Commuting Operations and Deterministic Execution in Parallel Programs

Martin Rinard

MIT CSAIL

Massachusetts Institute of Technology

Cambridge, MA 02139

Purpose of Talk

- Motivate need to
  - Recognize and exploit commuting operations
  - In deterministic parallel computations
- Present issues that arise when
  - Formalize concept of commuting operations (especially for linked data structures)
  - Formalize connection between commuting operations and deterministic execution

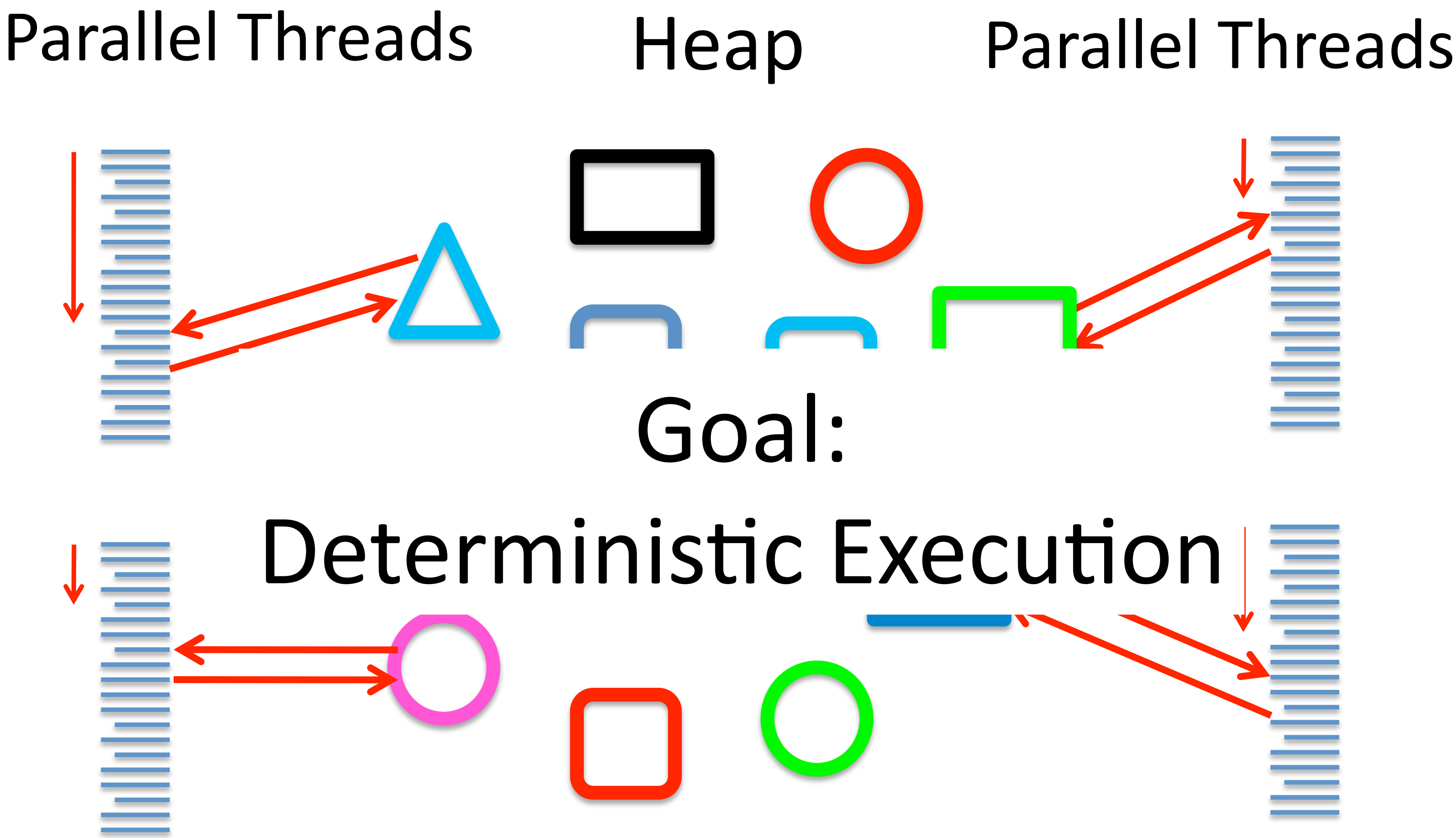
Context

- Static program verification
- Analyze program before it runs
- Two (dual) options
  - Either analyze parallel program,

    Verify that program will execute deterministically
    - If give program same input
    - All parallel executions will produce same output (generalize to equivalent outputs)
  - Or, analyze sequential program,

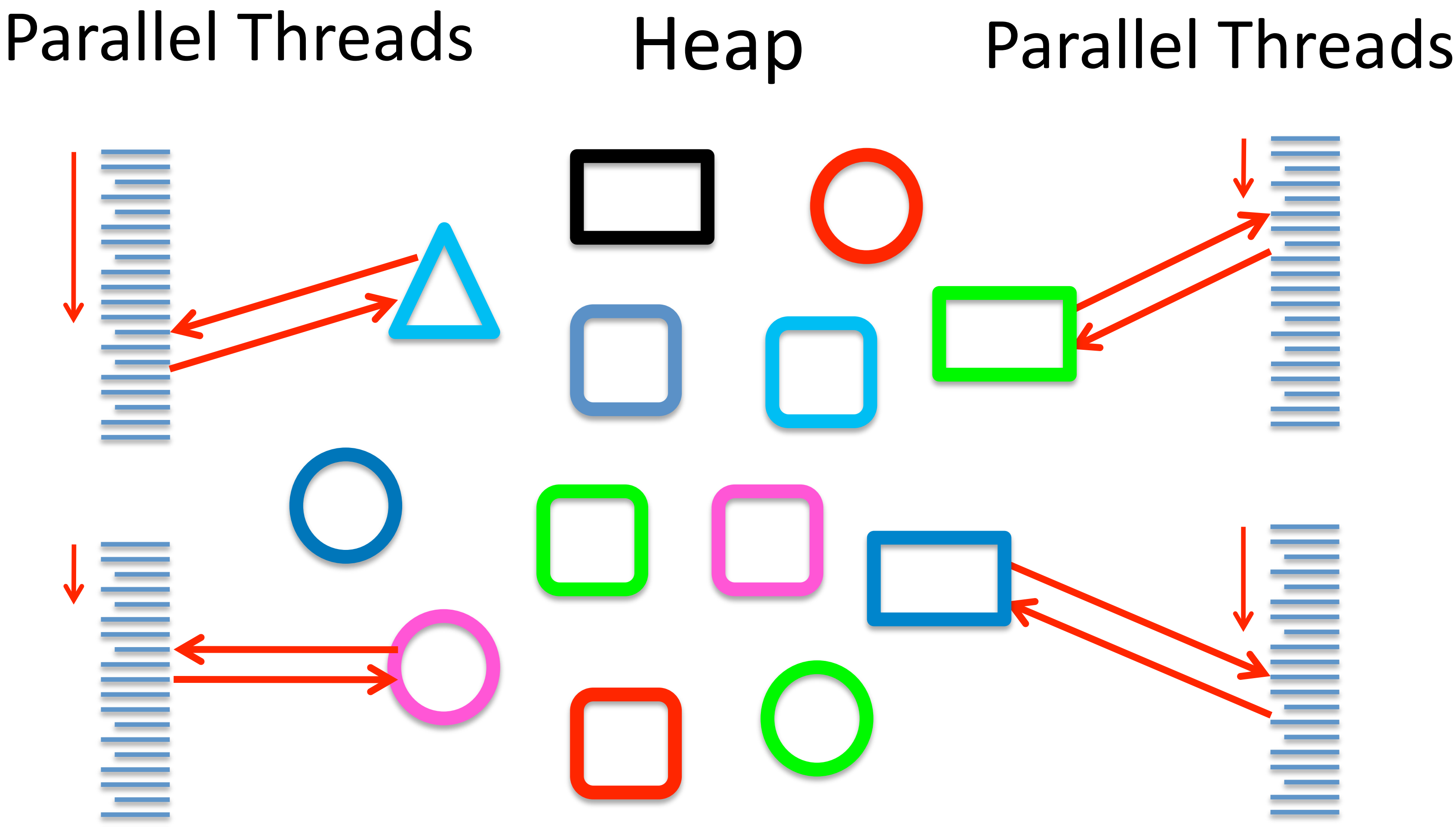
    Automatically generate deterministic parallel program

A Model of Parallel Computing



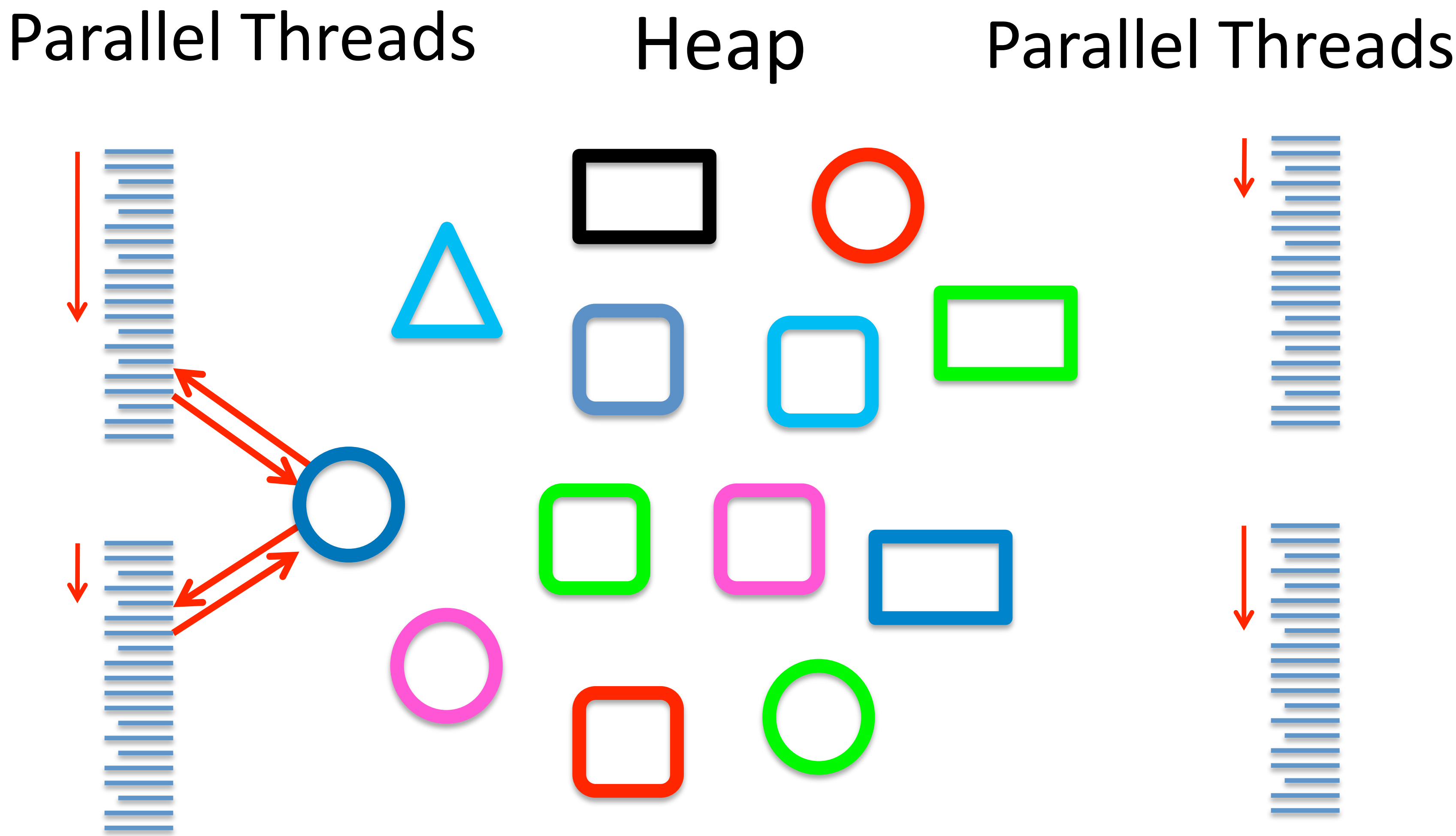
Parallel Updates: Read, Write

A Model of Parallel Computing



If Threads Update Disjoint Objects
Then Get Deterministic Execution

A Model of Parallel Computing

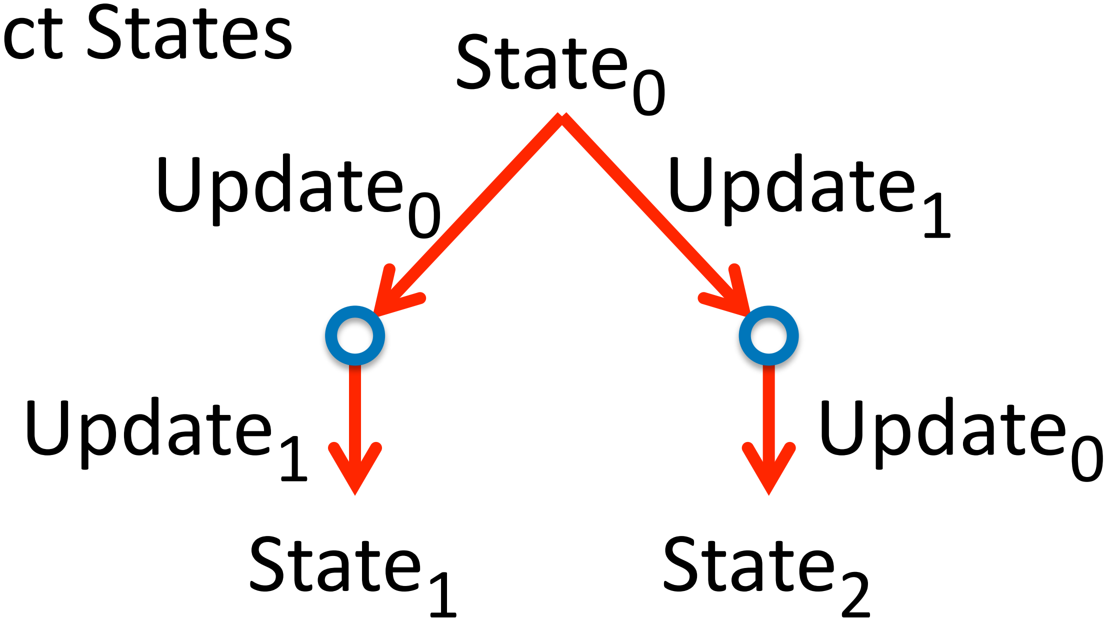


But If Threads Update Same Object

Then May Get Nondeterministic Execution

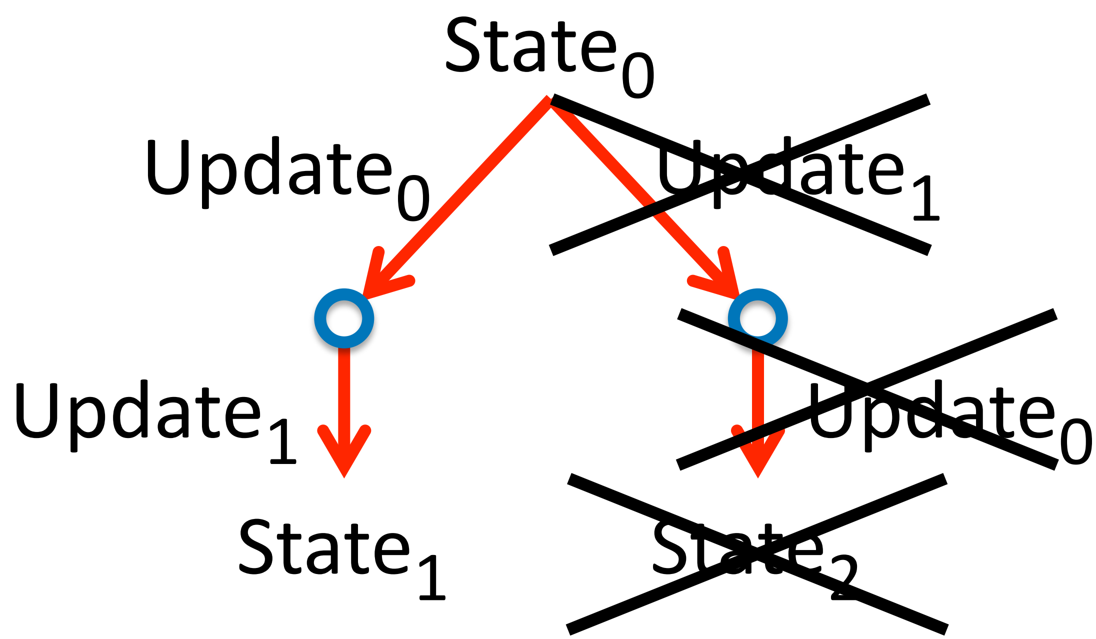
Issues With Conflicting Updates

- Atomicity Violations
  - Mutual exclusion locks, transactional memory, …
  - Not topic of this talk
- Divergent Object States

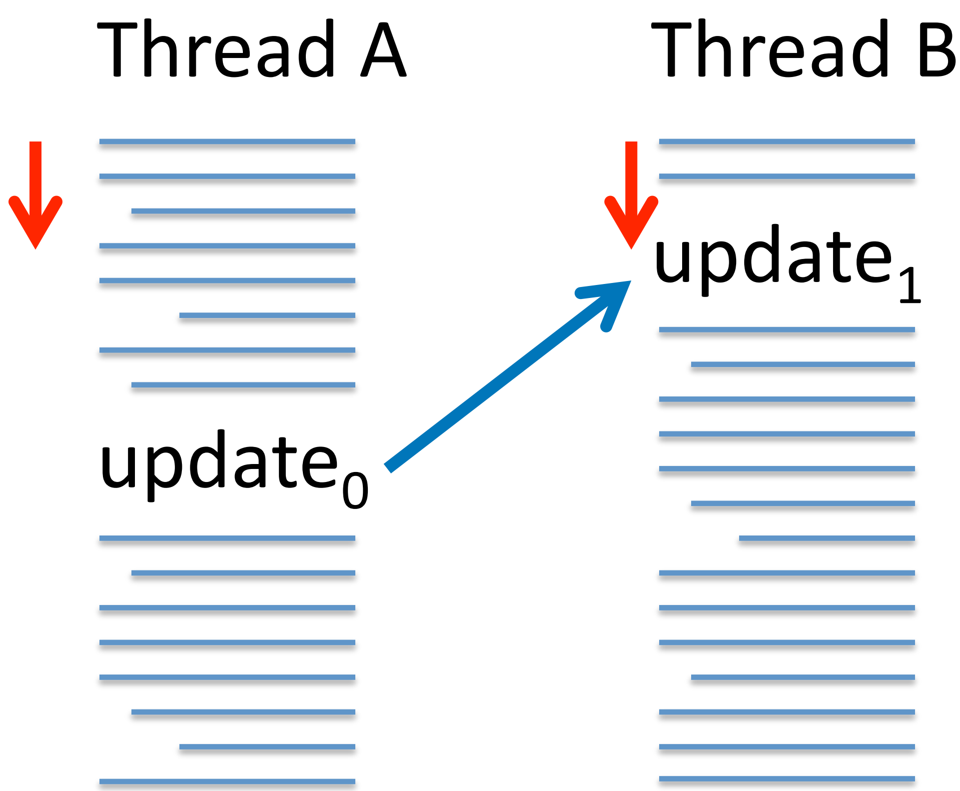


One Common Solution

- Totally order threads (serial program order)
- Execute updates in thread order



Enforcing Update Order

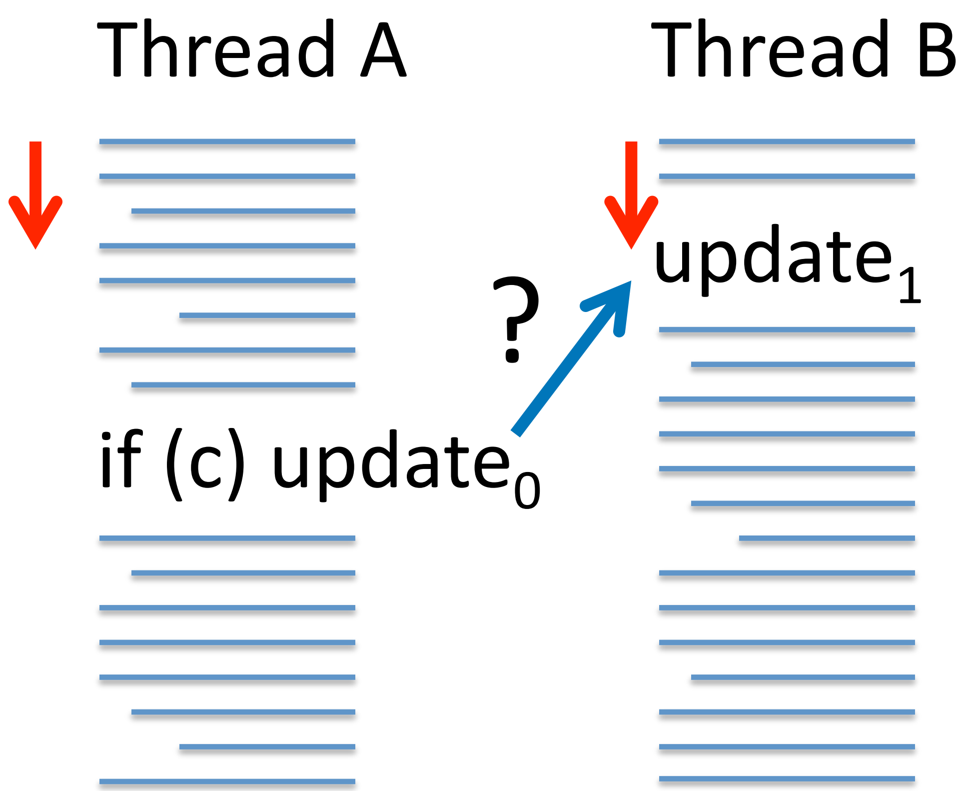


Need to Delay Thread B Update!

- Save Thread B state (time, space overhead)
- Context switch (time overhead)
- Wait for Thread A to finish update$_0$ (critical path gets longer)

Machine Gets Bogged Down With Heavyweight Mechanism

Enforcing Update Order



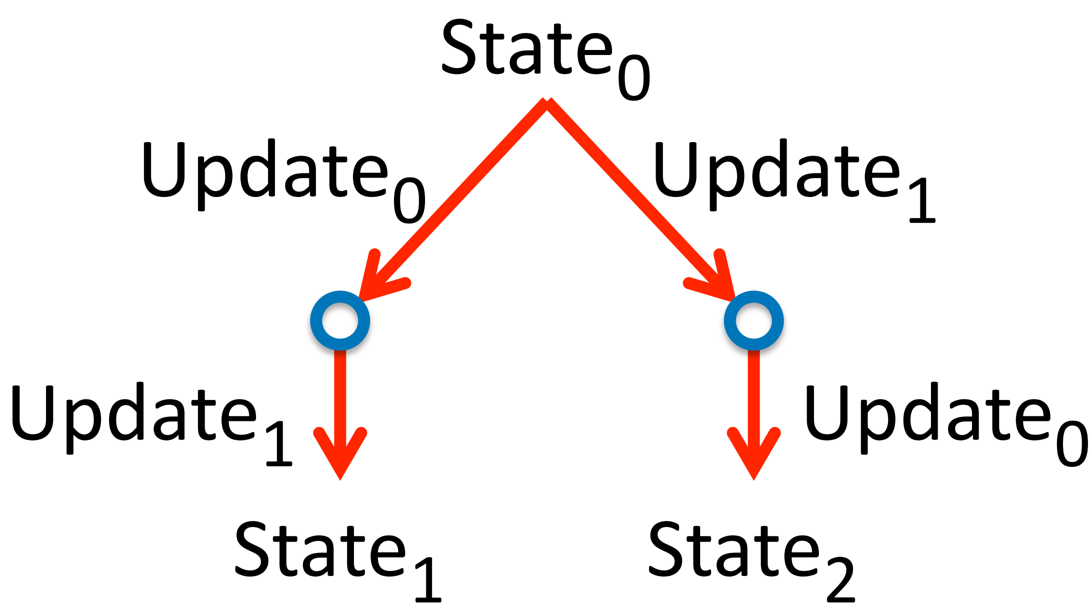
Need to Delay Thread B Update!

- Save Thread B state (time, space overhead)
- Context switch (time overhead)
- Wait for Thread A to finish update$_0$ (critical path gets longer)
- update$_0$ may not even happen!

Machine Gets Bogged Down With Heavyweight Mechanism

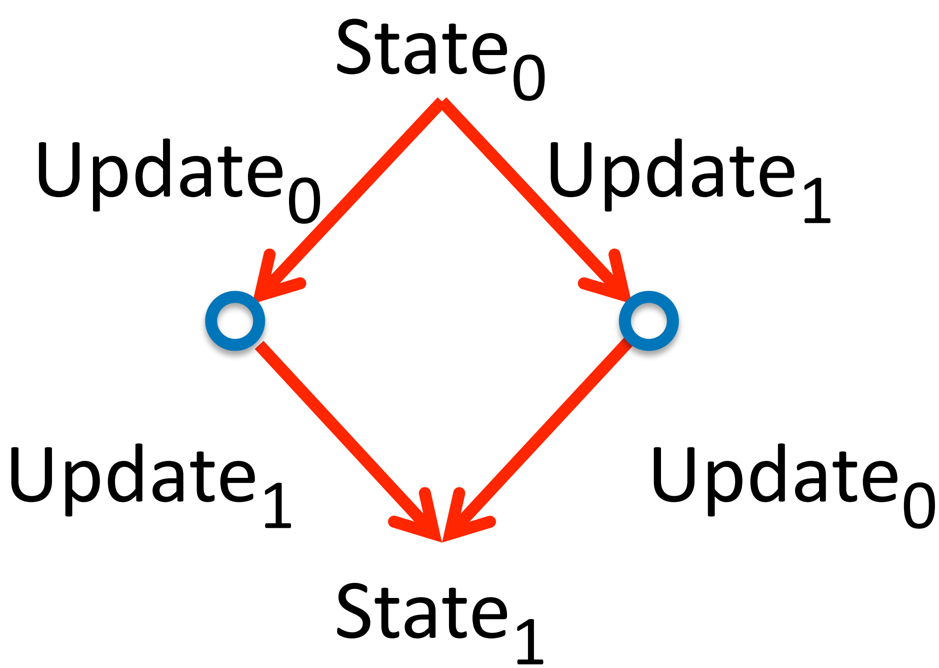
A Better Solution (when available)

Exploit Commuting Updates



A Better Solution (when available)

Exploit Commuting Updates



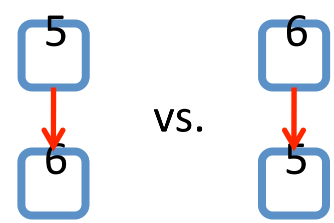
If All Conflicting Updates Commute
You Get Deterministic Execution

What Commuting Updates Give You

Only Need Atomicity Mechanism
Not Heavyweight Ordering Mechanism

Kinds of Commuting Updates

- Reads and Writes (Bernstein 1966)
  (x=6 || x=5), rest of computation does not access x
- Identical States (Rinard and Diniz 1996)
  (x+=6 || x+=5), some graph algorithms
- Semantically Equivalent States
  List l; (l.insert(5) || l.insert(6))



- Observationally Equivalent States
  List l; (l.insert(5) || l.insert(6)); print l.sum(); output = 11
  List l; (l.insert(5) || l.insert(6)); print l;
  output = 5 6 vs. output = 6 5

More Detailed Example (Map Implemented as Hash Table)

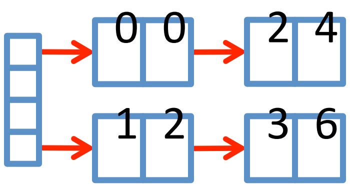
- How to formalize semantic commutativity
- Illustrate connection between
  - Semantic commutativity
  - Deterministic execution

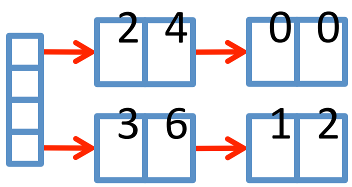
Semantic Commutativity

Concrete Implementation

```
class map {
  void insert(int key,int val);
  int lookup(int key);
}
parallel for (i = 0; i < n; i++)
  m.insert(i,f(i));
```

Calls to insert commute





One Outcome

Another Outcome

Abstract Specification

abstract state S ⊆ int X int;

S = (old S – {<key,_>})∪{<key,val>}

<key,val> ∈ S ⇒ ret = val

<key,_> ∉ S ⇒ ret = nil

S = { <i,f(i)> . 0 ≤ i < n }

{ <0,0>, <1,2>, <2,4>, <3,6>}

Always Get Same Abstract State

Connection Between Semantic Commutativity and Deterministic Execution

Key Question for Deterministic Execution

Does Rest of Program Observe Difference Between (Semantically Equivalent) Concrete States?

Depends On

Observations It Can Make

Observations It Does Make

What Observations Does Map Provide?

Calls to insert observe nothing

```
class map {
  void insert(int key,int val);
  int lookup(int key);
}
```

$S = (\text{old } S - \{<key,\_>\}) \cup \{<key,val>\}$

$<key,val> \in S \Rightarrow ret = val$

$<key,\_> \notin S \Rightarrow ret = nil$

Calls to lookup observe
- value that key maps to
- or nil (if key maps to no value)

If maps have same abstract states
- then program can't observe difference
- even if maps have different concrete states

Nondeterminism is contained within class

Program executes deterministically!

Putting Pieces Together

- If reorder insert operations
  - May get different concrete states
  - But abstract states are same
- Same abstract states imply same observables
- Same observables implies deterministic execution
- If reorder insert operations, still get deterministic execution
- Determinism conversion happens at class boundary

What About More Operations?

```
class map {
  void insert(int key,int val);
  int lookup(int key);
  Set<int> values();
}
parallel for (i = 0; i < n; i++)
   m.insert(i,f(i));

lastValue = -1;
for (v : m.values()) {

     if (lastValue > v) crash;
     lastValue = v;
}
```

← Returns set of values in map (values())

← Creates map (parallel for): Different concrete states, Same abstract states

← Iterates over set of values (for loop)

← Crashes if values come out in wrong order (if (lastValue > v) crash;)

Nondeterminism escapes via the values() operation

Different Scenario, Different Outcome

```
class map {
  void insert(int key,int val);
  int lookup(int key);
  Set<int> values();
}
parallel for (i = 0; i < n; i++)
   m.insert(i,f(i));

sum = 0;
for (v : m.values()) {
     sum += v;
}
```

Set<int> values(); ← Returns set of values in map

m.insert(i,f(i)); ← Creates map

Different concrete states

Same abstract states

for (v : m.values()) { ← Iterates over set

sum += v; ← Same result regardless of order!

Sum kills nondeterminism (outside class)

Research Agenda

- Verify semantic equivalence of different execution orders of operations on objects
  - Find operations that generate same abstract state
  - Or equivalent states (equivalence property)
- Assuming semantic equivalence, verify deterministic execution
  - Trace flow of information out of abstract state
  - Find out where nondeterminism is killed
    - Ideally killed inside class
    - In more challenging cases, killed outside class
  - Key concept – observational power

Commutativity Consumers

- *A Type and Effect System for Deterministic Parallel Java.*
  R. Bocchino, V. Adve, D. Dig, S. Adve, S. Heumann, R. Komuravelli, J. Overby, P. Simmons, H. Sung, and M. Vakilian, OOPSLA 2009
- *Revisiting the Sequential Programming Model for Multi-Core.*
  M. Bridges, N. Vachharajani, Y. Zhang, T. Jablin, and D. August, Micro 2007
- *Optimistic Parallelism Requires Abstractions.*
  M. Kulkarni, K. Pingali, B. Walter, G. Ramanarayanan, K. Bala, and L. Chew, PLDI 2007
- *The Design, Implementation, and Evaluation of Jade.*
  M. Rinard and M. Lam, TOPLAS 1997

Commutativity Producers

- Semantic Equivalence
  - *An Integrated Proof Language for Imperative Programs.* Karen Zee, Viktor Kuncak, and Martin Rinard, PLDI 2009
  - *Full Functional Verification of Linked Data Structures.* Karen Zee, Viktor Kuncak, and Martin Rinard, PLDI 2008
- Observational Equivalence
  - *Commutativity Analysis for Software Parallelization: Letting Program Transformations See the Big Picture*. Farhana Aleen and Nathan Clark, ASPLOS 2009
  - *Commutativity Analysis: A New Analysis Framework for Parallelizing Compilers.* Martin Rinard and Pedro Diniz, PLDI 1996

Bigger Picture

- Exploiting (semantic) commutativity will be a critical part of future parallel computing efforts
- Sophisticated tools for reasoning about software are (finally) now available
- Should be able to leverage this capability to
  - Formalize and verify semantic commutativity
  - Verify connection between semantic commutativity, observational equivalence, and deterministic execution
- Interesting research problem with significant practical impact

Am I Still Doing Research In This Area?

- Yes (static analysis/program verification)
  - Semantic equivalence of commuting operations
  - Observational determinism in presence of commuting operations
- And No (automatic parallelization)
  - Nondeterministic parallelizations of serial programs
  - Change result program produces
  - But with statistical accuracy guarantees

Application Characteristics Changing

- Accuracy/Quality of service key issue
- Correctness not even meaningful concept
  - Video encoding, image processing
  - Search/information retrieval
  - Machine learning
- Lots of flexibility in output
- How/should we exploit this fact?