Principles of Software Construction: Objects, Design and Concurrency

The Perils of Concurrency, part 2

Can't live with it.
Can't live without it.

15-214

toad

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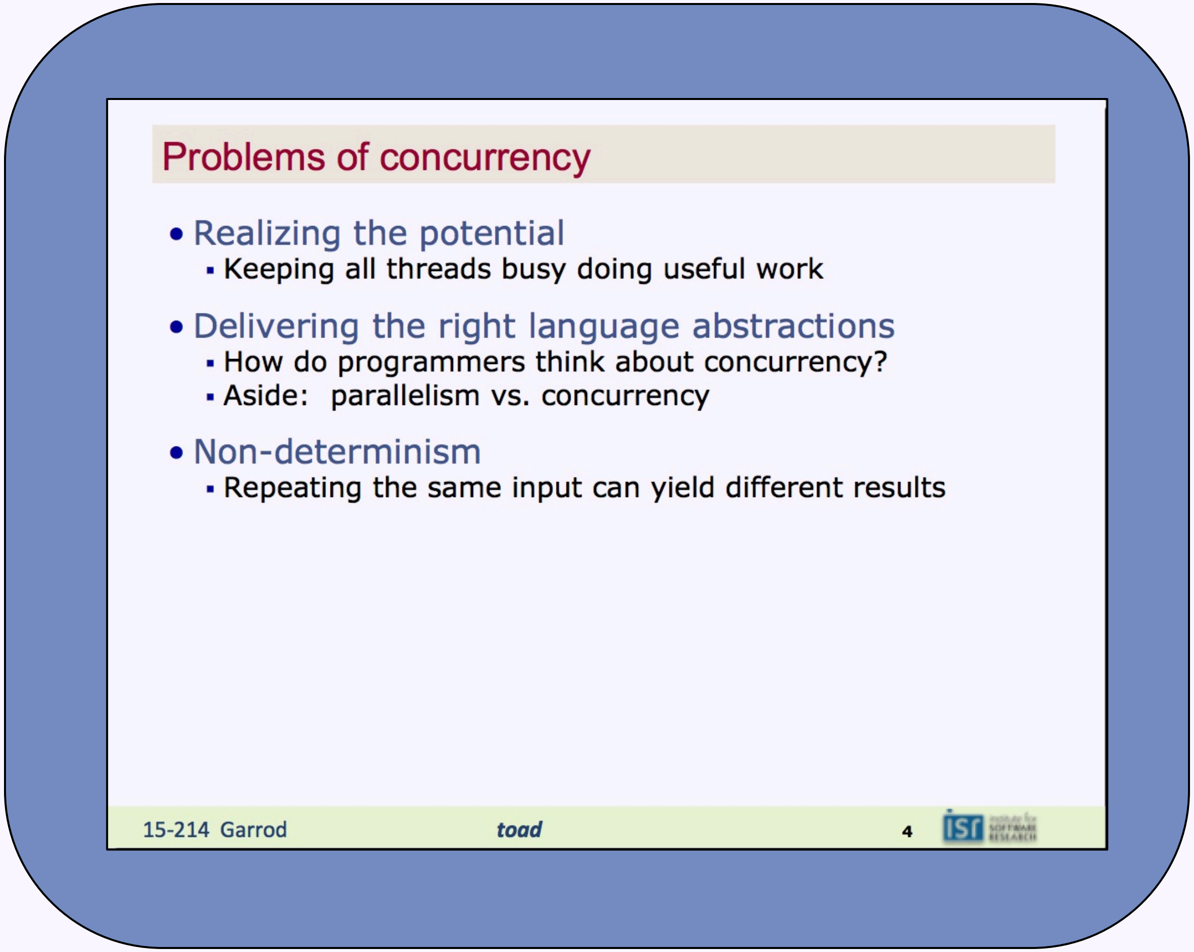
Last time: Concurrency, part 1

- The concurrency backstory
  - Motivation, goals, problems, …



Today: Concurrency, part 2

- Primitive concurrency in Java
  - Explicit synchronization with threads and shared memory
  - More concurrency problems
- Higher-level abstractions for concurrency (still mostly not today)
  - Data structures
  - Higher-level languages and frameworks
  - Hybrid approaches

Basic concurrency in Java

- The `java.lang.Runnable` interface

```
void             run();
```

- The `java.lang.Thread` class

```
Thread(Runnable r);
void             start();
static void      sleep(long millis);
void             join();
boolean          isAlive();
static Thread currentThread();
```

- See IncrementTest.java

Atomicity

- An action is *atomic* if it is indivisible
  - Effectively, it happens all at once
    - No effects of the action are visible until it is complete
    - No other actions have an effect during the action
- In Java, integer increment is not atomic

`i++;` is actually

1. Load data from variable `i`
2. Increment data by `1`
3. Store data to variable `i`

One concurrency problem: race conditions

- A *race condition* is when multiple threads access shared data and unexpected results occur depending on the order of their actions
- E.g., from IncrementTest.java:
  - Suppose `classData` starts with the value 41:

Thread A:

```
classData++;
```

Thread B:

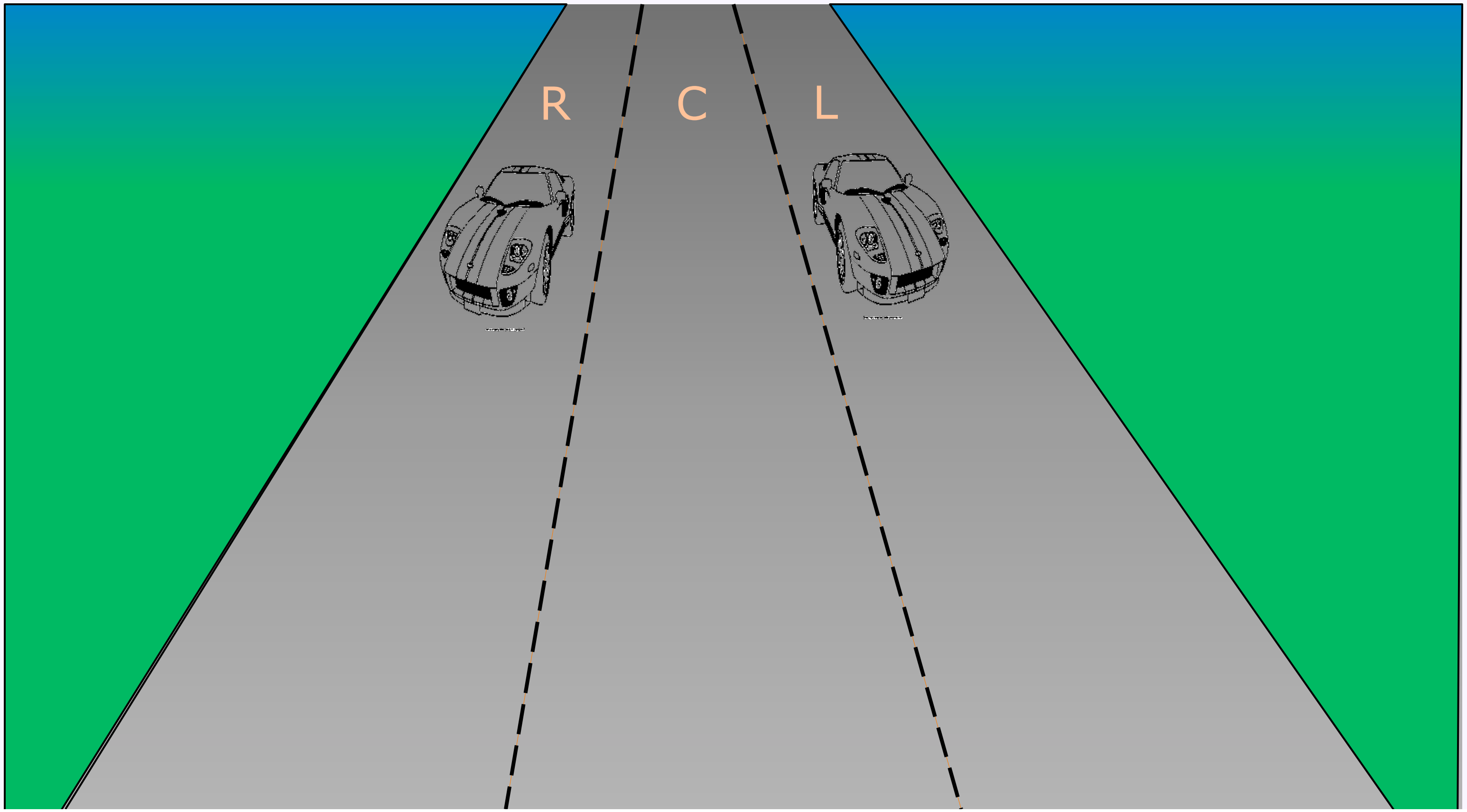
```
classData++;
```

One possible interleaving of actions:

1A. Load data(41) from `classData`
1B. Load data(41) from `classData`
2A. Increment data(41) by 1 -> 42
2B. Increment data(41) by 1 -> 42
3A. Store data(42) to `classData`
3B. Store data(42) to `classData`

Race conditions in real life

- E.g., check-then-act on the highway



Race conditions in real life

- E.g., check-then-act at the bank
  - The "debit-credit problem"

Alice, Bob, Bill,* and the *Bank

- **A. *Alice* to pay *Bob* $30**
  - **Bank actions**
    1. **Does Alice have $30 ?**
    2. **Give $30 to *Bob***
    3. **Take $30 from *Alice***

- **B. *Alice* to pay *Bill* $30**
  - **Bank actions**
    1. **Does Alice have $30 ?**
    2. **Give $30 to *Bill***
    3. **Take $30 from *Alice***

- **If *Alice* starts with $40, can *Bob* and *Bill* both get $30?**

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A.1
A.2
B.1
B.2
A.3
B.3!

Race conditions in *your* real life

- E.g., check-then-act in simple code

```
public class StringConverter {
    private Object o;
    public void set(Object o) {
        this.o = o;
    }
    public String get() {
        if (o == null) return "null";
        return o.toString();
    }
}
```

  - See StringConverter.java, Getter.java, Setter.java

Some actions are atomic

Thread A:

```
int i = 7;

i = 42;
```

Thread B:

```
ans = i;
```

- What are the possible values for `ans`?

Some actions are atomic

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`i:` **00000…00000111**

⋮

`i:` **00000…00101010**

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Thread B:

```
ans = i;
```

- What are the possible values for `ans`?

  i: 00000…00000111

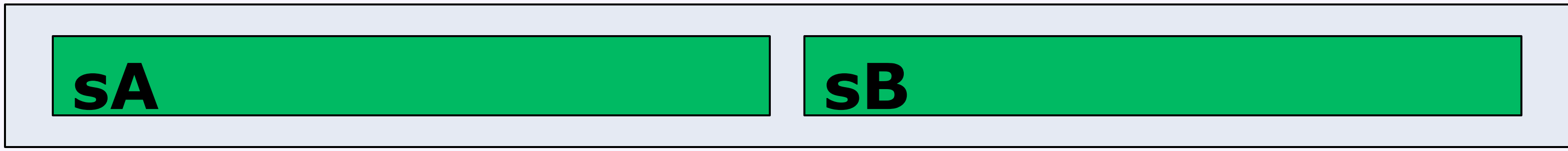
  ⋮

  i: 00000…00101010

- In Java:
  - Reading an int variable is atomic
  - Writing an int variable is atomic
  - Thankfully, ans: 00000…00101111 is not possible

Bad news: some simple actions are not atomic

- Consider a single 64-bit `long` value



  - Concurrently:
    - Thread 1 writing sA and sB
    - Thread 2 reading sA and sB
  - What could Thread 2 see?

Primitive concurrency control in Java

- Each Java object has an associated intrinsic lock
  - All locks are initially unowned
  - Each lock is *exclusive*: it can be owned by at most one thread at a time
- The `synchronized` keyword forces the current thread to obtain an object's intrinsic lock
  - E.g.,

```
synchronized void foo() { … } // locks "this"

synchronized(fromAcct) {
    if (fromAcct.getBalance() >= 30) {
        toAcct.deposit(30);
        fromAcct.withdrawal(30);
    }
}
```

- See SynchronizedIncrementTest.java

Primitive concurrency control in Java

- `java.lang.Object` allows some coordination via the intrinsic lock:

```
void wait();
void wait(long timeout);
void wait(long timeout, int nanos);
void notify();
void notifyAll();
```

- See Blocker.java, Notifier.java, NotifyExample.java

Primitive concurrency control in Java

- Each lock can be owned by only one thread at a time
- Locks are *re-entrant*: If a thread owns a lock, it can lock the lock multiple times
- A thread can own multiple locks

```
synchronized(lock1) {
    // do stuff that requires lock1

    synchronized(lock2) {
        // do stuff that requires both locks
    }

    // …
}
```

Another concurrency problem: deadlock

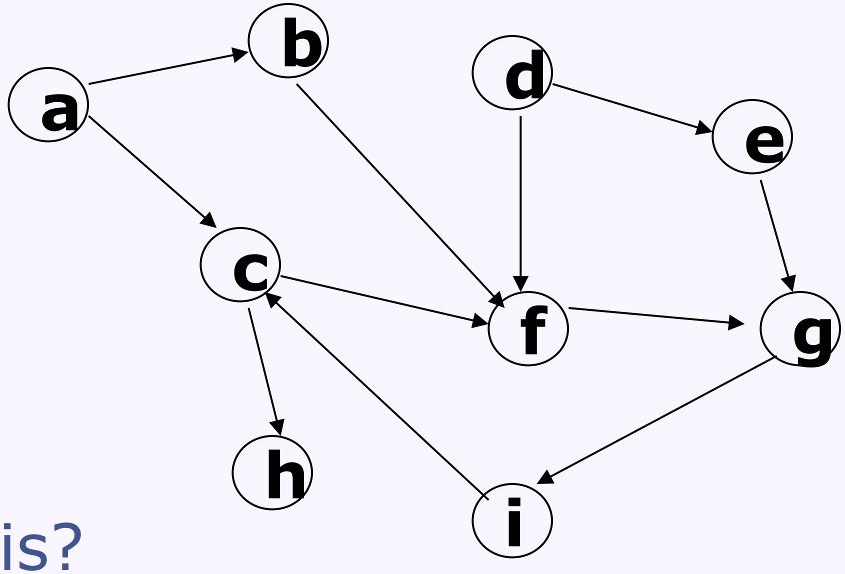
- E.g., Alice and Bob, unaware of each other, both need file *A* and network connection *B*
  - Alice gets lock for file *A*
  - Bob gets lock for network connection *B*
  - Alice tries to get lock for network connection *B*, and waits…
  - Bob tries to get lock for file *A*, and waits…
- See Counter.java and DeadlockExample.java

Dealing with deadlock (abstractly, not with Java)

- Detect deadlock
  - Statically?
  - Dynamically at run time?
- Avoid deadlock
- Alternative approaches
  - Automatic restarts
  - Optimistic concurrency control

Detecting deadlock with the waits-for graph

- The *waits-for graph* represents dependencies between threads
  - Each node in the graph represents a thread
  - A directed edge T1->T2 represents that thread T1 is waiting for a lock that T2 owns
- Deadlock has occurred iff the waits-for graph contains a cycle



- Got a problem with this?

Deadlock avoidance algorithms

- Prevent deadlock instead of detecting it
  - E.g., impose total order on all locks, require locks acquisition to satisfy that order
    - Thread:

      acquire(lock1)
      acquire(lock2)
      acquire(lock9)
      acquire(lock42) // now can't acquire lock30, etc…

    - Got a problem with this?

Avoiding deadlock with restarts

- One option: If thread needs a lock out of order, restart the thread
  - Get the new lock in order this time
- Another option: Arbitrarily kill and restart long-running threads

Avoiding deadlock with restarts

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- Another option: Arbitrarily kill and restart long-running threads
- Optimistic concurrency control
  - e.g., with a copy-on-write system
  - Don't lock, just detect conflicts later
    - Restart a thread if a conflict occurs

Another concurrency problem: livelock

Another concurrency problem: livelock

- In systems involving restarts, *livelock* can occur
  - Lack of progress due to repeated restarts
- *Starvation*: when some task(s) is(are) repeatedly restarted because of other tasks

Concurrency control in Java

- Using primitive synchronization, you are responsible for correctness:
  - Avoiding race conditions
  - Progress (avoiding deadlock)
- Java provides tools to help:
  - `volatile` fields
  - `java.util.concurrent.atomic`
  - `java.util.concurrent`

The Java *happens-before* relation

- Java guarantees a transitive, consistent order for some memory accesses
  - Within a thread, one action *happens-before* another action based on the usual program execution order
  - Release of a lock *happens-before* acquisition of the same lock
  - `Object.notify` *happens-before* `Object.wait` returns
  - `Thread.start` *happens-before* any action of the started thread
  - Write to a `volatile` field *happens-before* any subsequent read of the same field
  - …
- Assures ordering of reads and writes
  - A race condition can occur when reads and writes are not ordered by the happens-before relation

The `java.util.concurrent.atomic` package

- Concrete classes supporting atomic operations
  - `AtomicInteger`

    ```
    int  get();
    void set(int newValue);
    int  getAndSet(int newValue);
    int  getAndAdd(int delta);
    …
    ```

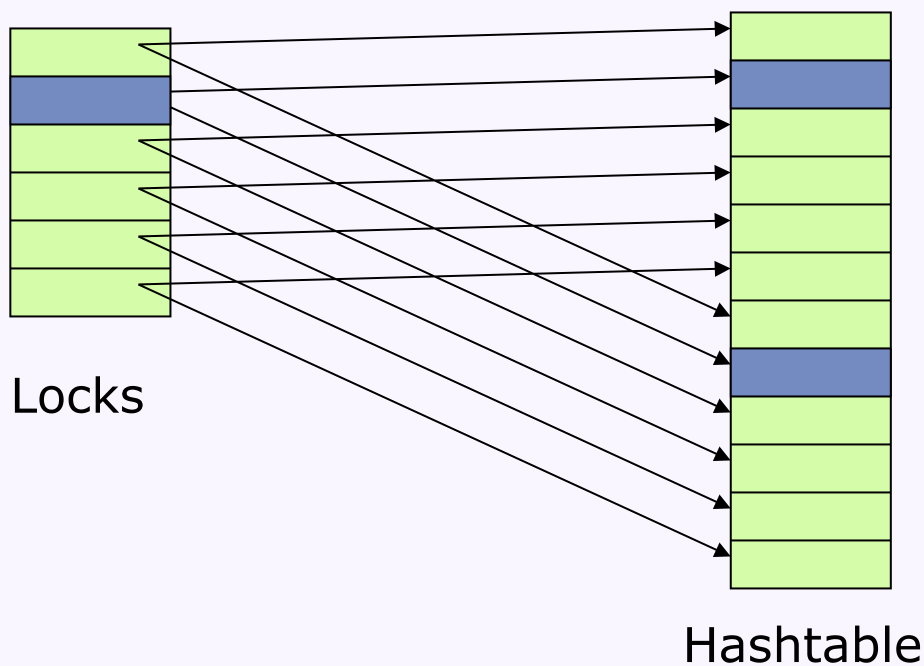
  - `AtomicIntegerArray`
  - `AtomicBoolean`
  - `AtomicLong`
  - …

The `java.util.concurrent` package

- Interfaces and concrete thread-safe data structure implementations
  - `ConcurrentHashMap`
  - `BlockingQueue`
    - `ArrayBlockingQueue`
    - `SynchronousQueue`
  - `CopyOnWriteArrayList`
  - …
- Other tools for high-performance multi-threading
  - `ThreadPools` and `Executor` services
  - `Locks` and `Latches`

java.util.concurrent.ConcurrentHashMap

- Implements java.util.Map<K,V>
  - High concurrency lock striping
    - Internally uses multiple locks, each dedicated to a region of the hash table
    - Locks just the part of the table you actually use
    - You use the ConcurrentHashMap like any other map…



Next week:

- Static analysis
  - JSure: A static analysis tool for concurrent programs