why are threads hard?

Performance: Latency vs. 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…

Latency and Throughput

- Latency and bandwidth only loosely coupled
  - Henry Ford: assembly lines increase bandwidth without reducing latency
- My factory takes 1 day to make a Model-T ford.
  - But I can start building a new car every 10 minutes
  - At 24 hrs/day, I can make 24 * 6 = 144 cars per day
  - A special order for 1 green car, still takes 1 day
  - Throughput is increased, but latency is not.
- 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

Latency, Throughput, and Threads

- Can threads improve throughput?
  - Yes, as long as there are parallel tasks and CPUs available
- Can threads improve latency?
  - Yes, especially when one task might block on another task's IO
- Can threads harm throughput?
  - Yes, each thread gets a time slice.
  - If # threads >> # CPUs, the %of CPU time each thread gets approaches 0
- Can threads harm latency?
  - Yes, especially when requests are short and there is little I/O

Threads can help or hurt: Understand when they help

So Why are Threads Hard?

- 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 often consist of multiple, visible steps
  - Example: x = x + 1 is not a single operation
    - read x from memory into a register
    - increment register
    - store register back to memory
- Goal:
  - Ensure that your concurrent program works under ALL possible interleavings

Thread 2
read
increment
store

Questions

- Do the following either completely succeed or completely fail?
- Writing an 8-bit byte to memory
  - A. Yes B. No
- Creating a file
  - A. Yes B. No
- Writing a 512-byte disk sector
  - A. Yes B. No

Sharing Amongst Threads Increases Performance

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

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

But can lead to problems…

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;

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

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

Critical Sections

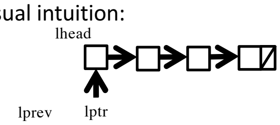
- Key abstraction: A group of instructions that cannot be interleaved
- Generally, critical sections execute under mutual exclusion
  - E.g., a critical section is the part of the recipe involving butter and salt – you know, the important part
- One critical section may wait for another
  - Key to good multi-core performance is minimizing the time in critical sections
    - While still rendering correct code!

The Need to Wait

- Very often, synchronization consists of one thread waiting for another to make a condition true
  - Master tells worker a request has arrived
  - Cleaning thread waits until all lanes are colored
- Until condition is true, thread can sleep
  - Ties synchronization to scheduling
- Mutual exclusion for data structure
  - Code can wait (wait)
  - Another thread signals (notify)

Example 2: Traverse a singly-linked list

- Suppose we want to find an element in a singly linked list, and move it to the head
- Visual intuition:



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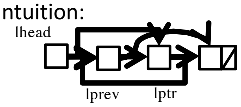


Even more real life, linked lists

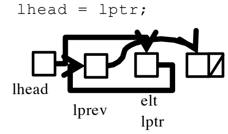
```
lprev = NULL;
for(lptr = lhead; lptr; lptr = lptr->next) {
   if(lptr->val == target){
      // Already head?, break
      if(lprev == NULL) break;
      // Move cell to head
      lprev->next = lptr->next;
      lptr->next = lhead;
      lhead = lptr;
      break;
   }
   lprev = lptr;
}
```

- Where is the critical section?

Even more real life, linked lists

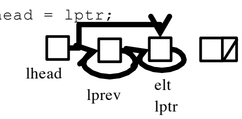
Thread 1

```
// Move cell to head
lprev->next = lptr->next;
lptr->next = lhead
lhead = lptr;
```



Thread 2

```
lprev->next = lptr->next;
lptr->next = lhead;
lhead = lptr;
```



- A critical section often needs to be larger than it first appears
  - The 3 key lines are not enough of a critical section

Even more real life, linked lists

Thread 1 Thread 2

```
if(lptr->val == target){
      elt = lptr;
      // Already head?, break
      if(lprev == NULL) break;
      // Move cell to head
      lprev->next = lptr->next;
      // lptr no longer in list
                                    for(lptr = lhead; lptr;
                                       lptr = lptr->next) {
                                       if(lptr->val == target){
```

- Putting entire search in a critical section reduces concurrency, but it is safe.

Safety and Liveness

- *Safety property* : "nothing bad happens"
  – holds in every finite execution prefix
    - Windows™ never crashes
    - a program never terminates with 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 (only 1 thread is alowed in at a time) before thread *i*'s request is granted.
  – A. Safety B. Liveness C. Both

Lecture Summary

- Understand the distinction between process & thread
- Understand motivation for threads
- Concepts of Throughput vs. Latency
- Intuition of why coordinating threads is hard
- Idea of mutual exclusion and critical sections
  – Much more on last two points to come