From Processes to Threads

Don Porter
Portions courtesy Emmett Witchel

Processes, Threads and Processors

- Hardware can execute N instruction streams at once
  - Uniprocessor, N==1
  - Dual-core, N==2
  - Sun’s Niagara T2 (2007) N == 64, but 8 groups of 8
- An OS can run 1 process on each processor at the same time
  - Concurrent execution increases performance
- An OS can run 1 thread on each processor at the same time

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

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

The Case for Threads

Consider the following code fragment

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

Is there a missed opportunity here? On a Uni-processor? On a Multi-processor?

The Case for Threads

Consider a Web server

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

How well does this web server perform?

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)*

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, pid, …)
- Examples:
  - OS-supported: Windows' threads, Sun's LWP, POSIX threads
  - Language-supported: Modula-3, Java
    - These are possibly going the way of the Dodo

Context switch time for which entity is greater?

1. Process
2. Thread

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 from client
  - get URL data from disk
  - send data over network

- What did we gain?

Overlapping Requests (Concurrency)

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
  - Same Instruction (or operation), Multiple Data (SIMD – easy)
  - 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 have their own…?

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

Threads vs. Processes

Threads

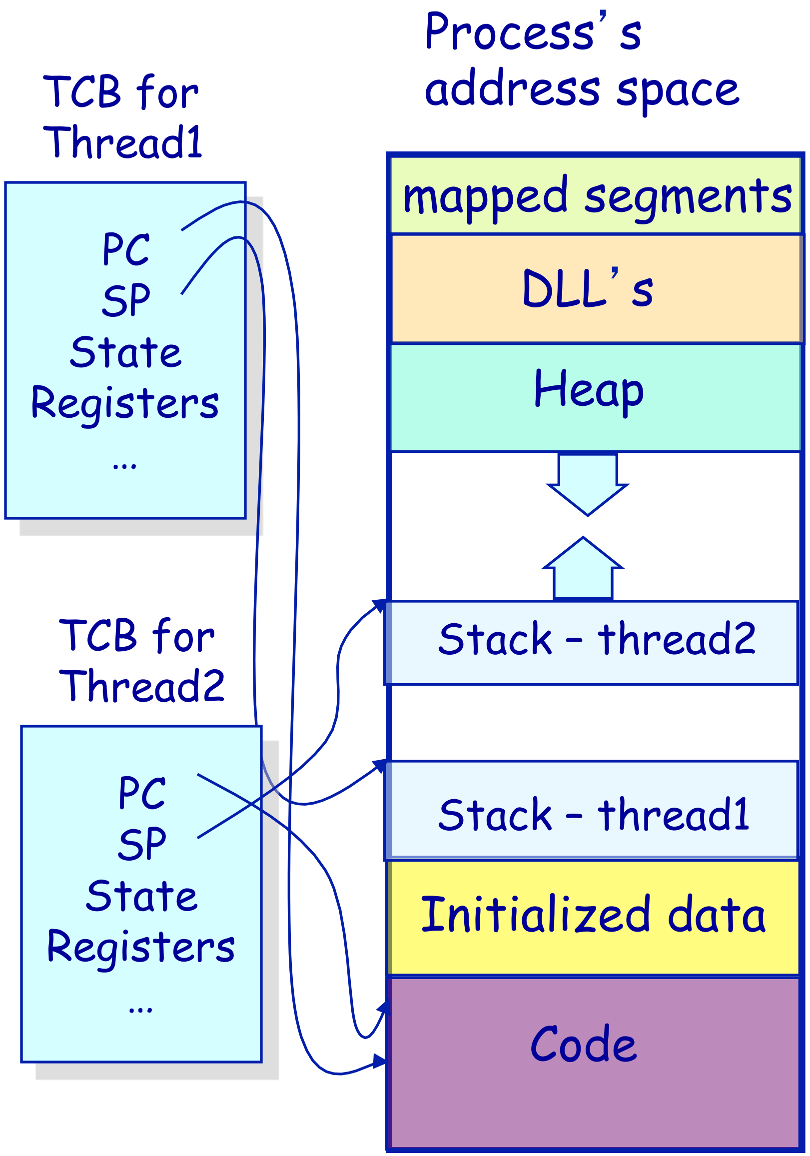
- A thread has no data segment or heap
- A thread cannot live on its own, it must live within a process
- There can be more than one thread in a process, the first thread calls main & has the process' s stack
- If a thread dies, its stack is reclaimed
- Inter-thread communication via memory.
- Each thread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

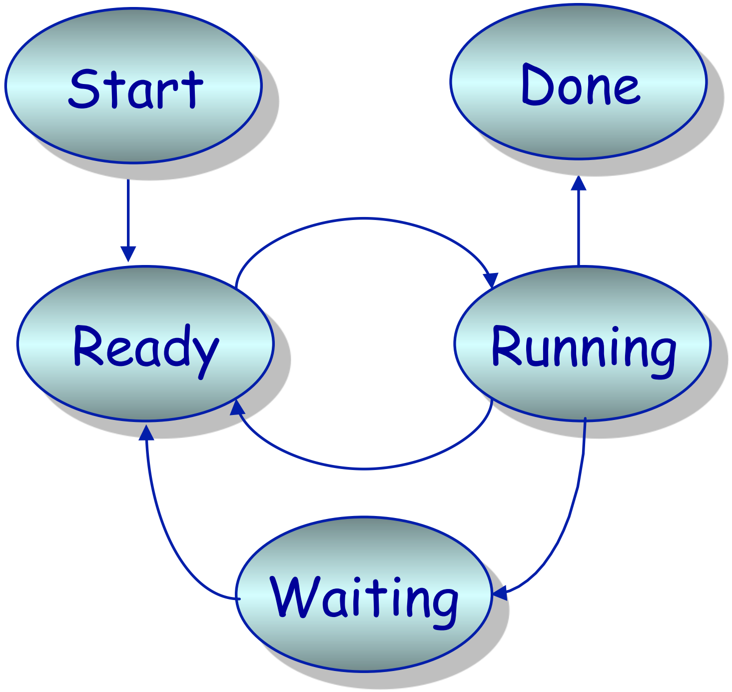
Implementing Threads

- 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, …



Threads' Life Cycle

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

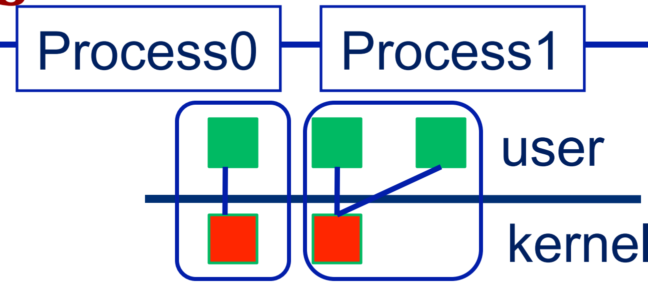


Threads have the same scheduling states as processes

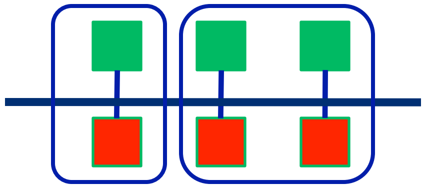
1. True ☺
2. False

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

User-level vs. Kernel-level threads



- User-level threads (M to 1 model)
  - + Fast to create and switch
  - + Natural fit for language-level threads
  - - Duplicate effort (2 thread schedulers)
    - The schedulers can fight with each other
  - - All user-level threads in process block on OS calls
    - E.g., read from file can block all threads



- Kernel-level threads (1 to 1 model)
  - + Kernel-level threads do not block process for syscall
  - + Only one scheduler (and kernel has global view)
  - - Can be difficult to make efficient (create & switch)

Languages vs. Systems

- Kernel-level threads have won for systems
  - Linux, Solaris 10, Windows
  - pthreads tend to be kernel-level threads
- User-level threads still used in some Java runtimes
  - User tells JVM how many underlying system threads
    - Default: 1 system thread
  - Java runtime intercepts blocking calls, makes them non-blocking
  - JNI code that makes blocking syscalls can block JVM
  - JVMs are phasing this out because kernel threads are efficient enough and intercepting system calls is complicated
- Kernel-level thread vs. process
  - Each process requires its own page table & hardware state (significant on the x86)

Editorial on User vs. Kernel threads

- There is a 25+ year history of debating user vs. kernel threads
  - These discussions are couched in grand principles
- The real issue is simple: Performance!!
  - If the kernel implementation of thread context switching is slow, everyone starts writing user-level thread packages
    - Java did this for a while
  - If the kernel implementation gets faster, everyone just uses kernel threads, since they are easier
    - Java does this now, Linux 2.6 overhauled its thread implementation

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
- 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

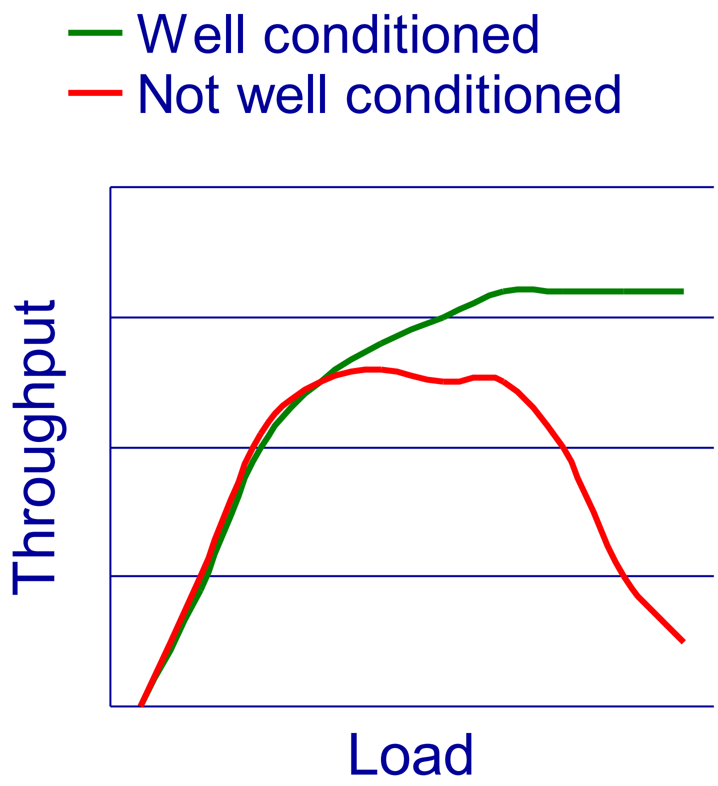
- Can threads improve throughput?
  - Yes, as long as there are parallel tasks and CPUs available
- Can threads improve latency?
  - Yes, especially when one task might block on another task's IO
- Can threads harm throughput?
  - Yes, each thread gets a time slice.
  - If # threads >> # CPUs, the %of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

Best Practices?

- For CPU-intensive work, applications generally create one thread per CPU
- For work with I/O, the number of threads is tuned to keep the CPU busy but not overloaded
  - E.g., 3 * # CPUs
  - Tuning effort often application-specific
- Applications like web servers often keep *thread pools*, or a set of n ready threads
  - New requests are assigned to an existing thread to avoid overloading the system
  - Plus, reduce setup/tear down costs!

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.



When a user level thread does I/O it blocks the entire process.

1. True ☺
2. False

Lecture Summary

- Understand the distinction between a process and thread
- Understand the motivation for threads
- Kernel vs. User threads
- Concepts of Throughput vs. Latency
- Thread pools