What’s “in” a process?

• A process consists of (at least):
  – An address space, containing
    • the code (instructions) for the running program
    • the data for the running program
  – Thread state, consisting of
    • The program counter (PC), indicating the next instruction
    • The stack pointer register (implying the stack it points to)
    • Other general purpose register values
  – A set of OS resources
    • open files, network connections, sound channels, ...

• That’s a lot of concepts bundled together!

• Today: decompose …
  – address space
  – thread of control (stack, stack pointer, program counter, registers)
  – OS resources
Module overview

- Big picture: Achieving concurrency/parallelism
- Kernel threads
- User-level threads

The Big Picture

- Threads are about concurrency and parallelism
  - Parallelism: physically simultaneous operations for performance
  - Concurrency: logically (and possibly physically) simultaneous operations for convenience/simplicity
- One way to get concurrency and parallelism is to use multiple processes
  - The programs (code) of distinct processes are isolated from each other
- Threads are another way to get concurrency and parallelism
  - Threads "share a process" – same address space, same OS resources
  - Threads have private stack, CPU state – are schedulable
Concurrency/Parallelism

• Imagine a web server, which might like to handle multiple requests concurrently
  – While waiting for the credit card server to approve a purchase for one client, it could be retrieving the data requested by another client from disk, and assembling the response for a third client from cached information

• Imagine a web client (browser), which might like to initiate multiple requests concurrently
  – The CSE home page has dozens of "src=..." html commands, each of which is going to involve a lot of sitting around! Wouldn’t it be nice to be able to launch these requests concurrently?

• Imagine a parallel program running on a multiprocessor, which might like to employ "physical concurrency"
  – For example, multiplying two large matrices – split the output matrix into k regions and compute the entries in each region concurrently, using k processors

What’s needed?

• In each of these examples of concurrency (web server, web client, parallel program):
  – Everybody wants to run the same code
  – Everybody wants to access the same data
  – Everybody has the same privileges
  – Everybody uses the same resources (open files, network connections, etc.)

• But you’d like to have multiple hardware execution states:
  – an execution stack and stack pointer (SP)
    • traces state of procedure calls made
  – the program counter (PC), indicating the next instruction
  – a set of general-purpose processor registers and their values
How could we achieve this?

- Given the process abstraction as we know it:
  - fork several processes
  - cause each to *map* to the same physical memory to share data
    - see the `shmget()` system call for one way to do this (kind of)
- This is like making a pig fly – it’s really inefficient
  - space: PCB, page tables, etc.
  - time: creating OS structures, fork/copy address space, etc.
- Some equally bad alternatives for some of the examples:
  - Entirely separate web servers
  - Manually programmed asynchronous programming (non-blocking I/O) in the web client (browser)

Can we do better?

- Key idea:
  - separate the concept of a *process* (address space, OS resources)
  - … from that of a minimal “*thread of control*” (execution state: stack, stack pointer, program counter, registers)
- This execution state is usually called a *thread*, or sometimes, a *lightweight process*
Threads and processes

- Most modern OS’s (Mach (Mac OS), Chorus, Windows, 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 / address space
  - address spaces, however, can have multiple threads executing within them
  - sharing data between threads is cheap: all see the same address space
  - creating threads is cheap too!
- Threads become the unit of scheduling
  - processes / address spaces are just containers in which threads execute

- Threads are concurrent executions sharing an address space (and some OS resources)
- Address spaces provide isolation
  - If you can’t name it, you can’t read or write it
- Hence, communicating between processes is expensive
  - Must go through the OS to move data from one address space to another
- Because threads are in the same address space, communication is simple/cheap
  - Just update a shared variable!
The design space

Key

address space

thread

MS/DOS

one thread per process
one process

older UNIXes

one thread per process
many processes

Java

many threads per process
one process

Mach, NT,
Chorus,
Linux, …

many threads per process
many processes

(old) Process address space

0xFFFFFFFF

stack
(dynamic allocated mem)

SP

0x00000000

address space

heap
(dynamic allocated mem)

code
(text segment)

static data
(data segment)

PC
(new) Address space with threads

Value of process/thread separation

• Concurrency (multithreading) is useful for:
  – handling concurrent events (e.g., web servers and clients)
  – building parallel programs (e.g., matrix multiply, ray tracing)
  – improving program structure (the Java argument)
• Multithreading is useful even on a uniprocessor
  – even though only one thread can run at a time
• Supporting multithreading – that is, separating the concept of a process (address space, files, etc.) from that of a minimal thread of control (execution state), is a big win
  – creating concurrency does not require creating new processes
  – “faster / better / cheaper”
Terminology

• Just a note that there’s the potential for some confusion …
  – Old world: "process" == “address space + OS resources + single thread"
  – New world: “process” typically refers to an address space + system resources + all of its threads …
    • When we mean the “address space” we need to be explicit
      “thread” refers to a single thread of control within a process / address space

• A bit like “kernel” and “operating system” …
  – Old world: “kernel” == “operating system” and runs in “kernel mode”
  – New world: “kernel” typically refers to the microkernel; lots of the operating system runs in user mode

“Where do threads come from, Mommy?”

• Natural answer: the OS is responsible for creating/managing threads
  – For example, the kernel call to create a new thread would
    • allocate an execution stack within the process address space
    • create and initialize a Thread Control Block
      – stack pointer, program counter, register values
    • stick it on the ready queue
  – We call these kernel threads
  – There is a “thread name space”
    • Thread id’s (TID’s)
    • TID’s are integers (surprise!)
Kernel threads

- OS now manages threads and processes / address spaces
  - 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're still pretty expensive for fine-grained use
  - orders of magnitude more expensive than a procedure call
  - thread operations are all system calls
    - context switch
    - argument checks
There is an alternative to kernel threads

- Threads can also be managed at the user level (that is, entirely from within the process)
  - A library linked into the program manages the threads
    - Because threads share the same address space, the thread manager doesn’t need to manipulate address spaces (which only the kernel can do)
    - Threads differ (roughly) only in hardware contexts (PC, SP, registers), which can be manipulated by user-level code
    - The thread package multiplexes user-level threads on top of kernel thread(s)
      - Each kernel thread is treated as a "virtual processor"
  - We call these user-level threads
User-level threads: what the kernel sees

- address space
- thread
- os kernel
- CPU

User-level threads: the full story

- user-level thread library
- Mach, NT, Chorus, Linux, ...
- kernel threads

(threads create, destroy, signal, wait, etc.)

(kernel thread create, destroy, signal, wait, etc.)
User-level threads

- User-level threads are small and fast
  - managed entirely by user-level library
    - E.g., pthreads (libpthreads.a)
  - each thread is represented simply by a PC, registers, a stack, and a small thread control block (TCB)
  - 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 (only the relative numbers matter; ignore the ancient CPU!):
  - Processes
    - fork/exit: 251 µs
  - Kernel threads
    - pthread_create()/pthread_join(): 94 µs (2.5x faster – ~150µs faster)
  - User-level threads
    - pthread_create()/pthread_join: 4.5 µs (another 20x faster - ~100µs faster)

Why?
User-level thread implementation

- The OS schedules the kernel thread
- The kernel thread executes user code, including the thread support library and its associated thread scheduler
- The thread scheduler determines when a user-level thread runs
  - it uses queues to keep track of what threads are doing: run, ready, wait
    - just like the OS and processes
    - but, implemented at user-level as a library

Thread interface

- This is taken from the POSIX pthreads API:
  - \texttt{rcode = pthread\_create(&t, attributes, start\_procedure)}
    - creates a new thread of control
    - new thread begins executing at start\_procedure
  - \texttt{pthread\_cond\_wait(condition\_variable, mutex)}
    - the calling thread blocks, sometimes called thread\_block()
  - \texttt{pthread\_signal(condition\_variable)}
    - starts a thread waiting on the condition variable
  - \texttt{pthread\_exit()}\texttt{\textbackslash n}
    - terminates the calling thread
  - \texttt{pthread\_wait(t)}
    - waits for the named thread to terminate
Thread context switch

• Very simple for user-level threads:
  – save context of currently running thread
    • push CPU state onto thread stack
  – restore context of the next thread
    • pop CPU state from next thread’s stack
  – return as the new thread
    • execution resumes at PC of next thread
  – Note: no changes to memory mapping required!

• 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

How to keep a user-level thread from hogging the CPU?

• Strategy 1: force everyone to cooperate
  – a thread willingly gives up the CPU by calling \texttt{yield()}\footnote{\texttt{yield()} calls into the scheduler, which context switches to another ready thread}
  – \texttt{yield()} calls into the scheduler, which context switches to another ready thread
  – what happens if a thread never calls \texttt{yield()}?

• Strategy 2: use preemption
  – scheduler requests that a timer interrupt be delivered by the OS periodically
    • usually delivered as a UNIX signal (\texttt{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
What if a thread tries to do I/O?

- The kernel thread "powering" it is lost for the duration of the (synchronous) I/O operation!
  - The kernel thread blocks in the OS, as always
  - It maroons with it the state of the user-level thread
- Could have one kernel thread "powering" each user-level thread
  - "common case" operations (e.g., synchronization) would be quick
- Could have a limited-size "pool" of kernel threads "powering" all the user-level threads in the address space
  - the kernel will be scheduling these threads, obliviously to what’s going on at user-level
What if the kernel preempts a thread holding a lock?

- Other threads will be unable to enter the critical section and will block (stall)

Addressing these problems

- Effective coordination of kernel decisions and user-level threads requires OS-to-user-level communication
  - OS notifies user-level that it is about to suspend a kernel thread
- This is called “scheduler activations”
  - a research paper from UW with huge effect on practice
  - 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
  - ACM TOCS 10,1

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Summary

- You really want multiple threads per address space
- Kernel threads are much more efficient than processes, but they’re still not cheap
  - all operations require a kernel call and parameter validation
- User-level threads are:
  - really fast/cheap
  - great for common-case operations
    - creation, synchronization, destruction
  - can suffer in uncommon cases due to kernel obliviousness
    - I/O
    - preemption of a lock-holder
- Scheduler activations are an answer
  - pretty subtle though

The design space