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 \textit{map} to the \textit{same} physical memory to share data
    • see the \texttt{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

<table>
<thead>
<tr>
<th>Key</th>
<th>Address space</th>
<th>Thread</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS/DOS</td>
<td>one thread per process</td>
<td>one process</td>
</tr>
<tr>
<td>Java</td>
<td>many threads per process</td>
<td>one process</td>
</tr>
<tr>
<td>older UNIXes</td>
<td>one thread per process</td>
<td>many processes</td>
</tr>
<tr>
<td>Mach, NT, Chorus, Linux, …</td>
<td>many threads per process</td>
<td>many processes</td>
</tr>
</tbody>
</table>
(old) Process address space

0xFFFFF0000

address space

0x00000000

stack
(dynamic allocated mem)

heap
(dynamic allocated mem)

static data
(data segment)

code
(text segment)

PC

SP
(new) Address space with threads

- Address space:
  - 0x00000000
  - 0xFFFFFFFF

- Address space with threads:
  - Code (text segment)
  - Static data (data segment)
  - Heap (dynamic allocated mem)
  - Thread 1 stack
  - Thread 2 stack
  - Thread 3 stack

- Stack pointers:
  - SP (T1)
  - SP (T2)
  - SP (T3)

- Program counters:
  - PC (T1)
  - PC (T2)
  - PC (T3)
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?”

• 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

Mach, NT, Chorus, Linux, …
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
“Where do threads come from” (2)

• 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

address space

thread

user-level thread library

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

os kernel

CPU
User-level threads: what the kernel sees
User-level threads: the full story

Mach, NT, Chorus, Linux, …

user-level thread library

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

kernel threads

(kernel thread create, destroy, signal, wait, etc.)

CPU

os kernel

thread

address space
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:
  - `rcode = pthread_create(&t, attributes, start_procedure)`
    - creates a new thread of control
    - new thread begins executing at `start_procedure`
  - `pthread_cond_wait(condition_variable, mutex)`
    - the calling thread blocks, sometimes called `thread_block()`
  - `pthread_signal(condition_variable)`
    - starts a thread waiting on the condition variable
  - `pthread_exit()`
    - terminates the calling thread
  - `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 `yield()`
  – `yield()` calls into the scheduler, which context switches to another ready thread
  – what happens if a thread never calls `yield()`?

• Strategy 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
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
Multiple kernel threads “powering” each address space

Kernel threads

User-level thread library

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

Address space

Thread

CPU

(os kernel

(kernel thread create, destroy, signal, wait, etc.)
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
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

MS/DOS

address space

thread

one thread/process

one process

many threads/process

one process

older UNIXes

Java

one thread/process

many processes

many threads/process

many processes

Mach, NT, Chorus, Linux, …