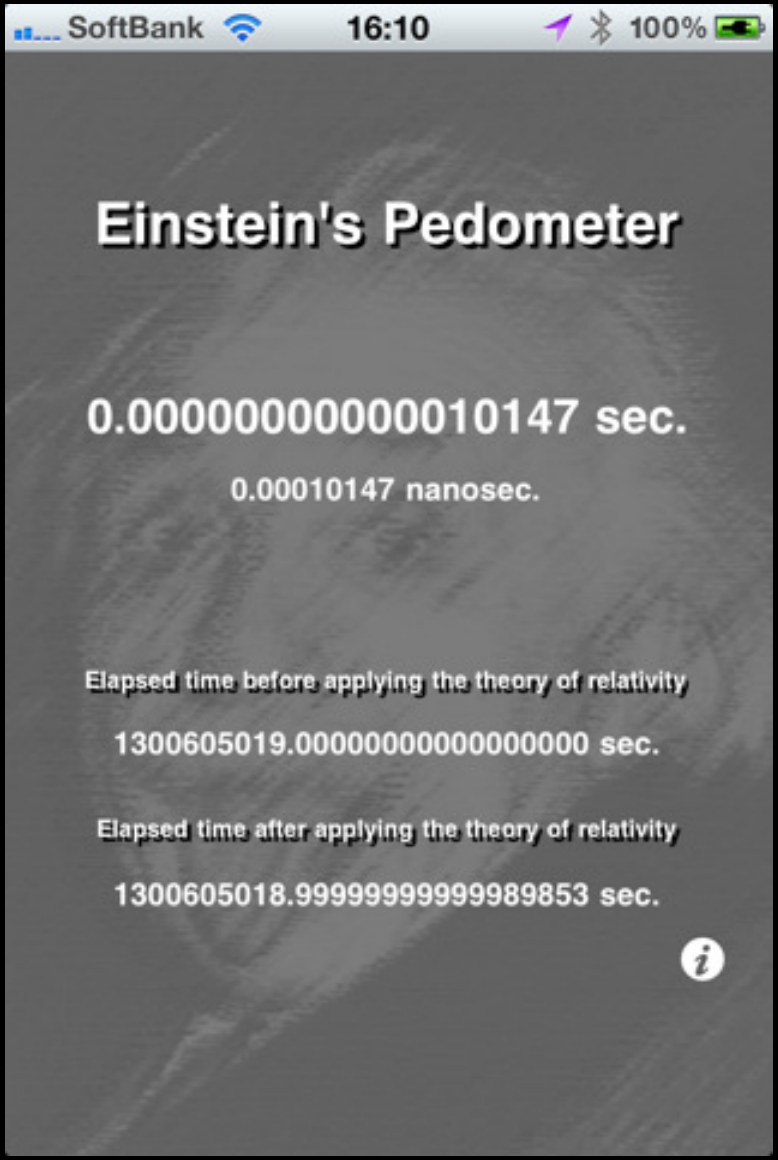

SoftBank
16:10
100%
Einstein's Pedometer
0.00000000000010147 sec.
0.00010147 nanosec.
Elapsed time before applying the theory of relativity
1300605019.00000000000000000 sec.
Elapsed time after applying the theory of relativity
1300605018.99999999999989853 sec.

Parallel Programming and Synchronization

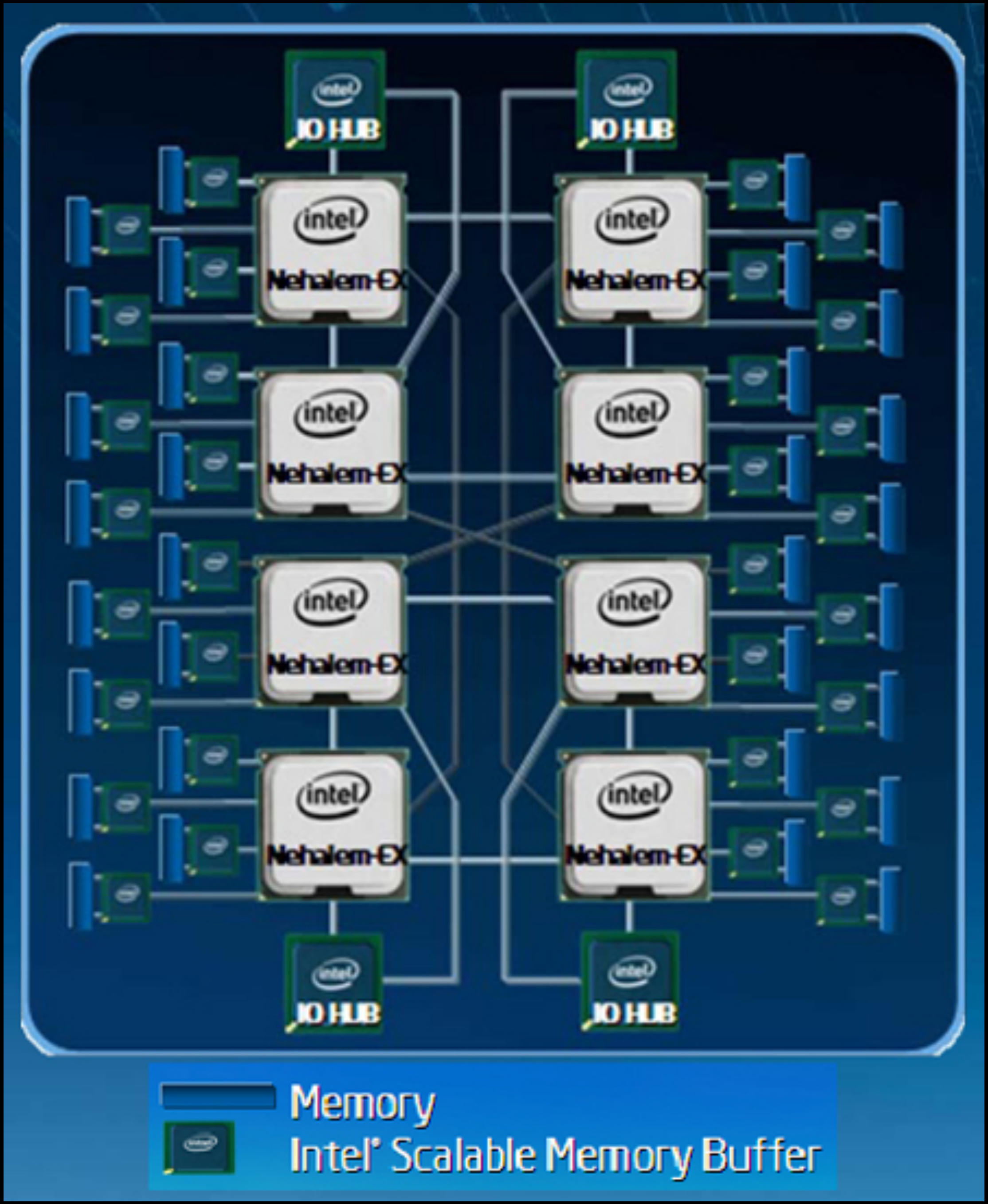
Guest Lecture: Kevin Walsh
CS 3410, Spring 2011
Computer Science
Cornell University

P&H Chapter 2.11

Multi-core is a reality…

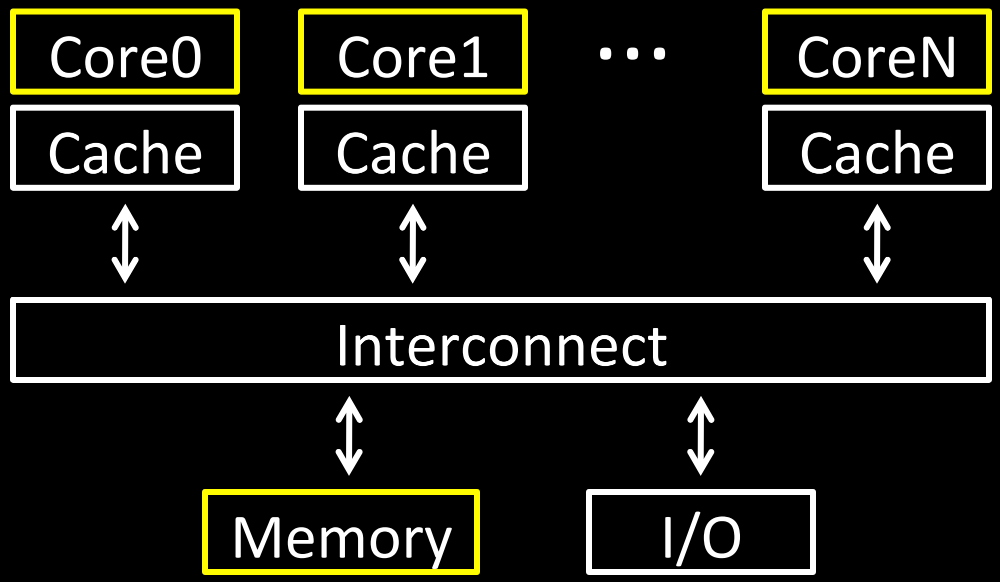
… but how do we write multi-core safe code?

Cache Coherence:
Necessary, but not Sufficient


IO HUB
IO HUB
Nehalem-EX
Nehalem-EX
Nehalem-EX
Nehalem-EX
Nehalem-EX
Nehalem-EX
Nehalem-EX
Nehalem-EX
IO HUB
IO HUB
Memory
Intel® Scalable Memory Buffer

Shared Memory Multiprocessor (SMP)

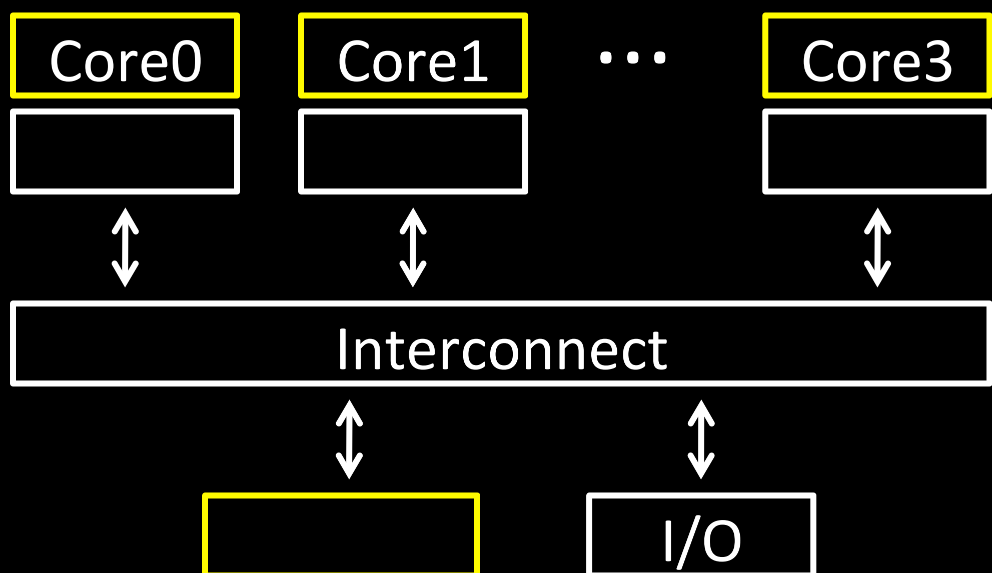
- Typical (today): 2 – 4 processor dies, 2 – 8 cores each
- Assume physical addresses (ignore virtual memory)
- Assume uniform memory access (ignore NUMA)



Shared Memory Multiprocessor (SMP)

What could possibly go wrong?

```
...
x = x+1
...
```




```
...
while (x==5) {
  // wait
}
...
```

Cache coherence defined...

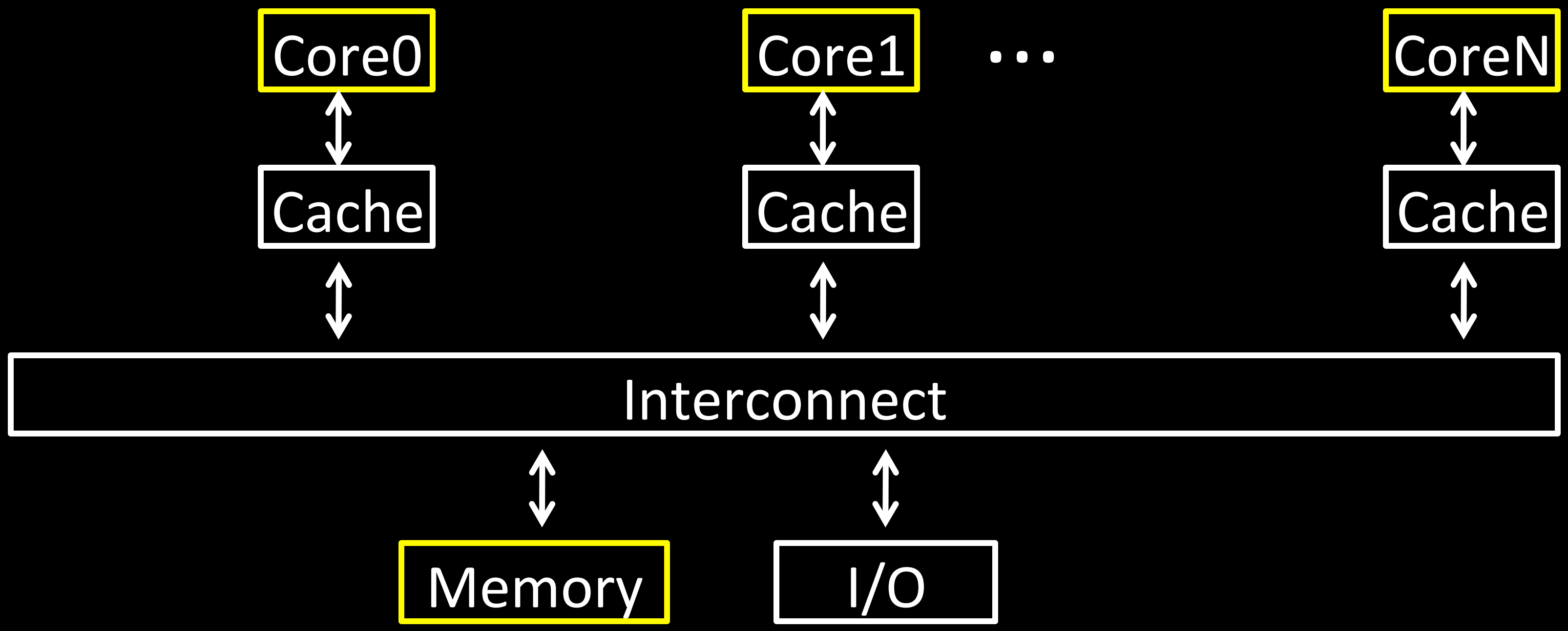
Informal: Reads return most recently written value

Formal: For concurrent processes P_1 and P_2

- P writes X before P reads X (with no intervening writes)
  ⇒ read returns written value
- P_1 writes X before P_2 reads X
  ⇒ read returns written value
- P_1 writes X and P_2 writes X
  ⇒ all processors see writes in the same order
  - all see the same final value for X

Recall: Snooping for Hardware Cache Coherence

- All caches monitor bus and all other caches
- Bus read: respond if you have dirty data
- Bus write: update/invalidate your copy of data



Example with cache coherence:

P_1	P_2
x = x +1	**while (x==5) ;**

Example with cache coherence:

P_1

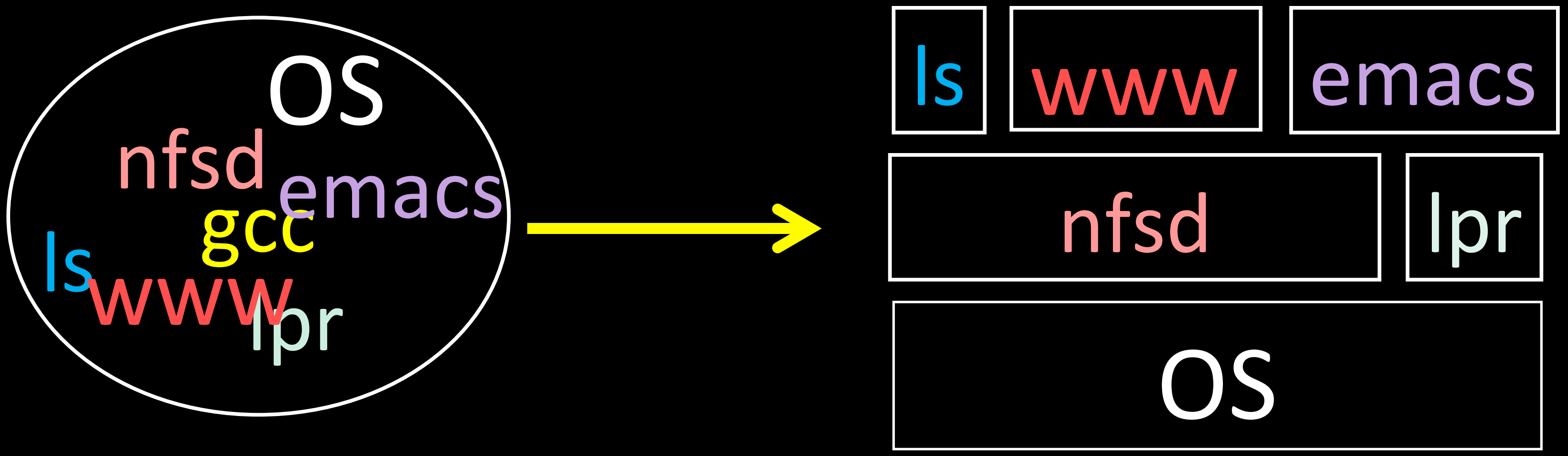
x = x +1

P_2

x = x + 1

Software Support for Synchronization and Coordination: Programs and Processes

How do we cope with lots of activity?



Simplicity? Separation into processes

Reliability? Isolation

Speed? Program-level parallelism

Process

OS abstraction of a running computation

- The unit of execution
- The unit of scheduling
- Execution state
  + address space

From process perspective

- a virtual CPU
- some virtual memory
- a virtual keyboard, screen, …

Program

“Blueprint” for a process

- Passive entity (bits on disk)
- Code + static data

Role of the OS

Context Switching

- Provides illusion that every process owns a CPU

Virtual Memory

- Provides illusion that process owns some memory

Device drivers & system calls

- Provides illusion that process owns a keyboard, …

To do:

How to start a process?

How do processes communicate / coordinate?

Creating Processes:
Fork

Q: How to create a process?

A: Double click

After boot, OS starts the first process

…which in turn creates other processes

- parent / child → the process tree

```
$ pstree | view -
init-+-NetworkManager-+-dhclient
     |-apache2
     |-chrome-+-chrome
     |        `-chrome
     |-chrome---chrome
     |-clementine
     |-clock-applet
     |-cron
     |-cupsd
     |-firefox---run-mozilla.sh---firefox-bin-+-plugin-cont
     |-gnome-screensaver
     |-grep
     |-in.tftpd
     |-ntpd
     `-sshd---sshd---sshd---bash-+-gcc---gcc---cc1
                                 |-pstree
                                 |-vim
                                 `-view
```

Init is a special case. For others…

Q: How does parent process create child process?

A: fork() system call

Wait. what? int fork() returns TWICE!

```
main(int ac, char **av) {
   int x = getpid(); // get current process ID from OS
   char *hi = av[1]; // get greeting from command line
   printf("I'm process %d\n", x);
   int id = fork();
   if (id == 0)
       printf("%s from %d\n", hi, getpid());
   else
       printf("%s from %d, child is %d\n", hi, getpid(), id);
}
$ gcc -o strange strange.c
$ ./strange "Hey"
I'm process 23511
Hey from 23512
Hey from 23511, child is 23512
```

Parent can pass information to child

- In fact, *all parent data* is passed to child
- But isolated after (C-O-W ensures changes are invisible)

Q: How to continue communicating?

A: Invent OS “IPC channels” : send(msg), recv(), …

Parent can pass information to child

- In fact, *all parent data* is passed to child
- But isolated after (C-O-W ensures changes are invisible)

Q: How to continue communicating?

A: Shared (Virtual) Memory!

Processes and Threads

Parallel programming with processes:

- They share almost everything
  code, shared mem, open files, filesystem privileges, …
- Pagetables will be *almost* identical
- Differences: PC, registers, stack

Recall: process = execution context + address space

Process

OS abstraction of a running computation

- The unit of execution
- The unit of scheduling
- Execution state
  \+ address space

From process perspective

- a virtual CPU
- some virtual memory
- a virtual keyboard, screen, …

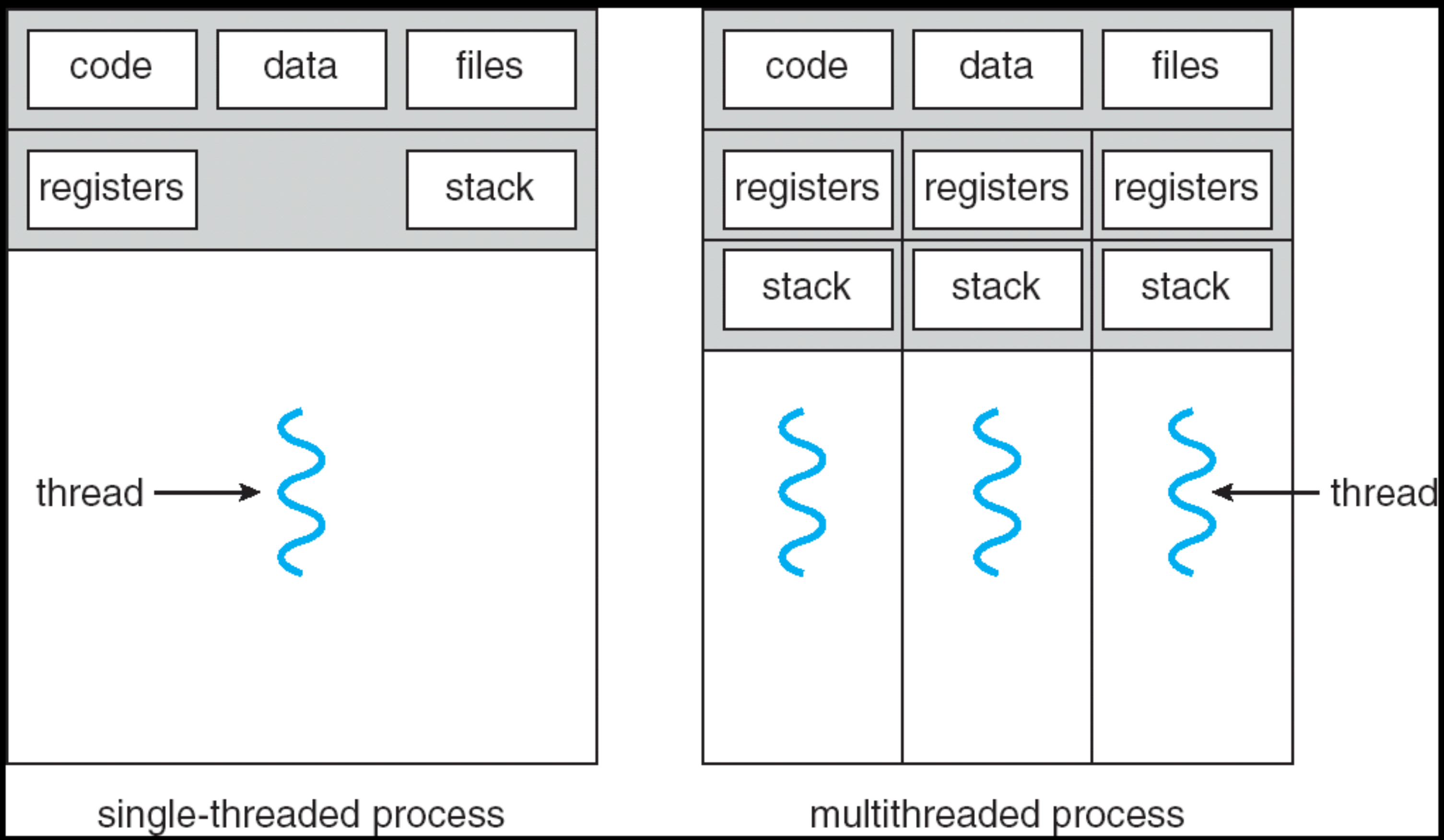
Thread

OS abstraction of a single thread of control

- The unit of scheduling
- Lives in one single process

From thread perspective

- one virtual CPU core on a virtual multi-core machine


code
data
files
registers
stack
thread
code
data
files
registers
registers
registers
stack
stack
stack
thread
single-threaded process
multithreaded process

```
#include <pthread.h>
int counter = 0;

void PrintHello(int arg) {
   printf(“I’m thread %d, counter is %d\n”, arg, counter++);
   ... do some work ...
   pthread_exit(NULL);
}

int main () {
   for (t = 0; t < 4; t++) {
       printf(“in main: creating thread %d\n", t);
       pthread_create(NULL, NULL, PrintHello, t);
    }
    pthread_exit(NULL);
}
```

```
in main: creating thread 0
I'm thread 0, counter is 0
in main: creating thread 1
I'm thread 1, counter is 1
in main: creating thread 2
in main: creating thread 3
I'm thread 3, counter is 2
I'm thread 2, counter is 3
```

If processes?

Example: Apache web server

```
void main() {
  setup();
  while (c = accept_connection()) {

     req = read_request(c);
     hits[req]++;
     send_response(c, req);


  }
  cleanup();
}
```

Example: Apache web server

Each client request handled by a separate thread (in parallel)

- Some shared state: hit counter, ...

Thread 52	Thread 205
`read hits`	`read hits`
`addi`	`addi`
`write hits`	`write hits`

(look familiar?)

Timing-dependent failure ⇒ race condition

- hard to reproduce ⇒ hard to debug

Within a thread: execution is sequential

Between threads?

- No ordering or timing guarantees
- Might even run on different cores at the same time

Problem: hard to program, hard to reason about

- Behavior can depend on subtle timing differences
- Bugs may be impossible to reproduce

Cache coherency isn't sufficient…

Need explicit synchronization to make sense of concurrency!

Managing Concurrency

Races, Critical Sections, and Mutexes

Concurrency Goals

Liveness

- Make forward progress

Efficiency

- Make good use of resources

Fairness

- Fair allocation of resources between threads

Correctness

- Threads are isolated (except when they aren't)

Race Condition

Timing-dependent error when accessing shared state

- Depends on scheduling happenstance
  … e.g. who wins "race" to the store instruction?

Concurrent Program Correctness = all possible schedules are safe

- Must consider *every possible* permutation
- In other words…

… the scheduler is your adversary

What if we can designate parts of the execution as critical sections

- Rule: only one thread can be "inside"

Thread 52	**Thread 205**
read hits addi write hits	read hits addi write hits

Q: How to implement critical section in code?

A: Lots of approaches….

Disable interrupts?

CSEnter() = disable interrupts (including clock)

CSExit() = re-enable interrupts

```
read hits
addi
write hits
```

Works for some kernel data-structures

Very bad idea for user code

Q: How to implement critical section in code?

A: Lots of approaches….

Modify OS scheduler?

CSEnter() = syscall to disable context switches

CSExit() = syscall to re-enable context switches

```
read hits
addi
write hits
```

Doesn't work if interrupts are part of the problem

Usually a bad idea anyway

Q: How to implement critical section in code?

A: Lots of approaches….

Mutual Exclusion Lock (mutex)

acquire(m): wait till it becomes free, then lock it

release(m): unlock it

```
apache_got_hit() {
    pthread_mutex_lock(m);
    hits = hits + 1;
    pthread_mutex_unlock(m)
}
```

Q: How to implement mutexes?