Deterministic Parallel Programming

Concepts and Practices

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How hard is parallel programming

- What's the result of this program?
- What is data race?
- Should data races be allowed?

```
Initially x = 0

Thread 1:                    Thread 2:
x = 1                        Output x
```

How hard is parallel programming

- What's the result of this program?
- Still data races?
- Is this program "correct"?

```
Thread 1:                    Thread 2:
lock                         lock
x = 1                        x = 2
unlock                       unlock
                             Output x
```

How about debugging a parallel program?

- In debug, we usually...
  - Check variable values at break points
  - Check register values for each processor
  - Monitoring certain variable's values
- Does scheduling matters?

```
parallel for i in [1..100]
  f(A[i])
```

Deterministic Parallel Programming

- General sense: behaves "in the same way"
- Easier to...
  - Construct and debug
  - Understand and maintain
- Scenario1: Debug a parallel program
- Scenario2: Verify an existing program
- Scenario3: Estimate time/space consumption

What's following?

- What *is* deterministic parallel programming
  - A formalized framework
    - Multiple interesting definitions
- Any implementations?
  - Deterministic *Programming Languages*
  - Deterministic *Implementations*

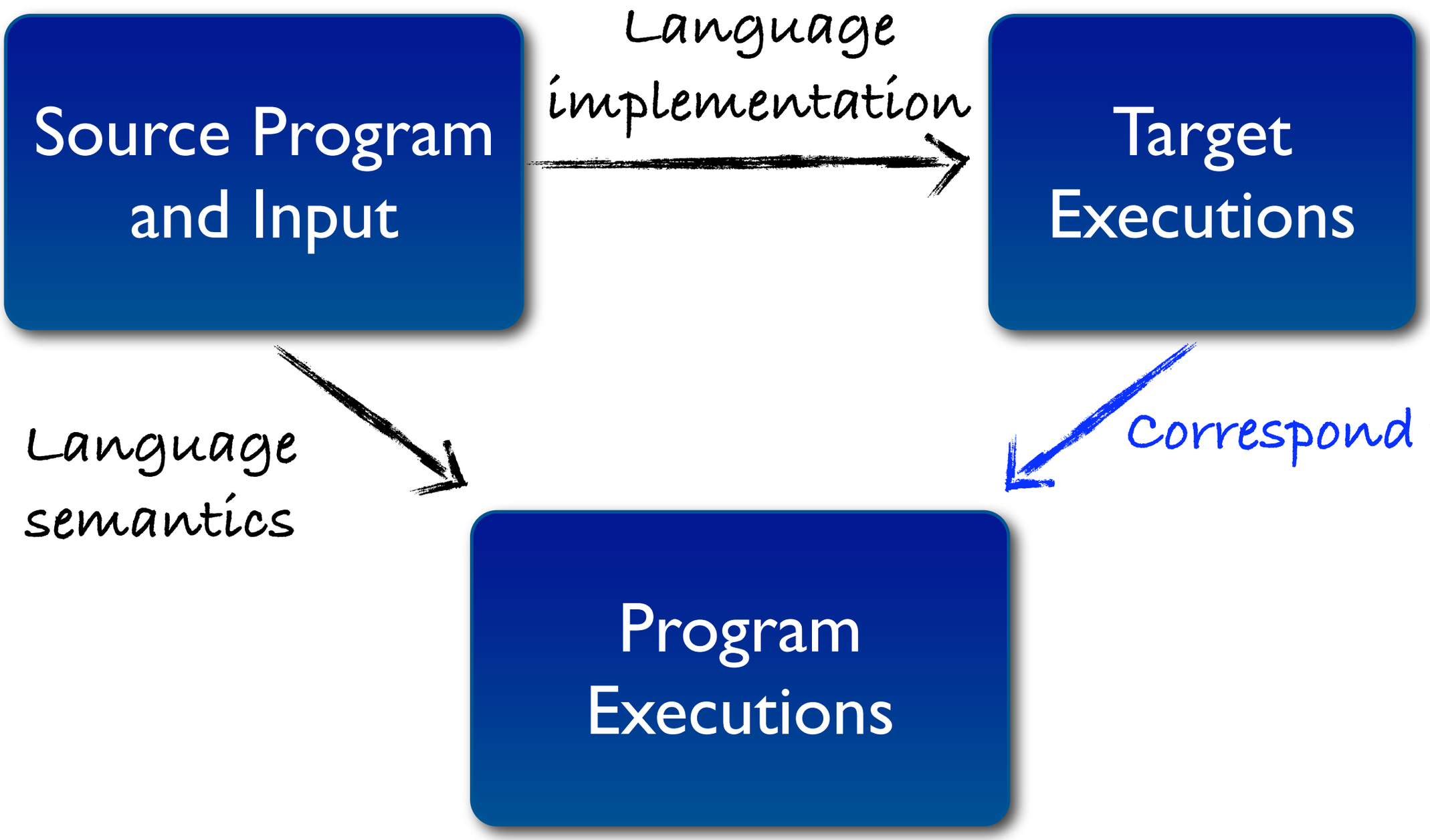
What *is* deterministic parallel programming?

We need a formal definition

Possible Definitions

- Computes the same output on a given input
- Terminates in the same state
- Computes *in the same way*
  - same time & space consumption
  - same visible states in debugger
  - as easy as sequential code to test and understand
- What exactly does "*in the same way*" mean?

Semantics & Implementations



Executions

- A 3-tuple E: (OP, $<_p$, $<_s$)
  - OP: set of operations *(op_name, val_list, tid)*
  - $<_p$: Program order
  - $<_s$: Synchronization order
- $<_{hb}$: Irreflexive transitive closure of $<_p$ and $<_s$
- Input & output: external events, ordered by $<_s$
- *ext(E)*: the sequence of external operations in E, without their thread ids

Proposed Framework

- A *program* is deterministic iff all of its program executions on a given input are *equivalent*
- A *language* is deterministic iff all its programs are deterministic
- An *implementation* is deterministic iff all the target executions of a given program on a given input correspond to program executions that are mutually *equivalent*

Example definitions of *equivalence*

What's Following?

- Provide and analyze 5 possible definitions
- All definitions guarantee the same output on the same input
- Assumptions
  - I/O operations operate on two unbounded vectors
  - I/O operations are fully synchronized

Singleton

- Two executions E1 and E2 are equivalent iff they are *exactly the same*
- Strictest definition of equivalence
  - Rules out "benign" differences of any kind among program executions

Singleton

- Good for repetitive debugging
  - Possible to guarantee same state when rerunning to a breakpoint
    - Monitored variables change deterministically
- Possible idiom: Independent split-merge
  - Access disjoint sets of variables
  - e.g., with parallel iterators or **`cobegin`**

Dataflow

- Two executions E1 and E2 are equivalent iff there is a bijection between their set of operations that preserves the dataflow:
  - the content *other than thread id* in each operation
  - the values each read returns

Dataflow

- Still good for repetitive debugging
  - Same values for same data watchpoints
  - Two executions may not reach the same global state when a breakpoint is triggered
- Without special purpose hardware, scalable performance for general programs may be difficult
- Idiom: bag of independent tasks

SyncOrder

- Two executions E1 and E2 are equivalent iff they synchronize in the same way
  - For example: grab a lock, send/recv or resolve conflicting transactions

SyncOrder

- Allows benign changes in data flow
- Not as good for repetitive debugging
  - No guarantee on global state at breakpoints
    - No guarantee on variable value changes
- Potentially cheaper to implement
  - instrument only synchronization ops
- Idiom: chaotic (racy) convergence

ExternalEvents

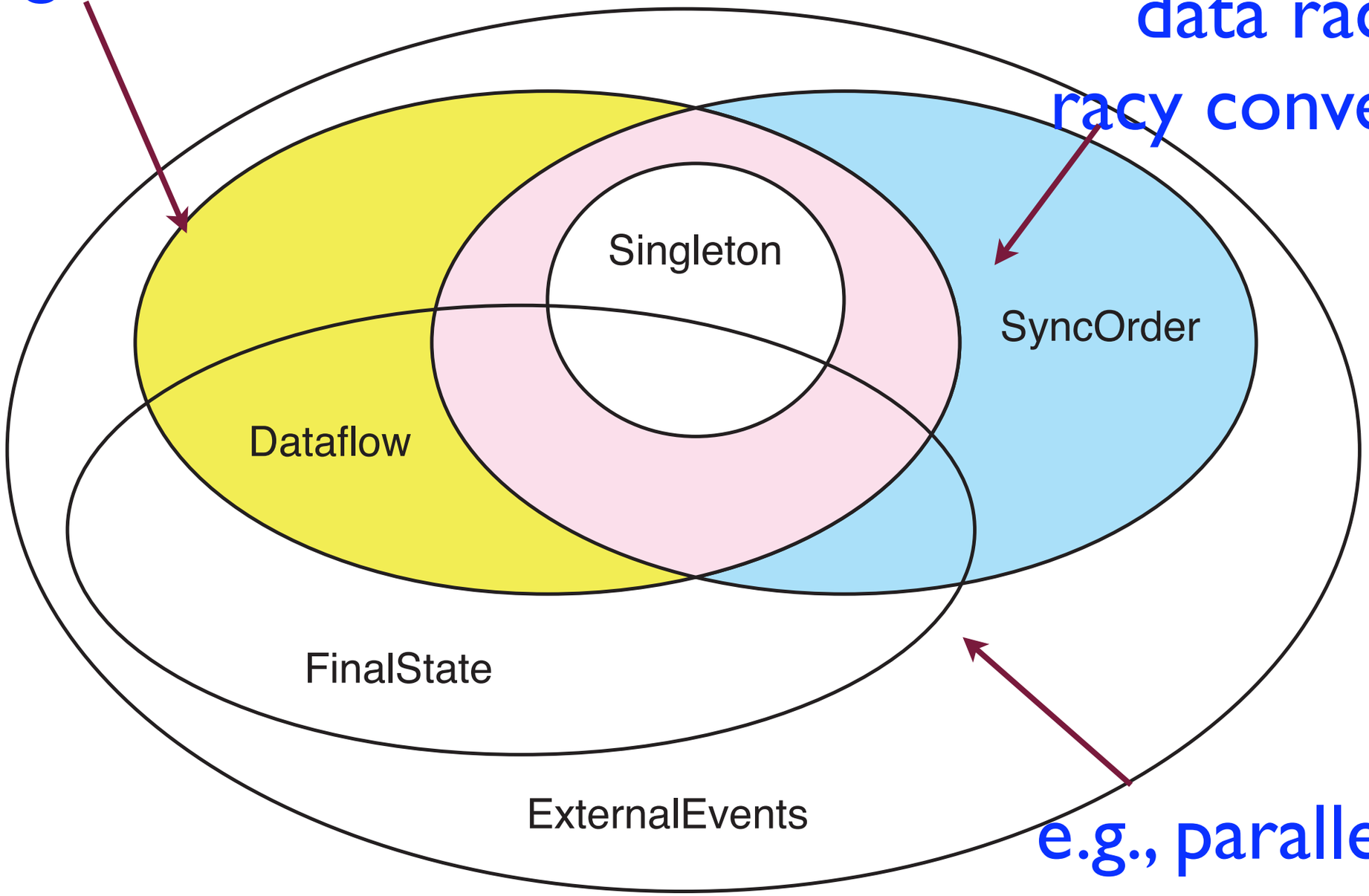
- Two executions E1 and E2 are equivalent iff they have the same output on the same input
- The minimal definition of determinism?
- Not very good for repetitive debugging
- Implementation cost is hard to predict
- Maximum flexibility for language design and implementation
- Possible idiom: parallel iterator with reduction

FinalState

- Two executions are equivalent iff they *both terminate* and *terminate with the same state*
- A variant of *ExternalEvents*
- Cannot handle non-terminating programs
- Disadvantages similar to *ExternalEvents*

benign synchronization races:
e.g., bag of tasks

benign non-trivial
data races: e.g.,
racy convergence



e.g., parallel loop
with reduction

Future Work

- Formalize definitions and proofs
- Consider additional definitions, connect them with programming idioms
- Accommodate conditional synchronization, spinning, operations like `rand`
- Consider deterministic *implementations*
- Implement and assess representative languages

What's following?

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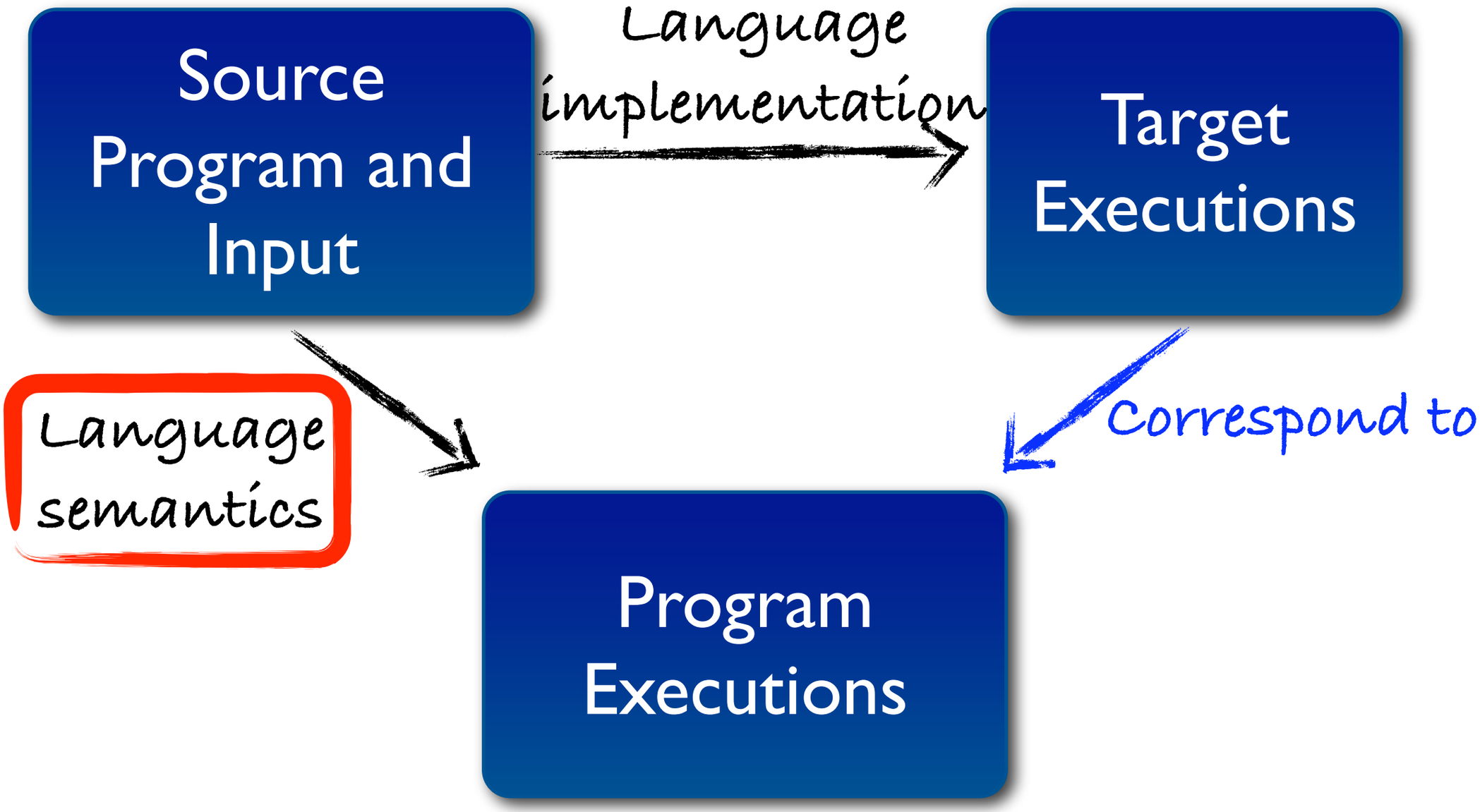
  - Deterministic *Programming Languages*
  - Deterministic *Implementations*

Deterministic Programming Languages



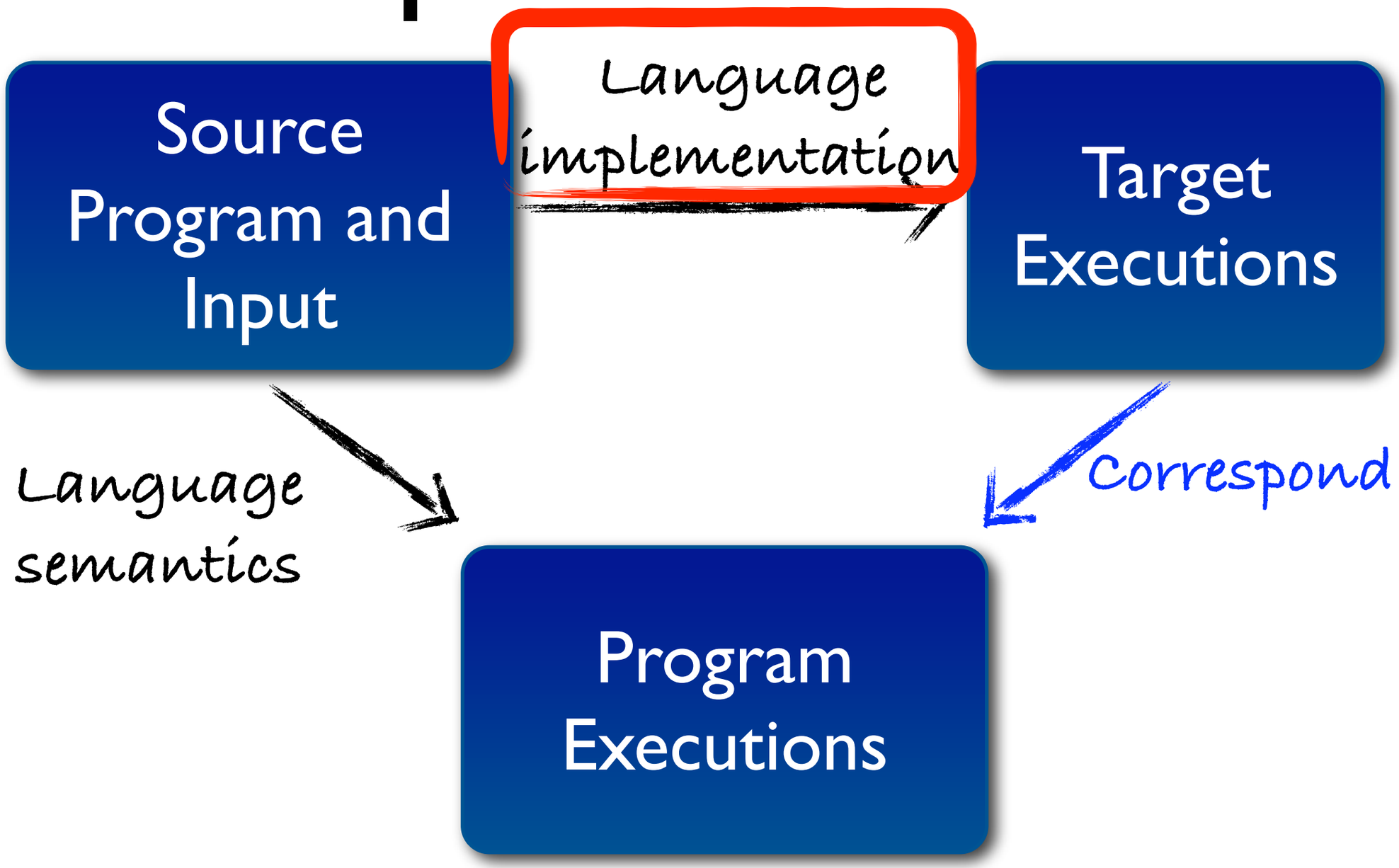
Deterministic Parallel Java

- Based on original Java language
- A changed type and effect system
  - Regions: Partitioning memory locations for disjoint constraints
  - Effects list: annotated memory effects
- Expressing parallelism: cobegin and foreach
- Not so easy to use...

Intel CnC

- A completely new parallel programming model
  - Data flow style programming
- Programmer specifies restrictions
  - Data and control dependencies
  - With built-in collections (item, tag, step)*
- Parallelism is hidden in collections' semantics
- Not strictly deterministic... (Until now)

Deterministic Implementations



Examples

- Pure software implementations
  - Determinator: OS support (special region and APIs)
  - CoreDet: Compiler and runtime extension
- Hardware-software hybrid
  - DMP and RCDC: architectural supported determinism for various memory models
- Problem: slow or expensive

One more thing...

- Deterministic *replay*
  - Different to deterministic *executions*
- Different focus
  - Deterministic executions: always produce equivalent executions
  - Deterministic replays: produce exactly the same execution as the recorded one

Thank you!

Q&A