

Concurrent & Distributed Systems

Lecture 1: Introduction to concurrency, threads, and mutual exclusion

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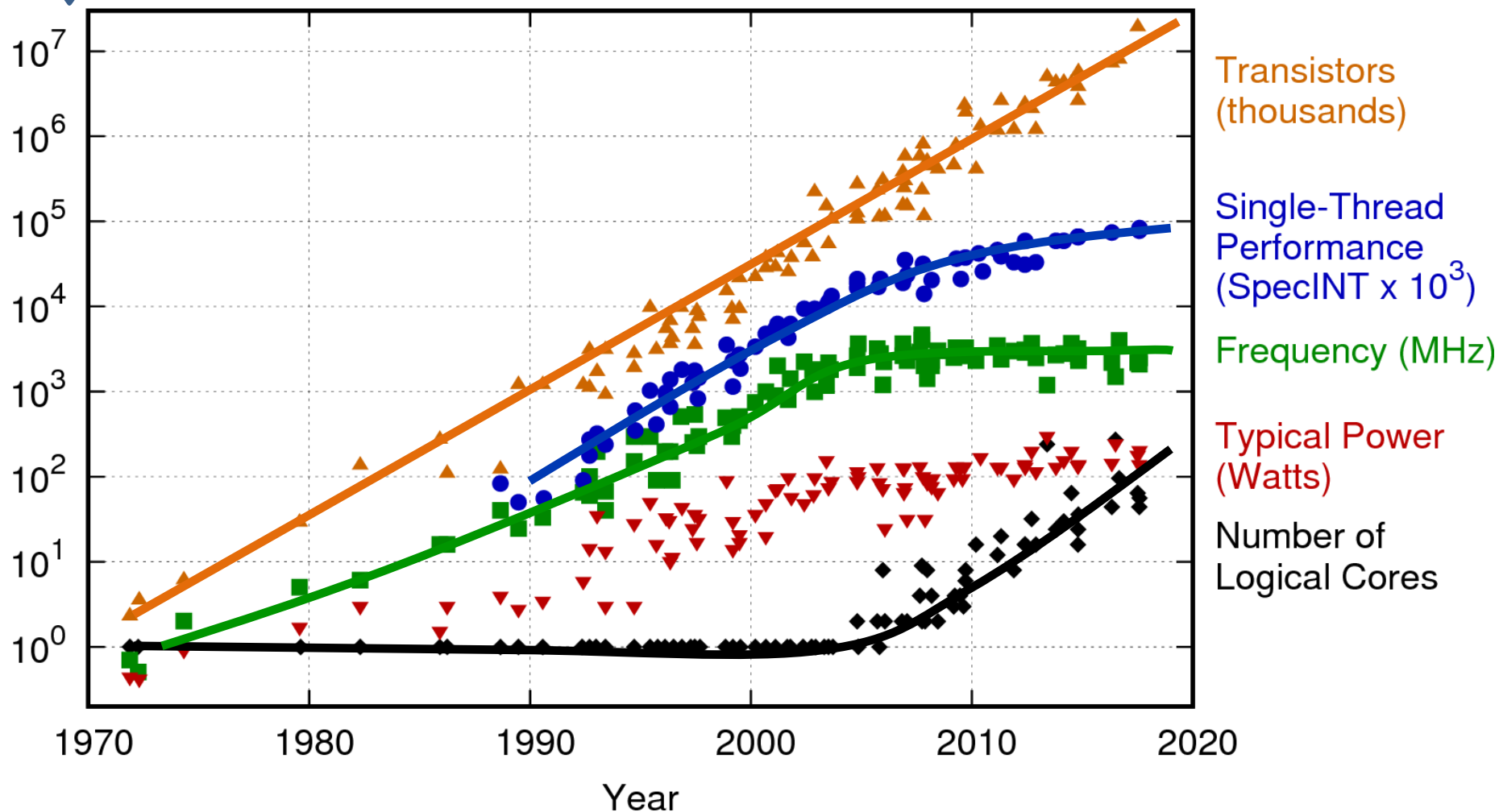
(With thanks to Dr Robert N. M. Watson and Dr Steven Hand)

Concurrent and Distributed Systems

- One course, two parts
 - 8 lectures on concurrent systems
 - 8 further lectures of distributed systems
- Similar interests and concerns:
 - **Scalability** given parallelism and distributed systems
 - Mask local or distributed **communications latency**
 - Importance in observing (or enforcing) **execution orders**
 - **Correctness** in the presence of concurrency (+debugging).
- Important differences
 - Underlying primitives: **shared memory** vs. **message passing**
 - Distributed systems experience **communications failure**
 - Distributed systems (may) experience **unbounded latency**
 - (Further) difficulty of **distributed time**.

log scale

42 Years of Microprocessor Trend Data



Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2017 by K. Rupp

<https://www.karlrupp.net/2018/02/42-years-of-microprocessor-trend-data/>

Concurrent systems outline

1. Introduction to concurrency, threads, and mutual exclusion.
2. Automata composition - safety and liveness.
3. Semaphores and associated design patterns.
4. CCR, monitors and concurrency in practice.
5. Deadlock, liveness and priority guarantees.
6. Concurrency without shared data; transactions.
7. Further transactions.
8. Crash recovery; lock free programming; (Transactional memory).

Recommended reading

- “*Operating Systems, Concurrent and Distributed Software Design*”, Jean Bacon and Tim Harris, Addison-Wesley 2003
- “Designing Data-Intensive Applications”, Martin Kleppmann O'Reilly Media 2017
- “*Modern Operating Systems*”, (3rd Ed), Andrew Tannenbaum, Prentice-Hall 2007
- “*Java Concurrency in Practice*”, Brian Goetz and others, Addison-Wesley 2006

Look in books for more detailed explanations of algorithms; lectures only present sketches.

What is concurrency?

- Computers appear to do many things at once
 - E.g. running multiple programs on a laptop
 - E.g. writing back data buffered in memory to the hard disk while the program(s) continue to execute
- In the first case, this may actually be an illusion
 - E.g. processes **time sharing** a single-cored CPU
- In the second, there is **true parallelism**
 - E.g. Direct Memory Access (DMA) transfers data between memory and I/O devices (e.g., NIC, SATA) at the same time as the CPU executes code
 - E.g., two CPUs execute code at the same time
- In both cases, we have a **concurrency**
 - Many things are occurring “at the same time”

In this course we will

- Investigate concurrency in computer systems
 - Processes, threads, interrupts, hardware
- Consider how to control concurrency
 - Mutual exclusion (locks, semaphores), condition synchronization, lock-free programming
- Learn about deadlock, livelock, priority inversion
 - And prevention, avoidance, detection, recovery
- See how abstraction can provide support for correct & fault-tolerant concurrent execution
 - Transactions, serialisability, concurrency control
- Look at techniques for anticipating and detecting deadlock
- Later, we will extend these ideas to distributed systems.

Recall: Processes and threads

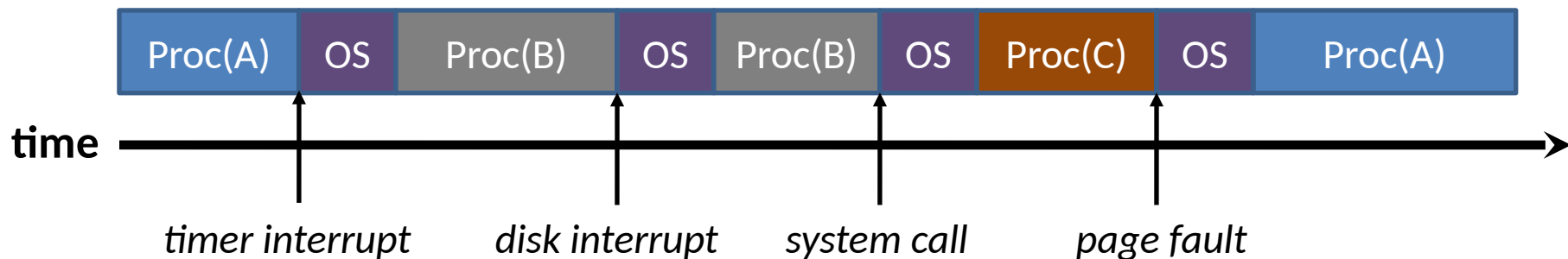
- **Processes** are instances of programs in execution
 - OS unit of protection & resource allocation
 - Has a virtual **address space**; and one or more threads
- **Threads** are entities managed by the **scheduler**
 - Represents an individual execution context
 - A thread control block (TCB) holds the saved context (registers, including stack pointer), scheduler info, etc
- Threads run in the **address spaces** of their process
 - (and also in the kernel address space on behalf of user code)
- **Context switches** occur when the OS saves the state of one thread and restores the state of another
 - If a switch is between threads in different processes, then process state is also switched – e.g., the address space.

Concurrency with a single CPU (1)

- **Process / OS** concurrency
 - Process X runs for a while (until **blocks** or **interrupted**)
 - OS runs for a while (e.g. does some TCP processing)
 - Process X resumes where it left off...
- **Inter-process** concurrency
 - Process X runs for a while; then OS; then Process Y; then OS; then Process Z; etc
- **Intra-process** concurrency
 - Process X has multiple threads X1, X2, X3, ...
 - X1 runs for a while; then X3; then X1; then X2; then ...

Concurrency with a single CPU (2)

- With just one CPU, can think of concurrency as **interleaving** of different executions, e.g.

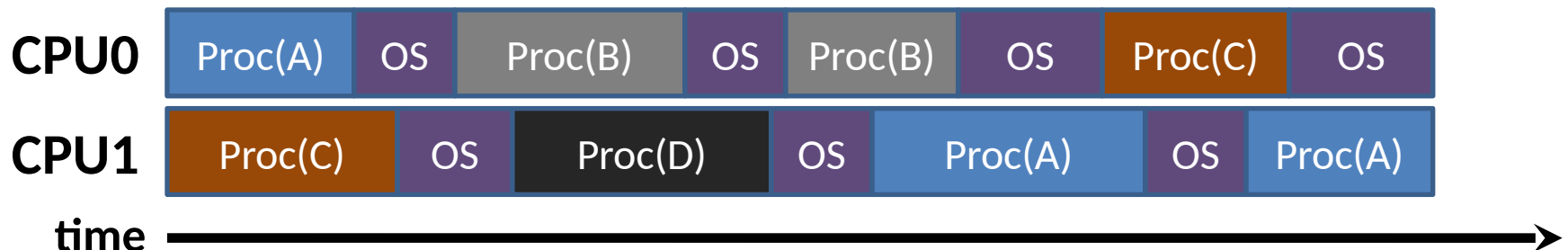


- Exactly where execution is interrupted and resumed is not usually known in advance...
 - this makes concurrency challenging!
- Generally should assume worst case behaviour

Non-deterministic or so complex as to be **unpredictable**

Concurrency with multiple CPUs (aka cores)

- Many modern systems have multiple CPUs
 - And even if don't, have other processing elements
- Hence things occur in parallel, e.g.



- Notice that the OS runs on both CPUs: tricky!
- More generally can have different threads of the same process executing on different CPUs too

What might this code do?

```
#define NUMTHREADS 4  
char *threadstr = "Thread";
```

Global variables are shared by all threads

```
void threadfn(int threadnum) {  
    sleep(rand(2)); // Sleep 0 or 1 seconds  
    printf("%s %d\n", threadstr, threadnum);  
}
```

Each thread has its own local variables

```
void main(void) {  
    threadid_t threads[NUMTHREADS]; // Thread IDs  
    int i; // Counter  
  
    for (i = 0; i < NUMTHREADS; i++)  
        threads[i] = thread_create(threadfn, i);  
  
    for (i = 0; i < NUMTHREADS; i++)  
        thread_join(threads[i]);  
}
```

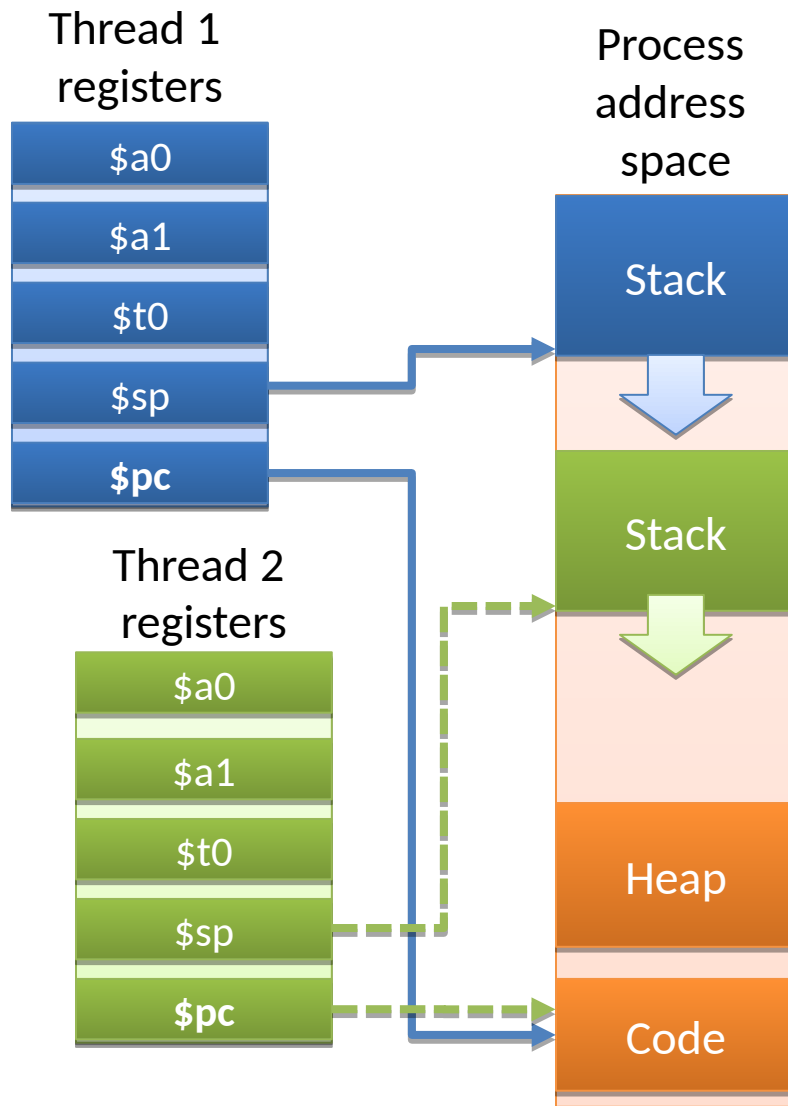
Additional threads are started explicitly


What **orders** could the `printf`s run in?

Possible orderings of this program

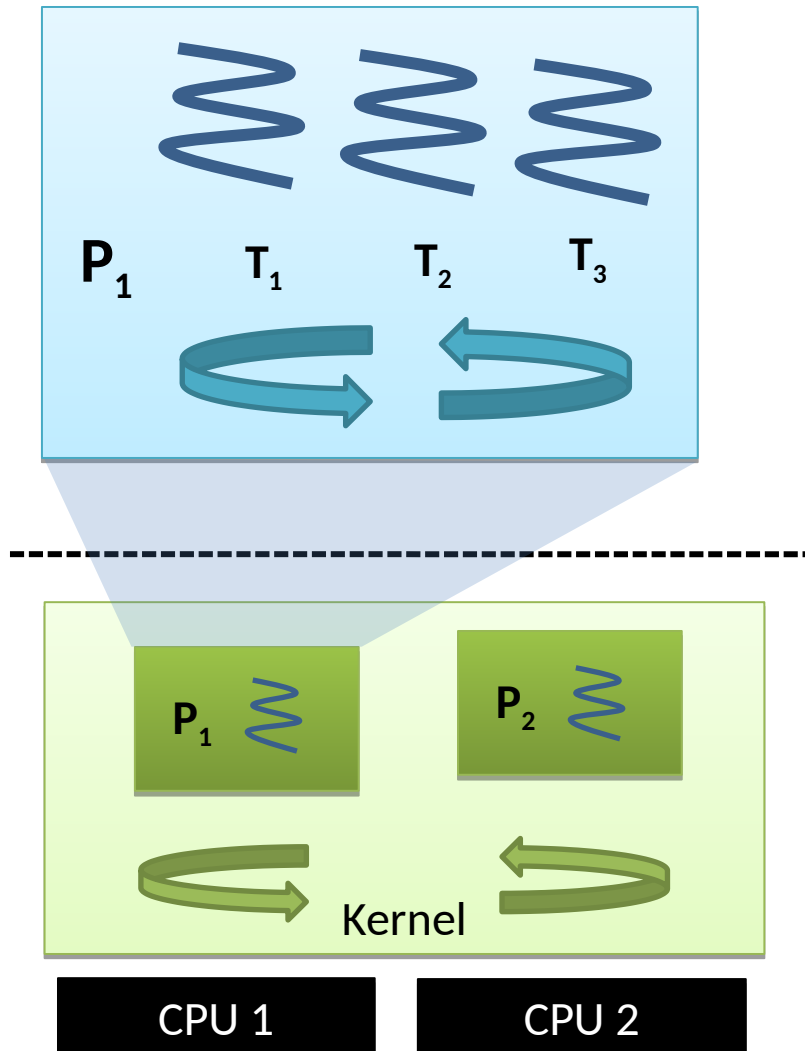
- What order could the **printf()**s occur in?
- Two sources of non-determinism in example:
 - **Program non-determinism**: Threads randomly sleep 0 or 1 seconds before printing
 - **Thread scheduling non-determinism**: Arbitrary order for unprioritised, concurrent wakeups, preemptions
- There are 4! (factorial) valid permutations
 - Assuming printf() is **indivisible**
 - Is printf() indivisible? Maybe.
- Even more potential **timings** of **printf()**s

Multiple threads within a process



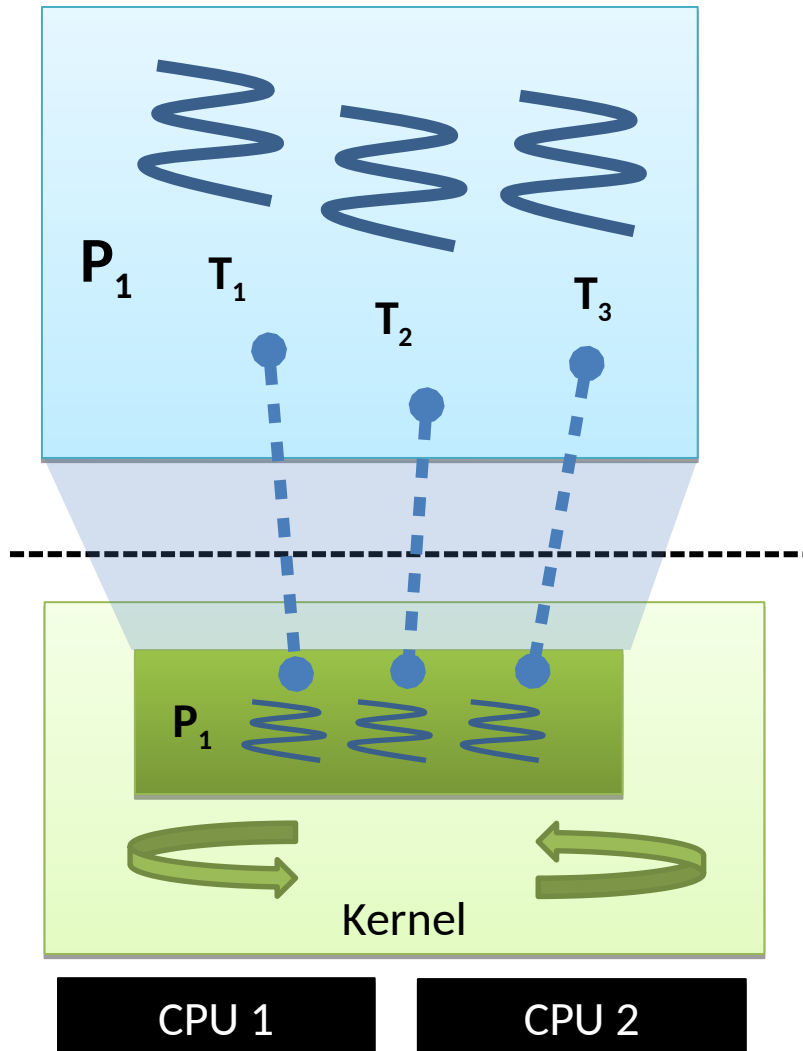
- A single-threaded process has **code**, a **heap**, a **stack**, **registers**
- **Additional threads** have their own registers and stacks
 - Per-thread **program counters** (**\$pc**) allow execution flows to differ
 - Per-thread **stack pointers** (**\$sp**) allow call stacks, local variables to differ
- Heap and code (+**global variables**) are shared between all threads
- Access to another thread's stack is possible in some languages – but  really discouraged!

1:N - user-level threading



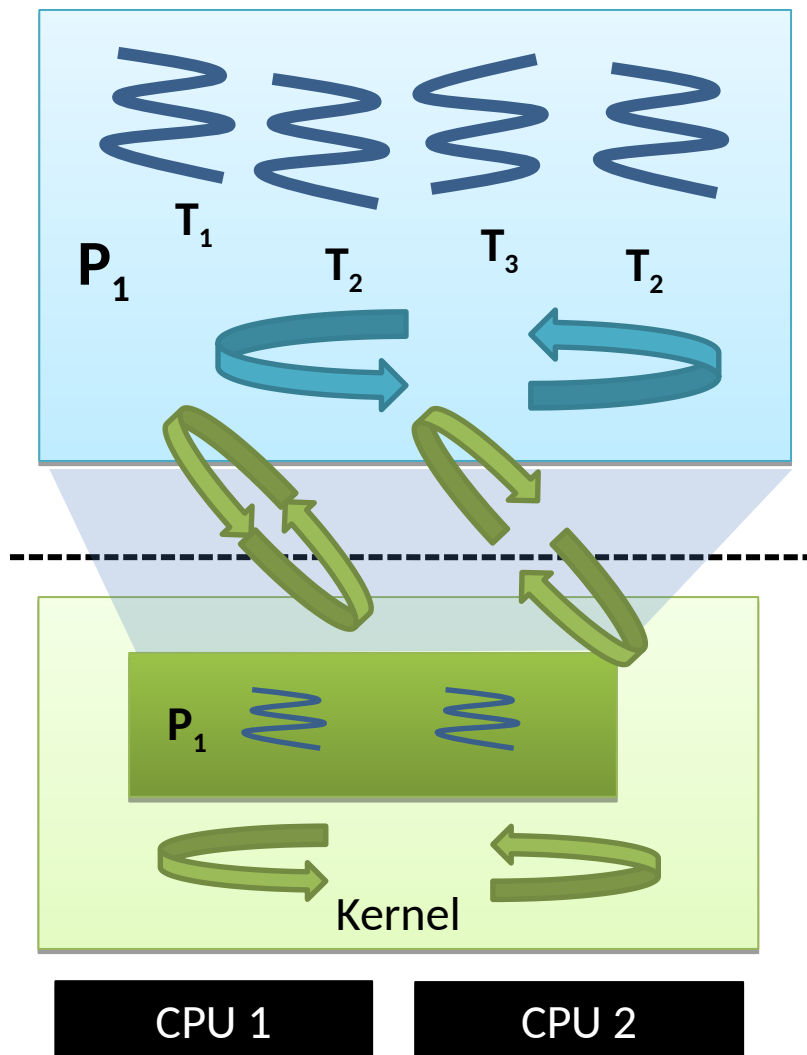
- **Kernel** only knows about (and schedules) processes
- A **userspace library** implements threads, context switching, scheduling, synchronisation, ...
 - E.g., the JVM or a threading library
- Advantages
 - Lightweight creation/termination + context switch; application-specific scheduling; OS independence
- Disadvantages
 - Awkward to handle blocking system calls or page faults, preemption; cannot use multiple CPUs
- Very early 1990s!

1:1 - kernel-level threading



- **Kernel** provides threads directly
 - By default, a process has one thread...
 - ... but can create more via system calls
- Kernel implements threads, thread context switching, scheduling, etc.
- **Userspace** thread library **1:1** maps **user threads** into **kernel threads**
- Advantages:
 - Handles preemption, blocking syscalls
 - Straightforward to use multiple CPUs
- Disadvantages:
 - Higher overhead (trap to kernel); less flexible; less portable
- Model of choice across major OSes
 - Windows, Linux, MacOS, FreeBSD, Solaris, ...

M:N - hybrid threading



- Best of both worlds?
 - **M:N threads**, **scheduler activations**, ...
- **Kernel** exposes a smaller number (**M**) of **activations** – typically 1:1 with CPUs
- **Userspace** schedules a larger number (**N**) of **threads** onto available activations
 - Kernel **upcalls** when a **thread blocks**, returning the activation to userspace
 - Kernel **upcalls** when a **thread wakes up**, userspace schedules it on an activation
 - Kernel controls **maximum parallelism** by limiting number of activations
- Removed from most OSes – why?
- Now: **Virtual Machine Monitors** (VMMs)
 - Each **Virtual CPU (VCPU)** is an activation
- Reappears in concurrency frameworks
 - E.g., Apple's Grand Central Dispatch (GCD)

Advantages of concurrency

- Allows us to overlap computation and I/O on a single machine
- Can simplify code structuring and/or improve responsiveness
 - E.g. one thread redraws the GUI, another handles user input, and another computes game logic
 - E.g. one thread per HTTP request
 - E.g. background GC thread in JVM/CLR
- Enables the seamless (?!) use of multiple CPUs –greater performance through parallel processing

Concurrent systems

- In general, have some number of **processes**...
 - ... each with some number of **threads** ...
 - ... running on some number of **computers**...
 - ... each with some number of **CPUs**.
- For this half of the course we'll focus on a single computer running a multi-threaded process
 - most problems & solutions generalize to multiple processes, CPUs, and machines, but more complex
 - (we'll look at distributed systems later in the term)
- Challenge: threads will access shared resources concurrently via their common address space

Example: Housemates Buying Beer

- Thread 1 (person 1)
 - 1.Look in fridge
 - 2.If no beer, go buy beer
 - 3.Put beer in fridge
- Thread 2 (person 2)
 - 1.Look in fridge
 - 2.If no beer, go buy beer
 - 3.Put beer in fridge
- In most cases, this works just fine...
 - But if both people look (step 1) before either refills the fridge (step 3)... we'll end up with too much beer!
 - Obviously more worrying if “look in fridge” is “check reactor”, and “buy beer” is “toggle safety system” ;-)

Solution #1: Leave a Note

- Thread 1 (person 1)
 - 1.Look in fridge
 - 2.If no beer & no note
 - 1.Leave note on fridge
 - 2.Go buy beer
 - 3.Put beer in fridge
 - 4.Remove note
- Thread 2 (person 2)
 - 1.Look in fridge
 - 2.If no beer & no note
 - 1.Leave note on fridge
 - 2.Go buy beer
 - 3.Put beer in fridge
 - 4.Remove note
- Probably works for human beings...
 - But computers are stooopid!
- Can you see the problem?

Non-Solution #1: Leave a Note

```
// thread 1
beer = checkFridge();
if(!beer) {
    if(!note) {
        note = 1;
        buyBeer();
        note = 0;
    }
}
```

```
// thread 2
beer = checkFridge();
if(!beer) {
    if(!note) {
        note = 1;
        buyBeer();
        note = 0;
    }
}
```

- Easier to see with pseudo-code...

Non-Solution #1: Leave a Note

```
// thread 1
beer = checkFridge();
if(!beer) {
  if(!note) {
```

context switch

```
    note = 1;
    buyBeer();
    note = 0;
  }
}
```

context switch

```
// thread 2
```

```
beer = checkFridge();
if(!beer) {
  if(!note) {
    note = 1;
    buyBeer();
    note = 0;
  }
}
```

- Easier to see with pseudo-code...

Non-Solution #1: Leave a Note

- Of course this won't happen all the time
 - Need threads to interleave in the just the right way (or just the wrong way ;-)
- Unfortunately code that is 'mostly correct' is much worse than code that is 'mostly wrong'!
 - Difficult to catch in testing, as occurs rarely
 - May even go away when running under debugger
 - e.g. only context switches threads when they block
 - (such bugs are sometimes called **Heisenbugs**)

Critical Sections & Mutual Exclusion

- The high-level problem here is that we have two threads trying to solve the same problem
 - Both execute `buyBeer()` concurrently
 - Ideally want only one thread doing that at a time
- We call this code a **critical section**
 - A piece of code which should never be concurrently executed by more than one thread
- Ensuring this involves **mutual exclusion**
 - If one thread is executing within a critical section, all other threads are prohibited from entering it

Achieving Mutual Exclusion

- One way is to let only one thread ever execute a particular critical section – e.g. a nominated beer buyer – but this restricts concurrency
- Alternatively our (broken) solution #1 was **trying** to provide mutual exclusion via the note
 - Leaving a note means “I’m in the critical section”;
 - Removing the note means “I’m done”
 - But, as we saw, it didn’t work ;-)
- This was because we could experience a context switch between reading ‘note’, and setting it

Non-Solution #1: Leave a Note

```
// thread 1
beer = checkFridge();
if(!beer) {
  if(!note) {
```

We decide to enter the critical section here...

But only mark the fact here ...

```
    note = 1;
    buyBeer();
    note = 0;
  }
}
```

context switch

```
// thread 2
```

```
beer = checkFridge();
if(!beer) {
  if(!note) {
    note = 1;
    buyBeer();
    note = 0;
```

context switch

These problems are referred to as **race conditions** in which multiple threads “race” with one another during conflicting access to shared resources

Atomicity

- What we want is for the checking of note and the (conditional) setting of note to happen without any other thread being involved
 - We don't care if another thread reads it after we're done; or sets it before we start our check
 - But once we start our check, we want to continue without any interruption
- If a sequence of operations (e.g. read-and-set) are made to occur as if one operation, we call them **atomic**
 - Since **indivisible** from the point of view of the program
- An atomic **read-and-set** operation is sufficient for us to implement a correct beer program

Solution #2: Atomic Note

```
// thread 1
beer = checkFridge();
if(!beer) {
    if(read-and-set(note)) {
        buyBeer();
        note = 0;
    }
}
```

```
// thread 2
beer = checkFridge();
if(!beer) {
    if(read-and-set(note)) {
        buyBeer();
        note = 0;
    }
}
```

- read-and-set(&address) **atomically** checks the value in memory and iff it is zero, sets it to one
 - returns 1 iff the value was changed from 0 -> 1
- This prevents the behavior we saw before, and is sufficient to implement a correct program...
 - although this is not that program :-)

Non-Solution #2: Atomic Note

```
// thread 1
beer = checkFridge();
if(!beer) {
```

context switch

```
    if(read-and-set(note)) {
        buyBeer();
        note = 0;
    }
}
```

context switch

```
// thread 2
```

```
beer = checkFridge();
if(!beer) {
    if(read-and-set(note)) {
        buyBeer();
        note = 0;
    }
}
```

- Our critical section doesn't cover enough!

General mutual exclusion

- We would like the ability to define a region of code as a critical section e.g.

```
// thread 1
ENTER_CS();
beer = checkFridge();
if(!beer)
    buyBeer();
LEAVE_CS();
```

```
// thread 2
ENTER_CS();
beer = checkFridge();
if(!beer)
    buyBeer();
LEAVE_CS();
```

- This should work ...
 - ... providing that our implementation of **ENTER_CS()** / **LEAVE_CS()** is correct

Implementing mutual exclusion

- One option is to prevent context switches
 - e.g. disable interrupts (for kernel threads), or set an in-memory flag (for user threads)
 - ENTER_CS() = “disable context switches”;
- LEAVE_CS() = “re-enable context switches”
- Can work but:
 - Rather brute force (stops all other threads, not just those who want to enter the critical section)
 - Potentially unsafe (if disable interrupts and then sleep waiting for a timer interrupt ;-)
 - And doesn't work across multiple CPUs

Implementing mutual exclusion

- Associate a **mutual exclusion lock** with each critical section, e.g. a variable **L**
 - (must ensure use correct lock variable!)
 - ENTER_CS() = “LOCK(L)”
 - LEAVE_CS() = “UNLOCK(L)”
- Can implement LOCK() using read-and-set():

```
LOCK(L) {  
    while(!read-and-set(L))  
        ; // do nothing  
}
```

```
UNLOCK(L) {  
    L = 0;  
}
```

Solution #3: mutual exclusion locks

```
// thread 1
LOCK(fridgeLock);
beer = checkFridge();
if(!beer)
    buyBeer();
UNLOCK(fridgeLock);
```

```
// thread 2
LOCK(fridgeLock);
beer = checkFridge();
if(!beer)
    buyBeer();
UNLOCK(fridgeLock);
```

- This is – finally! – a correct program
- Still not perfect
 - Lock might be held for quite a long time (e.g. imagine another person wanting to get the milk!)
 - Waiting threads waste CPU time (or worse)
 - **Contention** occurs when consumers have to wait for locks
- Mutual exclusion locks often known as **mutexes**
 - But we will prefer this term for **sleepable locks** – see Lecture 2
 - So think of the above as a **spin lock**

Summary + next time

- Definition of a concurrent system
- Origins of concurrency within a computer
- Processes and threads
- Challenge: concurrent access to shared resources
- Critical sections, mutual exclusion, race conditions, atomicity
- Mutual exclusion locks (mutexes)
- Next time:
 - Operating System and hardware instructions and structures,
 - Interacting automata view of concurrency,
 - Introduction to formal modelling of concurrency.