

Concurrent systems

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

Michaelmas 2017
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(With thanks to Dr Steven Hand)

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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**

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Concurrent systems outline

1. Introduction to concurrency, threads, and mutual exclusion
2. More mutual exclusion, semaphores, producer-consumer, and MRSW
3. CCR, monitors, concurrency in practice
4. Safety and liveness
5. Concurrency without shared data; transactions
6. Further transactions
7. Crash recovery; lock free programming; TM
8. Concurrent systems case study: FreeBSD Kernel

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Recommended reading

- ***“Operating Systems, Concurrent and Distributed Software Design”***, Jean Bacon and Tim Harris, Addison-Wesley 2003
- *“Modern Operating Systems”*, (3rd Ed), Andrew Tannenbaum, Prentice-Hall 2007
- *“Java Concurrency in Practice”*, Brian Goetz and others, Addison-Wesley 2006

Throughout the term, I will suggest you look in the Bacon and Harris for more detailed explanations of algorithms, as I can only present sketches in lecture.

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What is concurrency?

- Computers appear to do many things at once
 - E.g. running multiple programs on your 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 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”

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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
- Explore a detailed concurrent software case study
- Later, we will extend these ideas to distributed systems

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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

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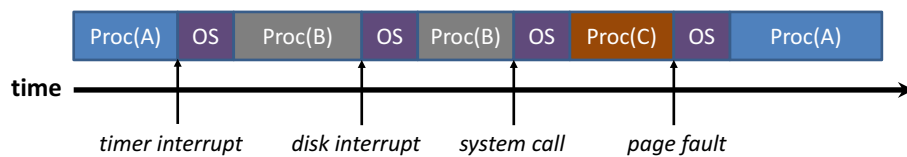
Concurrency with a single CPU (1)

- **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 ...

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Concurrency with a single CPU (2)

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



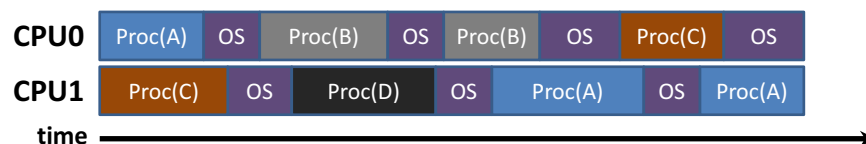
- Exactly where execution is interrupted and resumed is not usually known in advance...
 - this makes concurrency challenging!
- Generally should assume worst case behavior

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

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Concurrency with multiple processors

- Many modern systems have multiple CPUs
 - And even if don't, have other processing elements
- Hence things can 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

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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];
    int i;

    for (i = 0; i < NUMTHREADS; i++)
        threads[i] = thread_create(threadfn, i);

    for (i = 0; i < NUMTHREADS; i++)
        thread_join(threads[i]);
}
```

main() is called once at startup

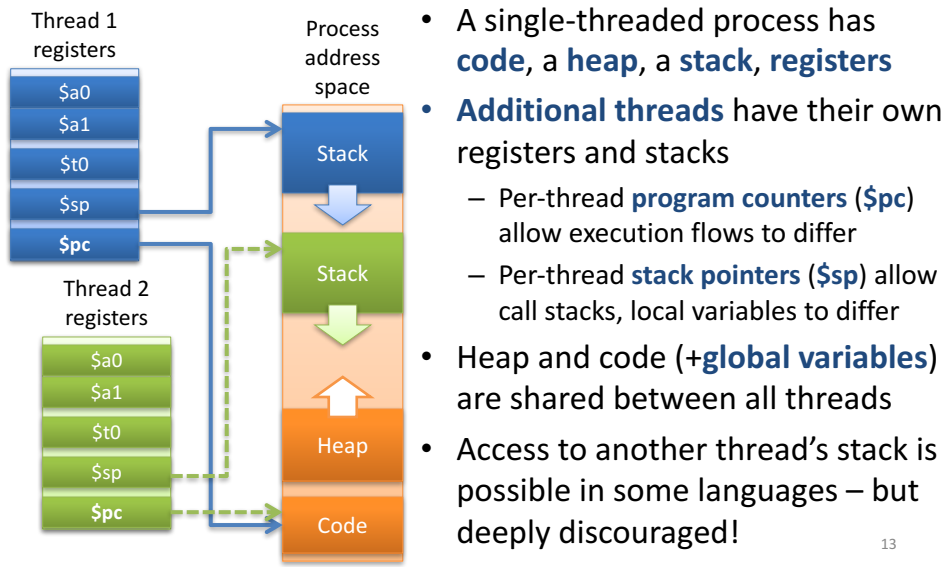
Additional threads are started explicitly

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

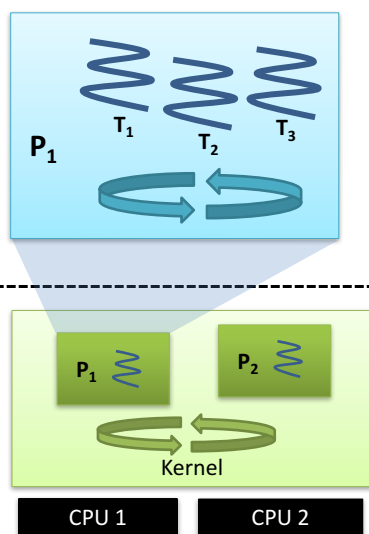
Possible orderings of this program

- 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



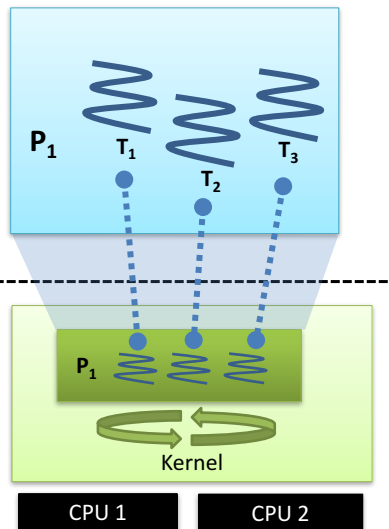
1:N - user-level threading



- **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!

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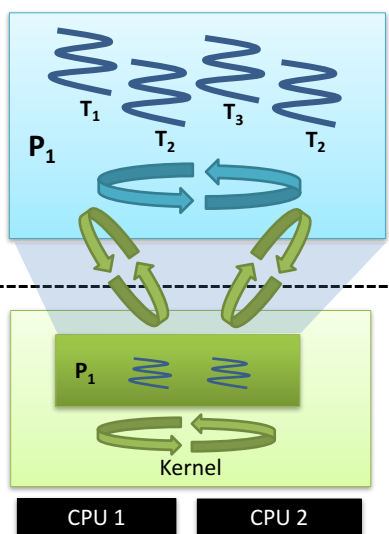
1:1 - kernel-level threading



- **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, ...

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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)

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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

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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

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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" ;-)

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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 stoopid!
- Can you see the problem?

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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...

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Non-Solution #1: Leave a Note

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

context switch

context switch

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

- Easier to see with pseudo-code...

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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**)

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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

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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

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Non-Solution #1: Leave a Note

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

We decide to enter the critical section here...

context switch

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;
```

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) 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

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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 :-)

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Non-Solution #2: Atomic Note

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

context switch

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

```
// thread 2
```

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

context switch

- Our critical section doesn't cover enough!

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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

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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

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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;
}
```

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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**

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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:
 - More on mutual exclusion
 - Hardware support for mutual exclusion
 - Semaphores for mutual exclusion, process synchronisation, and resource allocation
 - Producer-consumer relationships.

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