CSE 451: Operating Systems
Winter 2001

Lecture 5
Threads

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Today's agenda

- Administrivia
  - ...
- Final thoughts on processes
- Threads
  - lightweight execution contexts
  - kernel vs. user-level threads

Processes

- A process includes many things:
  - an address space (all the code and data pages)
    - protection boundary
  - OS resources (e.g., open files) and accounting info
  - hardware execution state (PC, SP, regs)
- Creating a new process is costly, because of all of the data structures that must be allocated/initialized
  - Linux: over 95 fields in task_struct
    - on a 700 MHz pentium, fork+exit = 251 microseconds, fork+exec = 1024 microseconds
- Interprocess communication is costly, since it must usually go through the OS
  - overhead of system calls
    - 0.46 microseconds on 700 MHz pentium

Parallel Programs

- Recall the web server example, which forks off copies of itself to handle multiple simultaneous tasks
  - or, imagine we have any parallel program on a multiprocessor
- To execute these, we need to:
  - create several processes that execute in parallel
  - cause each to map to the same address space to share data
    - see the `shmget()` system call for one way to do this (kind of)
  - have the OS schedule them in parallel
    - multiprogramming or true parallel processing on an SMP
- This is really inefficient
  - space: PCB, page tables, etc.
  - time: creating OS structures, fork and copy addr space, etc.

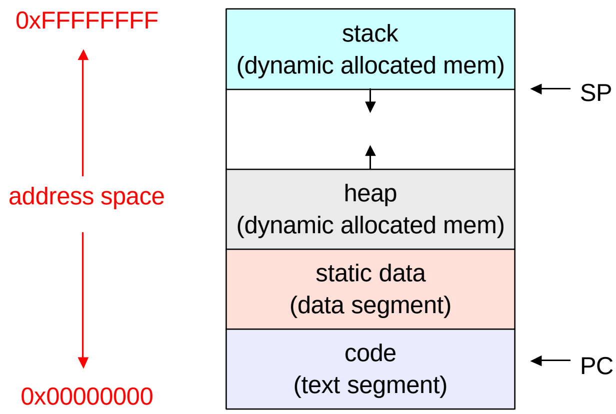
Can we do better?

- What's similar in these processes?
  - they all share the same code and data (address space)
  - they all share the same privileges
  - they all share the same resources (files, sockets, etc.)
- What's different?
  - each has its own hardware execution state
    - PC, registers, stack pointer, and stack
- Key idea:
  - separate the concept of
    - a process (address space, etc.) from that of
    - a minimal "thread of control" (execution state: PC, etc.)
  - this execution state is usually called a thread, or sometimes, a lightweight process

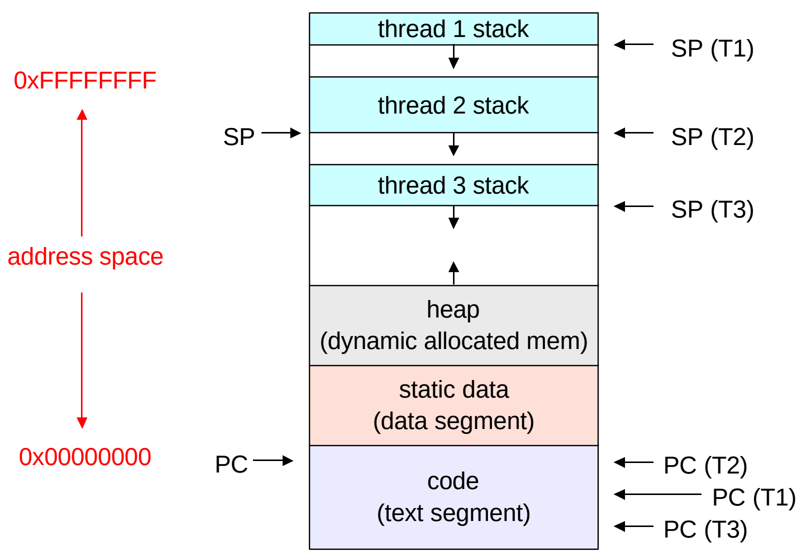
Threads and processes

- Most modern OS's (Mach, Chorus, NT, modern Unix) therefore support two entities:
  - the process, which defines the address space and general process attributes (such as open files, etc.)
  - the thread, which defines a sequential execution stream within a process
- A thread is bound to a single process
  - processes, however, can have multiple threads executing within them
  - sharing data between threads is cheap: all see same address space
- Threads become the unit of scheduling
  - processes are just containers in which threads execute

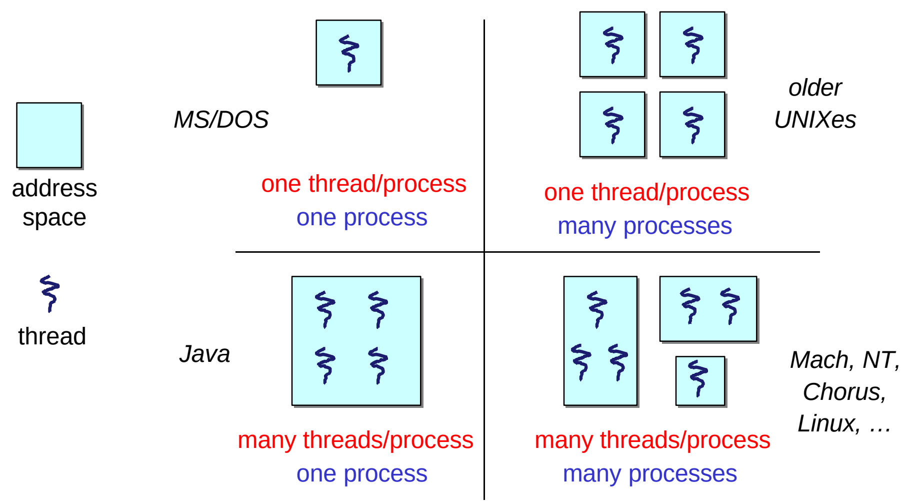
(old) Process address space



(new) Address space with threads



Thread Design Space



Process/Thread Separation

- Separating threads and processes makes it easier to support multi-threaded applications
  - creating concurrency does not require creating new processes
- Concurrency (multithreading) is useful for:
  - improving program structure (the Java argument)
  - handling concurrent events (e.g., web servers)
  - building parallel programs (e.g., raytracer)
- So, multithreading is useful even on a uniprocessor
  - even though only one thread can run at a time

Kernel thread and user-level threads

- Who is responsible for creating/managing threads?
- Two answers, in general:
  - the OS (kernel threads)
    - thread creation and management requires system calls
  - the user-level process (user-level threads)
    - a library linked into the program manages the threads
- Why is user-level thread management possible?
  - threads share the same address space
    - therefore the thread manager doesn't need to manipulate address spaces
  - threads only differ in hardware contexts (roughly)
    - PC, SP, registers
    - these can be manipulated by the user-level process itself!

Kernel Threads

- OS now manages threads *and* processes
  - all thread operations are implemented in the kernel
  - OS schedules all of the threads in a system
    - if one thread in a process blocks (e.g. on I/O), the OS knows about it, and can run other threads from that process
    - possible to overlap I/O and computation inside a process
- Kernel threads are cheaper than processes
  - less state to allocate and initialize
- But, they can still be too expensive
  - thread operations are all system calls
    - OS must perform all of the usual argument checks
    - but want them to be as fast as a procedure call!
  - must maintain kernel state for each thread
    - can place limit on # of simultaneous threads, typically ~1000

User-Level Threads

- To make threads cheap and fast, they need to be implemented at the user level
  - managed entirely by user-level library, e.g. `libpthreads.a`
- User-level threads are small and fast
  - each thread is represented simply by a PC, registers, a stack, and a small thread control block (TBC)
  - creating a thread, switching between threads, and synchronizing threads are done via procedure calls
    - no kernel involvement is necessary!
  - user-level thread operations can be 10-100x faster than kernel threads as a result

Performance example

- On a 700MHz Pentium running Linux 2.2.16:
  - Processes
    - `fork/exit`: 251 μs
  - Kernel threads
    - `pthread_create()/pthread_join()`: 94 μs
  - User-level threads
    - `pthread_create()/pthread_join`: 4.5 μs

User-level Thread Limitations

- But, user-level threads aren't perfect
  - tradeoff, as with everything else
- User-level threads are invisible to the OS
  - there is no integration with the OS
- As a result, the OS can make poor decisions
  - scheduling a process with only idle threads
  - blocking a process whose thread initiated I/O, even though the process has other threads that are ready to run
  - unscheduling a process with a thread holding a lock
- Solving this requires coordination between the kernel and the user-level thread manager

Coordinating K/L and U/L Threads

- Another possibility:
  - use both K/L and U/L threads in a single system
  - can associate a user-level thread with a kernel-level thread
  - or, can multiplex user-level threads on top of kernel threads
- "scheduler activations"
  - a research paper from UW with huge effect on industry
  - each process can request one or more kernel threads
    - process is given responsibility for mapping user-level threads onto kernel threads
    - kernel promises to notify user-level before it suspends or destroys a kernel thread
- pop question:
  - why would a process have more user-level threads than kernel threads?

Thread Interface

- This is taken from the POSIX pthreads API:
  - t = pthread_create(attributes, start_procedure)
    - creates a new thread of control
    - new thread begins executing at start_procedure
  - pthread_cond_wait(condition_variable)
    - the calling thread blocks, sometimes called thread_block()
  - pthread_signal(condition_variable)
    - starts the thread waiting on the condition variable
  - pthread_exit()
    - terminates the calling thread
  - pthread_wait(t)
    - waits for the named thread to terminate

User-level thread implementation

- a thread scheduler determines when a thread runs
  - it uses queues to keep track of what threads are doing
    - just like the OS and processes
    - but, implemented at user-level as a library
  - run queue: threads currently running
  - ready queue: threads ready to run
  - wait queue: threads blocked for some reason
    - maybe blocked on I/O, maybe blocked on a lock
- how can you prevent a thread from hogging the CPU?
  - how did the OS handle this?

Preemptive vs. non-preemptive

- Strategy 1: force everybody to cooperate
  - a thread willingly gives up the CPU by calling `yield()`
  - `yield()` calls into the scheduler, which context switches to another ready thread
  - what happens if a thread never calls `yield()`?
- Stategy 2: use preemption
  - scheduler requests that a timer interrupt be delivered by the OS periodically
    - usually delivered as a UNIX signal (man signal)
    - signals are just like software interrupts, but delivered to user-level by the OS instead of delivered to OS by hardware
  - at each timer interrupt, scheduler gains control and context switches as appropriate

Thread context switch

- Very simple for user-level threads:
  - save context of currently running thread
    - push machine state onto thread stack
  - restore context of the next thread
    - pop machine state from next thread's stack
  - return to caller as the new thread
    - execution resumes at PC of next thread
- This is all done by assembly language
  - it works at the level of the procedure calling convention
    - thus, it cannot be implemented using procedure calls