Parallel Programming and Synchronization

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P&H Chapter 2.11

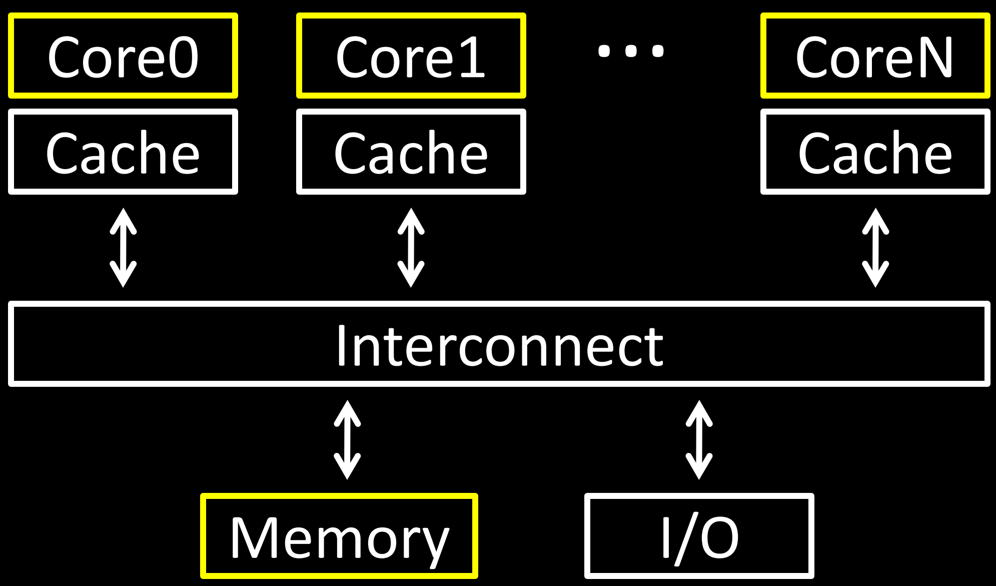
Multi-core is a reality…

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

Cache Coherence:
Necessary, but not Sufficient

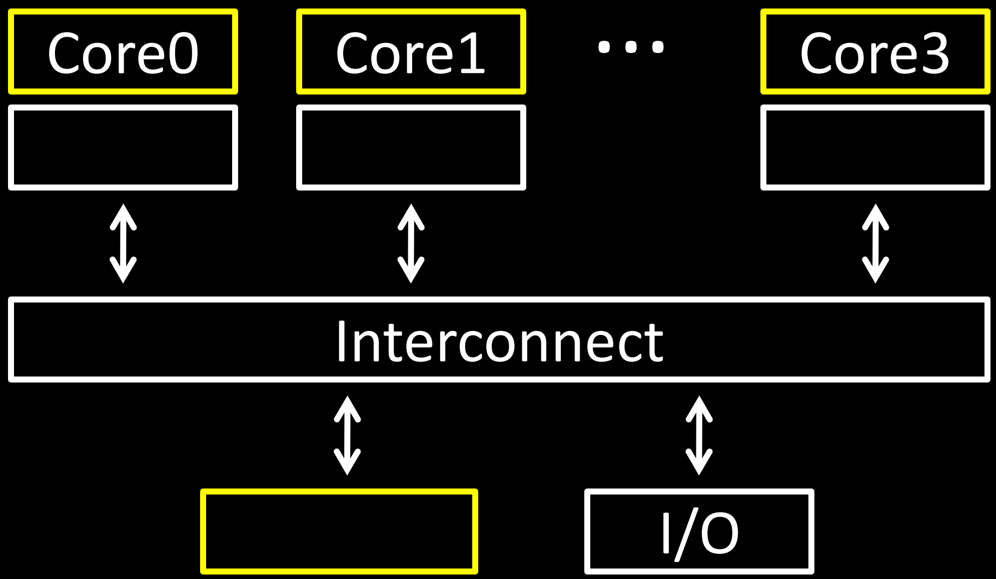
Shared Memory Multiprocessor (SMP)

- Suppose CPU cores share physical address space
- Assume write-through caches (write-back is worse!)



What could possibly go wrong?

...
x++
...



...
read x
...
read x
...

Cache coherence defined...

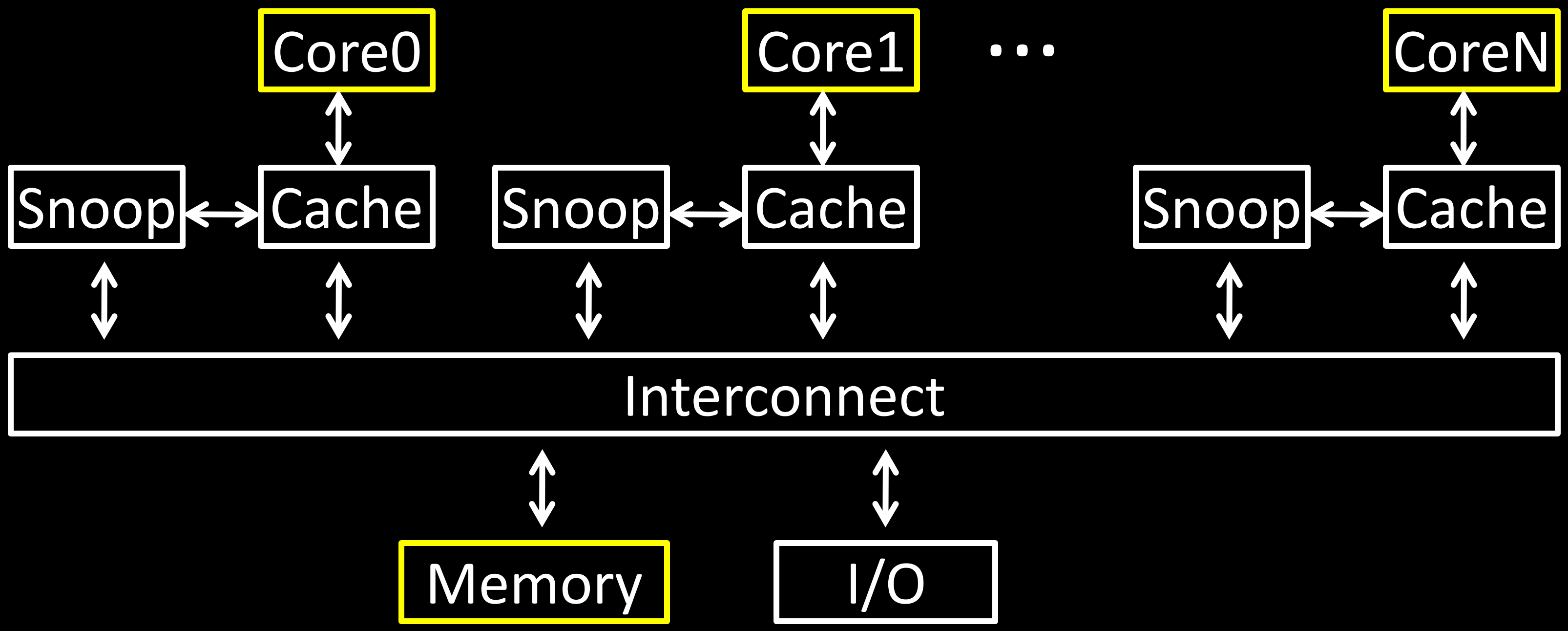
Informal: Reads return most recently written value

Formal: For concurrent processes P_1 and P_2

- P writes X before P reads X (with no intervening writes)
  $\Rightarrow$ read returns written value
- P_1 writes X before P_2 reads X
  $\Rightarrow$ read returns written value
- P_1 writes X and P_2 writes X
  $\Rightarrow$ 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
- In reality: very complicated, lots of corner cases



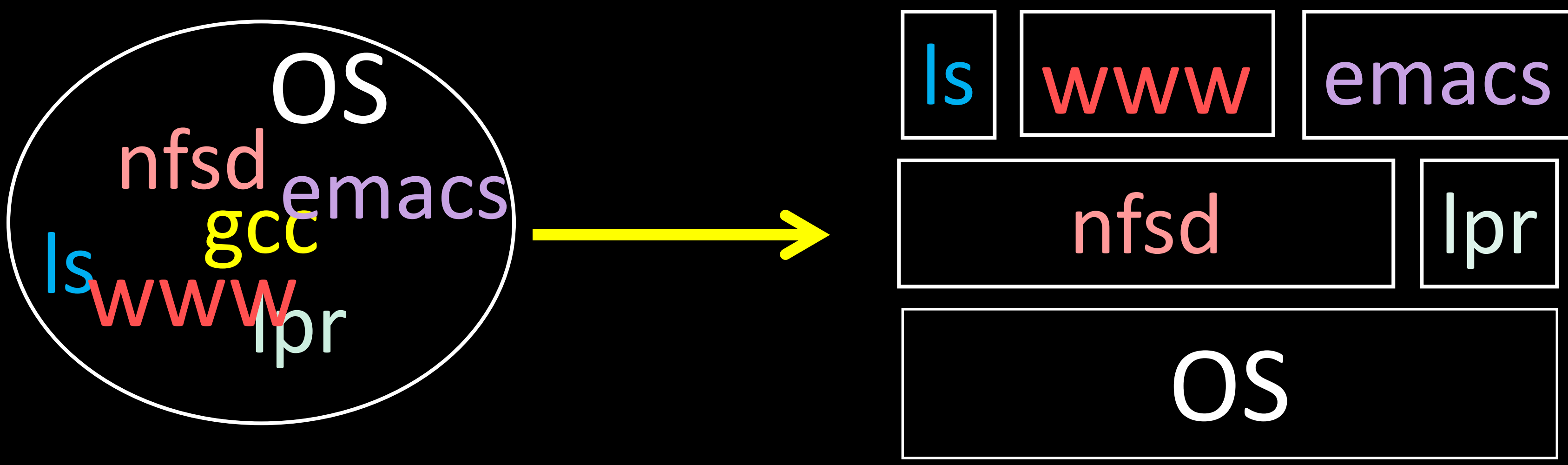
Is cache coherence enough?

P_1	P_2
…	…
x = x +1	**x = x + 1**
…	…

→ happens even on single-core (context switches!)

Programs and Processes

How do we cope with lots of activity?



Simplicity? Separation into processes

Reliability? Isolation (e.g. virtual memory)

Speed? Program-level parallelism (e.g. during I/O)

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? Double click?

After boot, OS starts the first process…

- e.g. *init*

…which in turn creates other processes

- parent / child → the process tree

Init is a special case. For others…

Q: How does parent process create child process?

A: fork() system call

- creates new address space
  (Copy-On-Write duplicate of parent's)
- creates new execution state in OS process table
  (Exact copy of parent's)
- returns child's id to parent
  (`context[parent_id]->v0 = child_id`)
- returns zero to child
  (`context[child_id]->v0 = 0`)

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 "Hi"
I'm process 23511
Hi from 23512
Hi from 23511, child is 23512
```

Parent can pass information to child

- In fact, *all parent data* is passed to child
- But isolated from then on…
  - C-O-W ensures they don’t see each other’s changes

Q: How to continue communicating?

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

A: Shared (Virtual) Memory!

- Before fork: allocate pages, mark as “shared”
- During fork: don’t set copy-on-write for these pages
- After fork: either can read/write

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, …

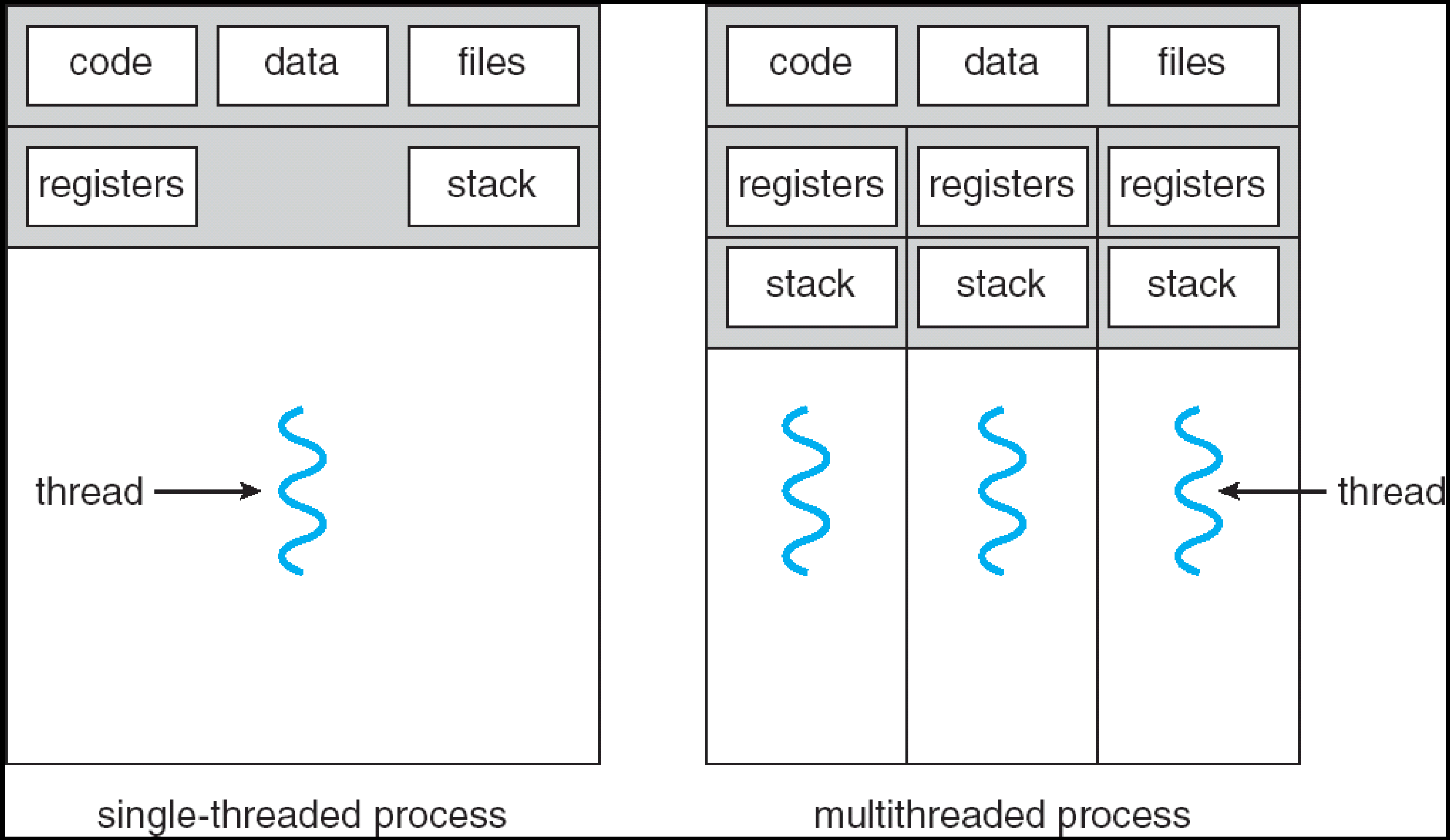
Thread

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
single-threaded process
code
data
files
registers
registers
registers
stack
stack
stack
thread
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 0, counter is 0
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

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
  … i.e. 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`	`read hits`
`addi`	`addi`
`write hits`	`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

Works for many kernel data-structures

- but only within a single core: why?

Very bad idea for user code

(important events are delayed… forever?)

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

Doesn’t work if interrupts are part of the problem
(e.g. won’t work for many kernel datastructures)

Usually a bad idea anyway
(caller forgets to CSExit? Or waits a long time?)

Q: How to implement critical section in code?

A: Lots of approaches….

Mutual Exclusion Lock (mutex)

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

release(m): free it

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

Q: How to implement mutexes?

A: next time…