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

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(With thanks to Dr Steven Hand)

Concurrent and distributed systems

• One course, two parts
  – 8 lectures on concurrent systems (Michaelmas term)
  – 8 further lectures of distributed systems (Lent term)
• 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**
Concurrent systems course 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

Recommended reading

- “Operating Systems, Concurrent and Distributed Software Design”, Jean Bacon and Tim Harris, Addison-Wesley 2003
- “Java Concurrency in Practice”, Brian Goetz and others, Addison-Wesley 2006
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”

In this course we will

- Investigate the ways in which concurrency can occur in a computer system
  - 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
- Next term, 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 sometimes in the kernel address space)
- 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

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 local variables to differ
- Heap and code (+globals) are shared between all threads
- Access to another thread’s stack is sometimes possible – but deeply discouraged!
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.

```
Proc(A)  OS  Proc(B)  OS  Proc(B)  OS  Proc(C)  OS  Proc(A)
```

• 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
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.

  \[
  \begin{array}{cccccccc}
    & \text{CPU0} & \text{CPU1} & \text{time} \\
    \text{Proc}(A) & \text{OS} & \text{Proc}(B) & \text{OS} & \text{Proc}(C) & \text{OS} & \text{Proc}(C) & \text{OS} \\
    \text{Proc}(C) & \text{OS} & \text{Proc}(D) & \text{OS} & \text{Proc}(A) & \text{OS} & \text{Proc}(A) & \text{OS} \\
  \end{array}
  \]

- 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 does this code do?

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

void threadfn(int threadnum) {
    sleep(rand(2));
    printf("%s %d \n", threadstr, threadnum);
}

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]);
}
```

- Global variables are shared by all threads
- Each thread has its own local variables
- `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: Program randomly sleeps 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
• Even more potential timings of `printf()`s

1:N - user-level threading

• **Kernel** only knows about (and schedules) processes
• **Userspace** implements threads, context switching, scheduling
  – E.g., in the JVM or a threading library
• Advantages
  – Lightweight creation/termination and 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 system calls
  - Straightforward to utilize multiple CPUs
- Disadvantages:
  - Higher overhead (trap to kernel); less flexible; less portable
- Threading model of choice across all major OSes today
  - Windows, Linux, Mac OS X, 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 blocked thread wakes up, userspace schedules it on an activation
  - Kernel controls maximum parallelism by limiting number of activations
- Feature removed from most OSes – why?
- Used in **Virtual Machine Monitors** (VMMs)
  - Each **Virtual CPU (VCPUs)** is an activation
- M:N 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 in Lent term)
- Challenge: threads will access shared resources concurrently via their common address space
Example: Housemates Buying Beer

• Thread 1 (person 1)  • Thread 2 (person 2)
  1. Look in fridge  1. Look in fridge
  2. If no beer, go buy beer  2. If no beer, go buy beer

• 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” ;-)
Non-Solution #1: Leave a Note

```java
// 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

```java
// 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

- 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) {
    note = 1;
    buyBeer();
    note = 0;
  }
}

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

We decide to enter the critical section here...

But only mark the fact here...

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

Solution #2: Atomic Note

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

```cpp
// 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

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

```plaintext
// 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.

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

```plaintext
// 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

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():

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

UNLOCK(L) {
    L = 0;
}
```
Solution #3: mutual exclusion locks

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

```c
// 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, and 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.