Concurrency & Synchronization

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Agenda

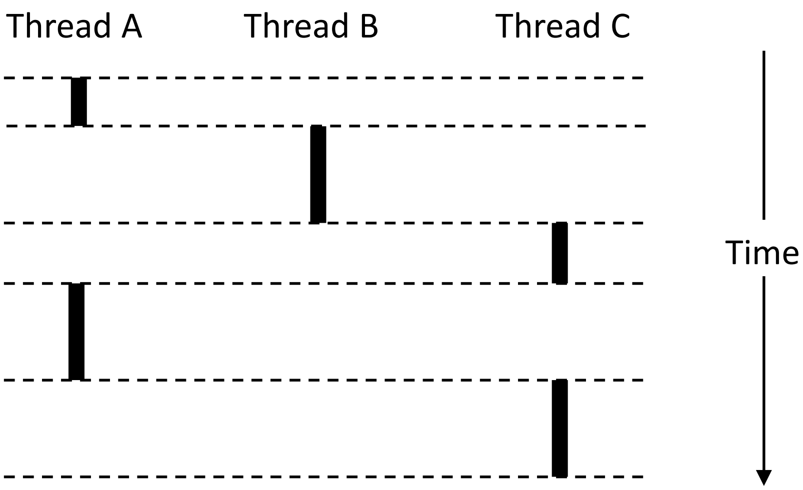
- Review basic concurrency concepts
  - Concurrency and parallelism
  - Data race and mutual exclusion
  - Locks

- New stuff
  - New concurrency issues: condition variables
  - How to implement locks and condition variables efficiently
    - Focusing on OS issues
  - A deeper understanding of concurrency bugs

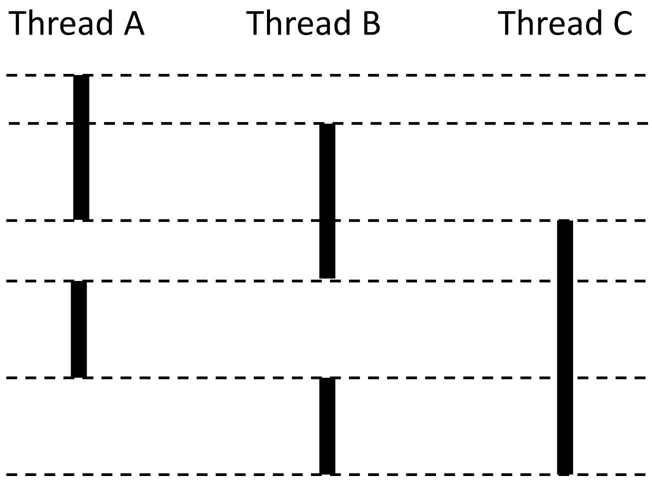
Concurrency Review

Concurrency and Parallelism

- Two tasks (threads, functions, instructions, etc.) are concurrent if their executions overlap in time
- Two tasks are parallel if they execute at the same time
  - A special case of concurrency
  - Parallel tasks have to execute on different processors



Run 3 threads on 1 processor



Run 3 threads on 2 processors

Sources of Concurrency

Question: How could one task run before the current one completes?

1) Tasks running on different processors

2) Context switching between tasks on the same processor
   - Preemptive as well as cooperative

3) Interrupts
   - Kernel mode: hardware interrupts and in-kernel exceptions
   - User mode: signals

Why Concurrent Programming?

- In user-mode
  - To utilize multiple processors
    - Multi- and many-core processors are here to stay
  - To improve application responsiveness in the presence of blocking operations
    - E.g., processing a UI input in the background without freezing the application
- In kernel-mode
  - Because user-mode often requires kernel-mode concurrency
    - Each thread in a multi-threaded program has a kernel-mode component (remember the iceberg?)
  - Also, because interrupts/exceptions can create unforeseen parallelism

Challenges of Concurrency

- Crux: execution order (**interleaving**) of instructions of concurrent tasks in <u>not generally under our control</u>
  - Single CPU: We can’t control scheduler decisions
  - Multi-CPU: We can’t control when, and how fast, each processor executes its instructions

- We need to control instruction interleaving for at least two reasons
  1) **Mutual exclusion**
  2) **Condition synchronization**

Mutual Exclusion

- Some computer resources cannot be accessed by multiple threads at the same time
  - E.g., a printer can’t print two documents at once
- **Mutual exclusion** is the term to indicate that some resource can only be used by one thread at a time
  - Active thread excludes its peers
- In concurrent programs, shared data structures are often mutually exclusive
  - Two threads adding to a linked list at the same time can corrupt the list

Why Mutual Exclusion for Shared Data?

- To avoid **data races**
- Imagine two concurrent threads executing this code
- What is your expected outcome?
- What are the possible outcomes?
- Undesirable things happen when concurrent tasks access shared data simultaneously
  - At lease one access should be a write for bad things to happen

C code:

```
balance += 1;
```

Assembly code:

```
mov 0x8049a1c, %eax
add $0x1, %eax
mov %eax, 0x8049a1c
```

Why Mutual Exclusion for Shared Data?

- As programmers, we are used to thinking sequentially
  - We break a functionality into a sequence of code lines or instructions

  → We almost always use more than one instruction/line of code to achieve our goal

- We are also used to think only about the results of the current piece of code
  - Difficult for us to think about the effect of a concurrent task monkeying around with the data we are using

- Is this human nature or just because of how we were taught programming?
  - The jury is out on this!

Why Mutual Exclusion for Shared Data?

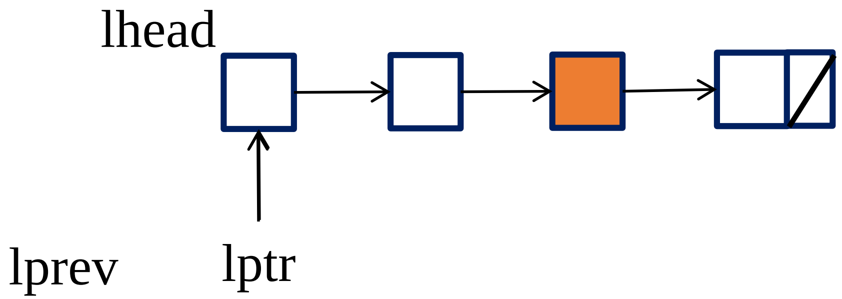
- To recap
  1) We have to do multiple things to implement an operation
     - Either do all of it, or none of it
     - Partial execution will result in an inconsistent state
  2) We don’t want anyone to touch the data we are using when doing that
     - We need isolation from others
- So, we need ***atomicity***
  - Do either all or none + in isolation

Why Mutual Exclusion for Shared Data?

- One way to (almost) achieve atomicity is…
- …to make sure we have ***exclusive*** access to our shared data for the length of time our ***critical*** instructions run
  - Hence, the name “mutual exclusion”
- A **critical section** of code is any piece of code that touches shared data (or more generally, accesses a shared resources)
  - It’s an abstraction to help us think more clearly about structure of concurrent code
- **Locks** are our main mechanisms to achieve mutual exclusion

Example: Traverse a Linked List

- Suppose we want to find an element in a singly linked list, and move it to the head
- Visual intuition:



Example: Traverse a Linked List

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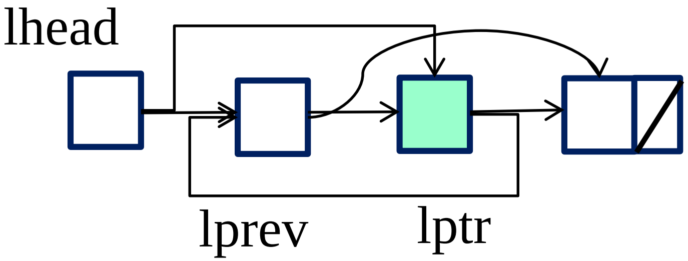


Example: Traverse a Linked List

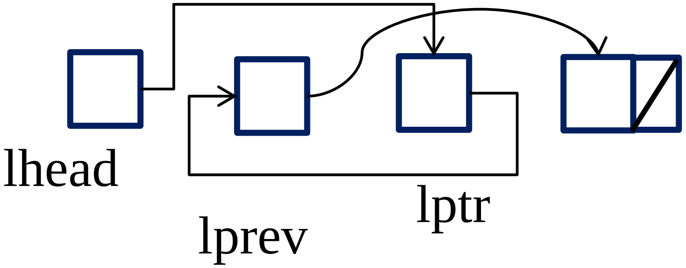
```
lprev = NULL;
for(lptr = lhead; lptr; lptr = lptr->next) {
   if(lptr->val == target){
       // Already head?, break
       if(lprev == NULL) break;
       // Move cell to head
       lprev->next = lptr->next;
       lptr->next = lhead;
       lhead = lptr;
       break;
   }
   lprev = lptr;
}
```

- Where is the critical section?

Example: Traverse a Linked List

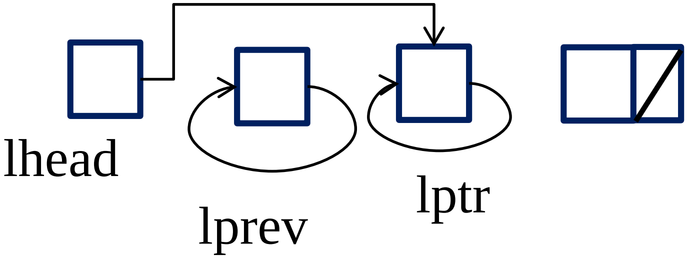
Thread 1

```
// Move cell to head
lprev->next = lptr->next;
lptr->next = lhead;
lhead = lptr;
```



Thread 2

```
// Move cell to head
lprev->next = lptr->next;
lptr->next = lhead;
lhead = lptr;
```



- A critical section often needs to be larger than it first appears
    - The 3 key lines are not enough of a critical section

Example: Traverse a Linked List

Thread 1

```
lprev = NULL;
for(lptr = lhead; lptr; lptr = lptr->next)
{
   if(lptr->val == target){
          // Already head?, break
          if(lprev == NULL) break;
          // Move cell to head
          lprev->next = lptr->next;
          lptr->next = lhead;
          lhead = lptr;
          break;
   }
   lprev = lptr; }
```

- Putting entire search in a critical section reduces concurrency, but it is safe
- Writing high-performance and correct concurrent programs is a (very) difficult task

Thread 2

```
lprev = NULL;
for(lptr = lhead; lptr; lptr = lptr-
>next) {
   if(lptr->val == target){
          // Already head?, break
          if(lprev == NULL) break;
          // Move cell to head
          …
```

Condition Synchronization

- Mutual exclusion is not all we need for concurrent programming
- Very often, synchronization consists of one task waiting for another to make a condition true
  - Ex1: master thread tells worker thread a request has arrived
    - Worker thread has to wait until this happen
  - Ex2: parent thread waits until a child thread terminates (`pthread_join()`)
- Until condition becomes true, thread can sleep
  - Ties synchronization to scheduling
- We use **condition variables** for this purpose (next lecture)