CSE 451: Operating Systems
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Module 4 - Threads

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Module Overview

1) Big Picture: Achieving Concurrency/Parallelism

2) Kernel Threads

3) User-Level Threads

4) Task/Work Queues

5) Event-driven Programming

6) Event-driven Programming Discussion

1. The Big Picture

- Threads are about concurrency and parallelism
  - Reminder:
    - Parallelism: physically simultaneous operations for performance
    - Concurrency: logically (and possibly physically) simultaneous operations for convenience
- One way to get concurrency and parallelism is using multiple processes
  - The programs (code) of distinct processes are isolated from each other, at run time and at coding time
- Threads are another way to get concurrency and parallelism
  - Threads “share a process”
  - Threads directly interact, at coding time and at run time

Process Parallelism

- Multiprogramming was developed to maximize CPU utilization
  - While one process is doing I/O, another one (or ten) are eligible to run on the CPU

- Example 1:
  - While I'm working in a bash terminal on attu, so are 10 other people
  - While I'm running gcc on attu, someone else is running emacs, some else a.out, …

Example 2: Process Parallelism For A Single User

- Imagine that I execute:
  - `$ egrep '[0-9]{3}-[0-9]{2}-[0-9]{4}' foo.txt`
- If I were doing this a lot, and I cared about speed, and foo.txt is big enough (and the pattern slow enough), then I might instead execute:
  - `$ cat foo.txt | egrep '[0-9]{3}-[0-9]{2}-[0-9]{4}'`
- Why?
- Hey, it's parallelism!

Example 2 (cont.)

- `$ cat foo.txt | egrep '[0-9]{3}-[0-9]{2}-[0-9]{4}'`

- You can easily imagine it's a lot easier to write `cat` and a limited version of `egrep` separately than to write a performant version of `egrep`
  - Hey, it's concurrency!

- If you wanted `egrep` alone to be able to overlap reading the file with doing the pattern match, you should implement it like the process solution!
  - One "thread" reads the file, and puts successive lines in a buffer
  - Another thread takes lines out of the buffer, and pattern matches

- This will be quite a bit faster than the process solution
  - Why?
    - You have to get around the isolation barriers of the processes
    - Threads (within a single process) are not isolated from each other, so coordinating them is much cheaper

Example 2 Discussion

- The process parallelism worked because the communication required between cat and egrep was simple enough that a pipe suffices
  - Requirements:
    - Communication is one-way
    - Communication is a stream
- If the two processes needed more complicated communication, processes and pipes wouldn't be handy
  - E.g., both actors need to update a common data structure

Example 3: A Very Strained Analogy - Browsers

- Imagine you want to look at both the latest international news (http://global.nytimes.com/?iht) and the latest hockey scores (http://espn.go.com/nhl)

- You can:
  - Start two browser instances, and look at one page in each, or
  - Start one browser instance, and bring up each page in its own tab

- Tabs come up quicker... (and consume less screen real-estate, and generally seem lighter weight, and ...)

2. Kernel Threads

- Up to now, a process is:
  - An address space (code + data)
  - OS resources (open files, etc.)
  - A stack (procedure call trace + local variables)
  - A PC + general purpose register values
- Let's separate the concepts in that:
  - An address space
  - OS resources
  - A (kernel) thread
- Threads are <u>concurrent executions sharing an address space</u> (and some OS resources)

Kernel Threads vs. Processes

- Address spaces provide isolation
  - If you can't name it, you can't read or write it
- Hence, communicating between processes is difficult
  - Have to go through the OS to move data out of one address space and into another
- Because threads are in the same address space, communication is simple/cheap:
  - Just update a (non-local) variable!

Example Opportunities for Threads

- 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 46 “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?

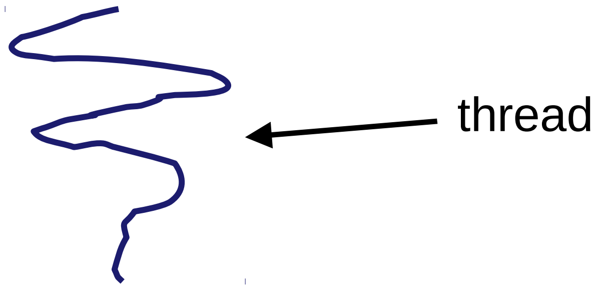
- Imagine a single parallel program running on a multiprocessor, which might like to employ “physical concurrency”
  - For example, multiplying two large matrices – split the output matrix into k regions and compute the entries in each region concurrently, using k processors

Implementing Threads

- Given the process abstraction as we know it, we *could*:
  - 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?

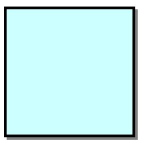
- Key idea:
  - separate the concept of a process (address space, OS resources)
  - … from that of a minimal "thread of control" (execution state: stack, stack pointer, program counter, registers)
- This execution state is usually called a thread



Threads and processes

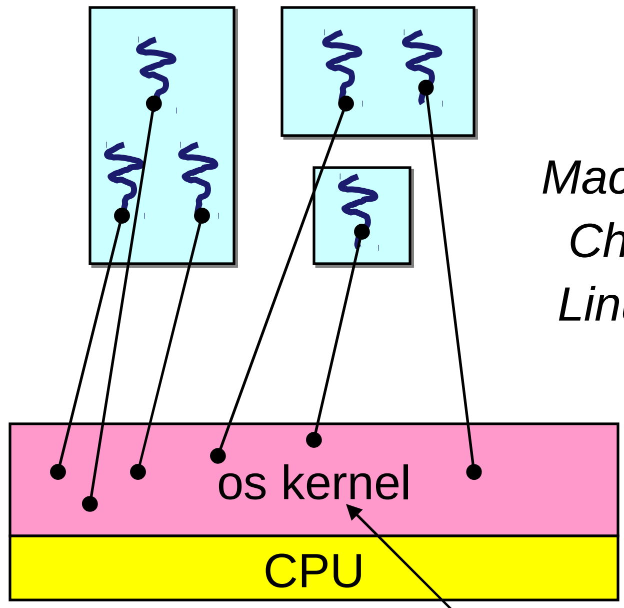
- Most modern OS's (Mach (Mac OS), Chorus, Windows, UNIX) therefore support two entities:
  - the process, which defines the address space and general process attributes (such as open files, etc.)
  - the thread, which defines a sequential execution stream within a process
- A thread is bound to a single 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

Kernel threads



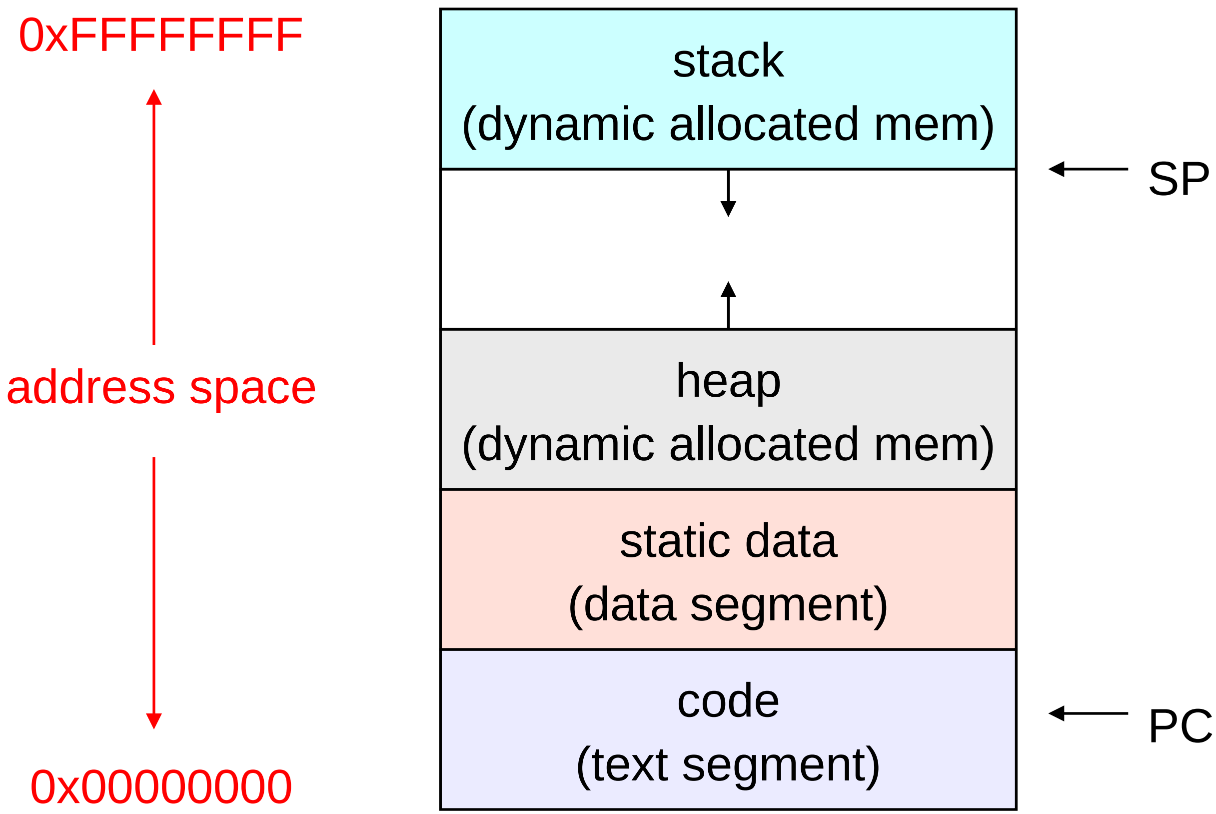
address space

thread

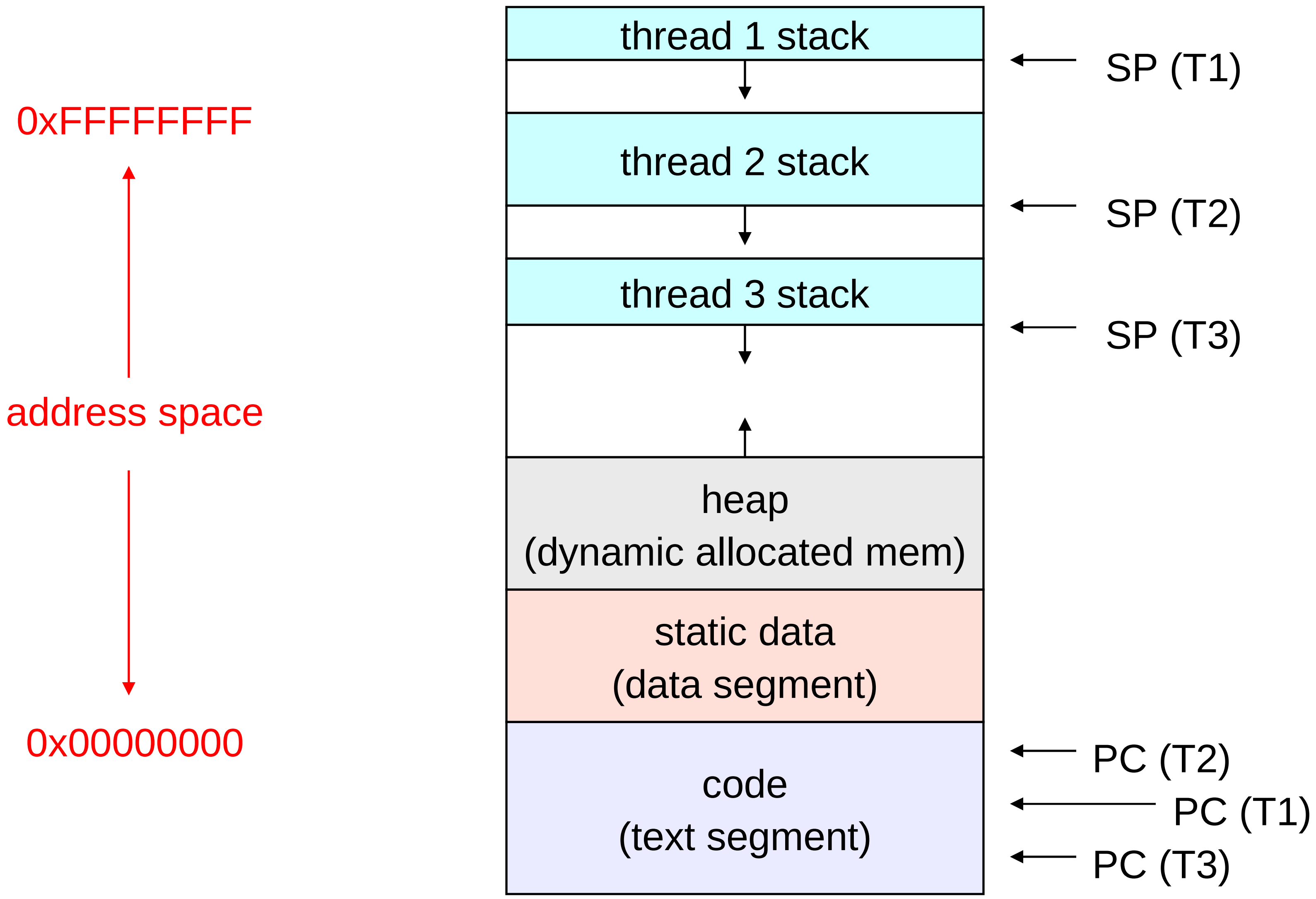


Mach, NT,
Chorus,
Linux, …

(old) Process address space



(new) Address space with threads



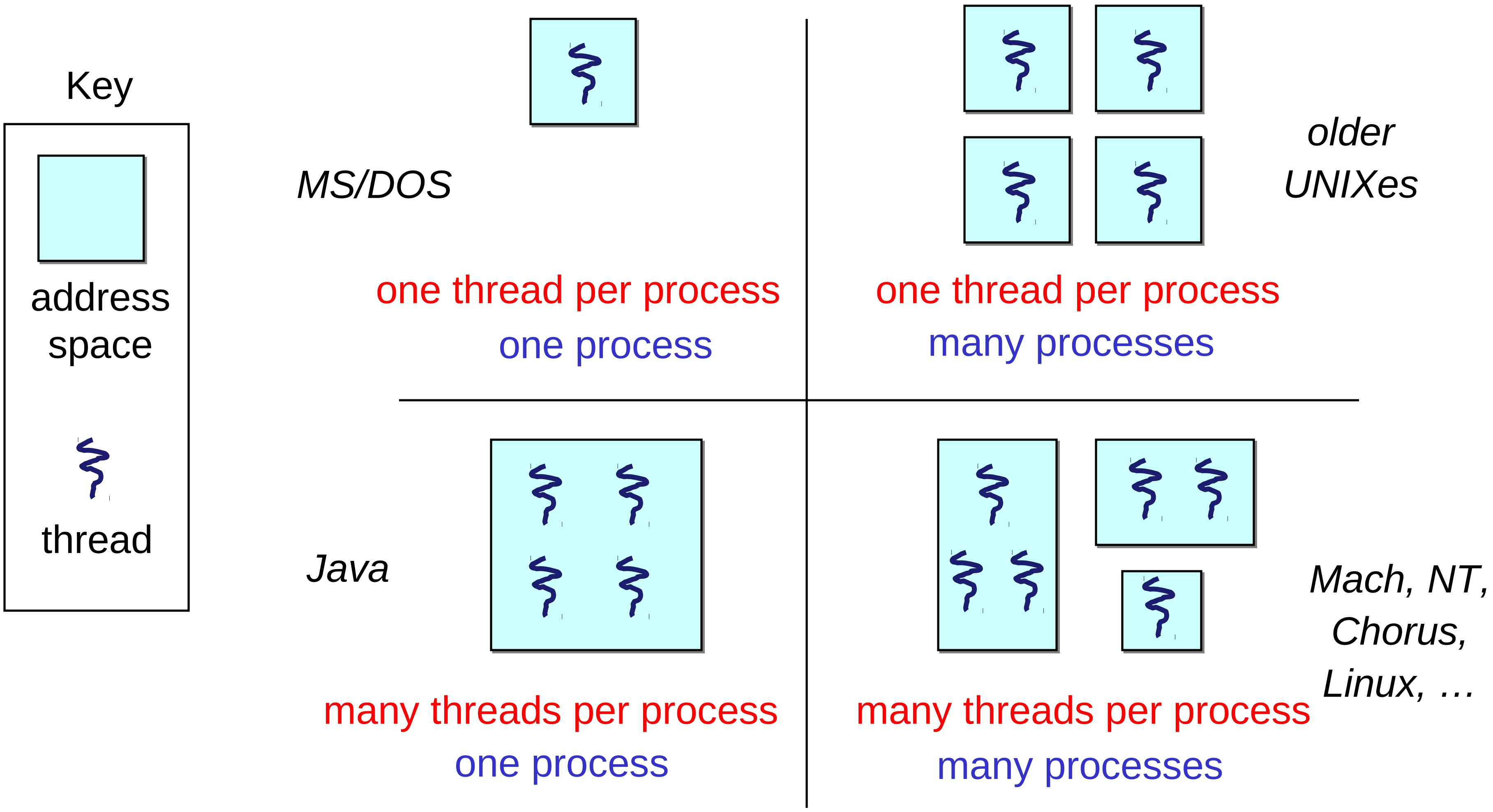
Terminology

- 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

The design space



Where do (kernel) threads come from?

- Natural answer: the kernel 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 (TCB)
      - stack pointer, program counter, register values
    - stick it on the ready queue
  - There is a “thread name space”
    - Thread id's (tid's)
    - tid's are integers (surprise!)

Kernel thread summary

- OS now manages threads *and* processes / address spaces
  - all thread operations are implemented in the kernel
    - e.g., thread creation
  - 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

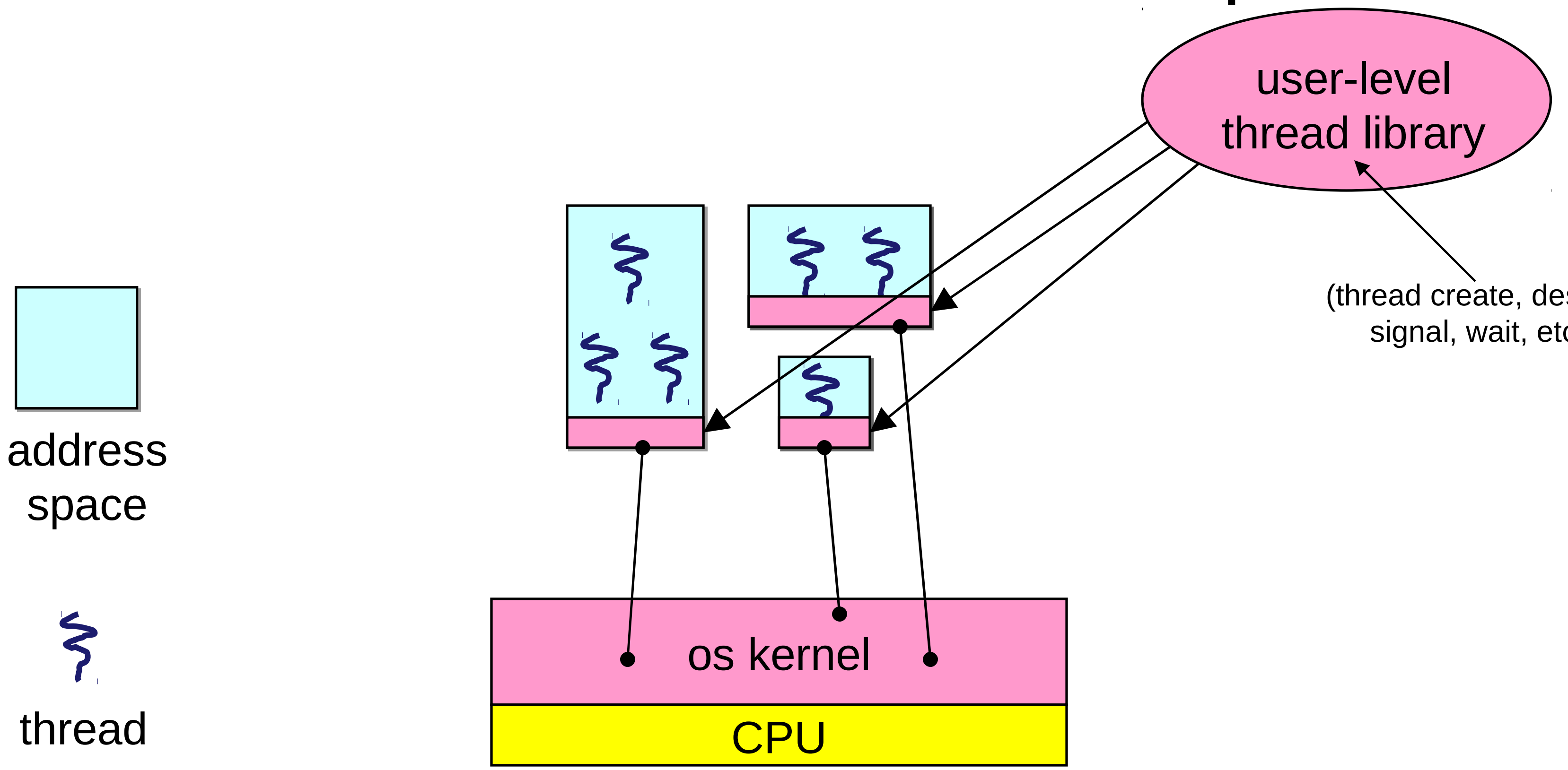
- Kernel threads are cheaper than processes
  - less state to allocate and initialize

- 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
  - must maintain kernel state for each thread

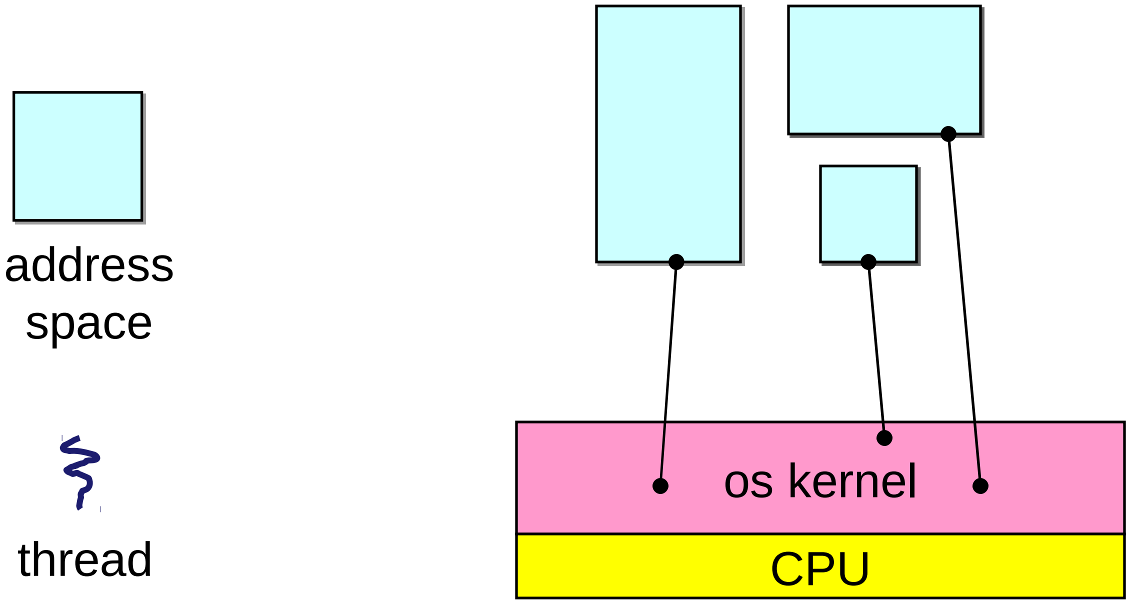
3. User-Level Threads

- There is an alternative to kernel threads
- Threads can also be created and 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

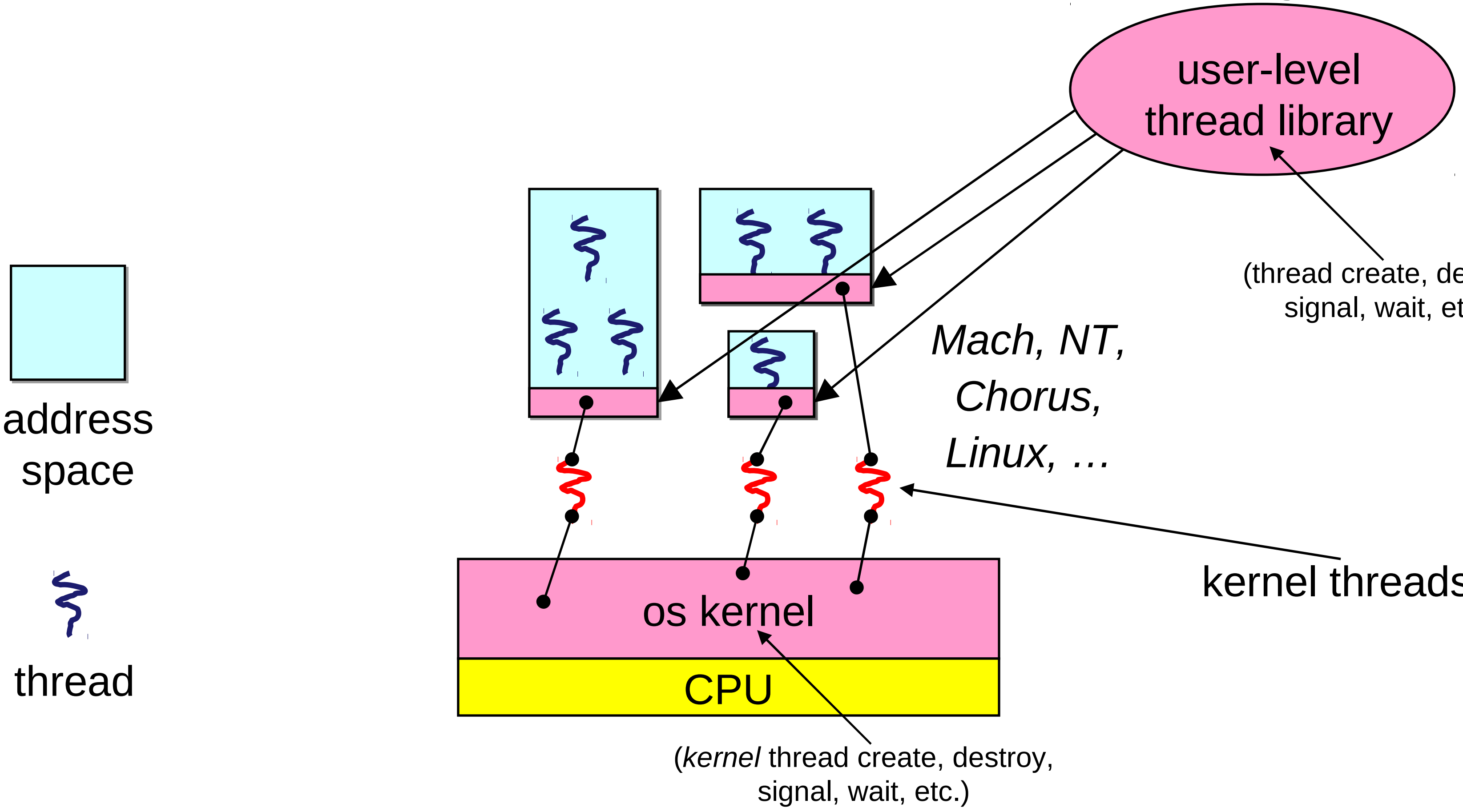
User-level threads example



User-level threads: what the kernel sees



User-level threads: the full story



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

- Still need kernel threads…

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)**
  - User-level threads
    - **`pthread_create()/pthread_join`**: 4.5 μs **(another 21x faster)**

User-level thread implementation

- The OS dispatches the kernel thread
- This 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 blocked thread (one 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

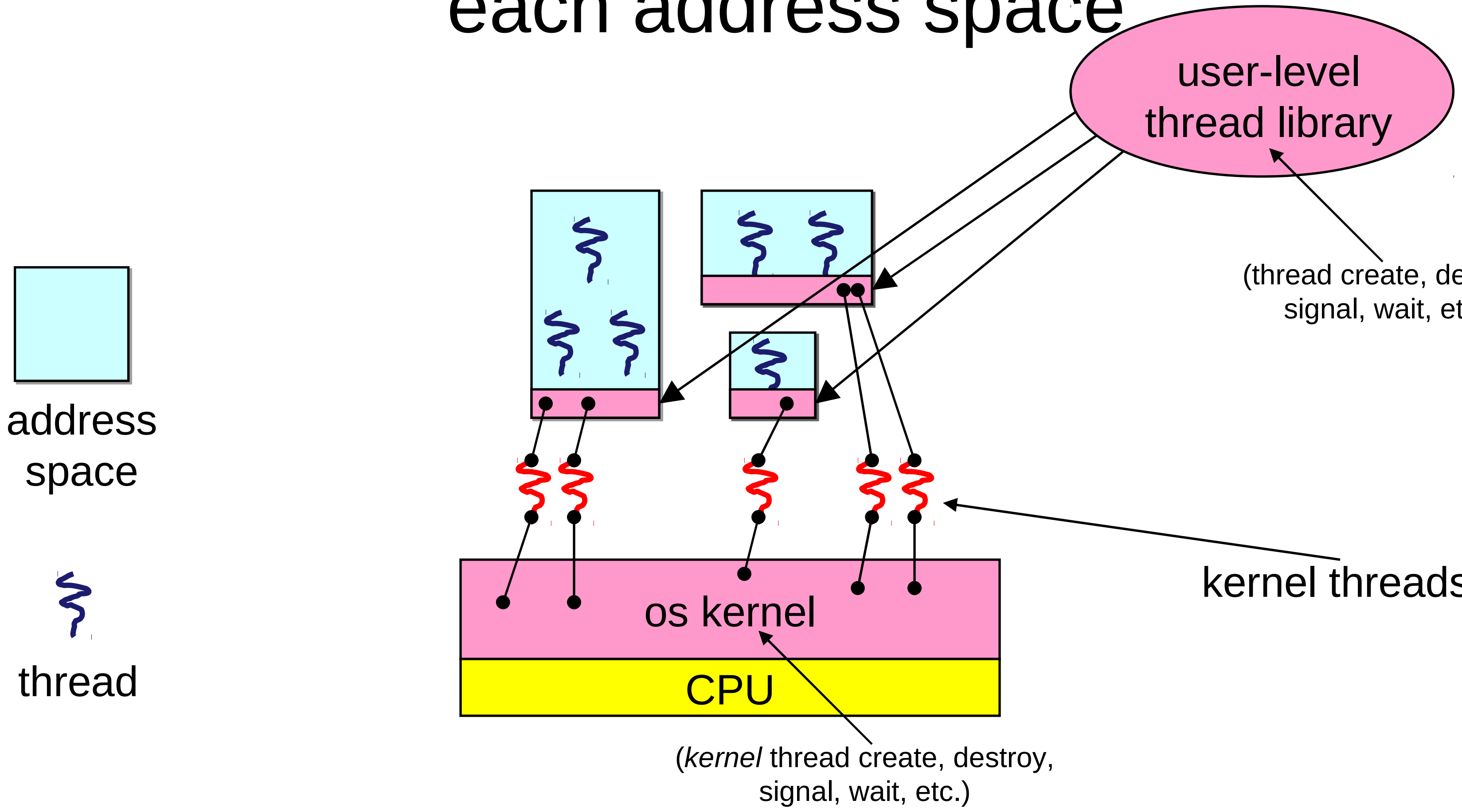
What if a thread tries to do I/O?

- 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
    - Where was it executing? What were the register values?

- 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



Addressing This Problem

- 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 or destroy a kernel thread

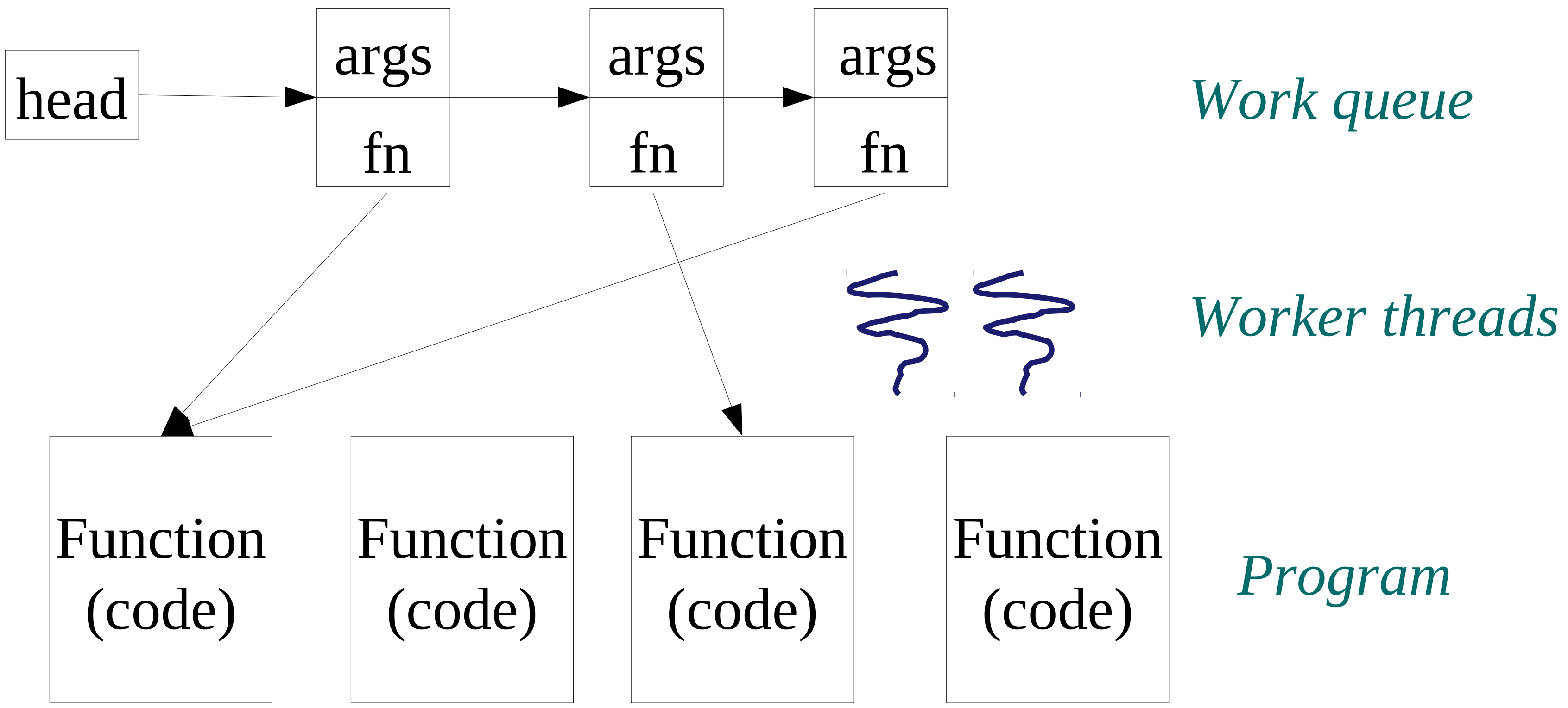
- User-level thread package is then responsible for multiplexing its threads on the available kernel threads

- This is called scheduler activations

4. Task/Work Queues

- Work queues (aka task queues) are yet another approach to concurrency/parallelism
- A “task” is a method pointer and arguments
  - Note: I didn't mention “a stack”
- A task represents work to be done, starting at some particular procedure, called with a particular set of arguments

Work queue picture



Why do this?

- One way to think of it is as an application of caching to improve performance
  - We create the worker threads once
  - That's caching the work of creating their stacks, initializing TCBs, etc.
- Work queues are most appropriate when the tasks are of known, finite duration
  - Open ended tasks, like “read network packets as they come in and put them in a queue”, are probably not tasks
- Tasks support fine-grained parallelism
  - Not much work in each “unit of parallelism”
  - cf. “coarse-grained parallelism”

An ideal application: row sums

- ```
  for (i=0; i<n; i++) {
      b[i] = 0;
      for (j=0; j<m; j++) {
          b[i] += a[i][j];
       }
  }
  ```
- Turn inner loop into a procedure
- Put n tasks on the queue, all pointing to that procedure, but with args `i=0,1,2,...,n-1`
- Notes:
  - work is well defined/finite
  - The tasks never block
    - No worries about marooning a thread
  ```

There are a lot of unanswered questions

- How many threads execute the tasks?
  - User-level or kernel threads?
- Should the work queue guarantee any kind of ordering of task execution? Priorities?
- Can tasks synchronize? How?
- How small should a task be?
  - Chunking: Increasing granularity by combining logically distinct tasks into a single one
    - E.g., executing 10 row sums instead of one
- Is it a “task” if it might block?

5. Event-driven Programming

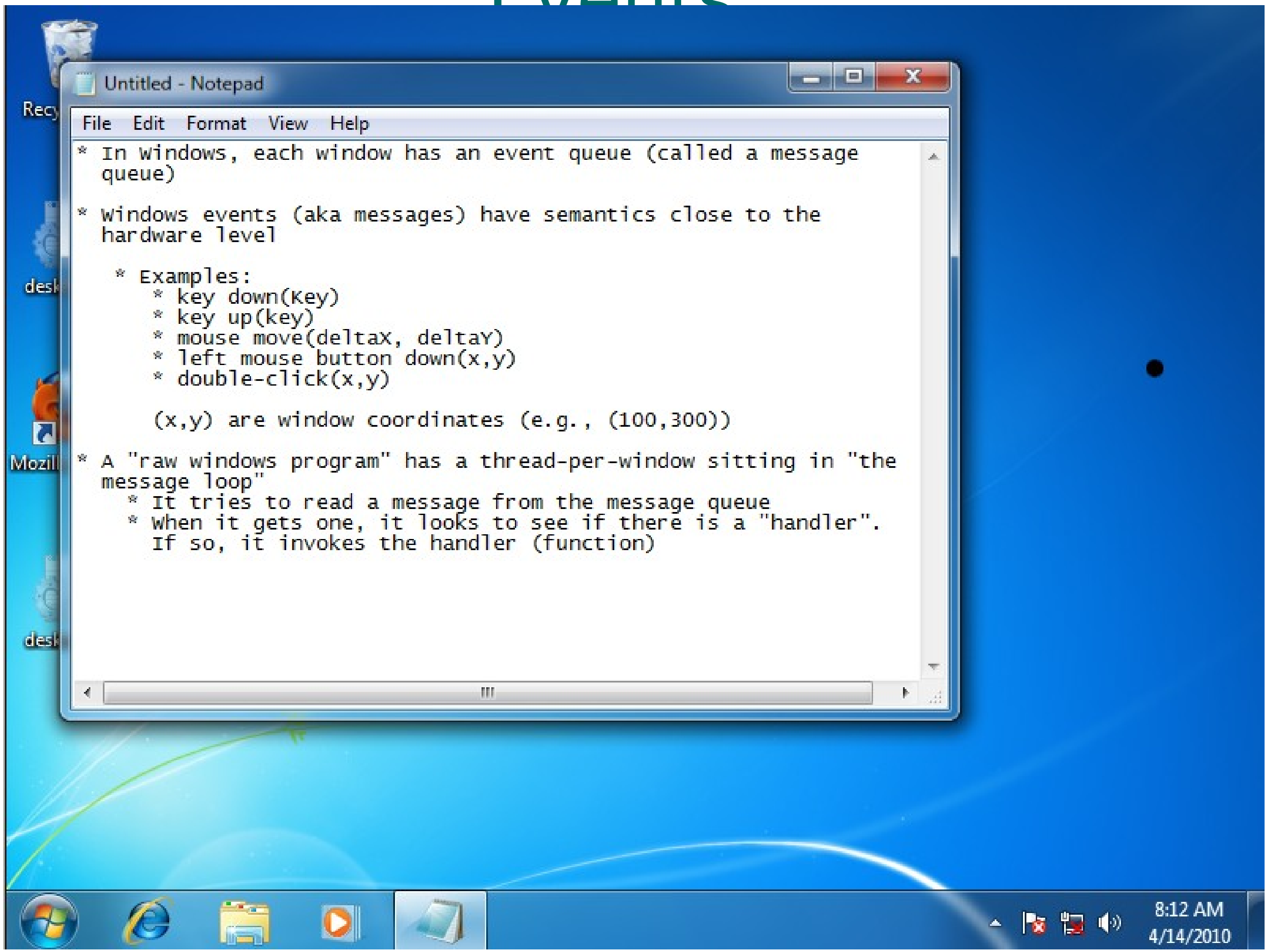
- Events are are asynchronous software notifications
  - Asynchronous: they happen any time
  - Software: they are raised by some running code
  - Notification: they are not an explicit control flow change
    - Not a procedure call

- *Note the similarities to work queues*

- They're an extremely common programming paradigm
  - Especially for GUI programming
  - Also for other domains

- Basic control flow:
  - Software registers a handler (function) for a particular event type
  - When the event occurs, the handler is (eventually) invoked

Example 1: System Generated Events



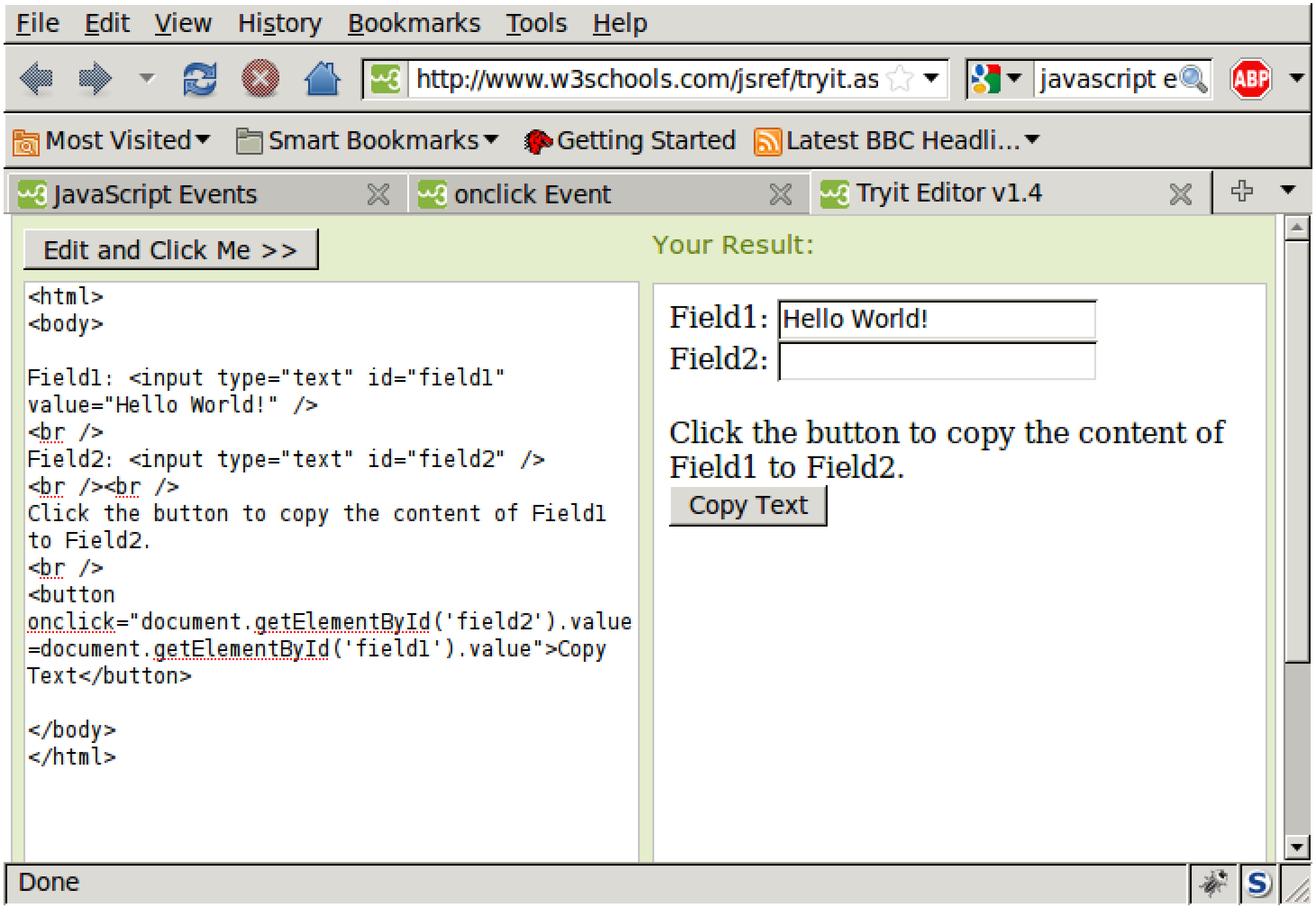
Semantically Richer Events

- Note that the windows events aren't exactly convenient
  - “left button down(100,300)”
    - The user clicked on something, but what?

- The software application must convert this to something meaningful
  - Figure out that (100,300) is in “File” in the menu bar

- A distinct event system layer can be built at this layer, on top of raw events

Example 2: Javascript



6. Event-driven Programming Discussion

- The event mechanism decouples the caller from the callee
  - The caller never heard of the callee code
    - It just knows the name of an event
  - There may be 0, 1, or many handlers registered for an event
    - The caller doesn't know or care
- Programmers need to know the event namespace at coding time
  - Not the names of pieces of code (e.g., methods)

Binding Time

- Binding is the process of translating one name to another name
  - E.g., a function name to a memory address
- There are choices…
  - Early binding:
    - At code time (you embed a procedure name in your code)
    - At link time (static libraries)
  - Late binding
    - At run time (dynamic link libraries)
- Events introduce a level of indirection to binding
  - A famous aphorism of David Wheeler goes: “All problems in computer science can be solved by another level of indirection” (*Wikipedia: indirection)*

More Uses

- Plug-in architectures
  - Eclipse, Firefox, ...
  - These are frameworks, designed to support multiple as-yet-unwritten applications "running inside them"
  - Plug-in can get event notifications (e.g., button click) and do whatever it does

- "Publish-subscribe" systems
  - Events with guards
    - Publish a data record
    - Subscribe to data records meeting the guard (criteria)
    - Get a notification when a record is published that meets your guard
    - Especially handy in distributed systems

Summary

- Sometimes (often) multiple threads of control, sharing an address space, is the easiest way to program functionality
  - Threads are handy!
- Kernel threads are much more efficient than processes, but they're still not cheap
  - all operations require a kernel call and argument validation
- User-level threads are:
  - 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
- Work queues are even faster/cheaper
  - Most appropriate for limited executions
- Event-driven programming is an important specialization / extension