‘now’
‘happens-before’
‘later’

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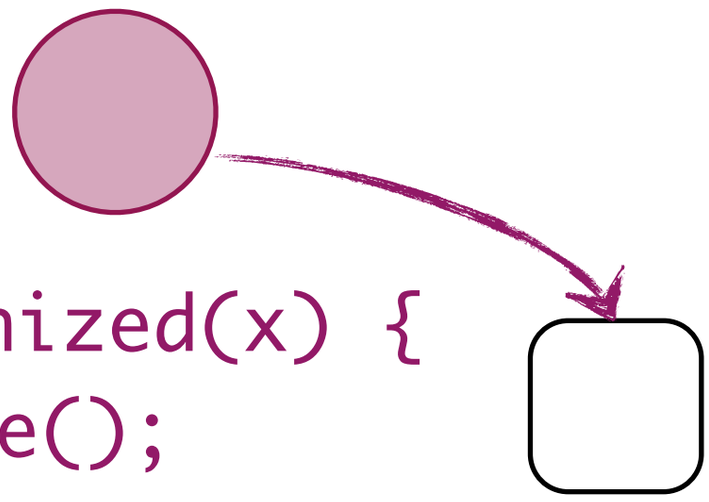
Thomas R. Gross
ETH Zurich, Switzerland

Static Schedule Analysis with Explicit Happens-before Relationships

Example

Example

task A

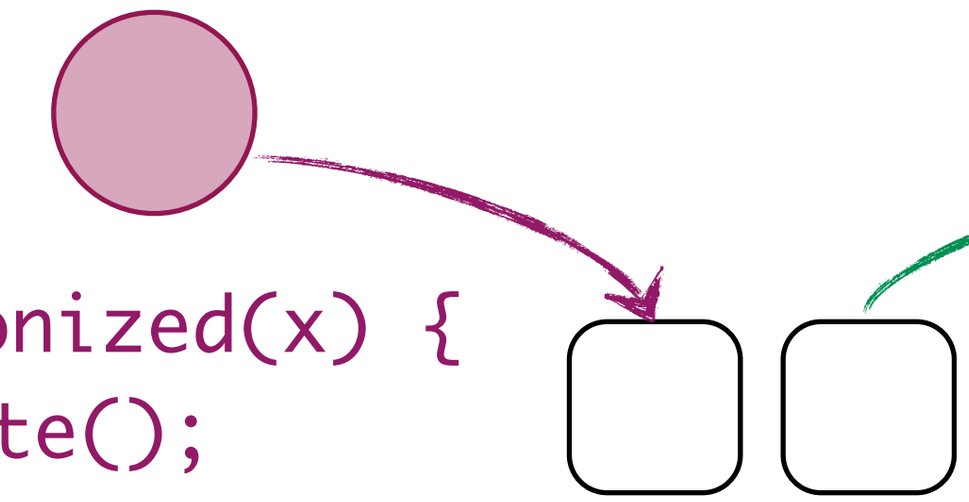


```
synchronized(x) {
  x.write();
}
```

Example

task A

task B



```
synchronized(x) {
  x.write();
}
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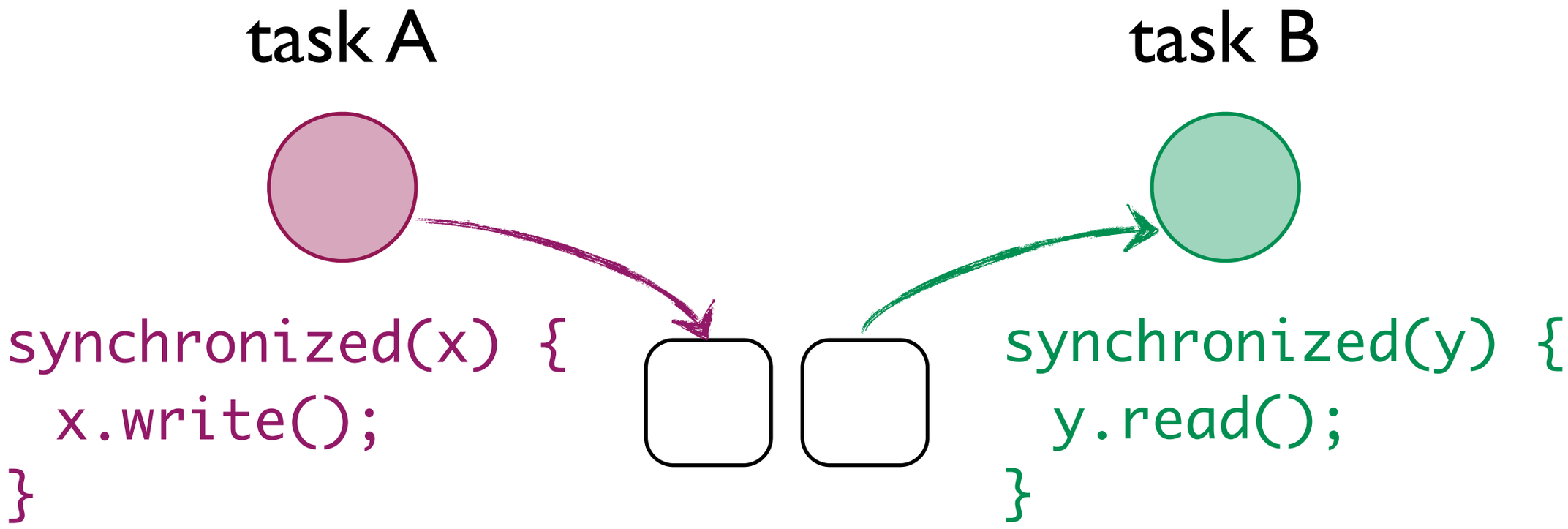
```
synchronized(y) {
  y.read();
}
```

Example

- Can we remove synchronization for x, y?



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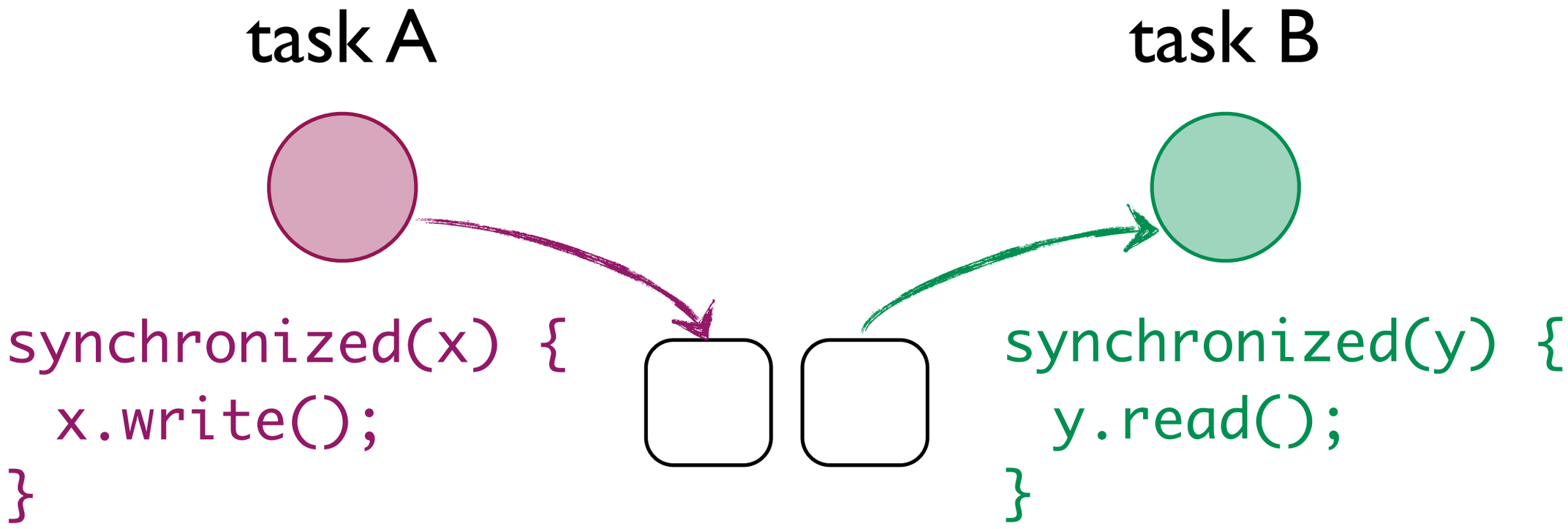

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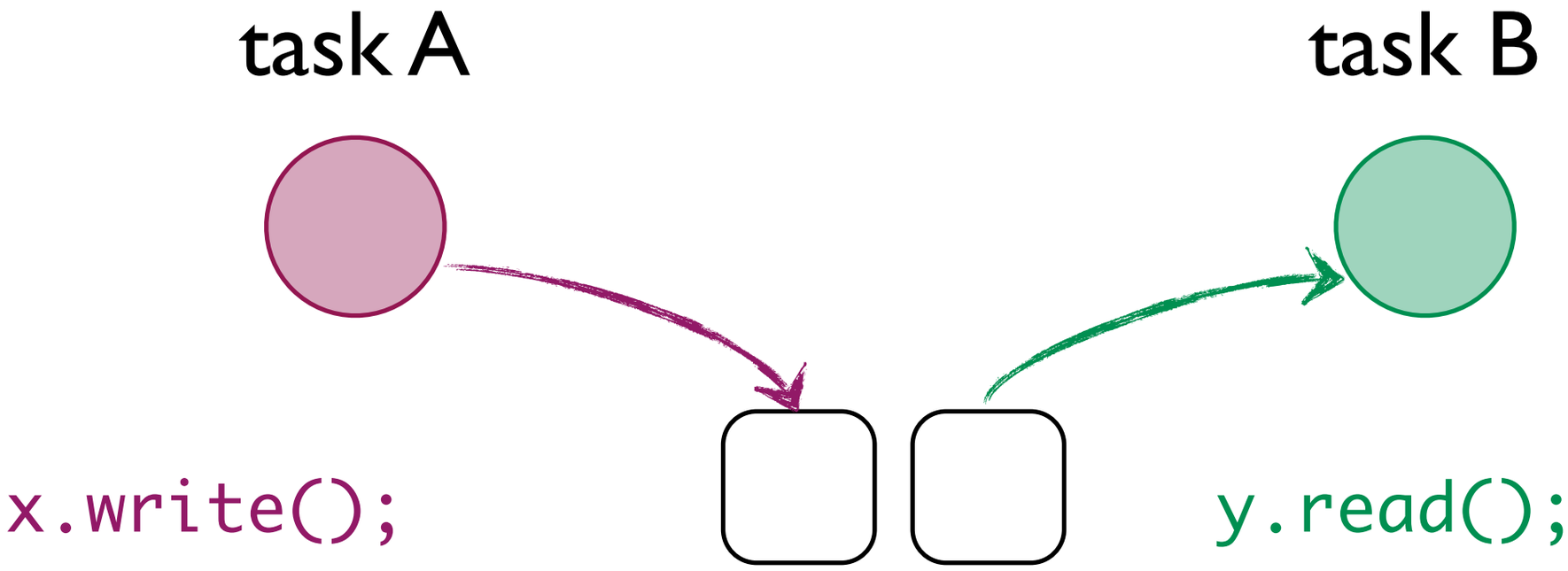

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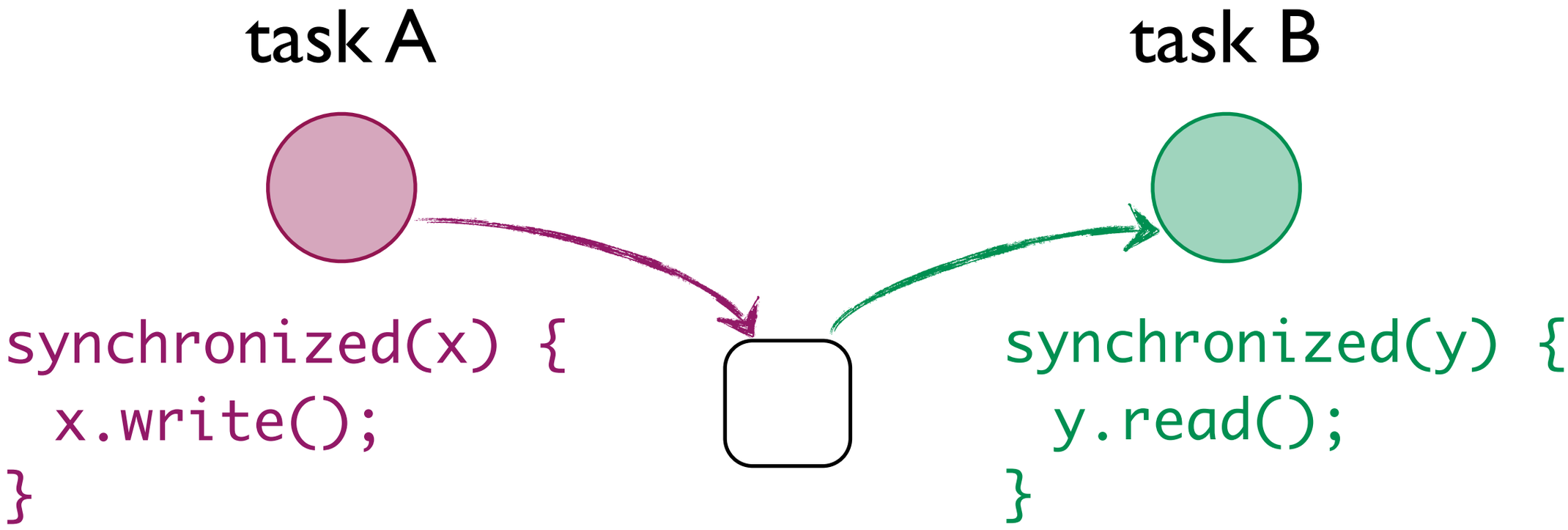

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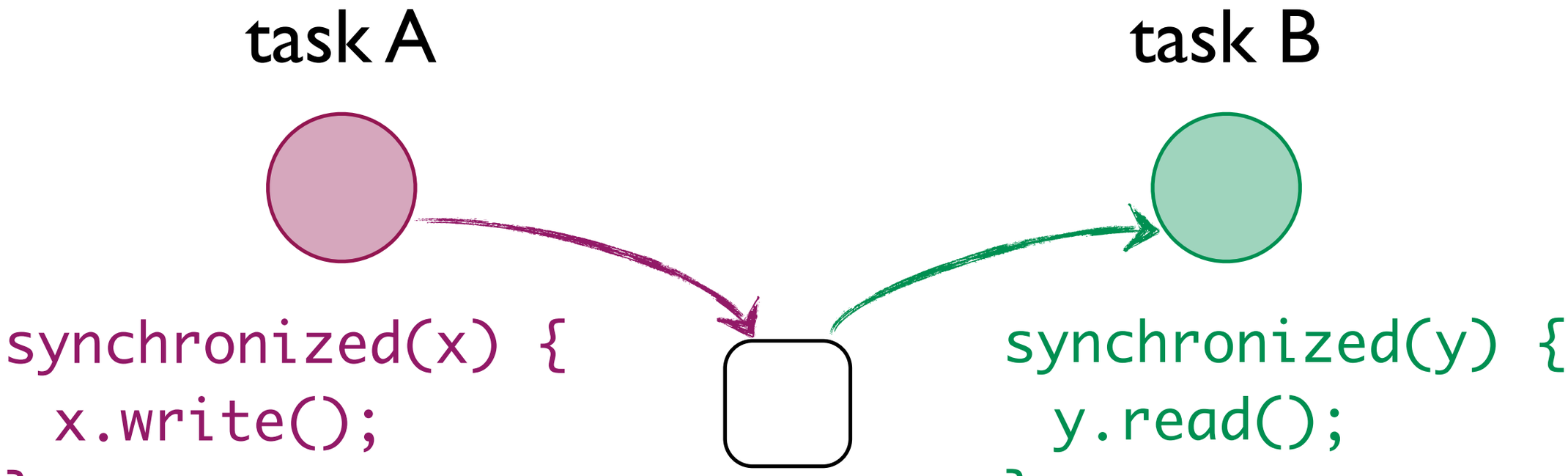

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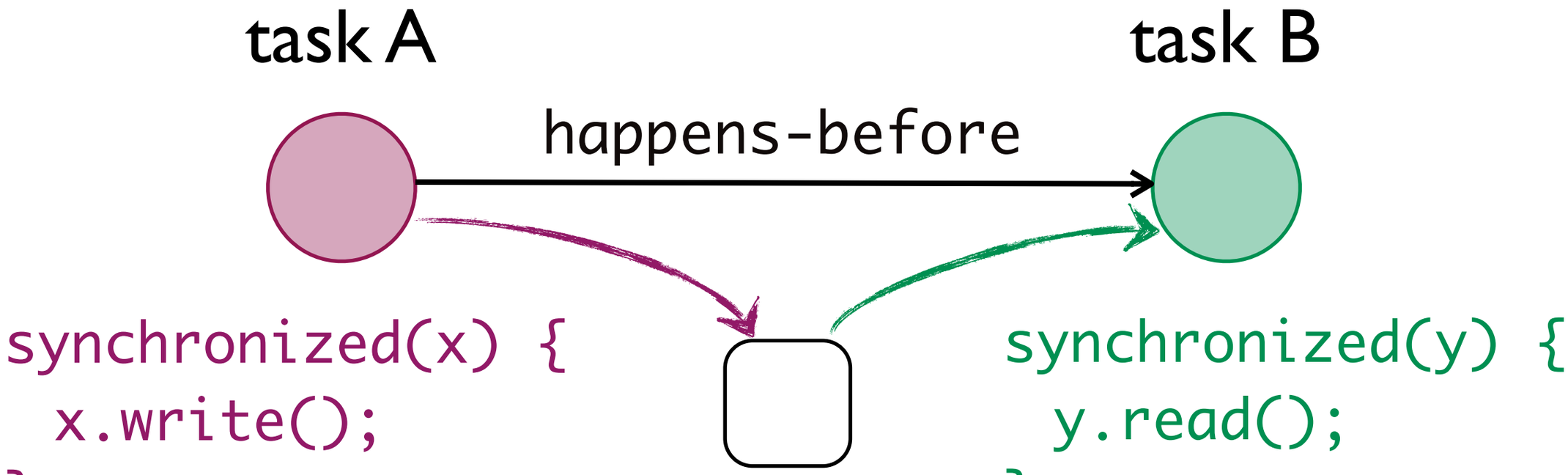

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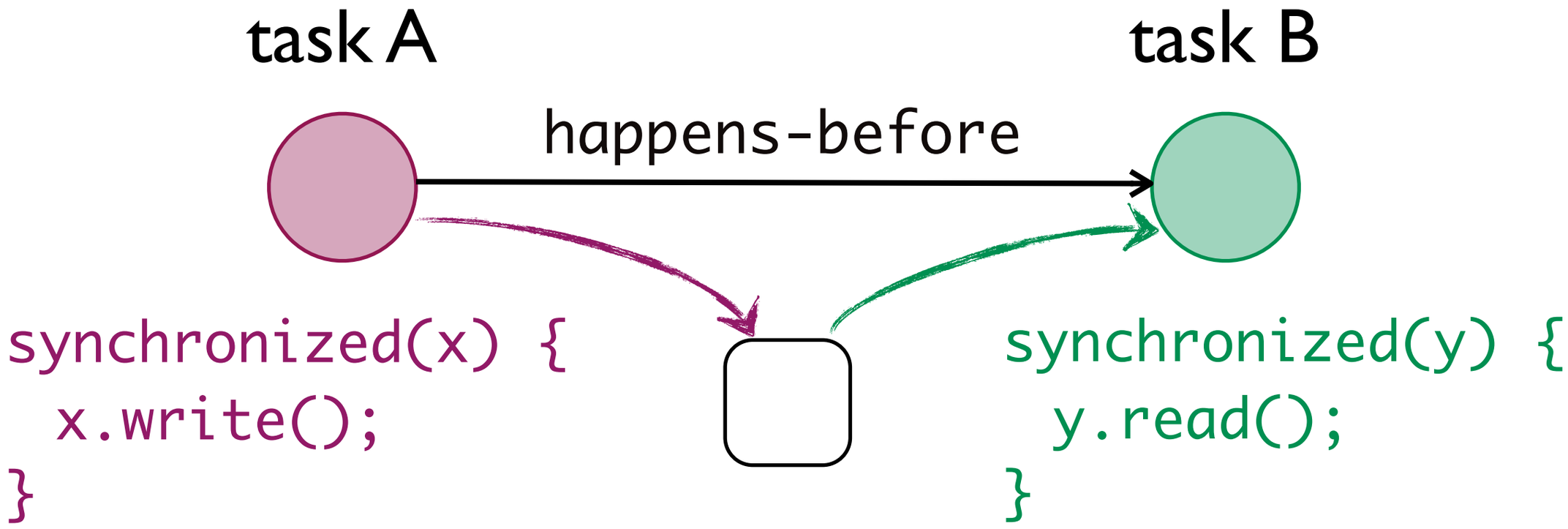

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☑ Ordered memory access

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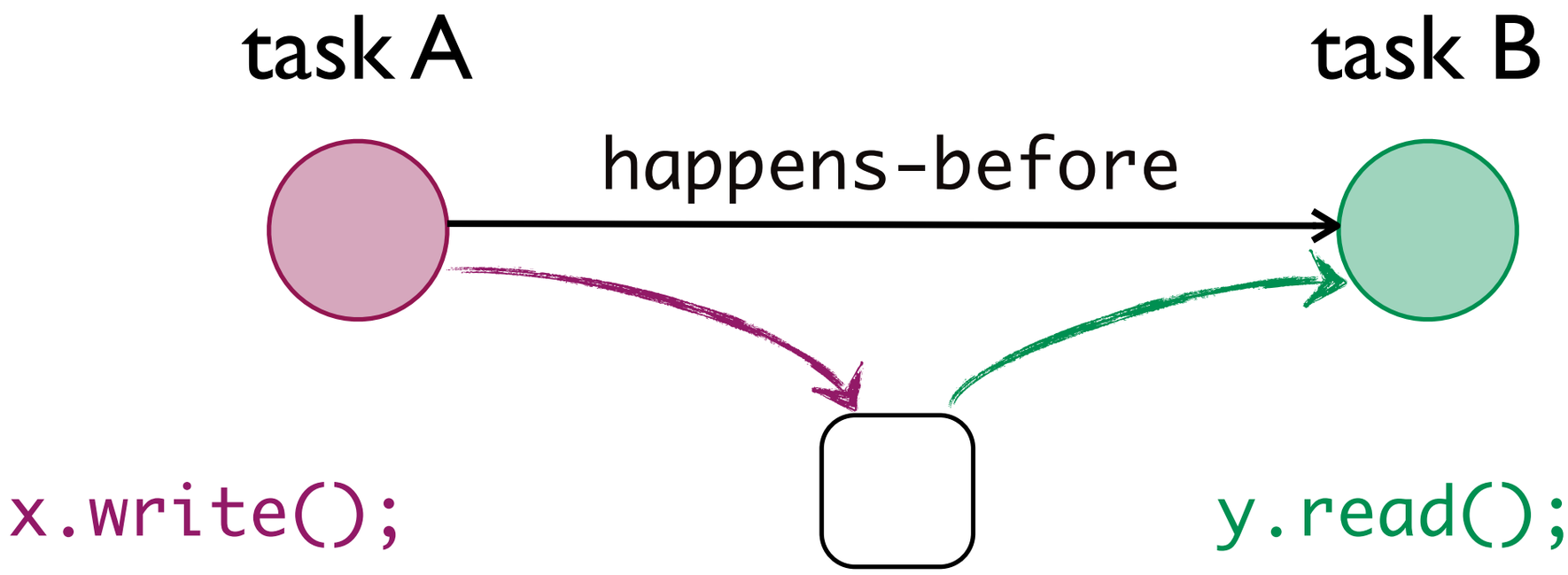

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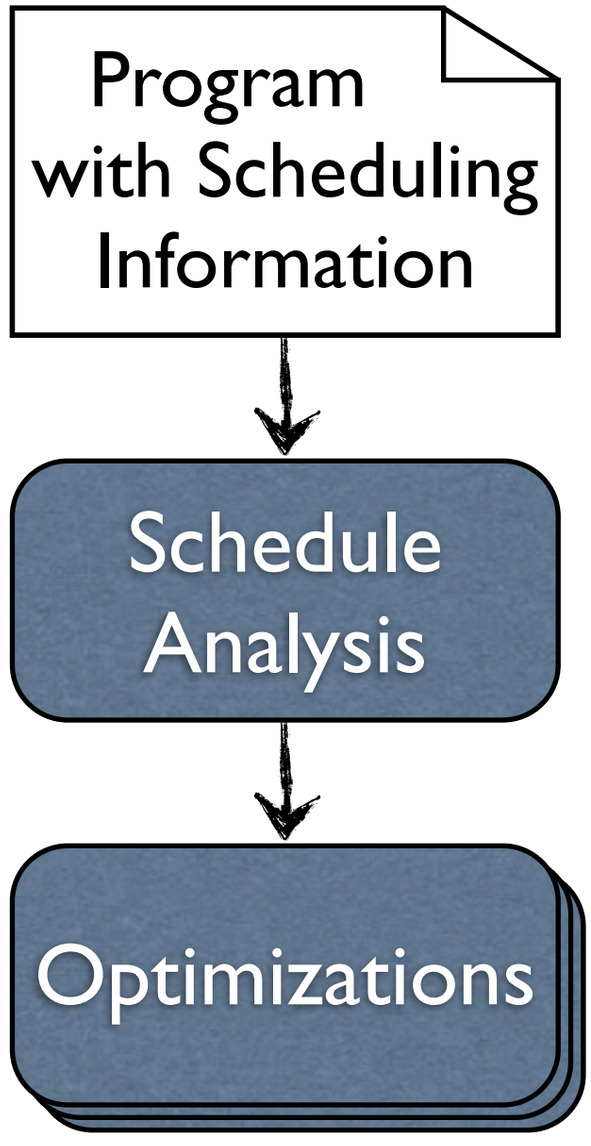
☑ Ordered memory access

Motivation

- Compilers profit from static knowledge about runtime schedules
- Optimizations today must reinvent own analyses
- Our goal: factor out analysis of task schedules
  - Simplification + integration of optimizations
  - Additional knowledge of happens-before relationships increases optimization potential

Schedule Analysis Overview



Outline

- Motivation
- Explicit Scheduling
- Genuine Edge Test
- Schedule Analysis
- Concluding Remarks

Explicit Scheduling Model

- A program representation that:
  - Contains explicit scheduling information
  - Allows for static reasoning
- General enough for *structured* (fork/join, Cilk, OpenMP) and *unstructured* parallelism (threads)
- Pre-processing step transforms traditional programs into programs with explicit scheduling

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- Keyword now references currently executing activation

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```
a → b;
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- Implicit happens-before relationship between scheduling task and scheduled task
  - Gives scheduling task time to add happens-before relationships

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  task doWrite() {...}
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  task doCompute() {
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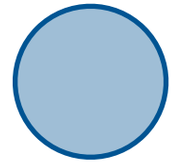


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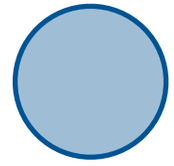


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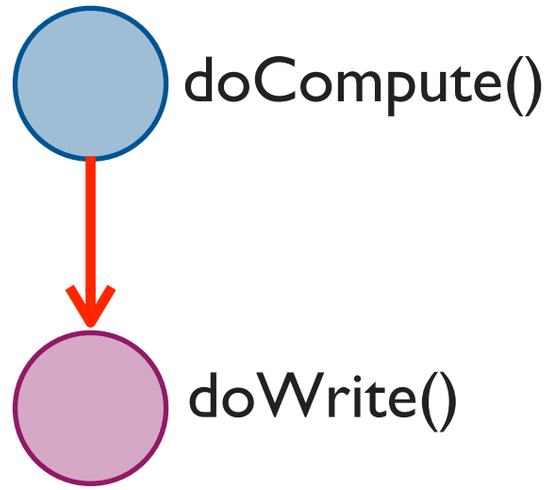

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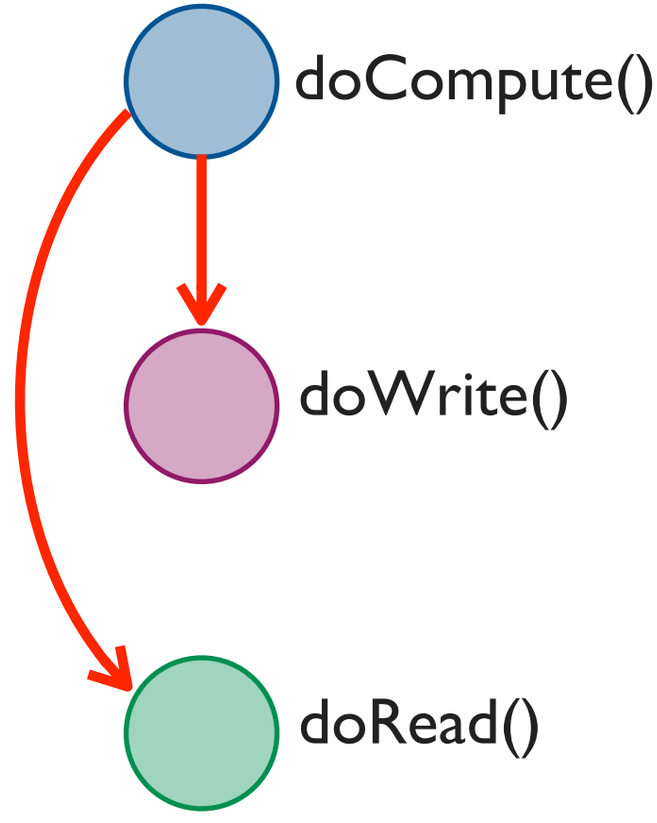

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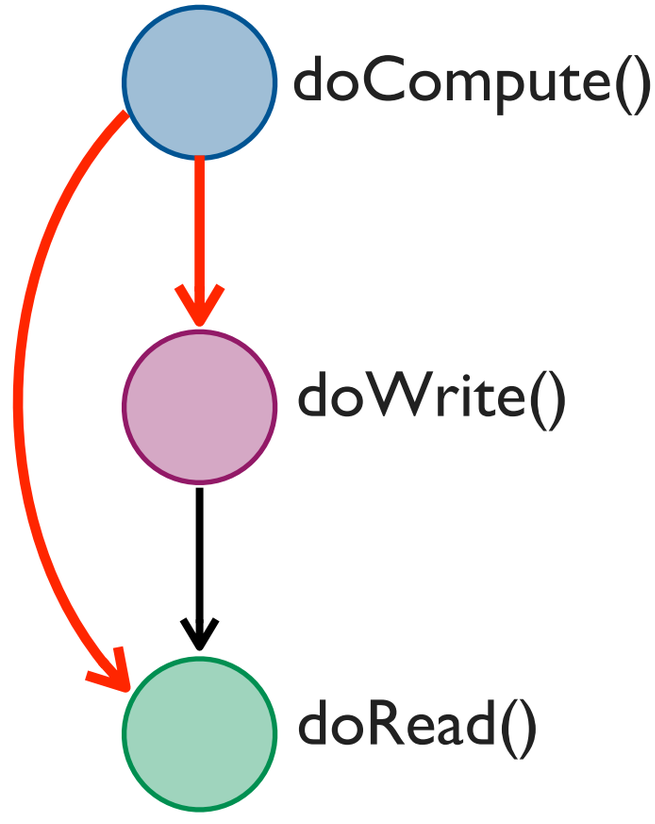

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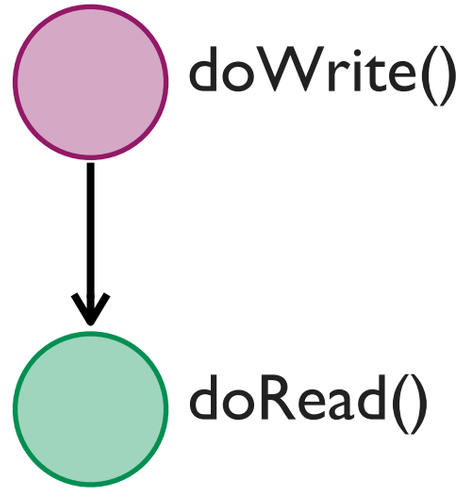

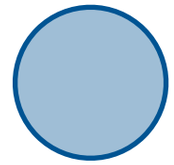


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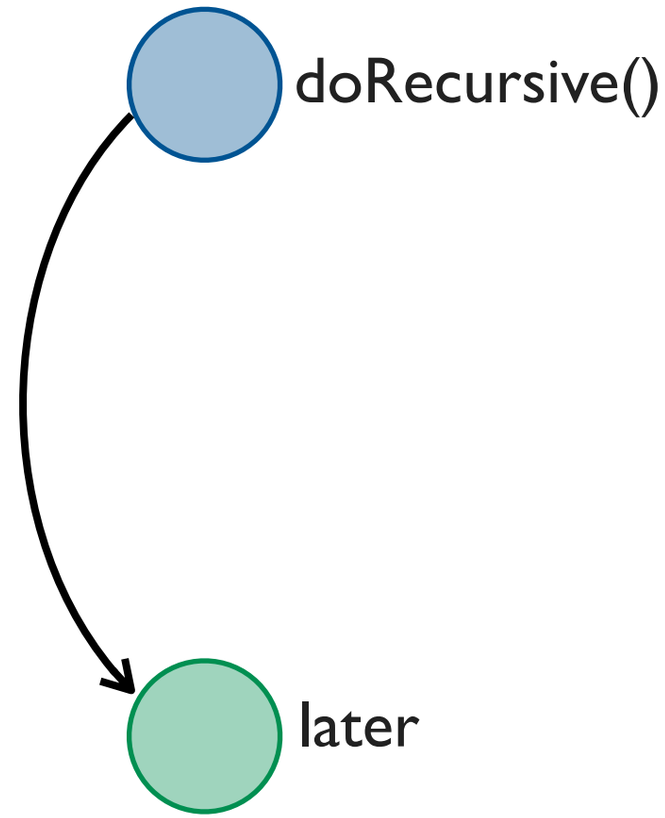

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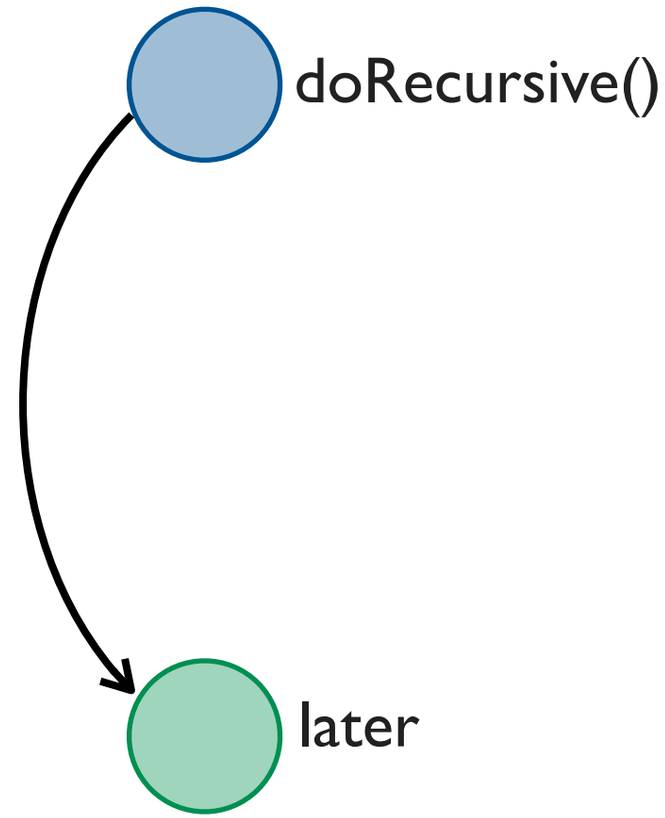

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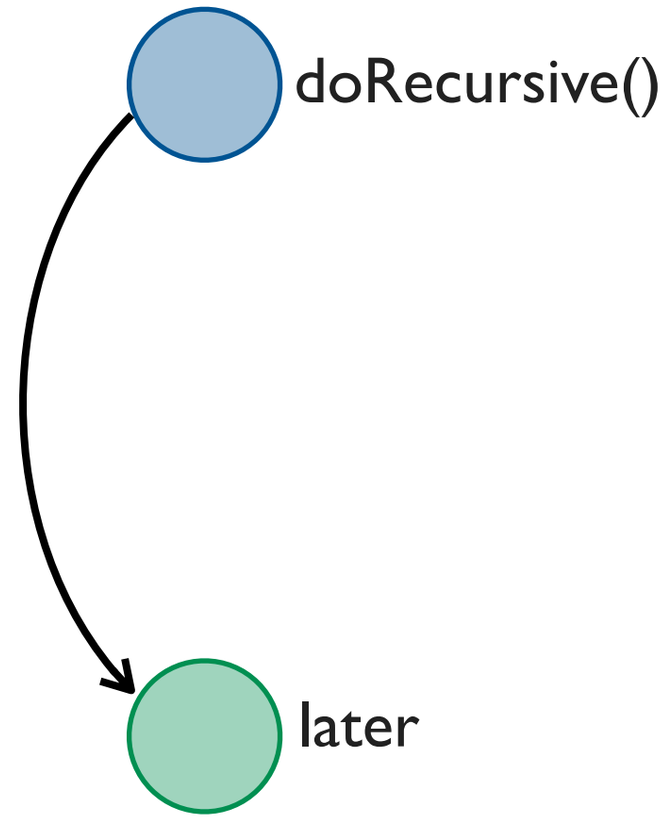

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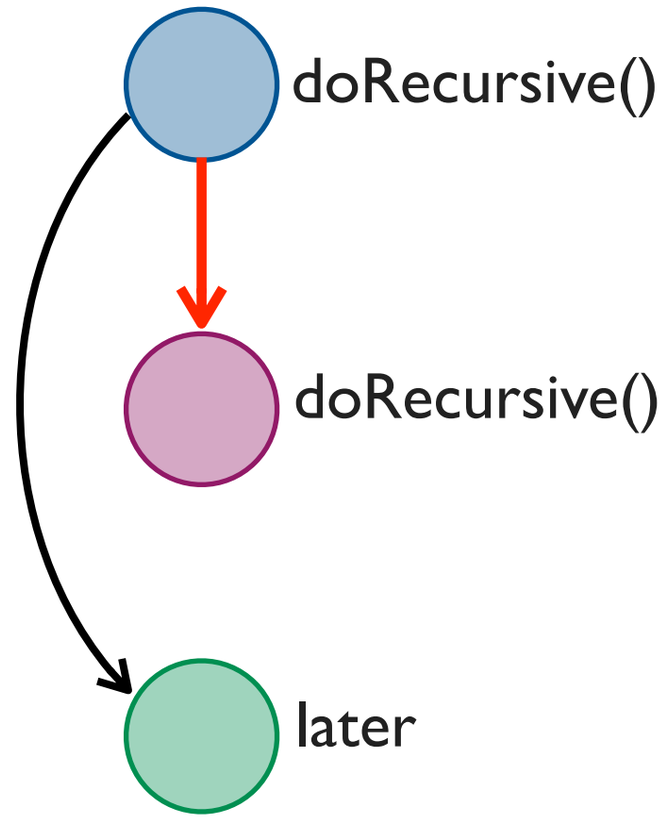

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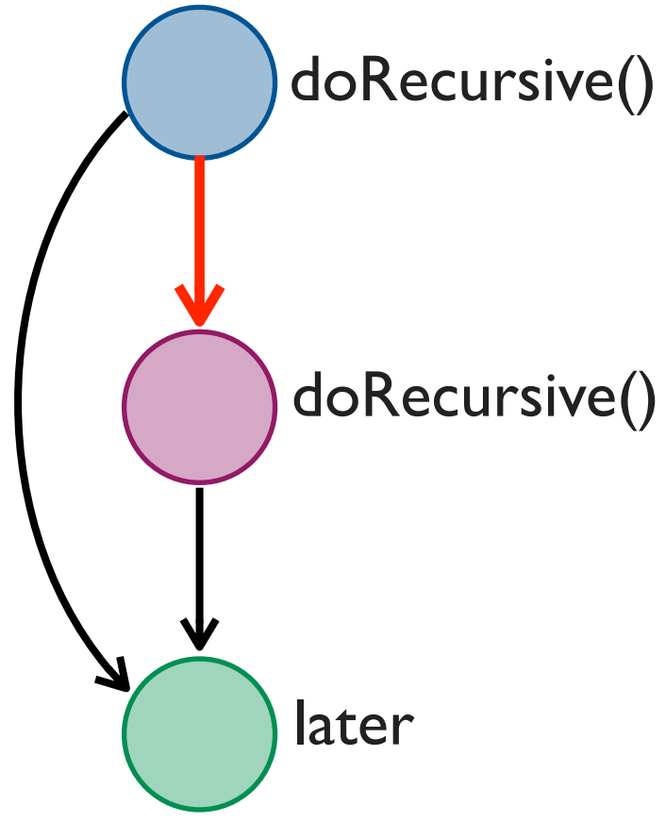

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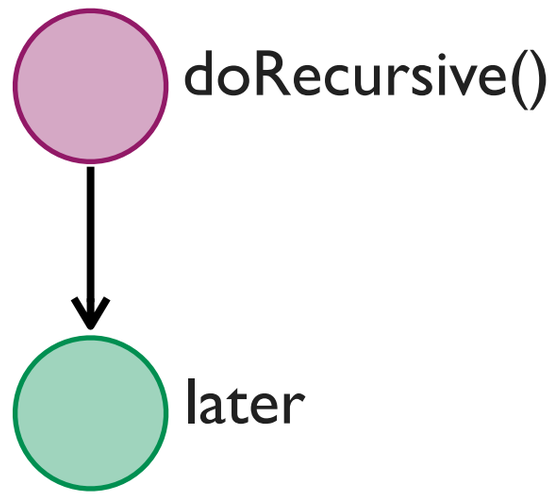

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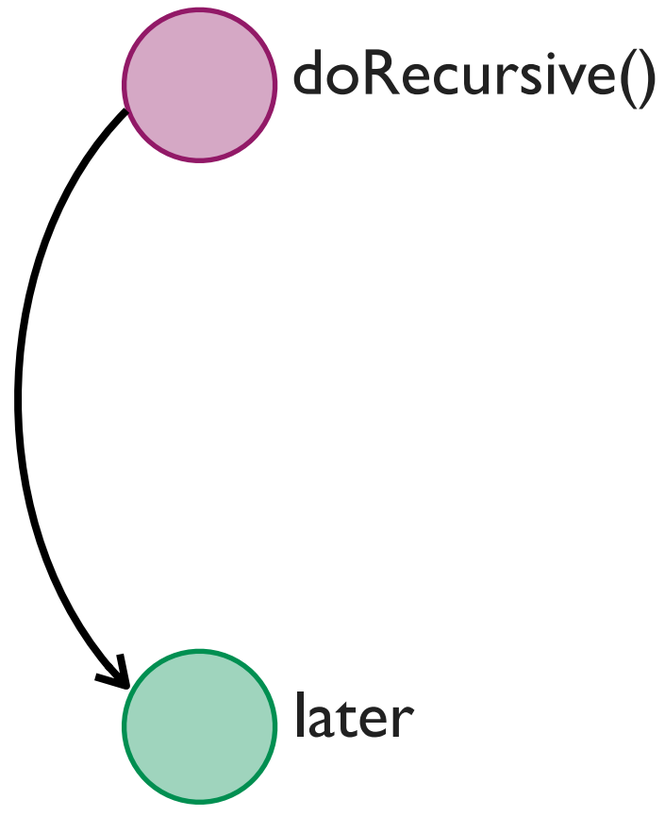

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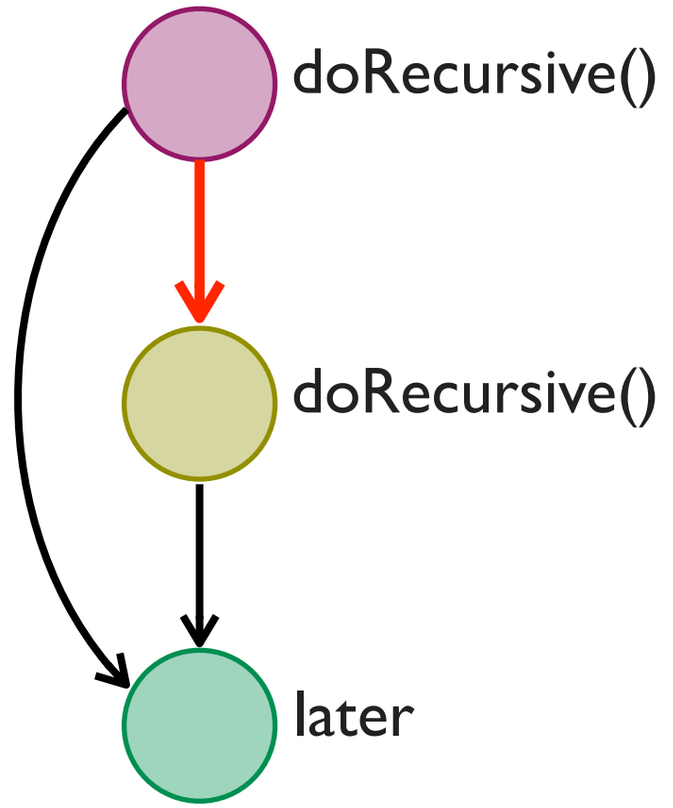

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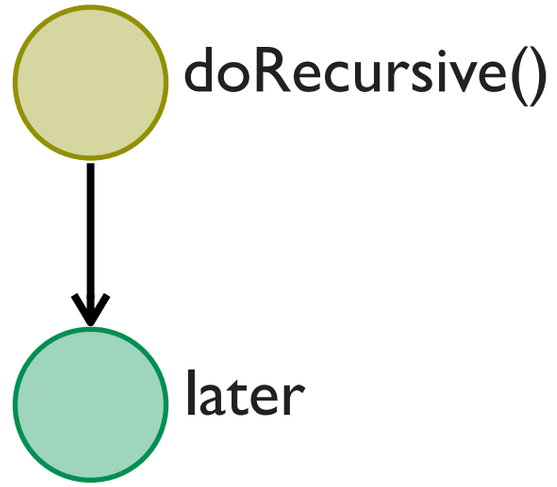

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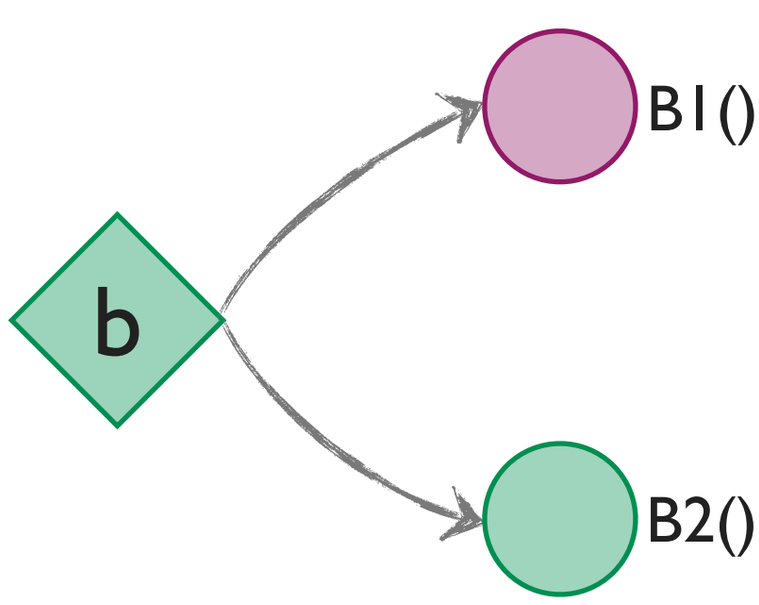

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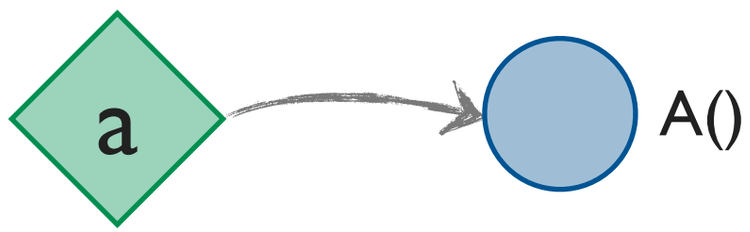

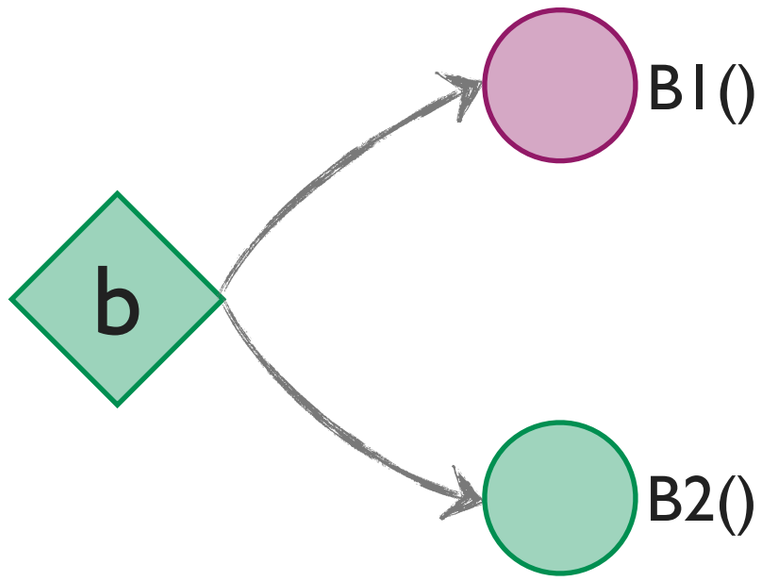

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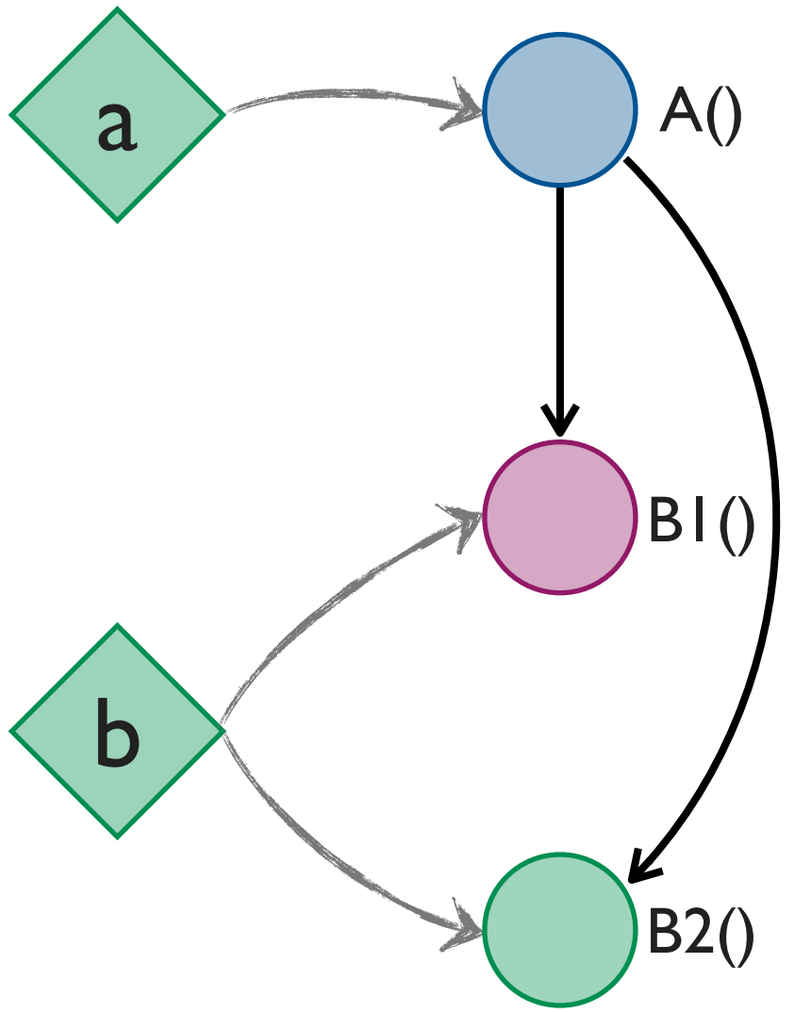

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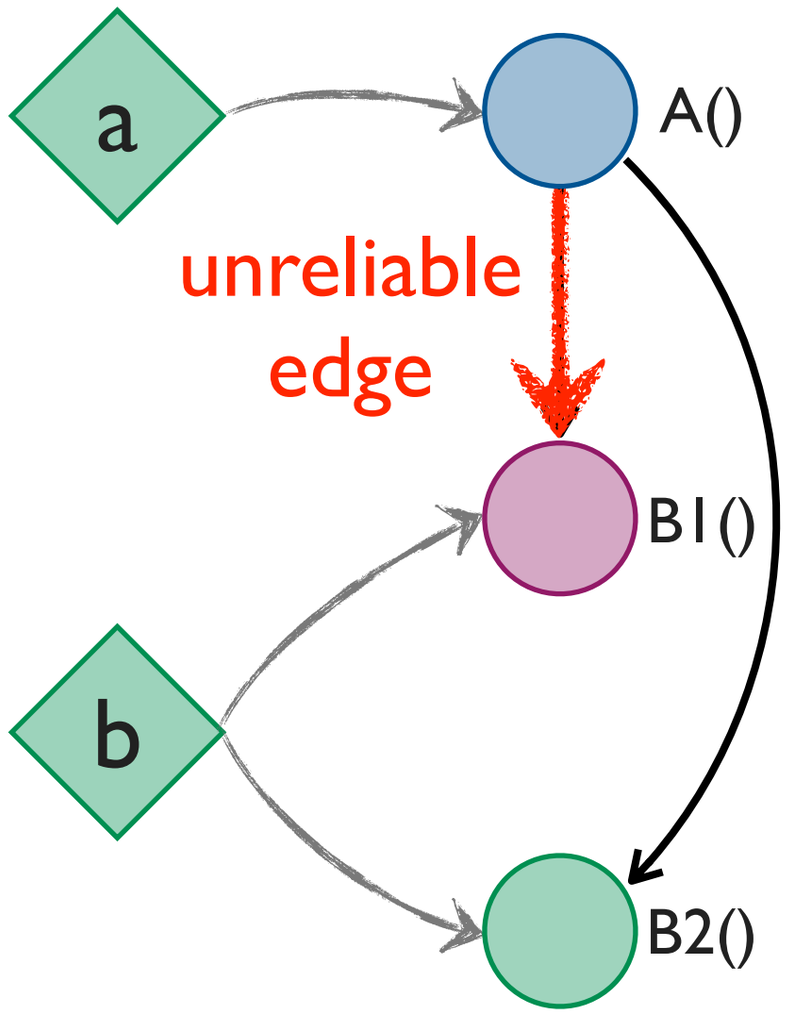

Genuine Edges

- An edge x → y is *genuine* **if activation** of x implies edge has been created

Types of Edges

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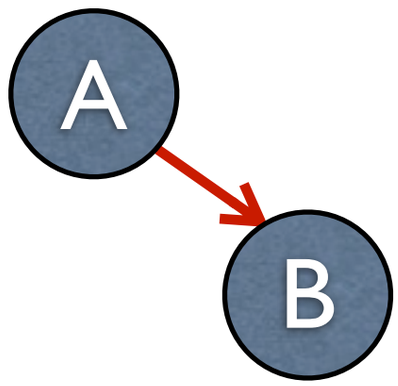
- *creation edges:* **A schedules B**



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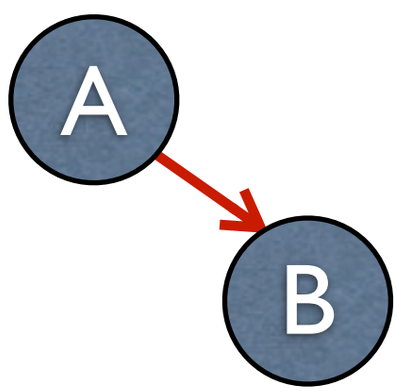

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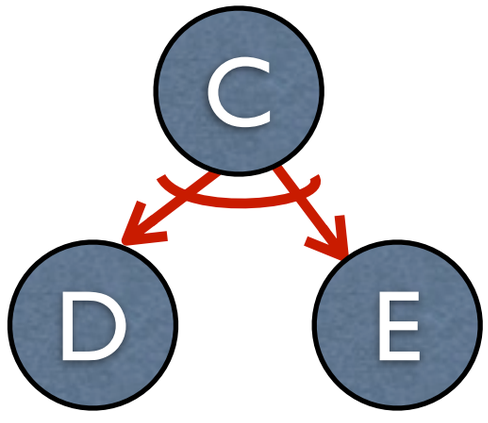

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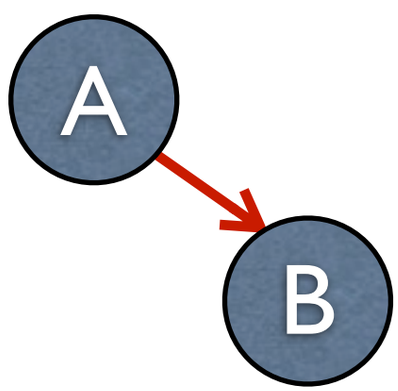

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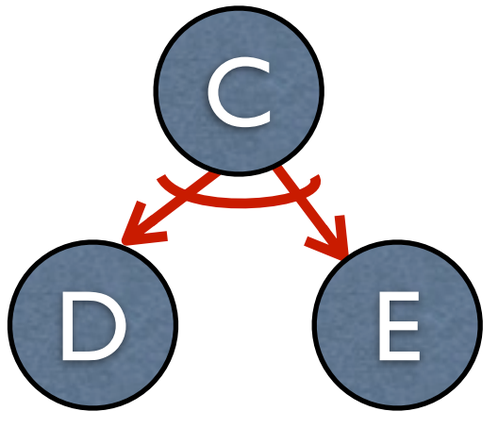
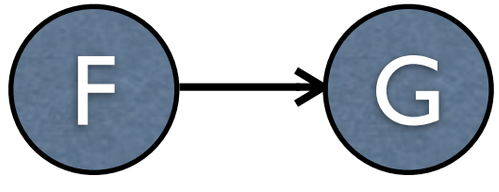


- *explicit →-statement:* **F happens-before G**



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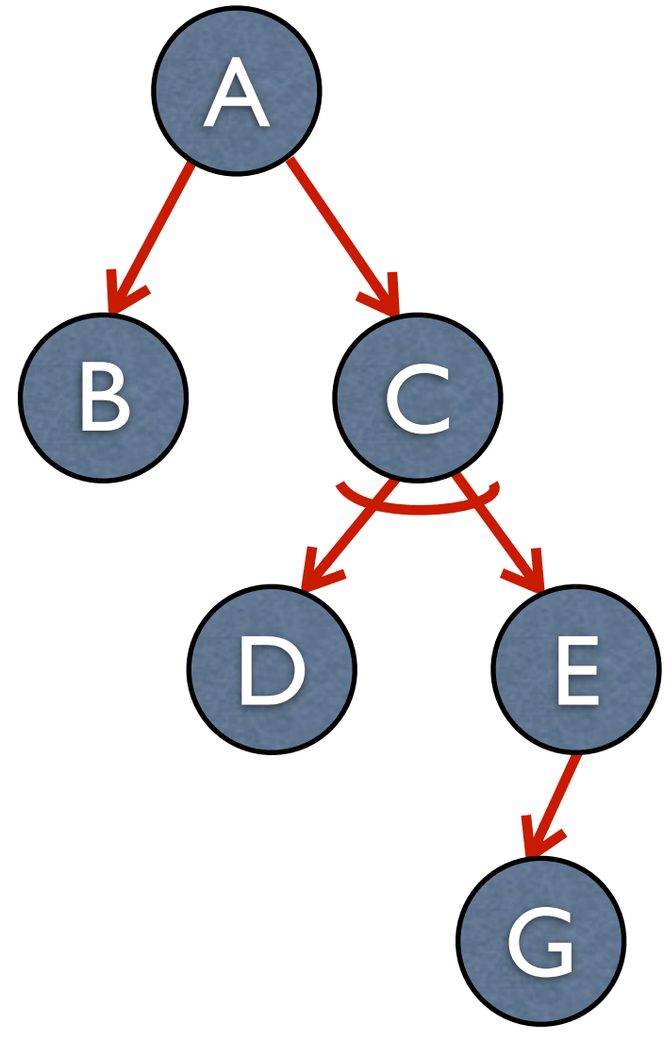

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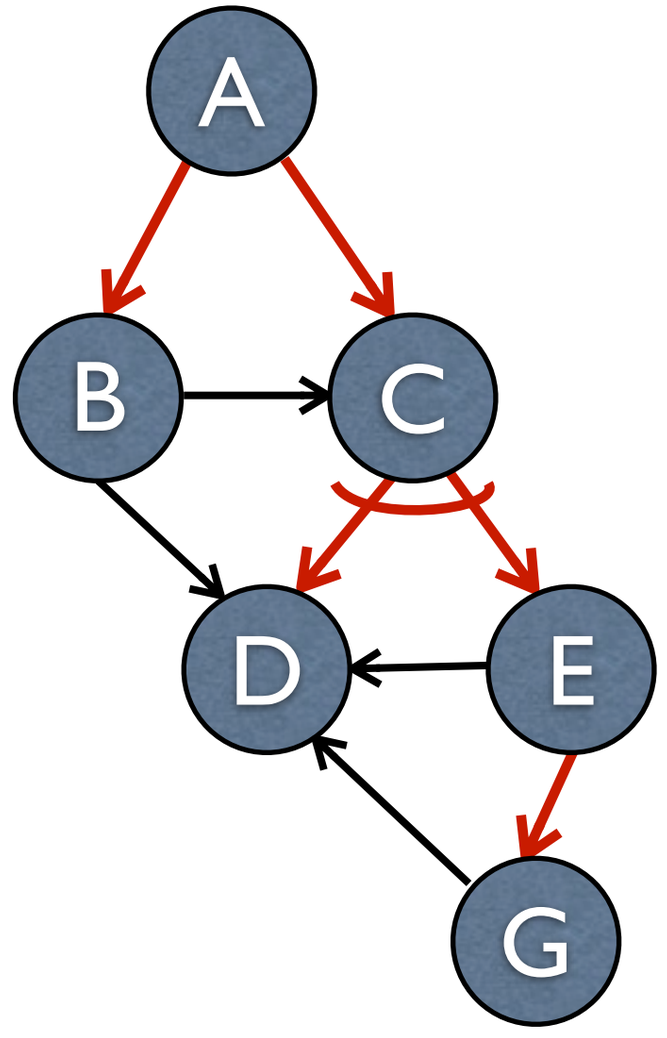

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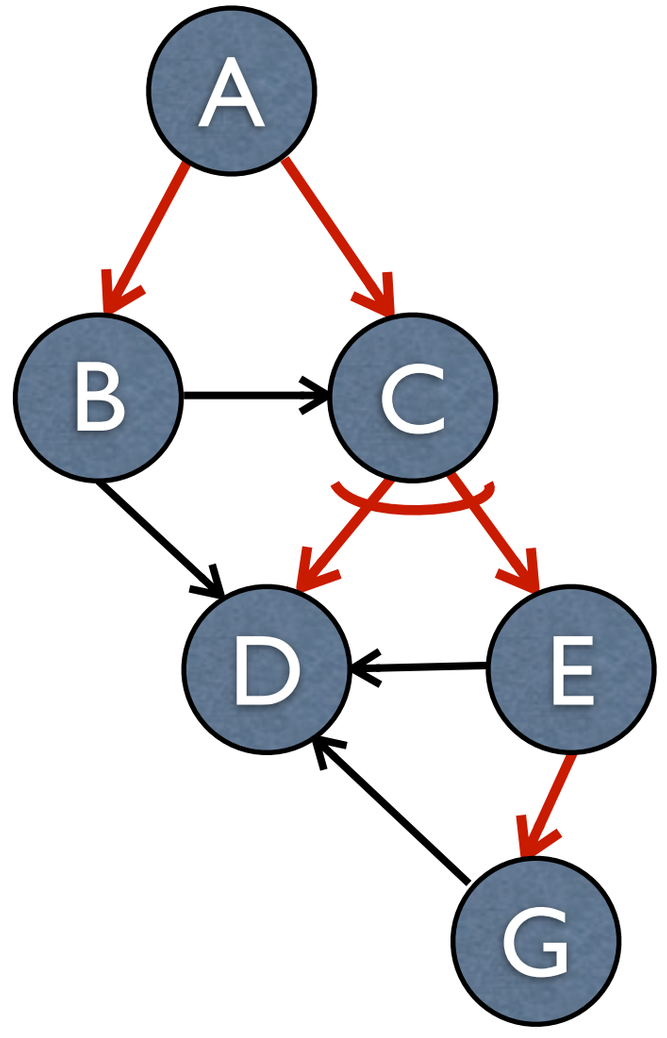
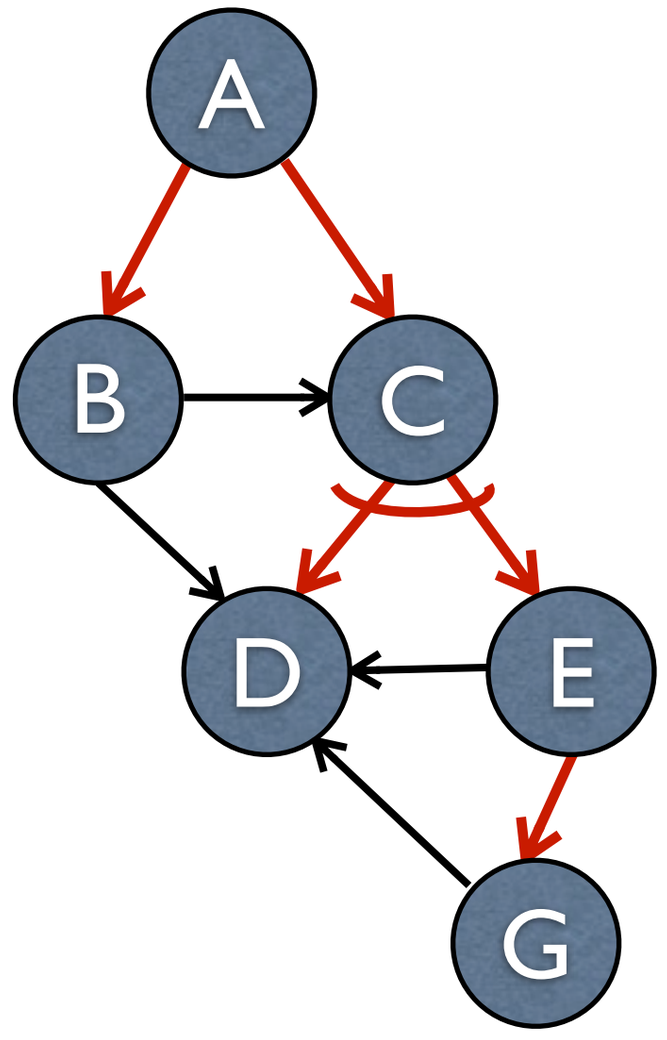
- Creation Tree: a *spanning tree* embedded in schedule

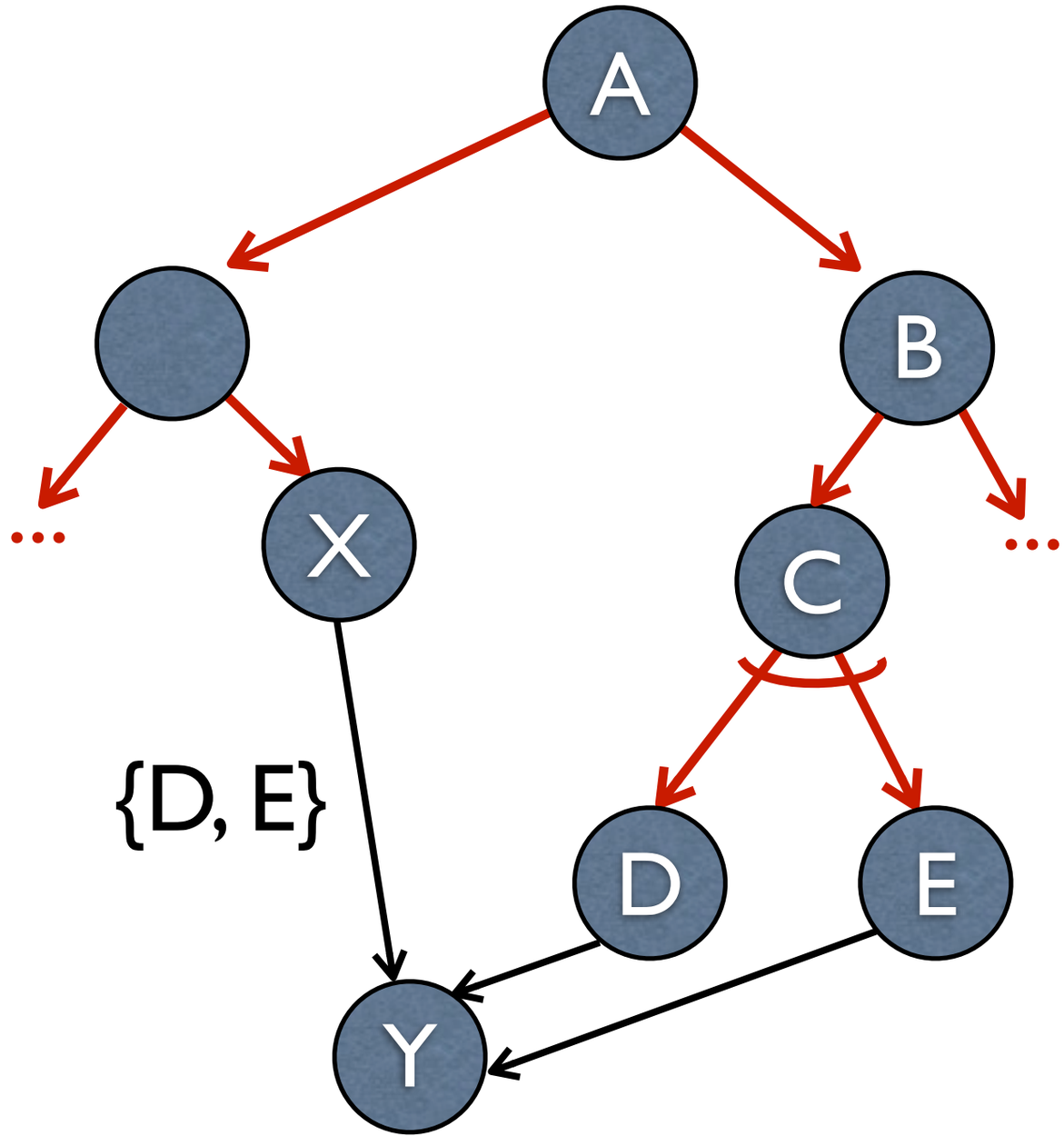


Creation Tree

- Every activation is created by exactly one parent activation
- Creation Tree: a *spanning tree* embedded in schedule
- Useful property:
  - Execution of child implies the completion of parent
  - Creation edges are *genuine*

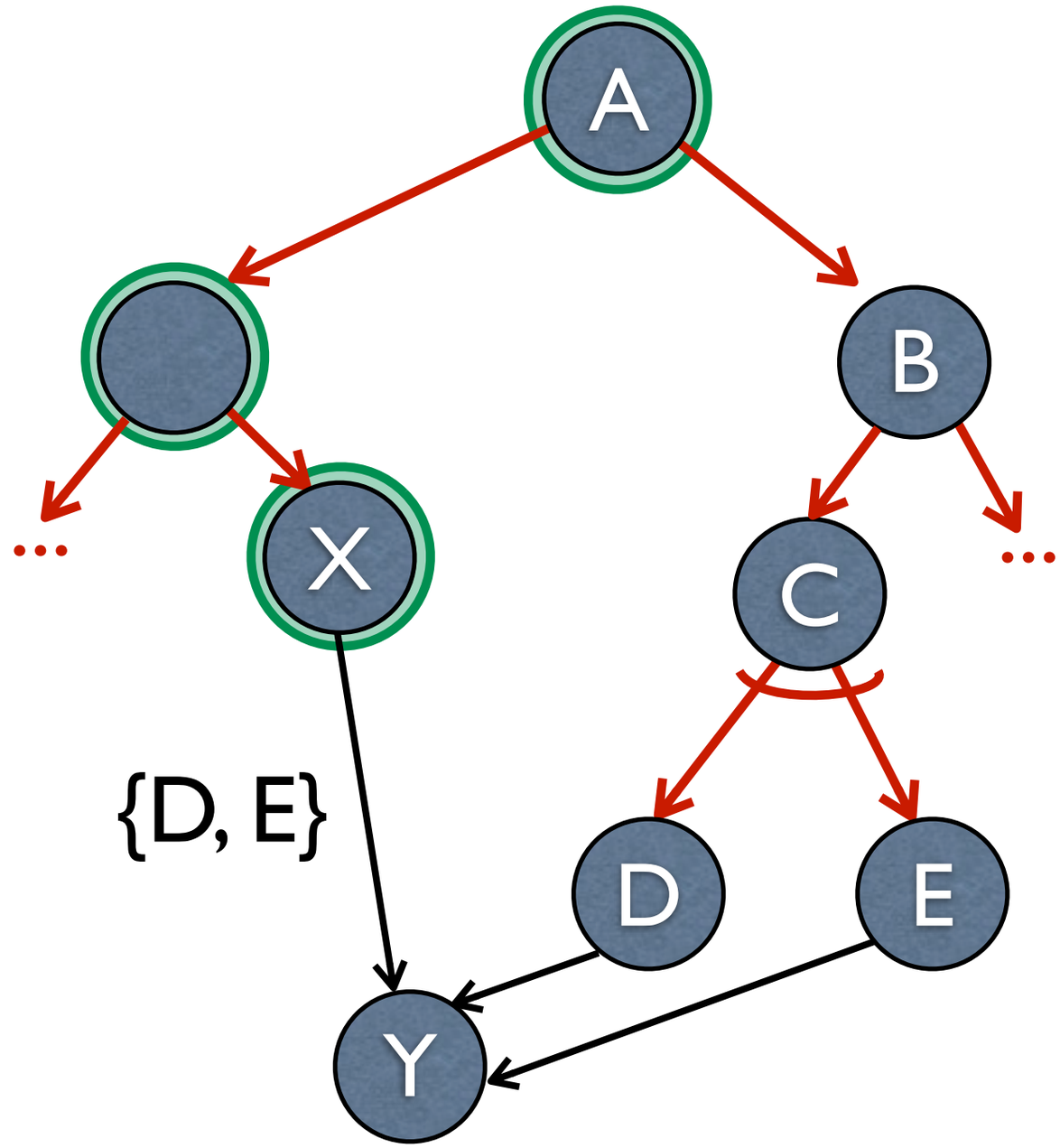


Computing Genuine Edges



Computing Genuine Edges

1. Mark all parents of x ("the fence")



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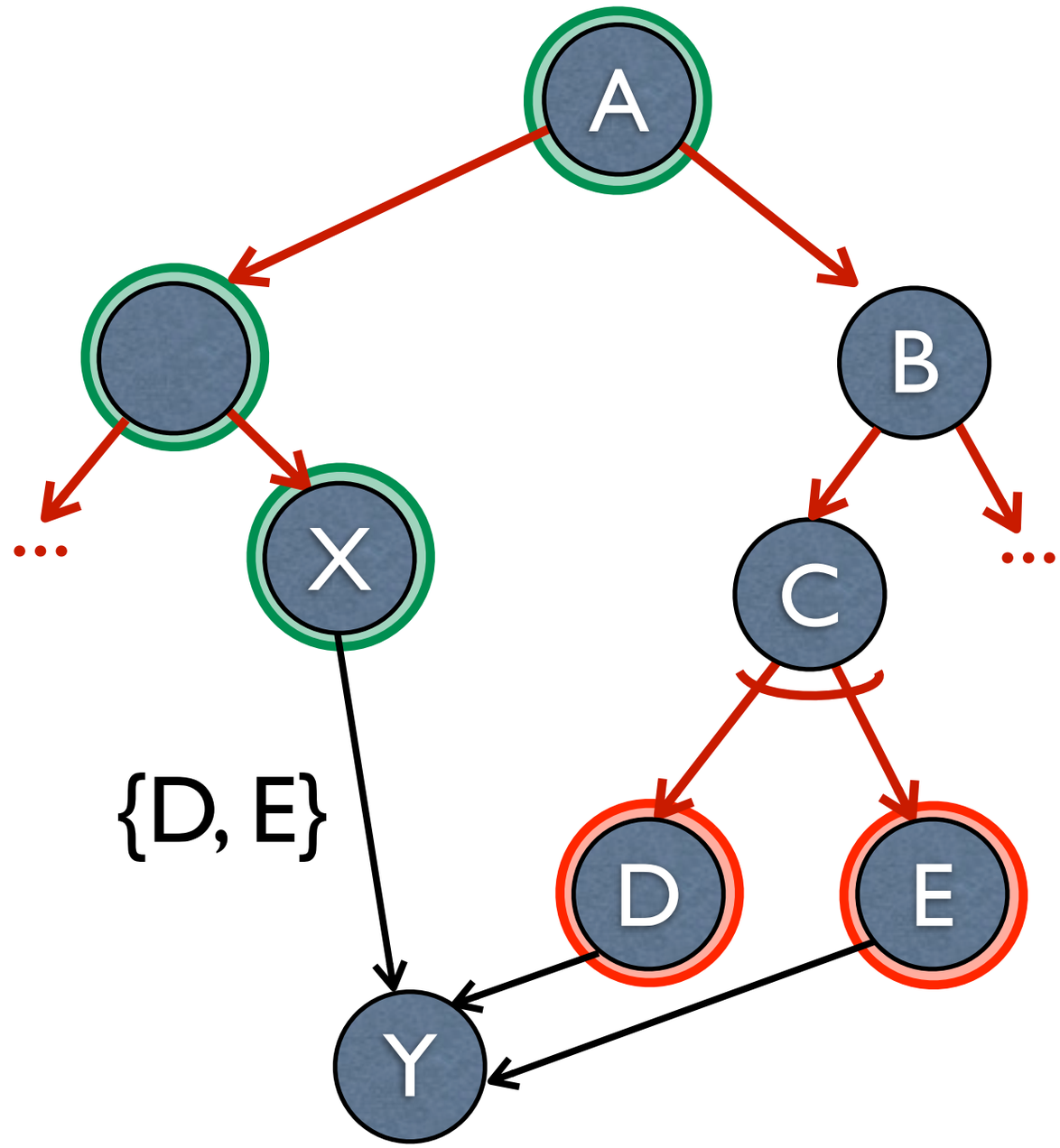

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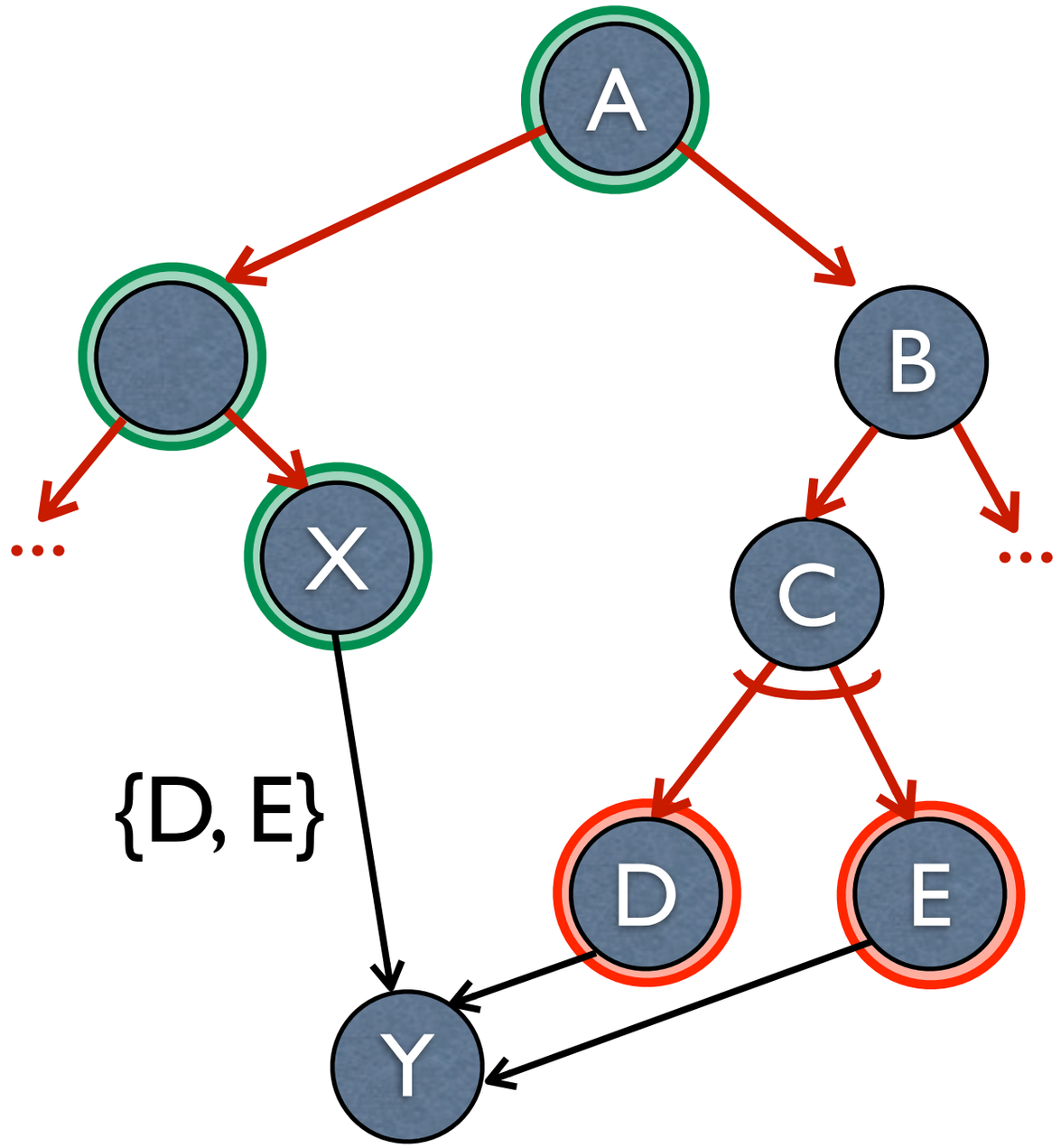

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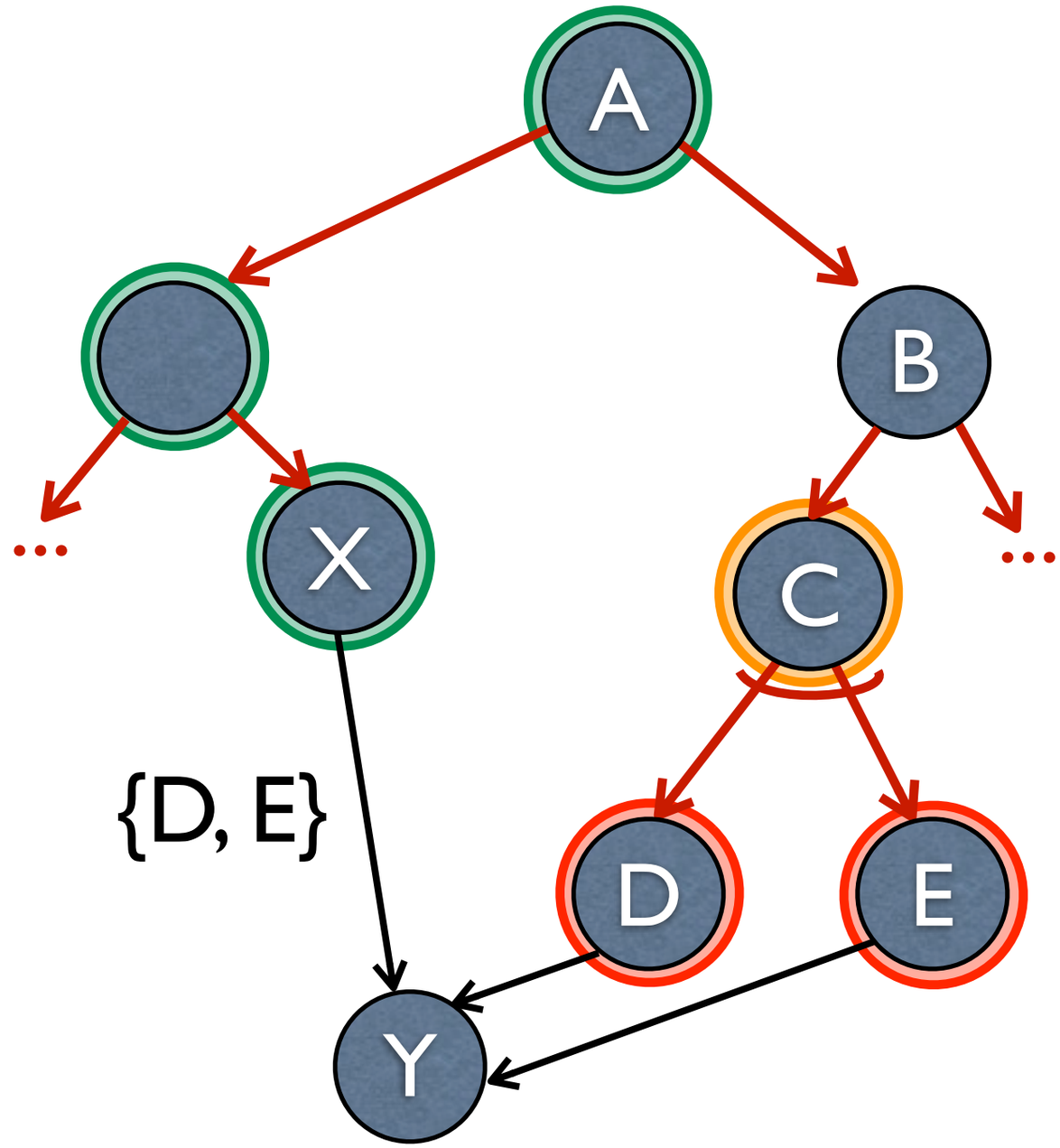

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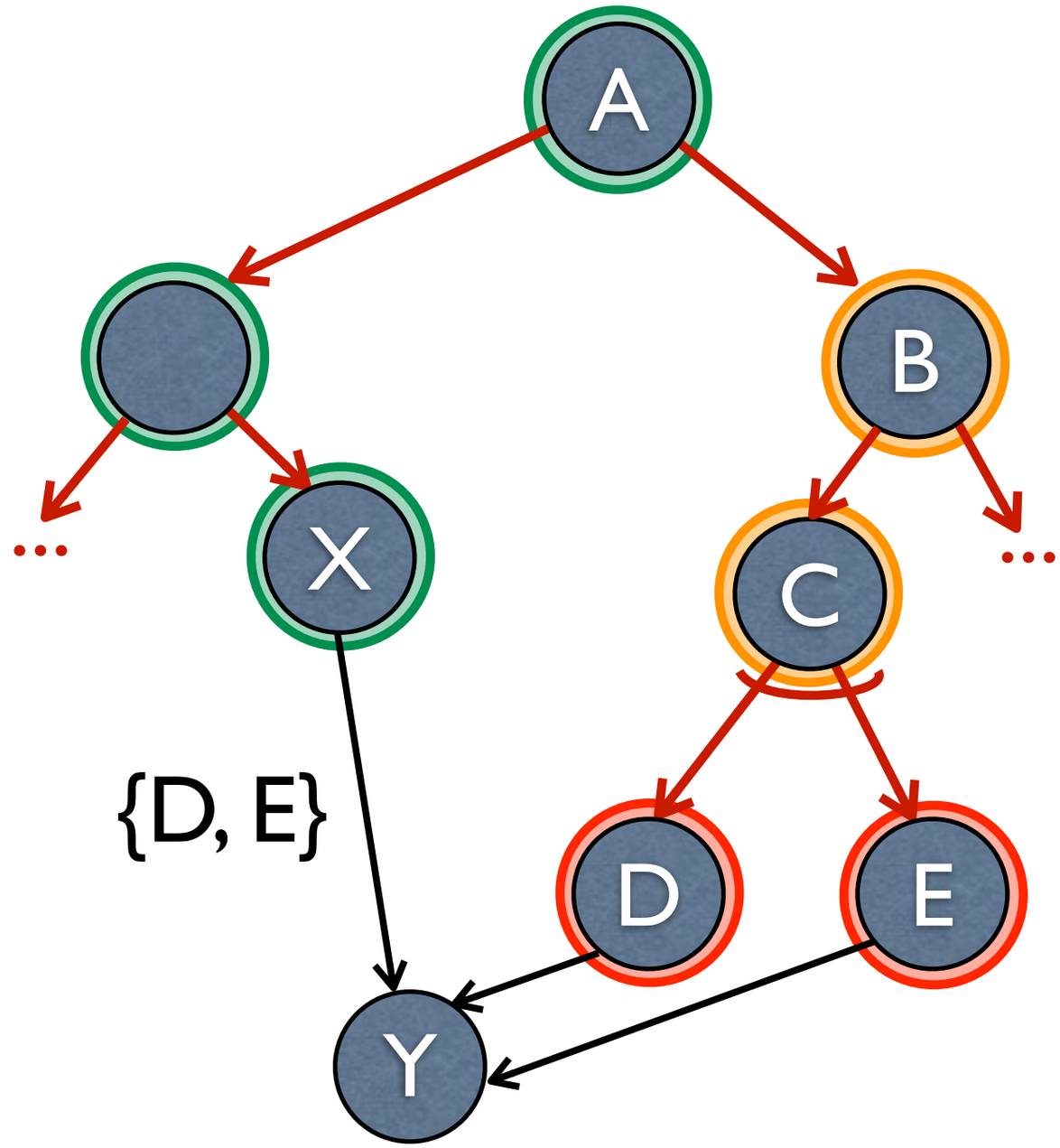

Computing Genuine Edges

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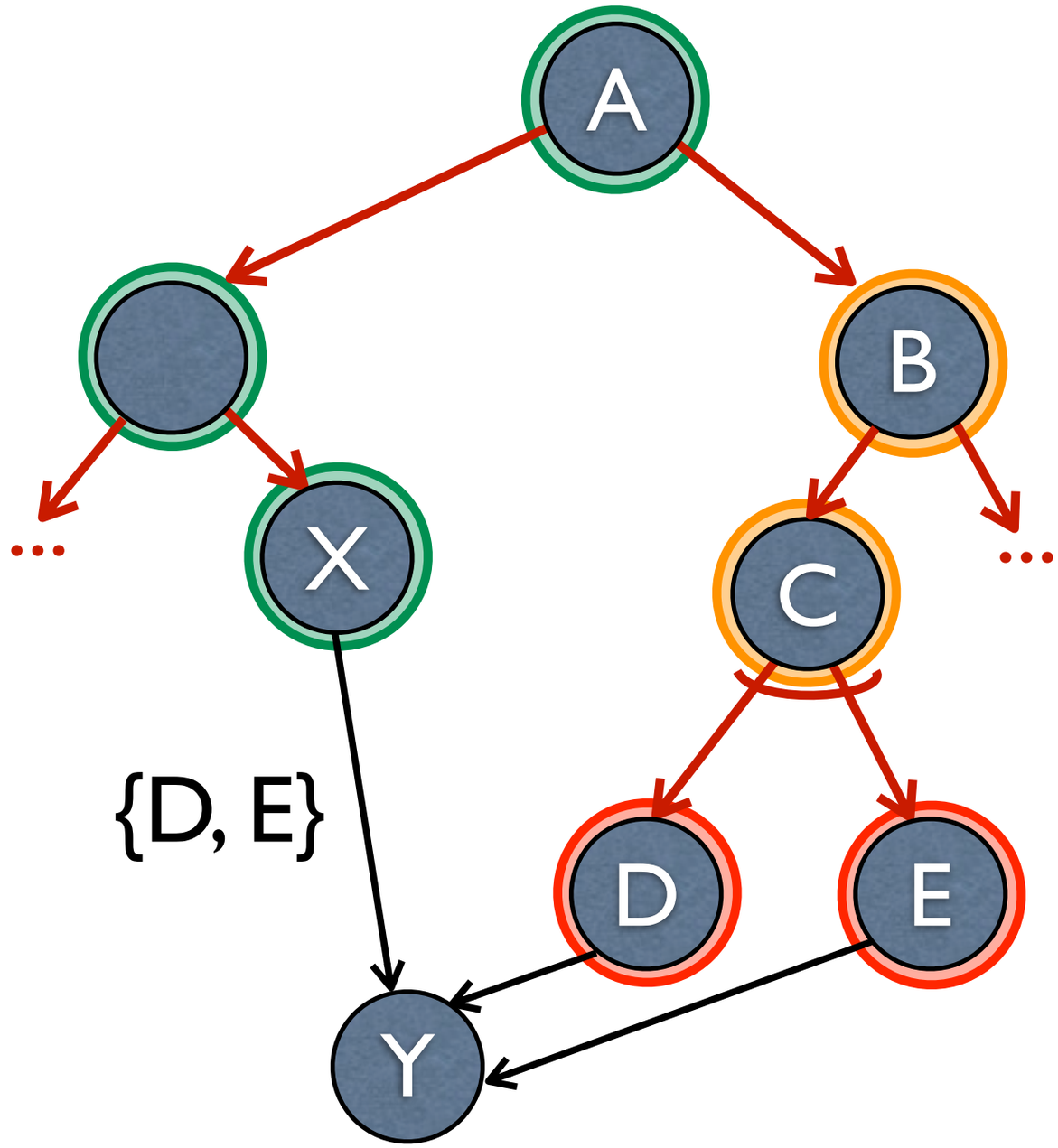
4. Stop when a parent of x is touched



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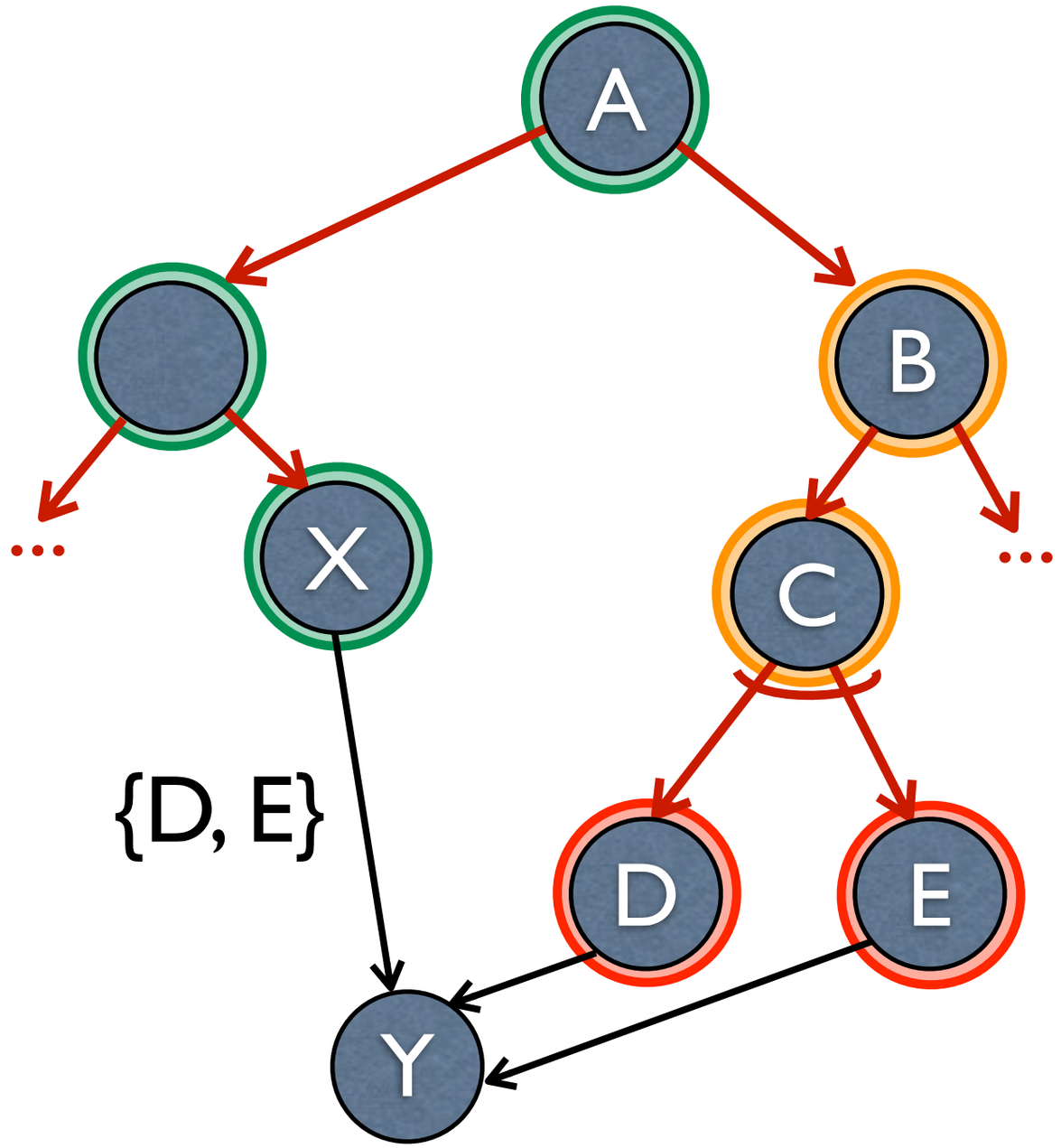

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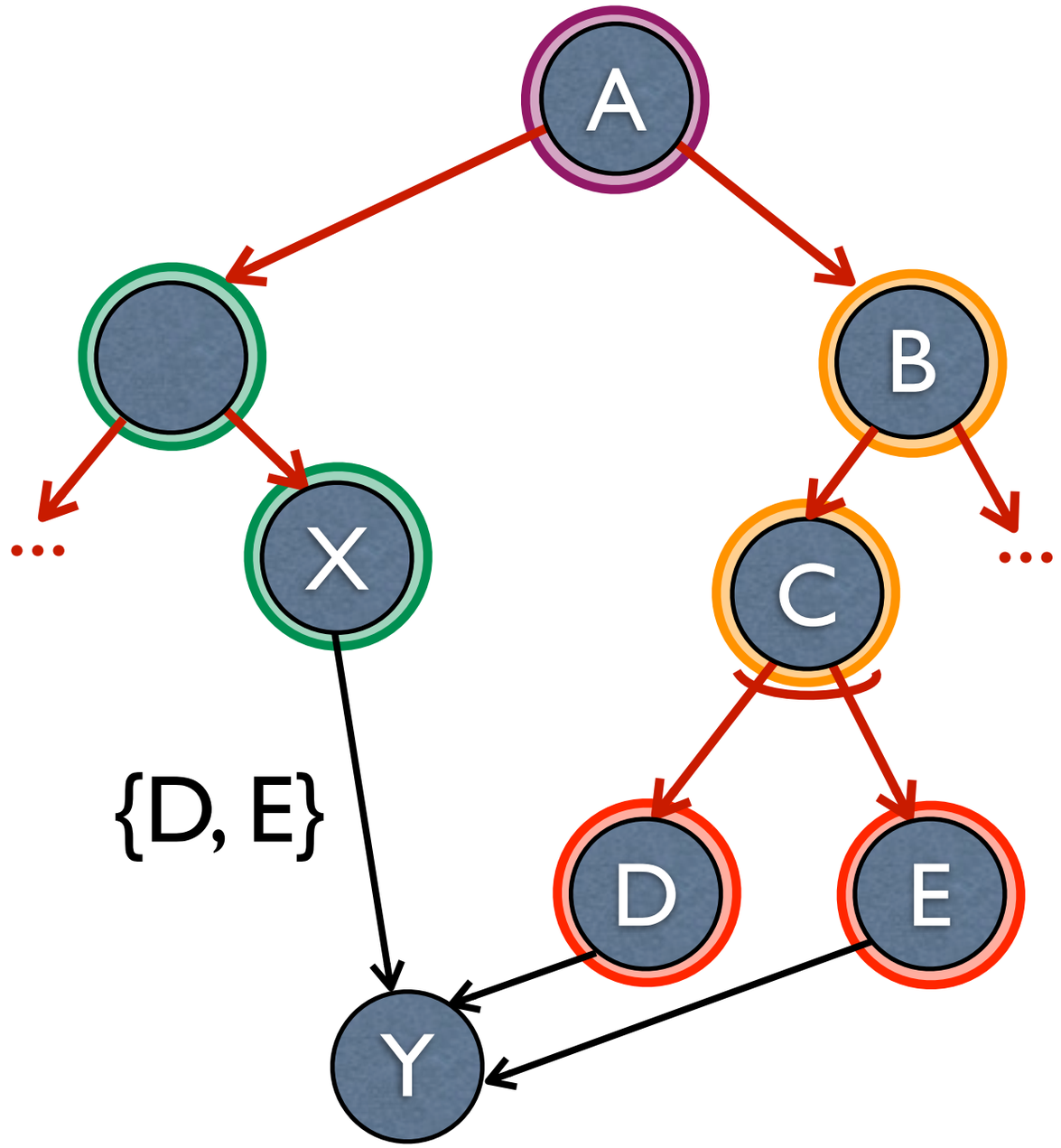
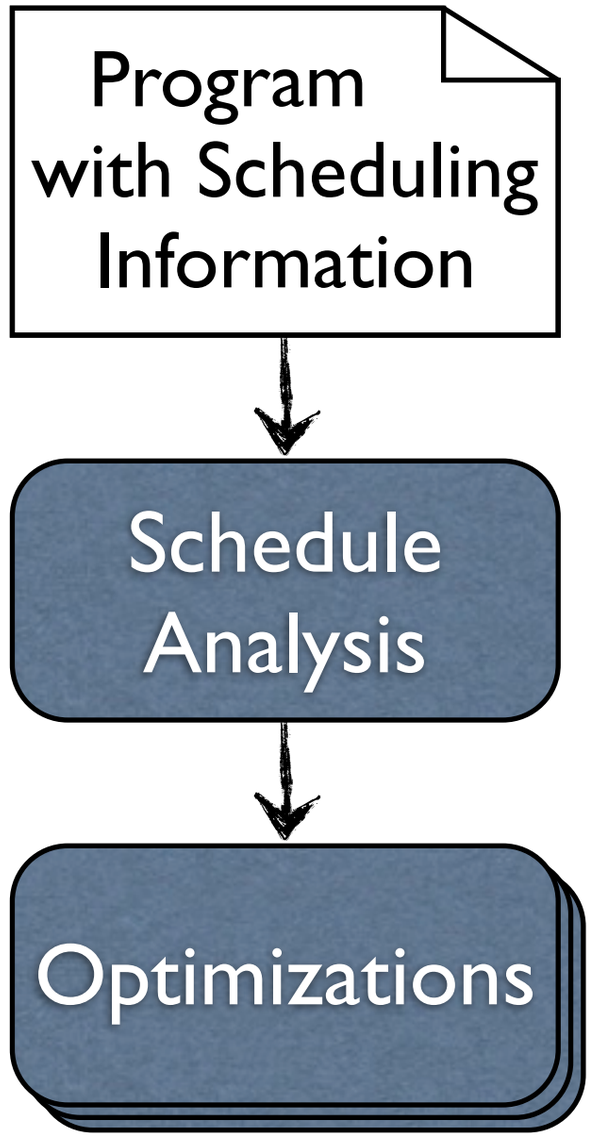


Outline

- Motivation
- Explicit Scheduling
- Genuine Edge Test
- Schedule Analysis
- Concluding Remarks

Schedule Analysis Overview



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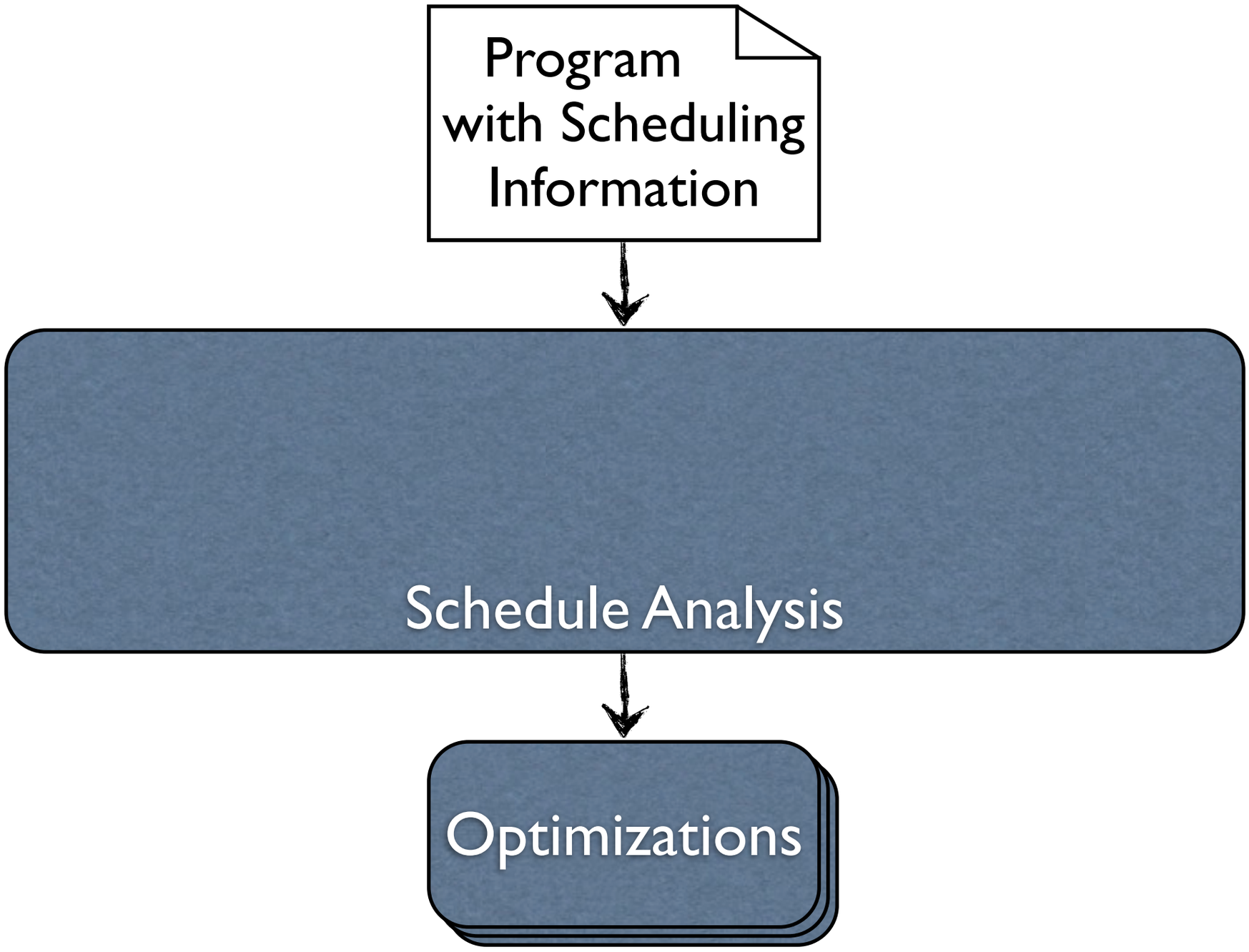

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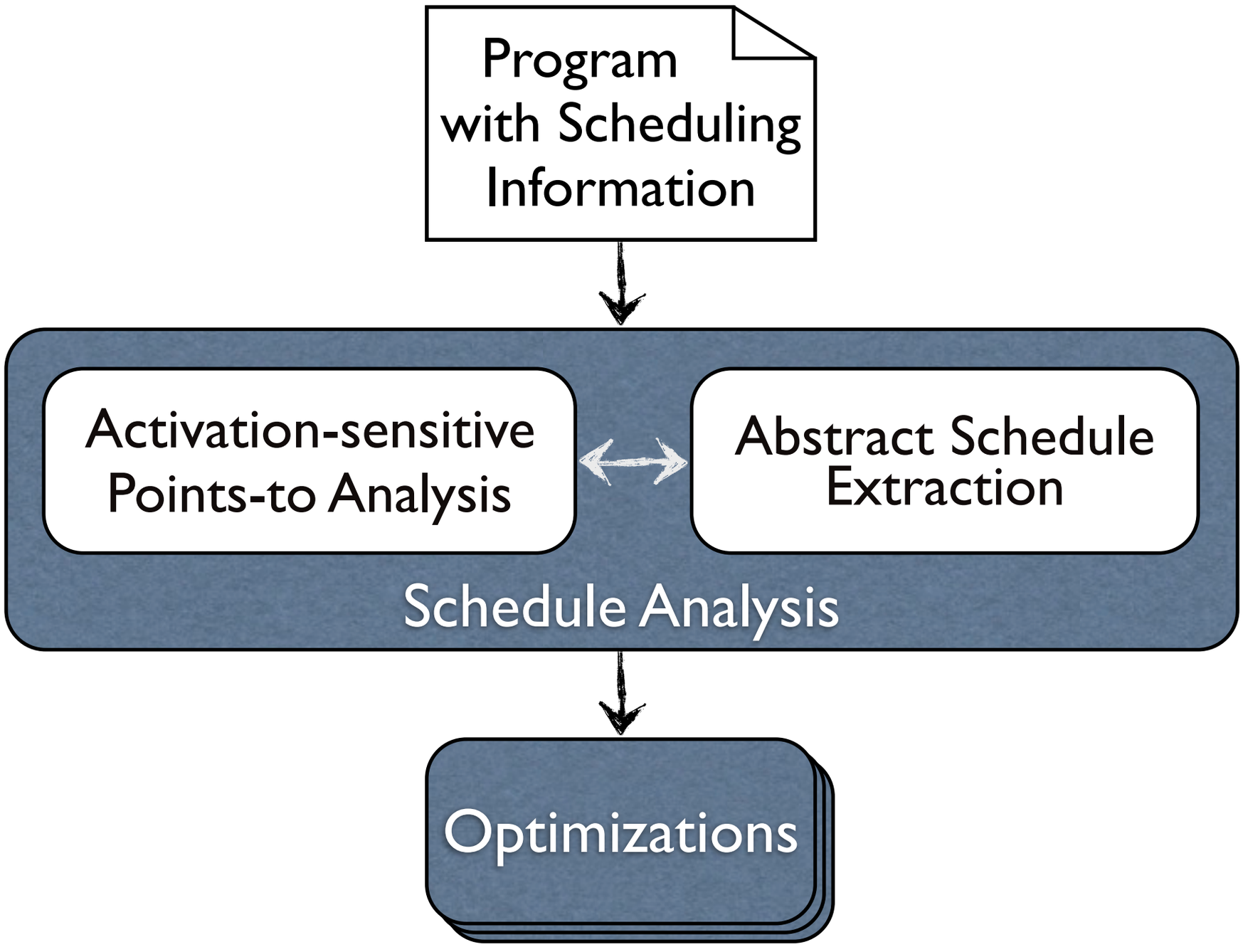

Points-to Analysis

- Computes points-to sets for each program variable
- Activation-sensitive
- →-statements handled in Schedule Extraction phase
- Treats `schedule` statements as method calls
  - Parameters are bound at schedule-time
  - Flow-insensitive with respect to calls

Schedule Extraction

```
task A() {
  T x = new T();
  T y = random ? new T() : x;

  Activation b = schedule B(x);
  Activation c = schedule C(y);

  b → c;
}
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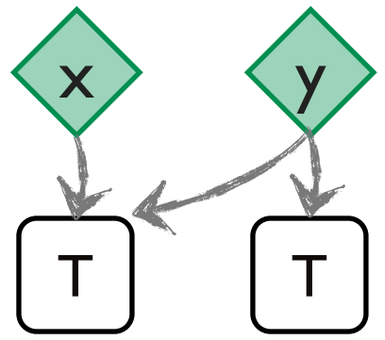

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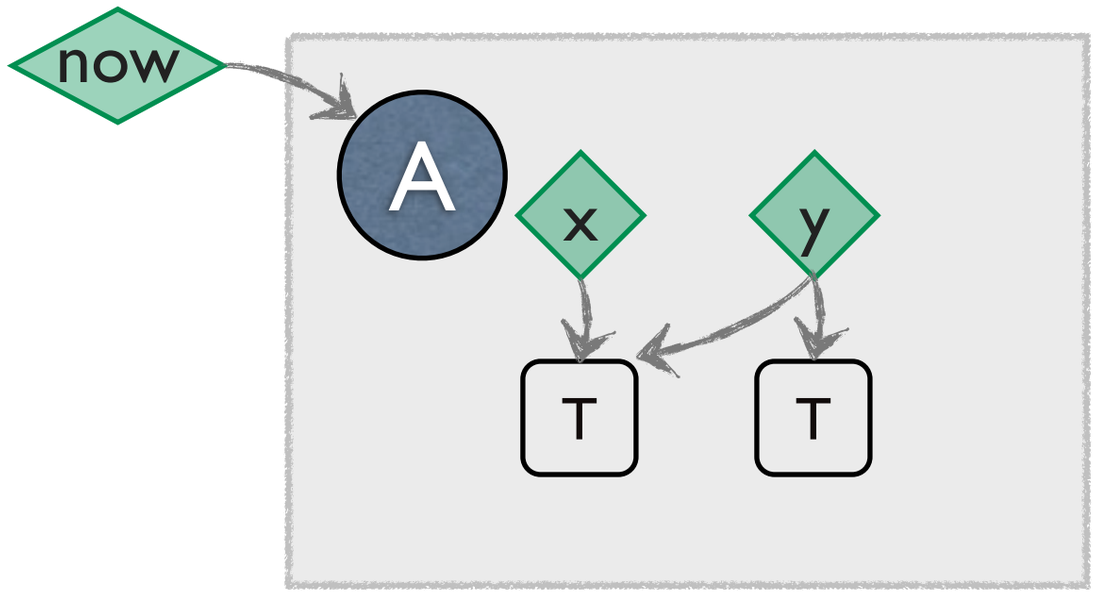

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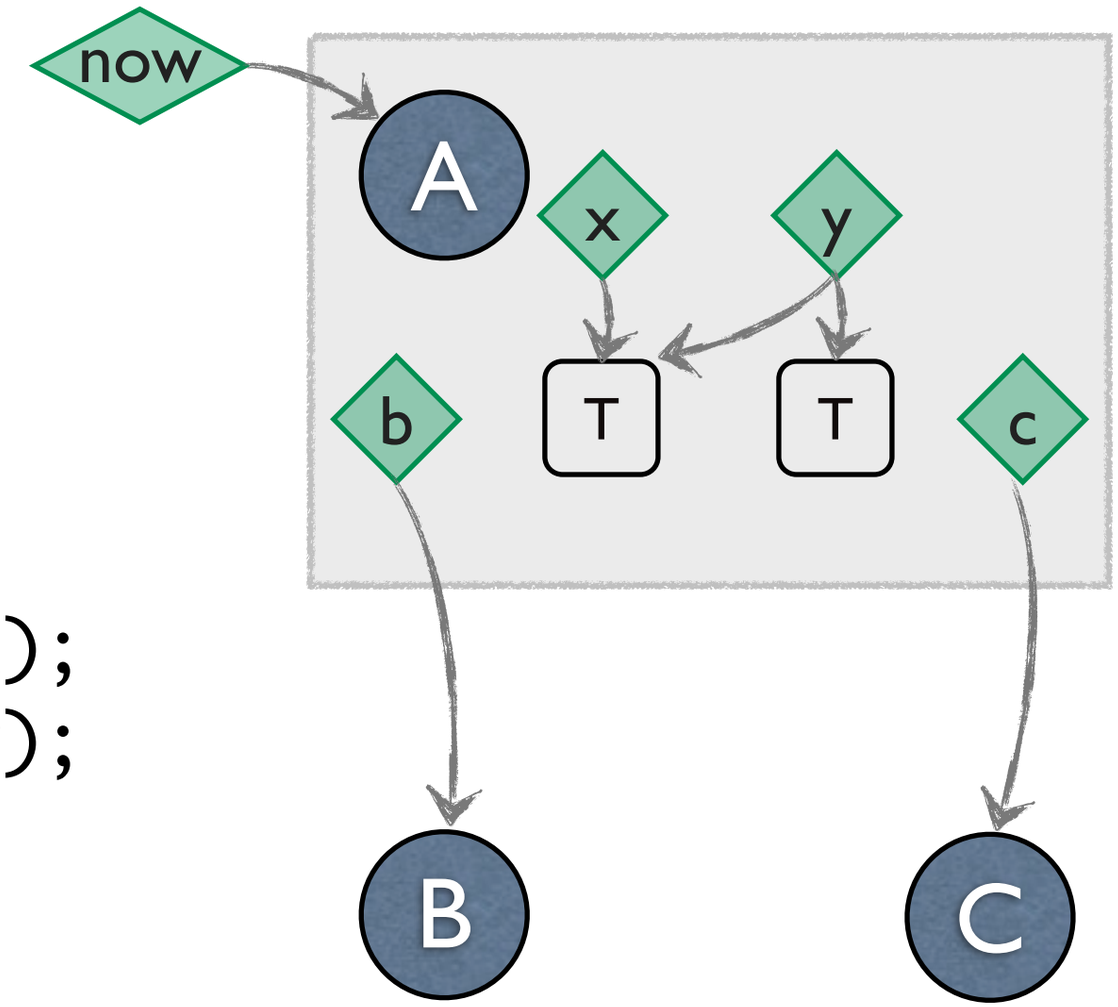

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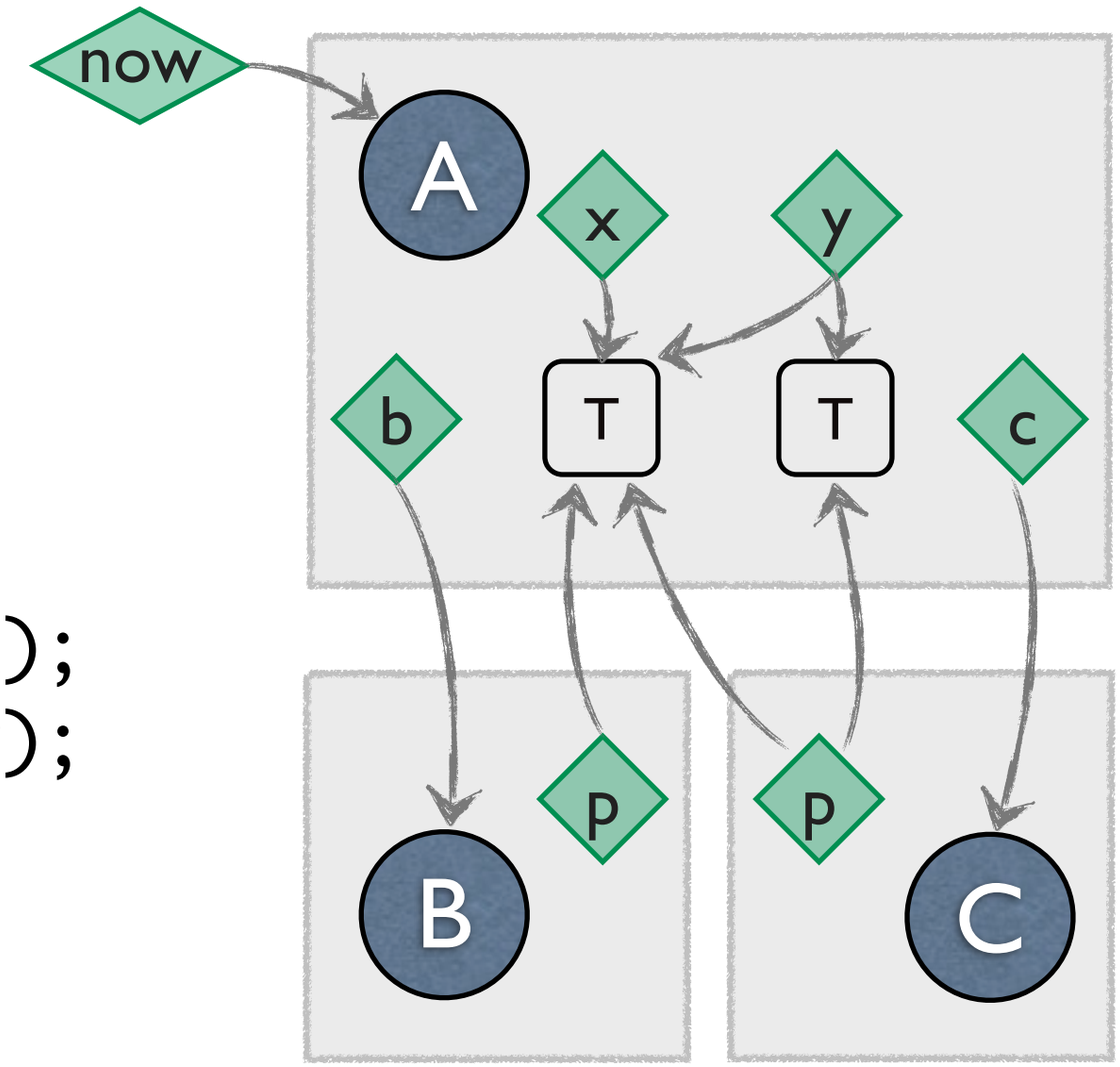

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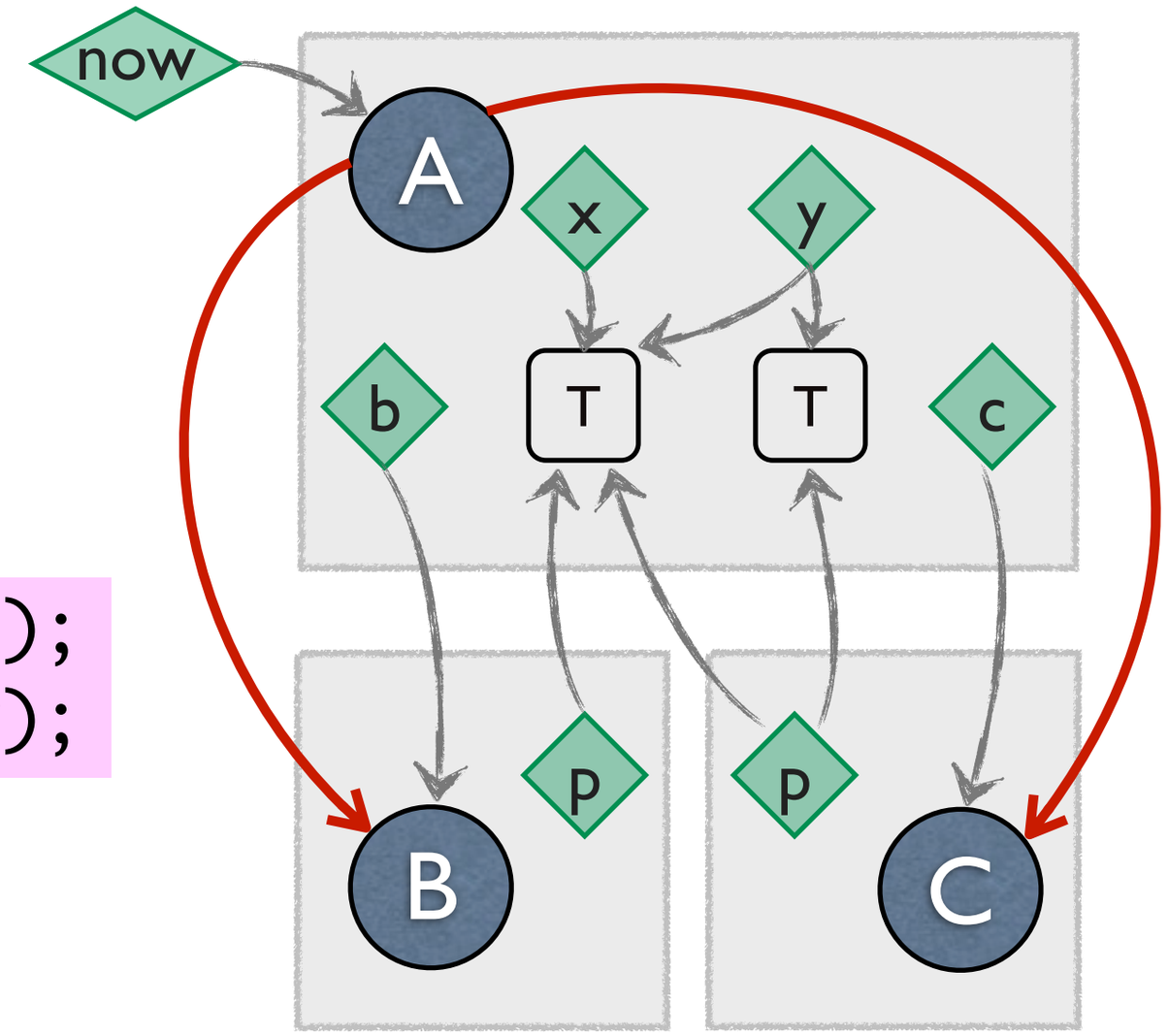

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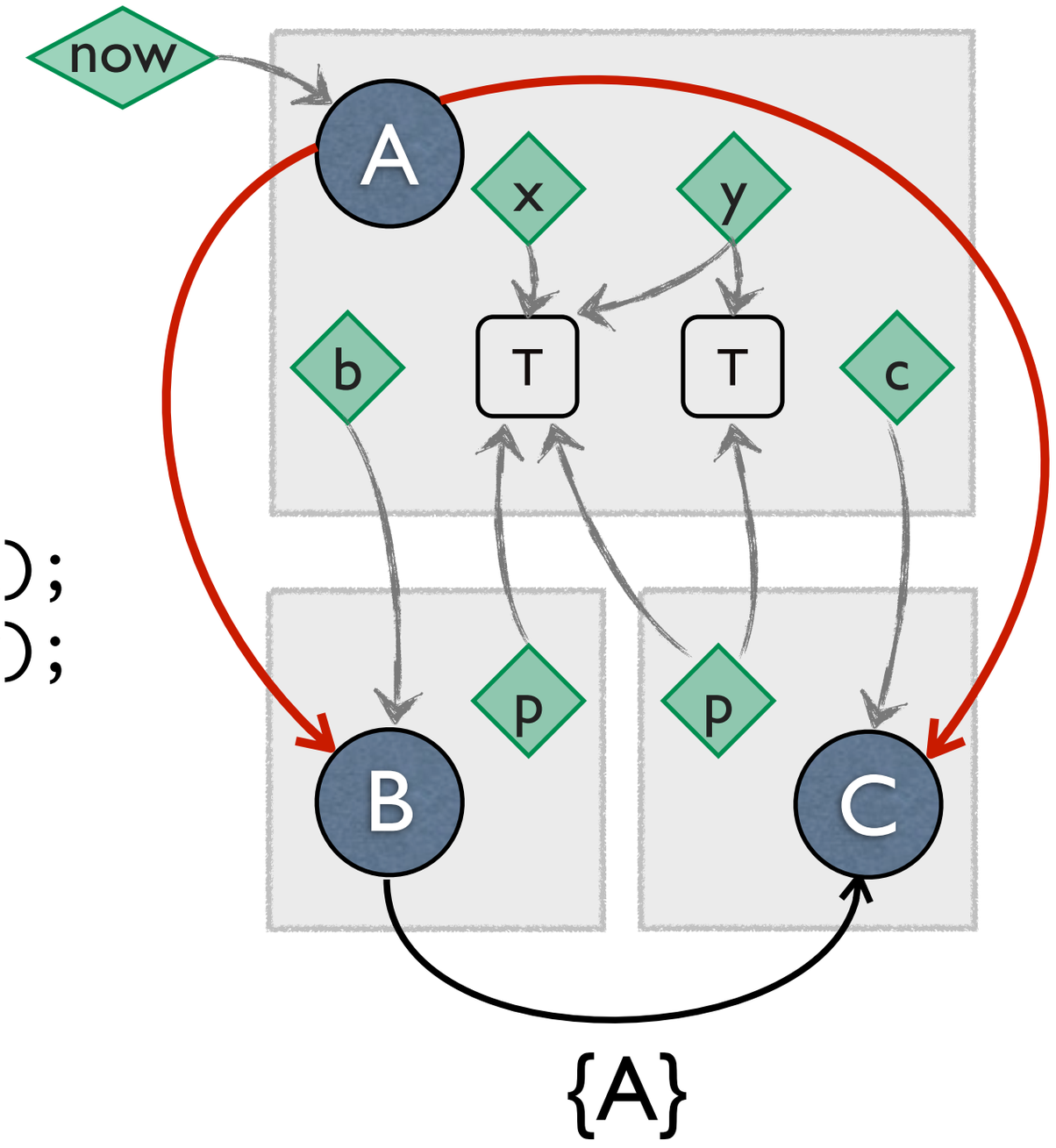

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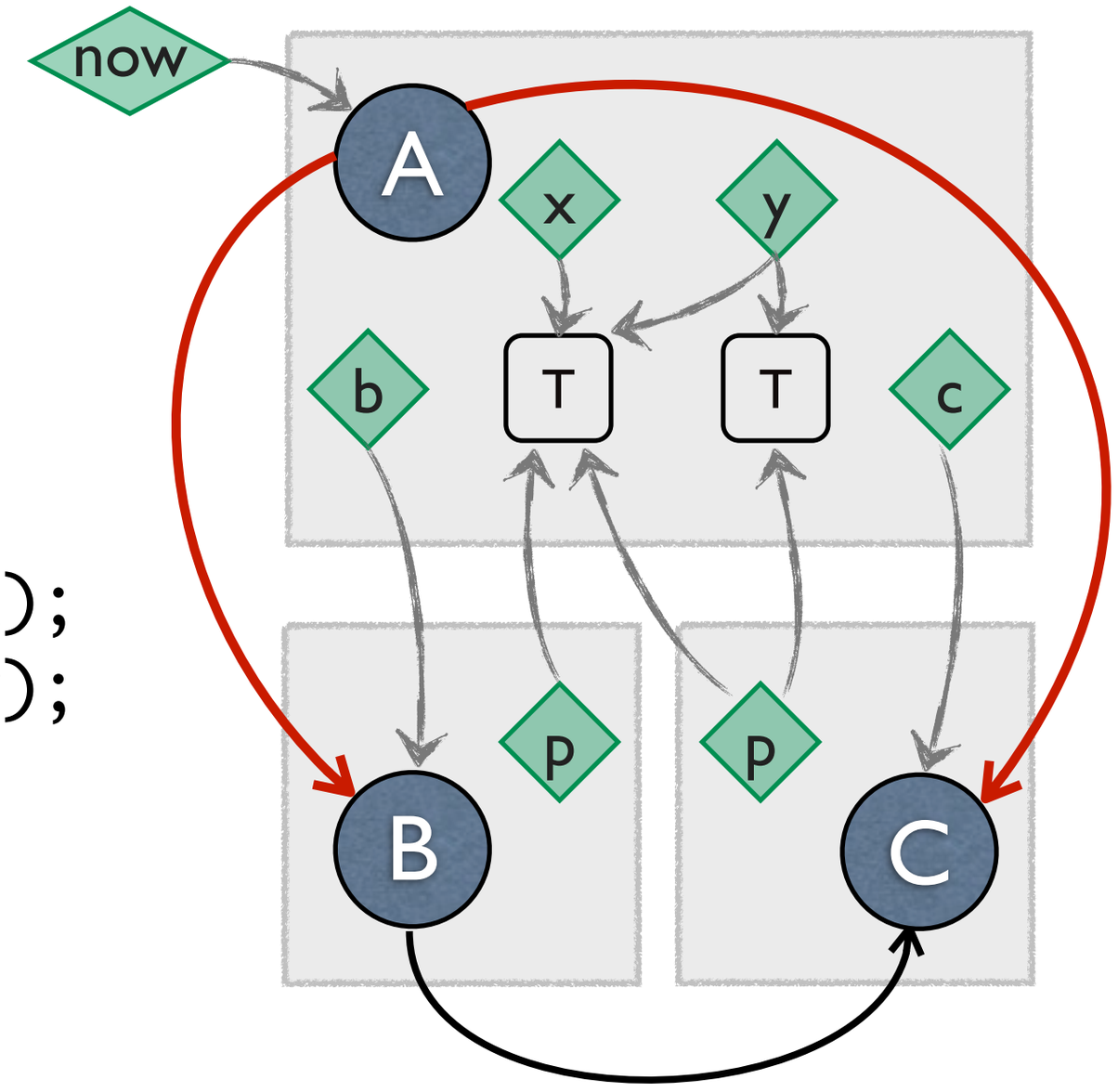

☑ Genuine {A}

Using Schedule Analysis

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- Analyze programs that mix different parallelism styles:
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Using Schedule Analysis

- Analyze programs that mix different parallelism styles:
  - Threads, fork/join, intervals, ...
- Analyze programs that mix different synchronization:
  - e.g., lock-based and STM in the same program [LCPC 2010]
- Optimizations directly profit from improvements of the schedule analysis

Conclusion

Future compilers must understand the scheduling of tasks at runtime

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Future compilers must understand the scheduling of tasks at runtime

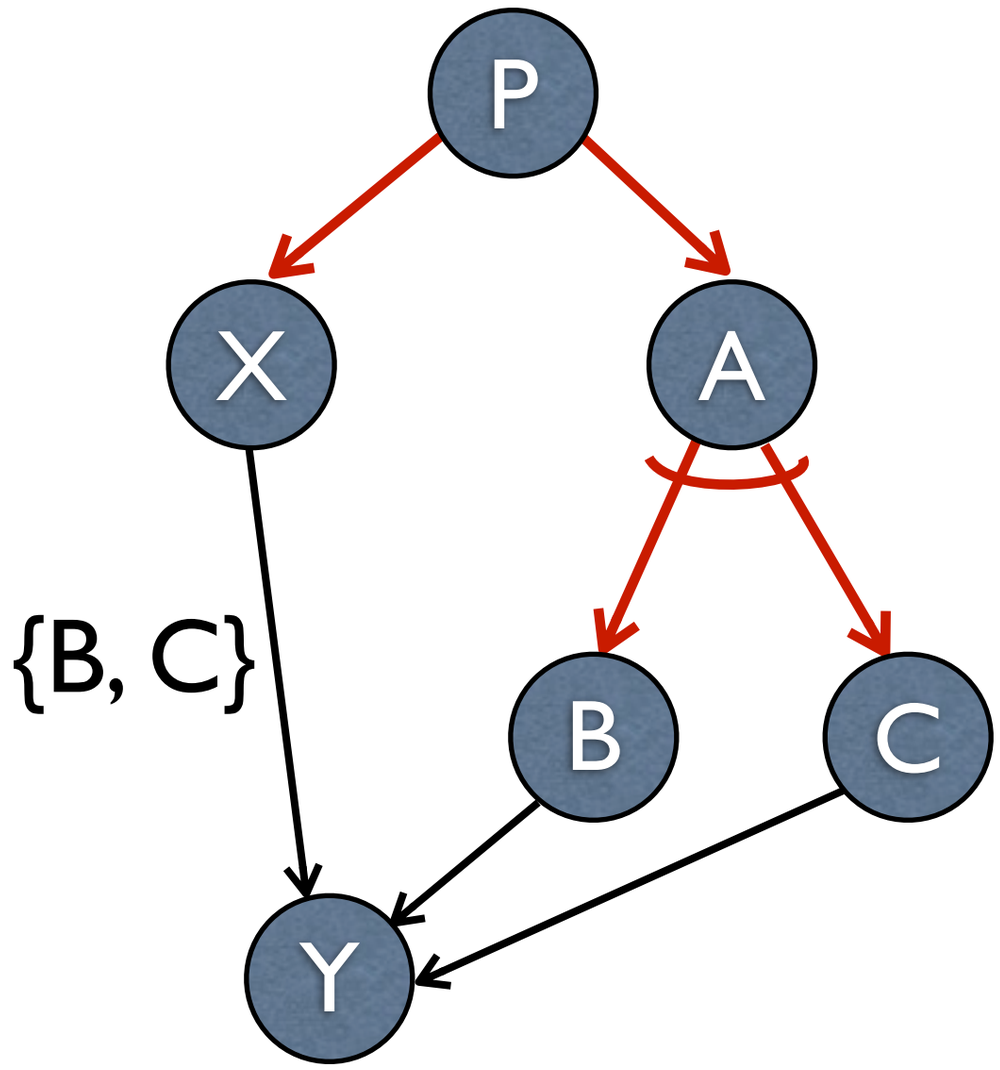
Think "points-to-analysis" for schedules

- What do do with that stuff now?
  - cite lcpc (showed sync removal, in addition lcpc shows stm)
  - think alias analysis for parallel programs

Concluding Remarks

- now→later: simple abstraction to capture explicit scheduling constraints
- Used by programmer or as intermediate representation in compiler
- Explicit happens-before relationships enable static analysis of runtime schedules
  - Schedule Analysis as basis for optimizations
  - Integration in a single optimizing compiler

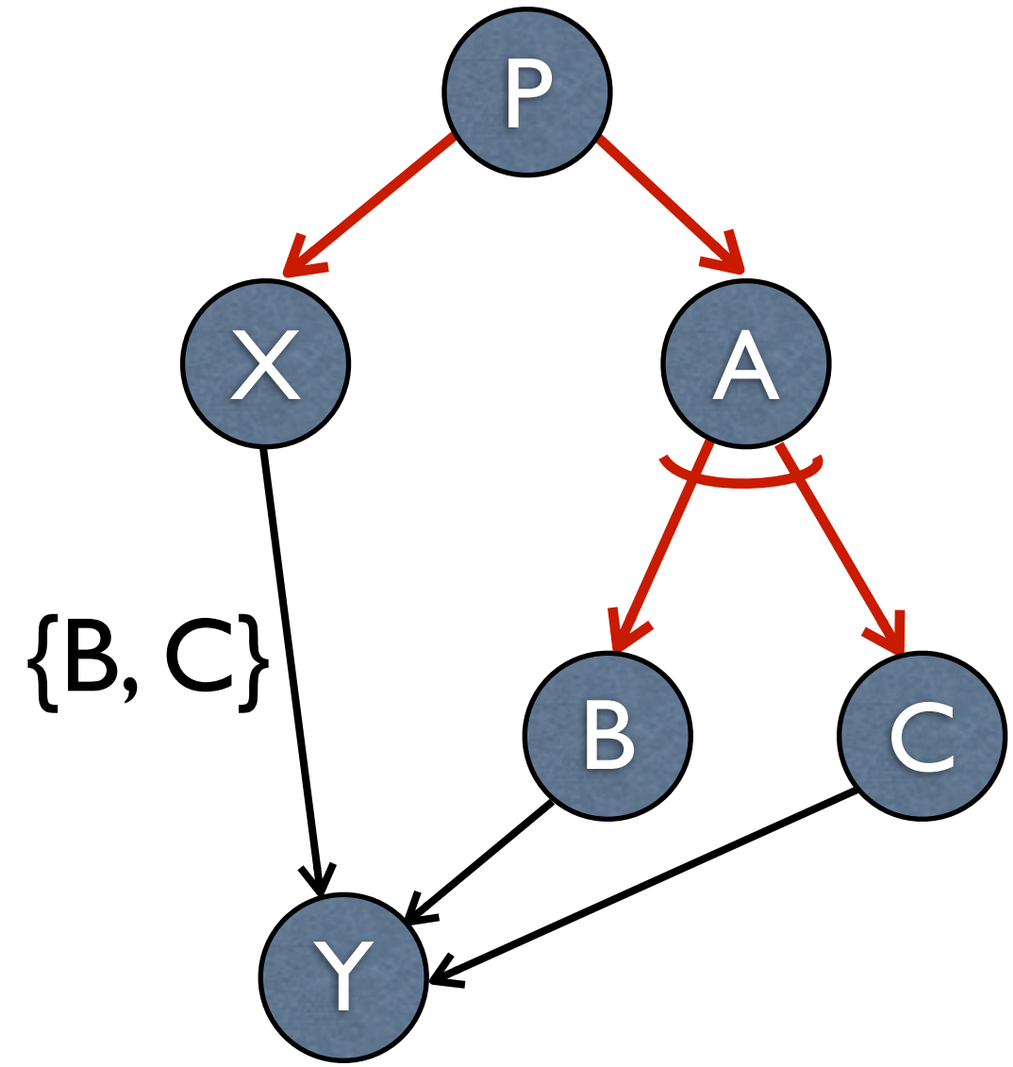
Genuine Explicit Edges



Genuine Explicit Edges

- An edge $x \rightarrow y$ is genuine if activation of x implies edge has been created:

$$x \Rightarrow x \rightarrow y$$



Conditional Edges

- Static analysis is imprecise
  - Conditional activation
  - Conditional creation of edges
- Question: can the analysis *rely* on a happens-before edge?
  - If *yes*, **we call the edge** *genuine*

Structural Properties

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- Schedules must form a directed acyclic graph (DAG)
  - For *progress* and *liveness* of activations

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- Schedules must form a directed acyclic graph (DAG)
  - For *progress* and *liveness* of activations
- Possible relations between two activations:
  - *sequential:* execution is strictly ordered
  - *exclusive:* activations can never co-exist at runtime
  - *(potentially) parallel:* neither sequential nor exclusive

Related Work

- Pointer Analysis for Parallel Programs [Rugina, Rinard '03]
  - Interference information for fork/join parallelism
- Combined with Escape Analysis [Salcianu, Rinard '01], [Nanda, Ramesh '03]
  - Compute Points-to sets, no ordering
- May-happen-in-parallel [Naumovich et al. '99]
  - For X10 (structured parallelism)
- May-happen-before [Barik '05]
  - Happens-before relations in thread creation trees