PROVING THINGS ABOUT CONCURRENT PROGRAMS

Lecture 24 – CS2110 – Spring 2013

Overview

- Two weeks ago we looked at techniques for proving things about recursive algorithms
  - We saw that in general, recursion matches with the notion of an inductive proof

- How can one reason about a concurrent algorithm?
  - We still want proofs of correctness
  - Techniques aren't identical but we often use induction
  - Induction isn't the only way to prove things

Safety and Liveness

- When a program uses multiple threads, we need to worry about many things
  - Are concurrent memory accesses correctly synchronized?
  - Do the threads "interfere" with one-another?
  - Can a deadlock arise?
  - What if some single thread gets blocked but the others continue to run?
  - Could an infinite loop arise in which threads get stuck running, but making no progress?

Safety and Liveness

- Leslie Lamport suggested that we think about the question in terms of ***safety*** and ***liveness***
  - A program is *safe* if nothing bad happens. The guarantee that concurrently accessed memory will be locked first is a *safety property*.
    - The property is also called **mutual exclusion**
  - A program is live if good things eventually happen. The guarantee that all threads get to make progress is a *liveness property*

Proper synchronization

- Consider a program with multiple threads in it
  - Perhaps threads T1 and T2
  - They share some objects

- First, we need to ask if the shared objects are **thread safe**
  - Every access protected by synchronized() { … }

Hardware needs synchronization too!

- As we saw last week, the hardware itself may malfunction if we omit synchronization!
  - Modern CPUs sometimes reorder operations to execute them faster, usually because some slow event (like fetching something from memory) occurs, and leaves the CPU with time to kill
  - So it might look ahead and find some stuff that can safely be done a bit early

Hardware needs synchronization too!

- Without synchronization locks, if a thread updates objects the thread itself always sees the exact updates in the order they were done

- But other threads on other cores could see them out of order and could see some updates but not others

- Java **volatile** keyword: warns compiler that a global variable isn't protected by synchronization. Volatile is difficult to use correctly.

Interleavings

- Suppose that a program correctly locks all accesses to shared objects, or uses volatile correctly
- Would it now be safe?
- Issue that arises involves *interleavings*

Interleavings

- Suppose threads A and B are executing
- A updates Object X, and then B changes X
  - Was this order "enforced by the program" or could it be an accident of thread scheduling?
- Ideally, when threads interact we would like to control ordering so that it will be predictable

Determinism

- What Lamport would call a safety property
- A program is *deterministic* if it produces the identical results every time it is run with identical input
  - This is desirable
- A program is *non deterministic* if the same inputs sometimes result in different outcomes
  - This is confusing and can signal problems

Linearizability

- Concept was proposed by Wing and Herlihy
  - Start with your concurrent program
  - But prove that it behaves like a non-concurrent program that does the same operations in some "linear" order
    - *Idea behind proof: if the effect of two executions is the same, then we can treat them as equivalent*
- Program is concurrent yet acts deterministic
- Not all programs are linearizable

We also worry about Deadlock

- Deadlock occurs if two or more threads are unable to execute because each is waiting for the other to do something, and both are blocked

- This is typically a buggy situation and hence we also need to prove that our concurrent code can't deadlock

Deadlock

- Recall from last week

- Deadlock depends on four conditions
  - A wait-for cycle
  - Locks that are held until the thread finishes what it wants to do, not released
  - No preemption of locks
  - Mutual exclusion

Revisit: Deadlock avoidance

- Suppose that threads acquire locks in some standard order. *Thm: deadlock cannot occur!*
  - Slightly oversimplified proof: A deadlock means that there is some cycle of threads A, B…. T each waiting for the next to take some action.
  - Consider thread A and assume A holds lock X_a.
    - A is waiting on B: A wants a lock X_b and B holds that lock.
    - Now look at B: it holds X_b and wants X_c.
    - We eventually get to thread T that holds X_t and wants X_a
    - But per our rules $X_a < X_b < \ldots. X_t < X_a$: a contradiction! QED
  - Notice that this is similar to an inductive argument

Induction connection?

- Base case focuses on two threads, A and T
  - A is holding X_A and wants X_T
  - T is holding X_T and will wait for A
  - But T is violating policy. So we can't deadlock with two threads

- Induction case: assume no deadlocks with n-1 threads. Show no deadlocks with n threads.
  - We won't write this out in logic, but we could.

Paris traffic circles: Deadlock in action

- Paris has a strange rule at some traffic circles: *priorité a droite*
- Traffic circles around, say, the Arc de Triomphe
- Roads enter from the right
- You must yield to let them enter

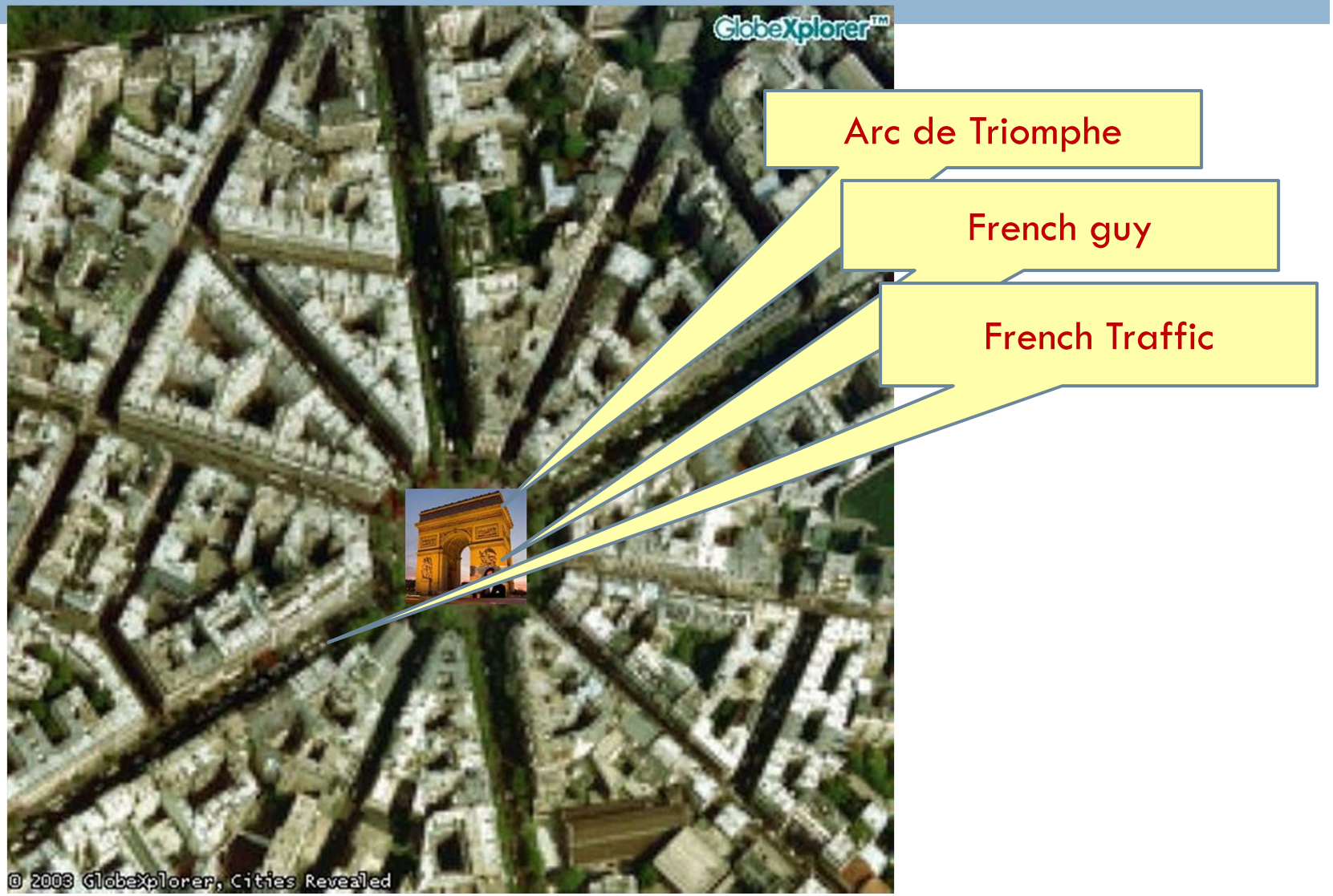
Paris traffic circle: *priorité a droite*

- An issue at Place d'Etoile and Place Victor Hugo (rest of France uses *priorité a gauche*)

- Think of cars as threads and "space" as objects
  - If thread A occupies a space that thread B wishes to enter, then B waits for A
  - Under this rule, deadlocks can form!

- To see this, look for a wait-for cycle

Why is *priorité a droite* a bad rule?



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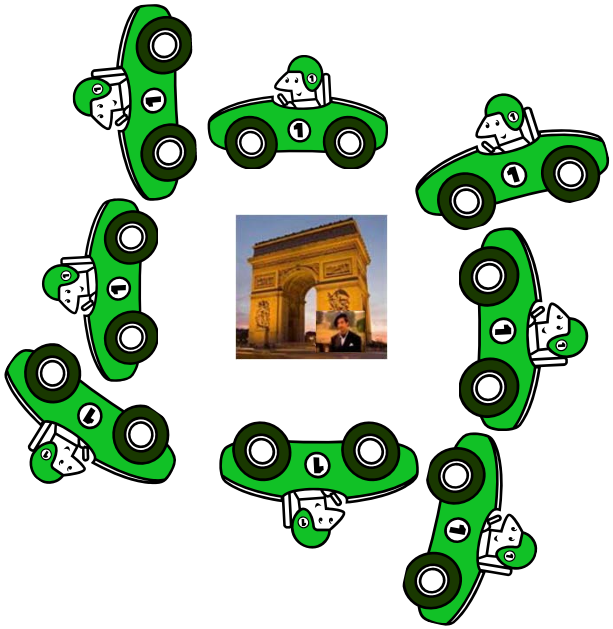

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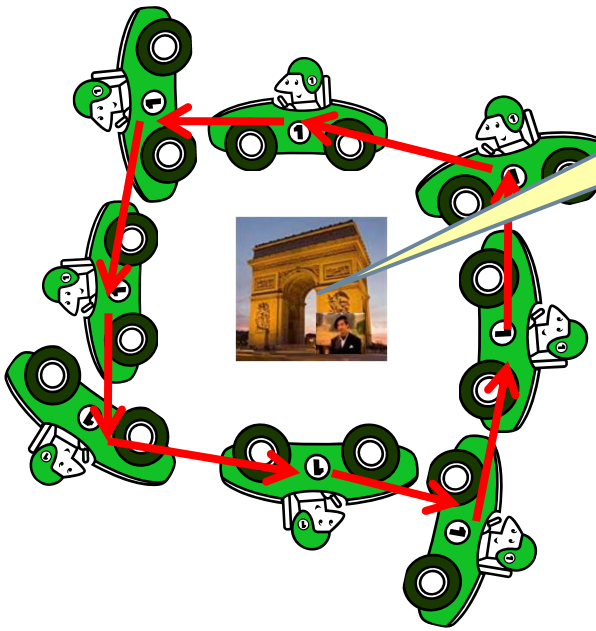


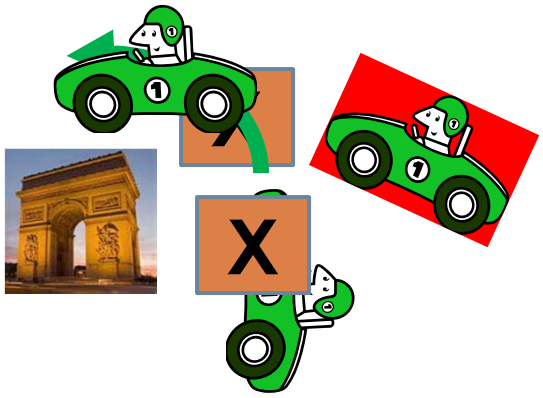
Ooh la la! Quel catastrophe!

But why is this specific to *priorité a droite*?

- With *priorité a gauche* cars already in the circle have priority over cars trying to enter
- Cars can drive around the circle until each car gets to its desired exit road and the traffic drains away
  - In fact can drive around and around if they like
  - Deadlock can't arise!

Inductive proof?

- Again, lends itself to an inductive proof
- Here's the key step in graphical form:
  - Assume we are not yet deadlocked: there is at least one space "X" free on the traffic circle
  - Red and Green cars both want to advance into X
  - Green is on the left, so it wins
  - This leaves space behind it



As a proof

- Two base cases
  - Traffic circle is “fully populated”.
    - Then traffic can rotate around circle until cars reach their exit streets and leave
    - So: some event can occur (not deadlocked)
  - Traffic circle has at least one gap
    - Priority-a-gauche ensures that the in-circle traffic will claim it, not the car contending to enter from right
    - So: some event can occur (not deadlocked)

As a proof

- Inductive case
  - Assumes that "chains" of k cars are deadlock free
  - Add one car
    - If you add it in the circle, it waits for the car in front to move (which it will, by induction), then follows it
    - If you add it outside the circle, it can only enter if there is no contention with any car in the circle
    - So: not deadlocked with chains of length k+1
- We conclude: the circle itself won't deadlock!

But are cars happy?

- A car trying to enter might have bad luck and wait… forever!
  - This is called « starvation »

"Mr. Limbkins, I beg your pardon, sir! Oliver Twist has asked for more!"

There was a general start. Horror was depicted on every countenance.

"For more!" said Mr. Limbkins. "Compose yourself, Bumble, and answer me distinctly. Do I understand that he asked for more, after he had eaten the supper allotted by the dietary?"

"He did, sir," replied Bumble.

"That boy will be hung," said the gentleman in the white waistcoat. "I know that boy will be hung

Starvation

- We say that a thread **starves** if it can't execute
  - A common reason: some thread locks a resource but forgets to unlock it
  - Not a deadlock because only one thread is stuck
- We want a starvation-free solution
- Lamport calls this a **liveness** property

What did this example show?

- We can sometimes prevent deadlock by controlling the "order" that contending threads grab resources
  - Priorite a gauche is such a rule.
  - But this also creates risk of starvation
- Ensuring that a system is both deadlock and starvation free requires clever design
  - Arc de Triomphe: would need some way to ensure that the "entry order" is fair

Recap

- To prove a concurrent program correct we need to
  - Prove that the shared memory is accessed safely
  - Prove that threads can make useful progress
    - No deadlocks or livelocks or starvation
    - Some notion of “fairness”
  - Guarantee determinism (optional, but useful)

- In practice this is very hard to do because of the vast number of possible interleavings

Debugging concurrent programs

- When we add threads to a program, or create a threaded program, debugging becomes more challenging
  - Without threads we think only about the "straight line" execution of our code
  - With threads need to think about all the orderings that can arise as they get scheduled

Bugs in concurrent programs

- In addition to regular kinds of bugs they often have bugs specific to concurrency!
  - Non-determinism and race conditions
  - Deadlock, livelock, starvation
  - Harder to reason about

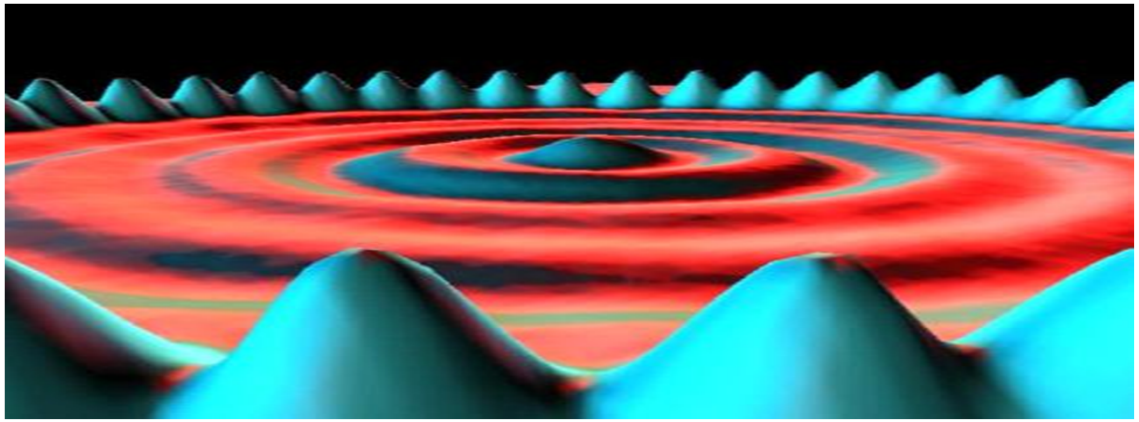
Bugs in concurrent programs

- Bruce Lindsay once suggested that there are two kinds of bugs
  - Bohrbugs are like the Bohr model of the nucleus: we can track them down and exterminate them
    - Most deterministic, non-concurrent programs only have Bohrbugs and this is a good thing
  - Heisenbugs are hard to pin down: the closer you look the more they shift around, like a Heisenberg model of the atomic nucleus (a "cloud")

Bugs in concurrent programs

- Concurrent programs often have latent Heisenbugs
  - Something that happened a while ago was the case
  - And the thread scheduling order may determine when you actually see the crash!

Where's the ~~electron~~ bug*?*



Bugs in concurrent programs

- Concurrent programs notorious for Heisenbugs
- You tend to focus on their eventual effect
  - But that was the *symptom*, not the cause!
  - You work endlessly but aren't actually even looking at the thing that caused the problem!
- And the debugger might cause the problem to shift around

Adding threads to unsafe code

- Modern fad: Adding threading to a program so that it can benefit from multicore hardware
  - Start with a program that was built without threads. Then introduce threads and synchronization
  - If you weren't the original designer, this is a risky way to work!

Our recommendations?

- Threads are an unavoidable evil
  - We need them for performance and responsiveness
  - But they make it (much) harder to prove things about our programs
  - Must use them cautiously and in very controlled ways

- Linearizability can greatly simplify analysis
- Use inductive style of proofs to reason about chains of threads that wait for one-another