Static Analysis of Dynamic Schedules

and its Application to Optimization of Parallel Programs

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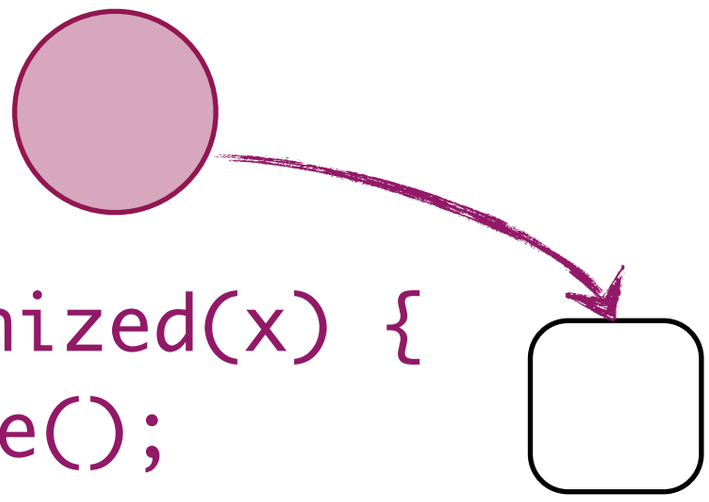
Example

Example

task A

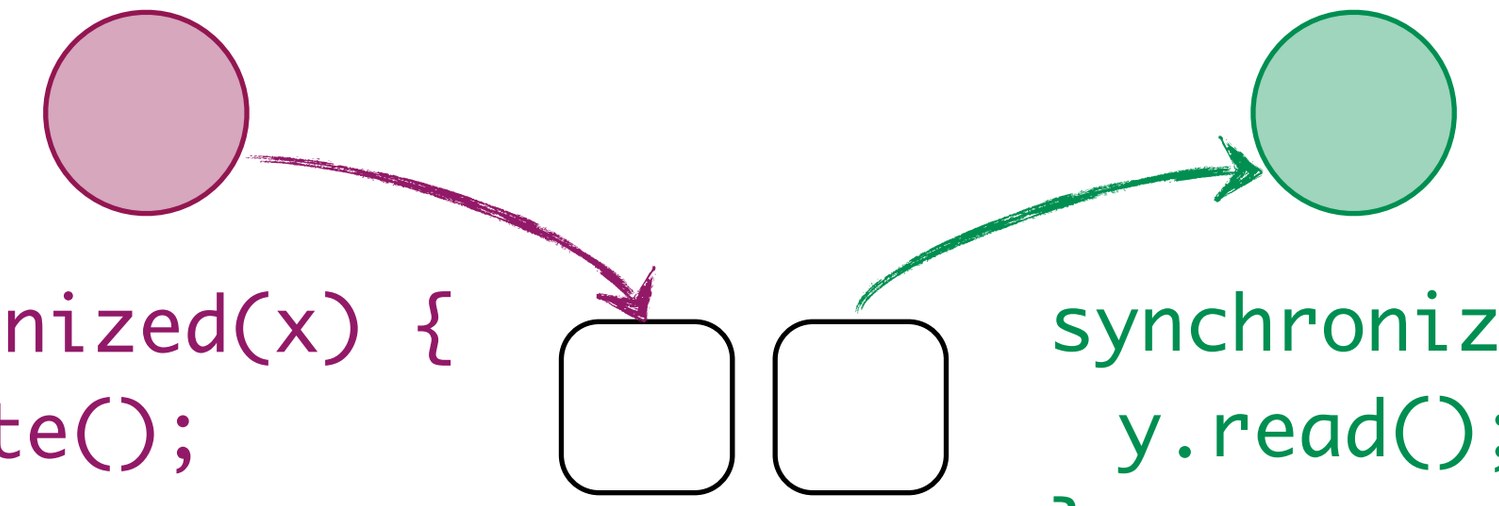


```
synchronized(x) {
  x.write();
}
```

Example

task A

task B



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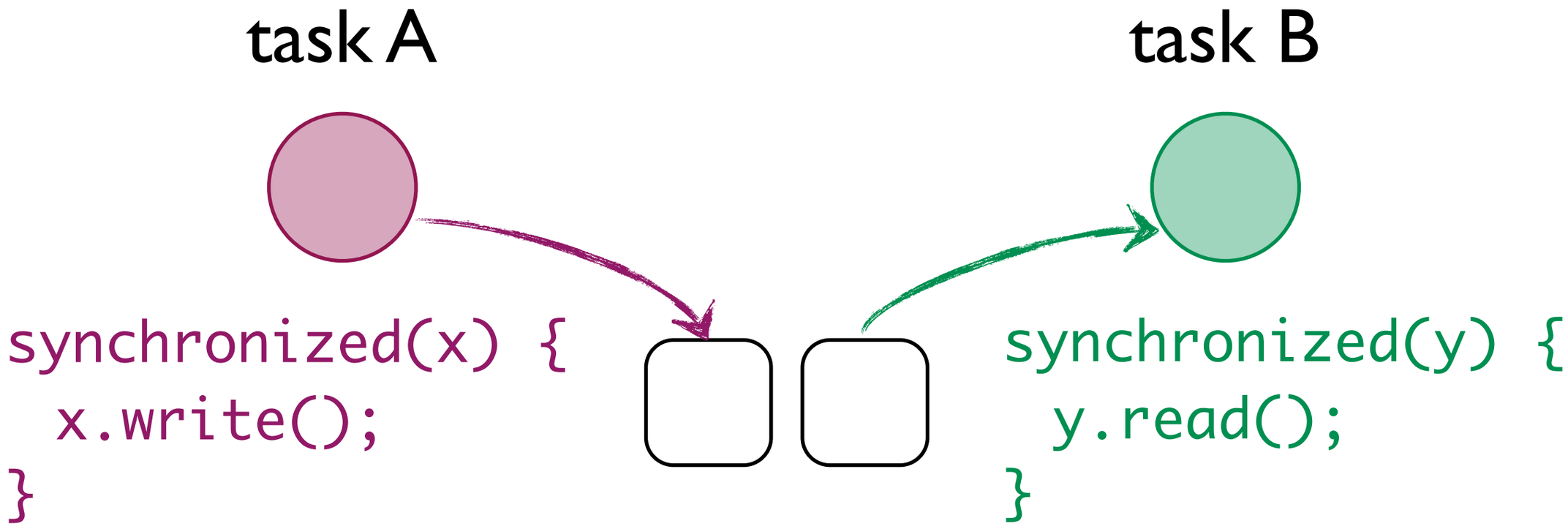
```
synchronized(y) {
  y.read();
}
```

Example

- Can we remove synchronization for x, y?



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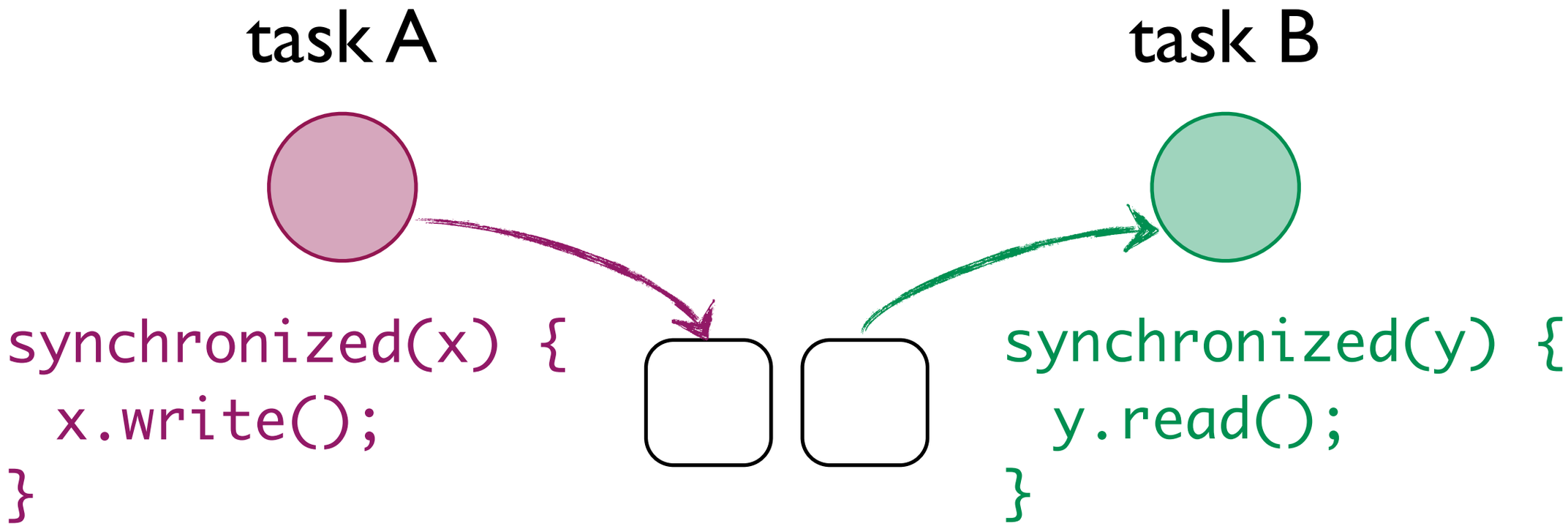

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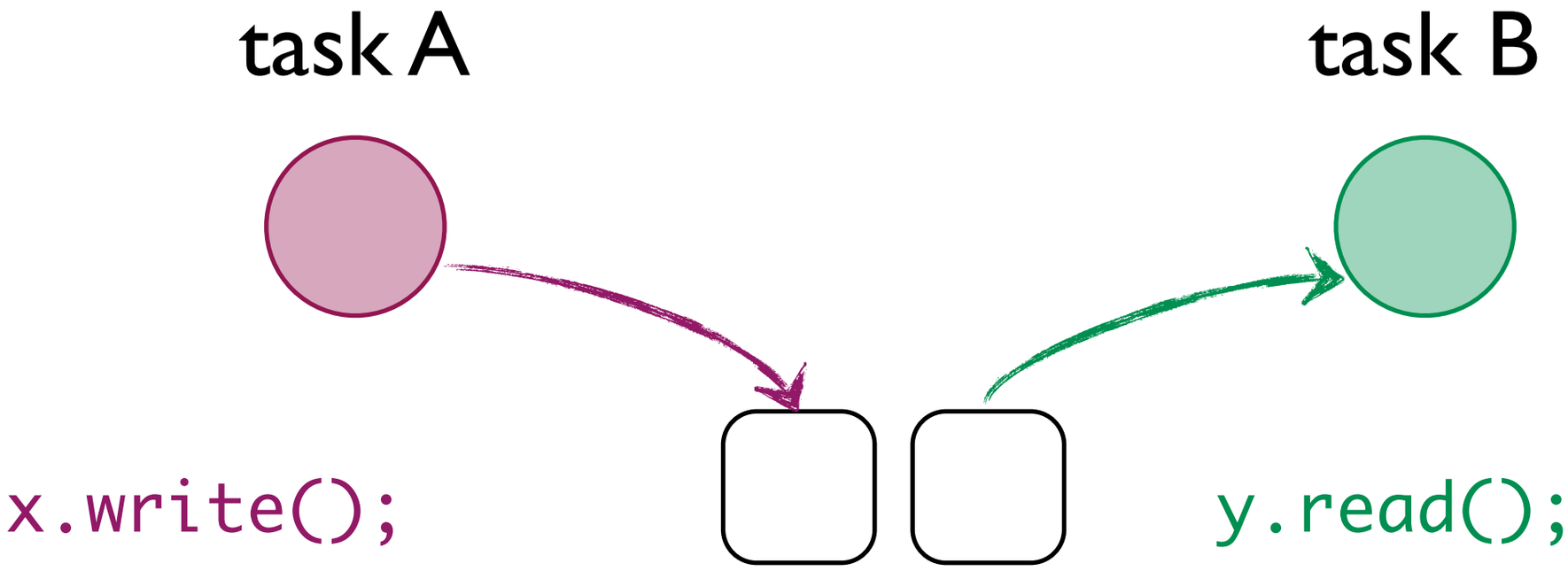

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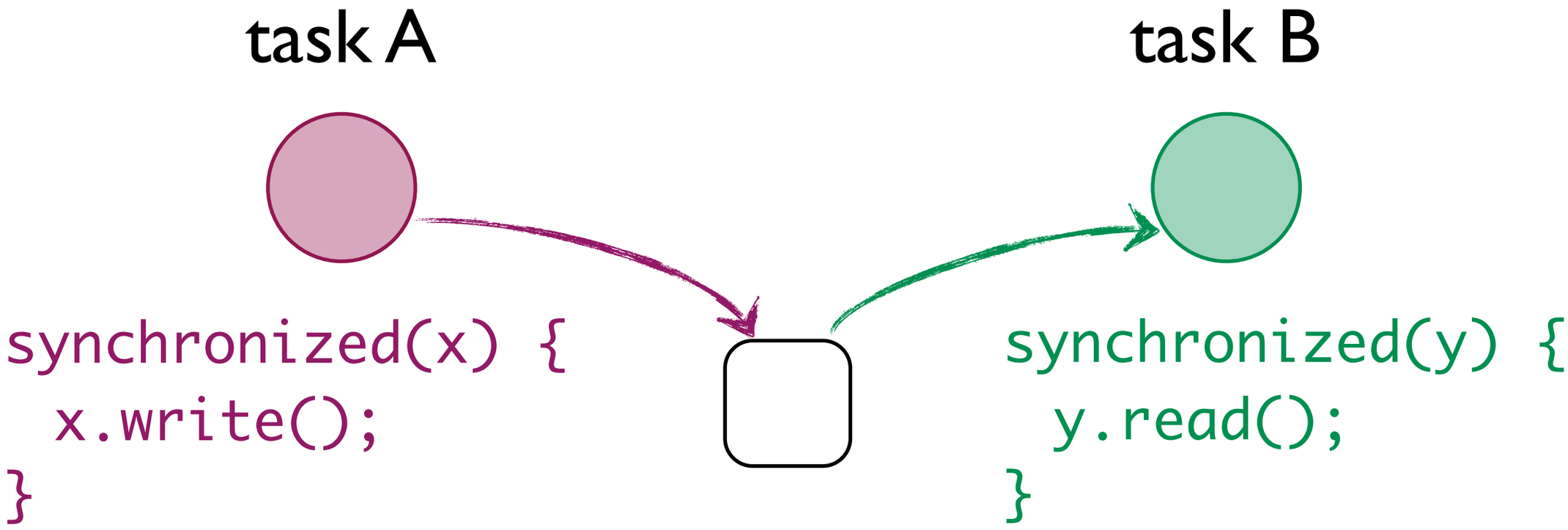

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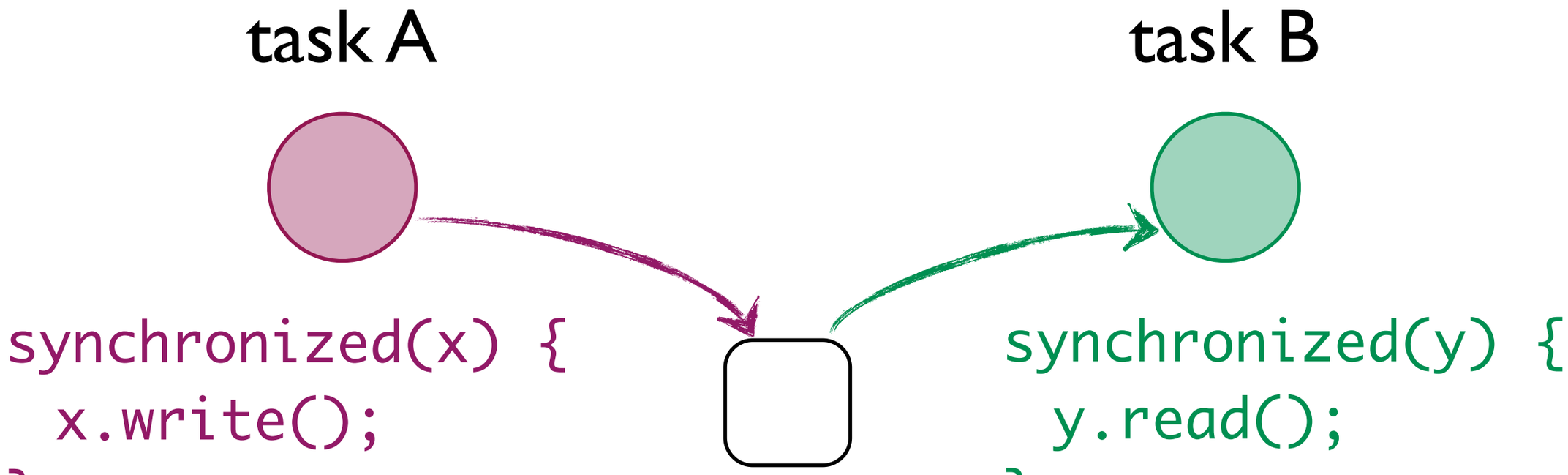

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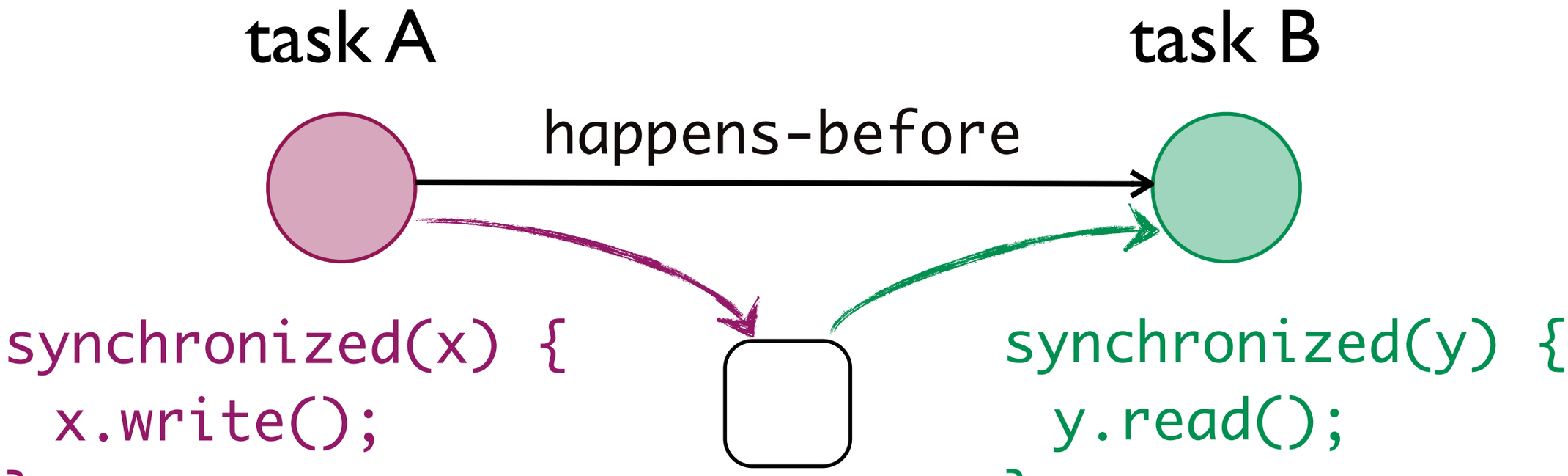

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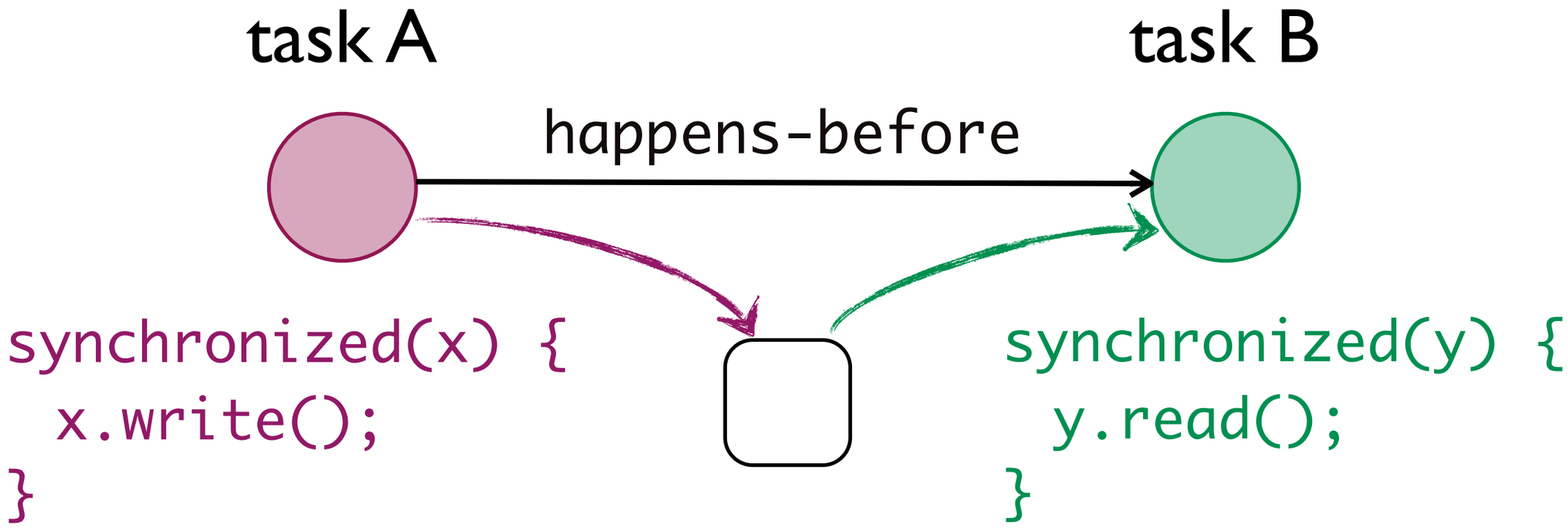

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☑ Ordered memory access

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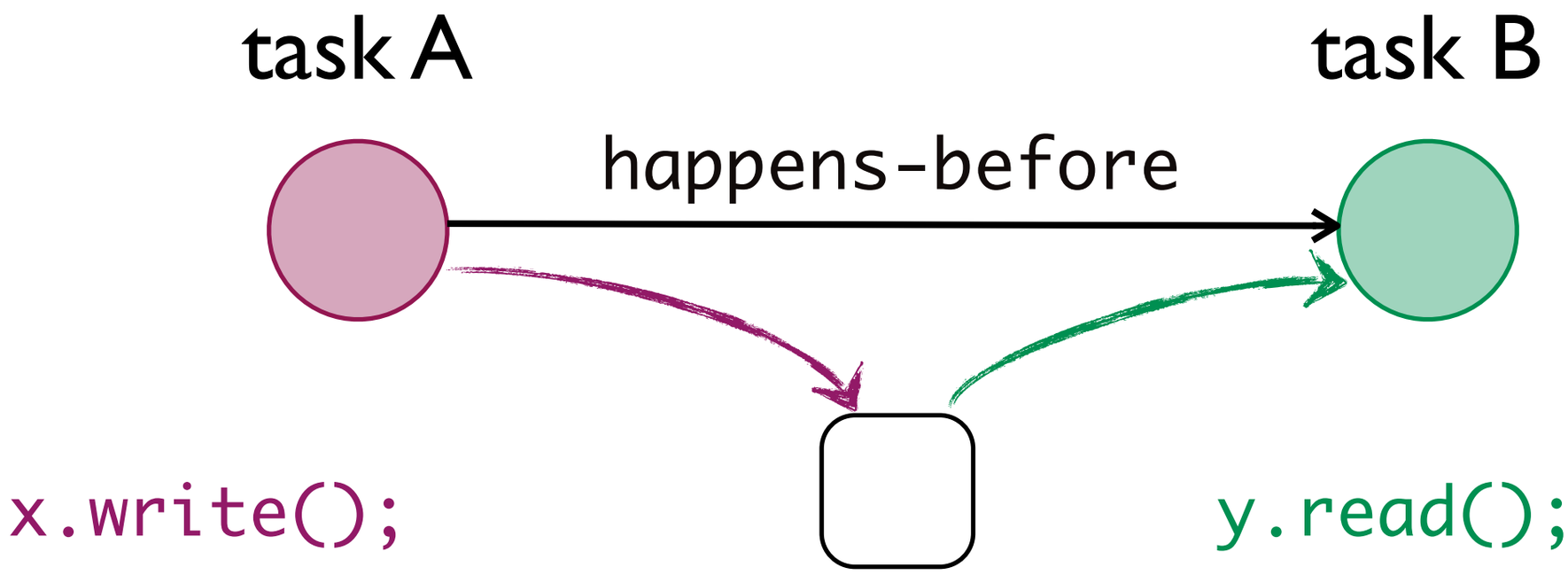


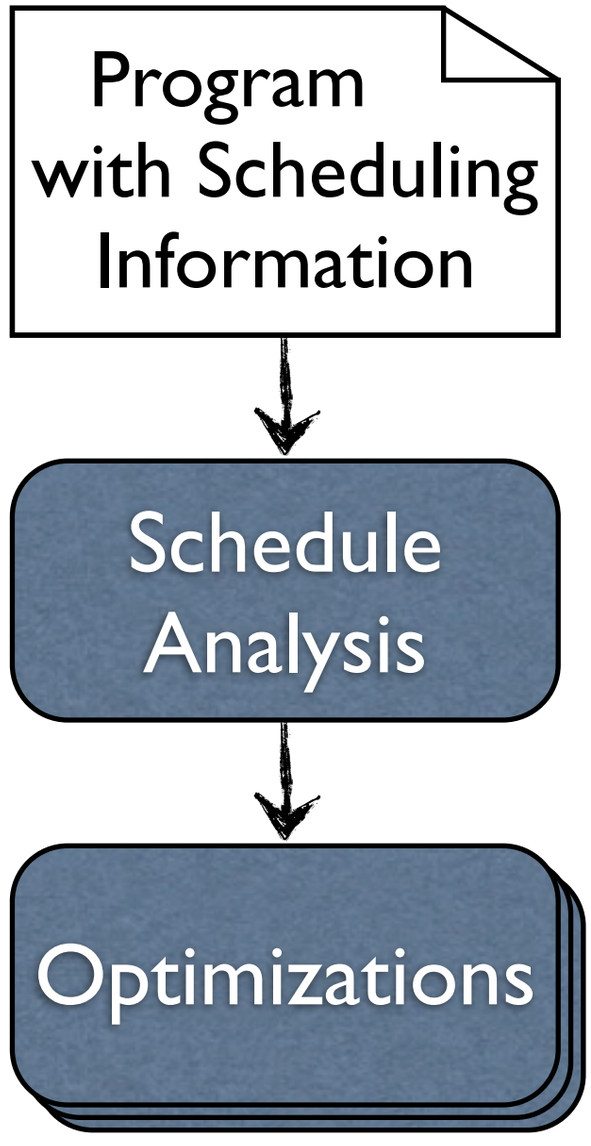
☒ Aliased

☑ Ordered memory access

Motivation

- Optimizations 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
  - Task ordering information increases optimization potential

Schedule Analysis Overview



Outline

- Motivation
- Explicit Scheduling
- Schedule Analysis
- Optimizing Strong Atomicity Overhead
- Related Work
- 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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Explicit Scheduling

- A `task` method is similar to a regular method:
  - code that is executed in the context of `this`
- Instead of *calling* a task method, one *schedules* it for later execution:

```
Activation b = schedule obj.bar(42);
```

Explicit Scheduling (2)

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- →-statement creates explicit happens-before relationship:

```
a → b;
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- At runtime, scheduler constantly chooses executable activations

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class MyClass {
  task doWrite() {...}
  task doRead() {...}
  task doCompute() {
    Activation write = schedule doWrite();
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    write → read;
  }
}
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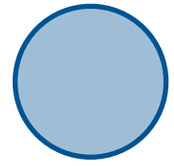


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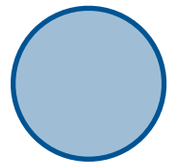

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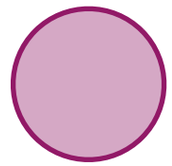

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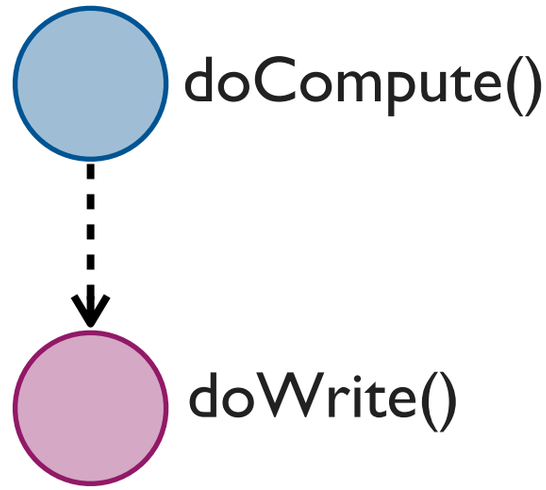

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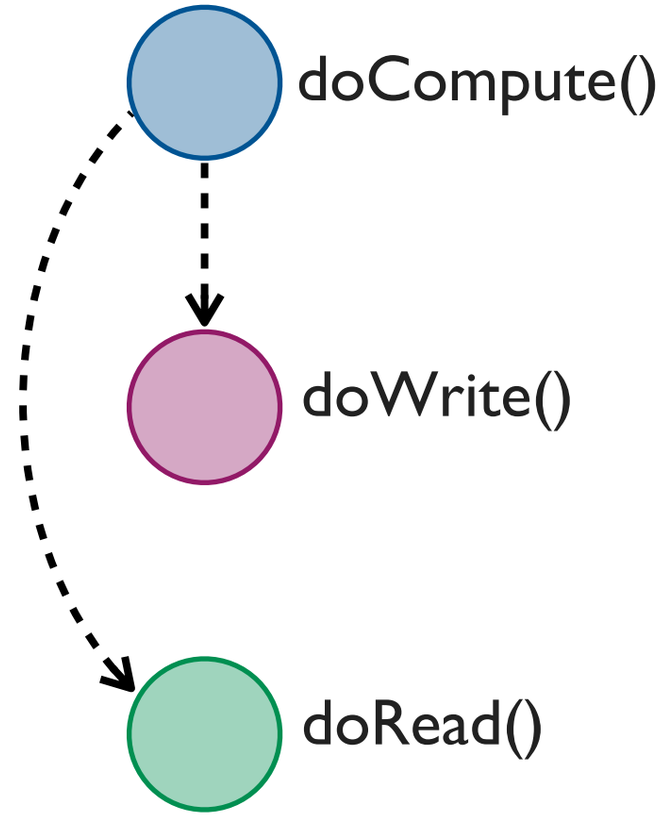

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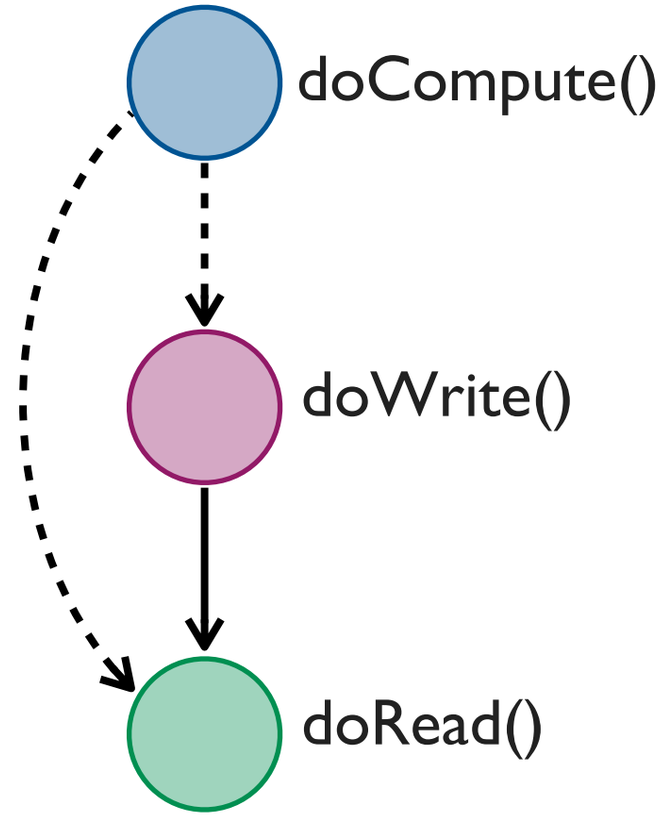

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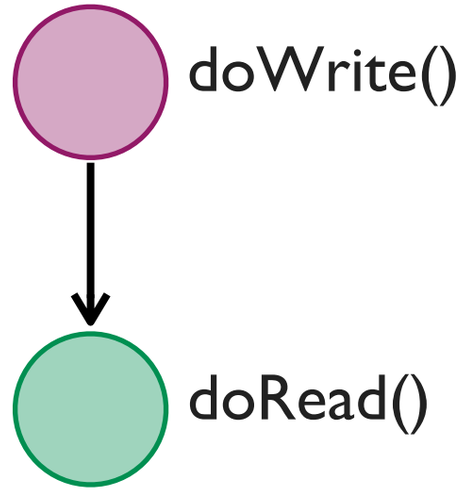

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mayInterfere(p1, p2) :-
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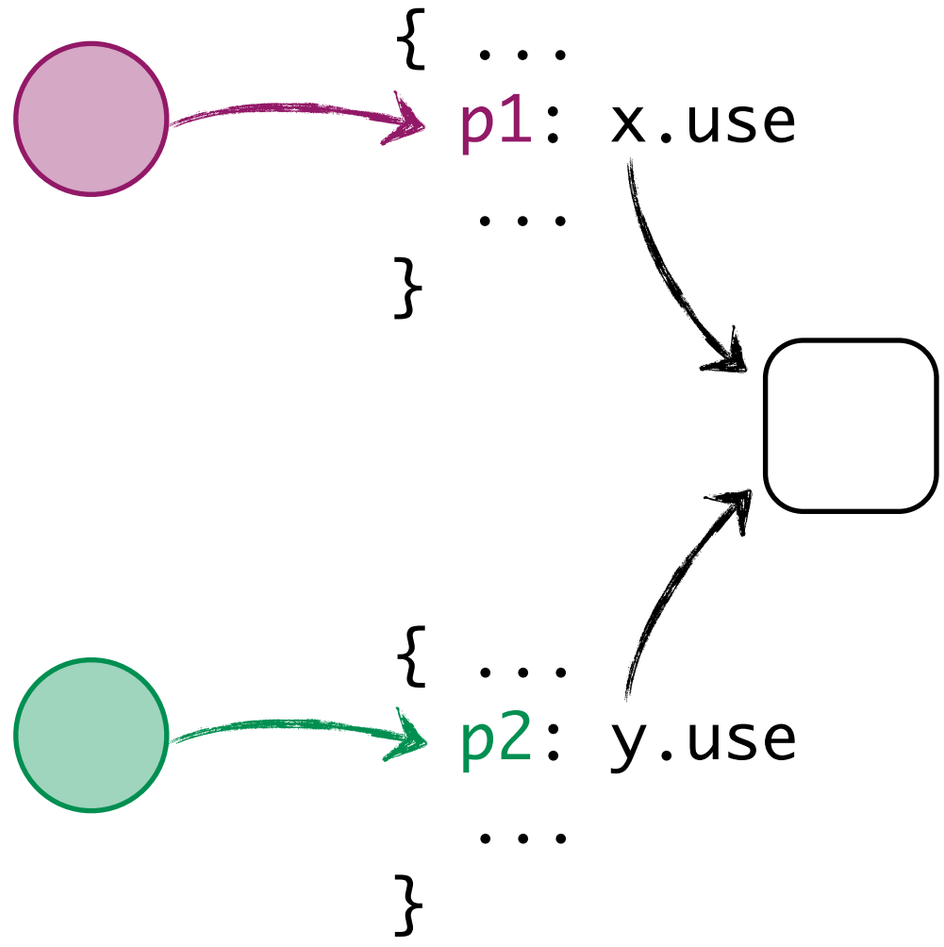

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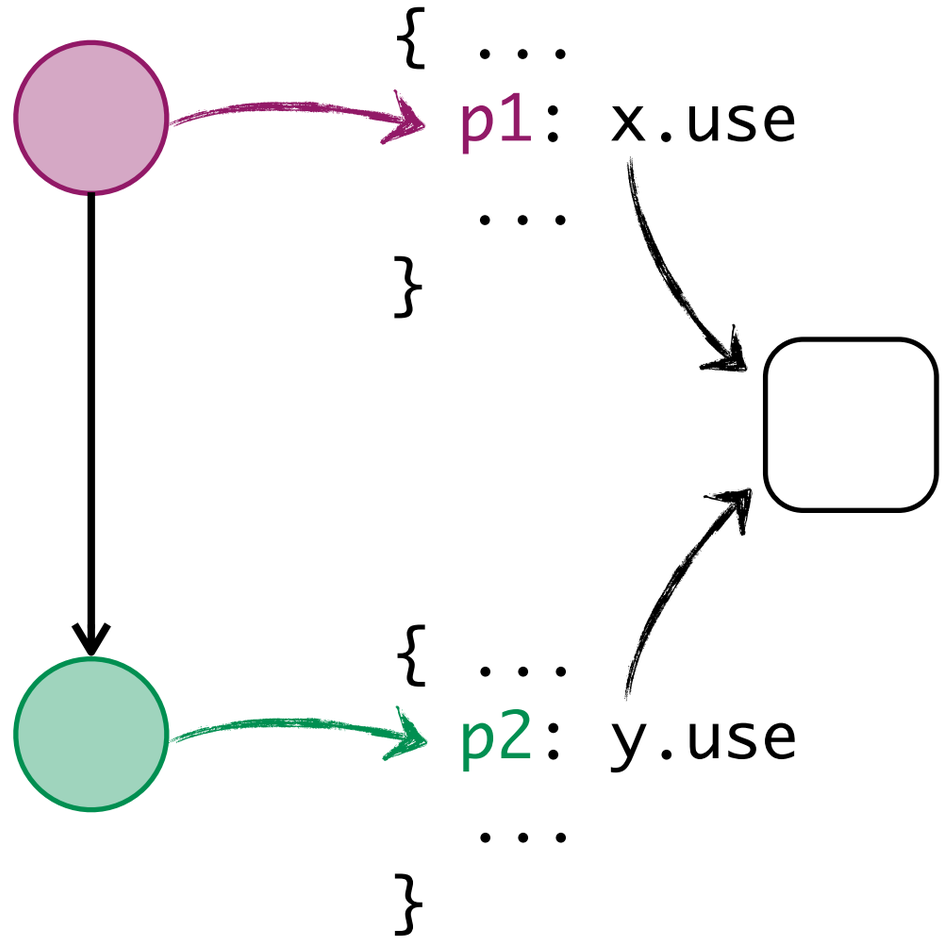

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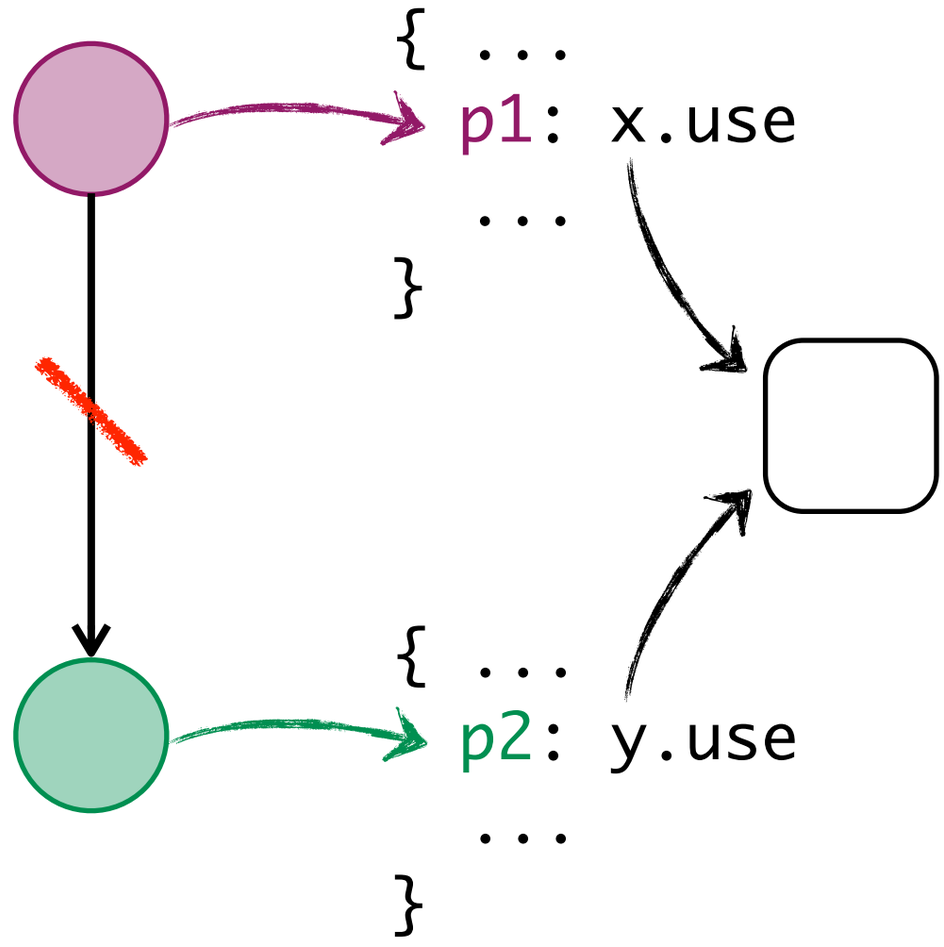
- ☒ Same Object
- ☒ Different Activations
- ☒ Not Ordered



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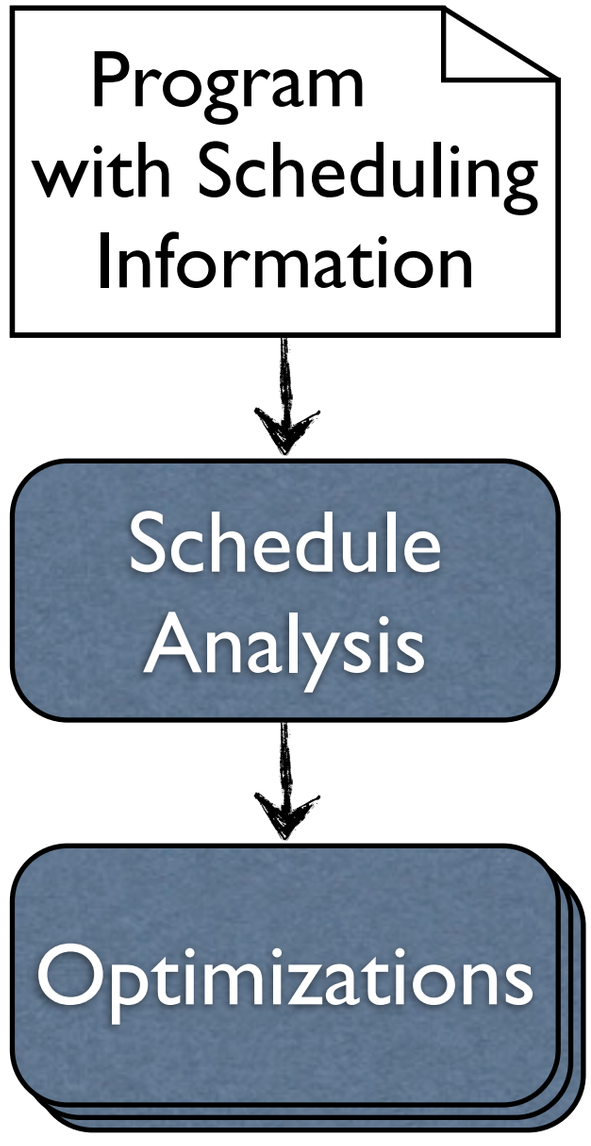

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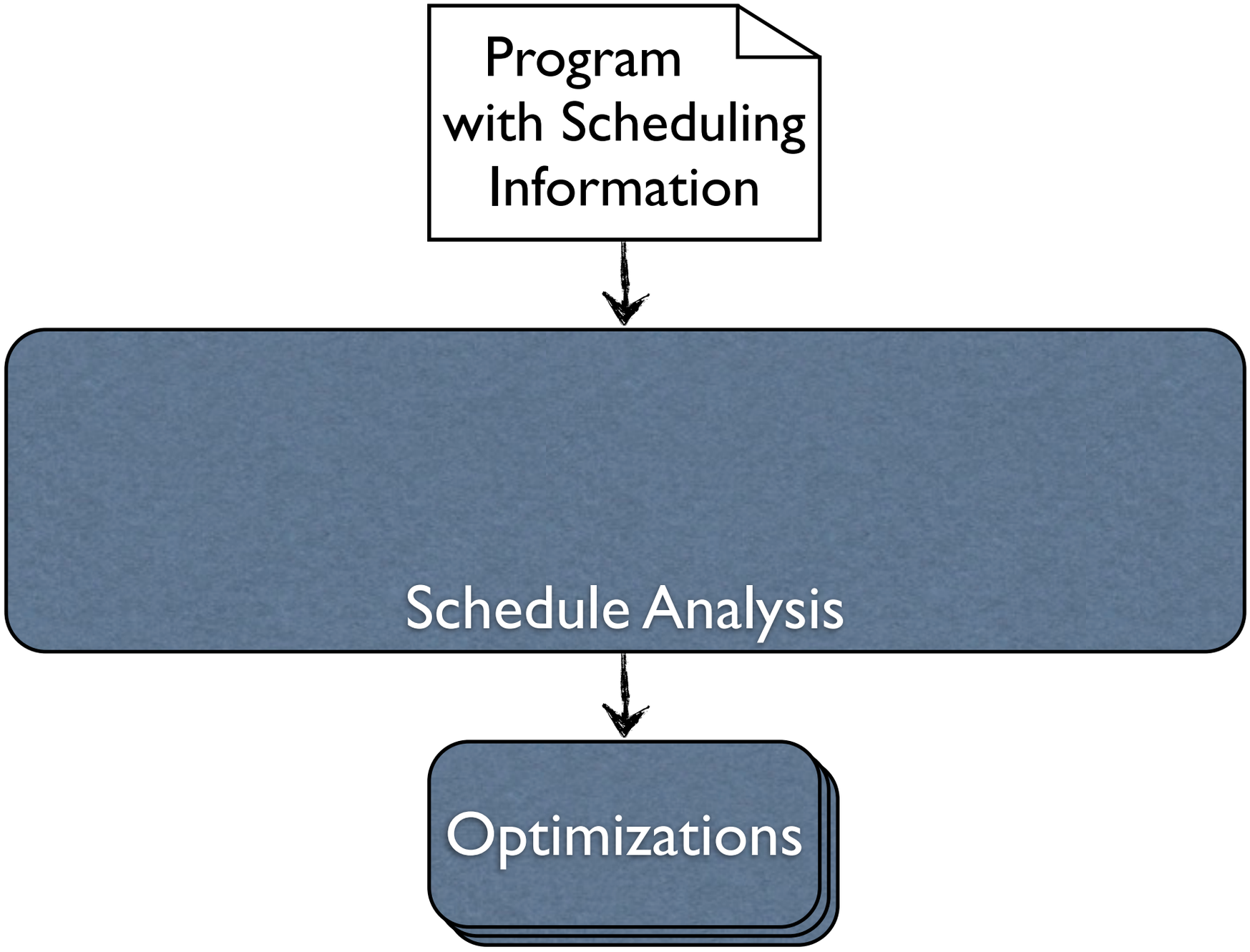

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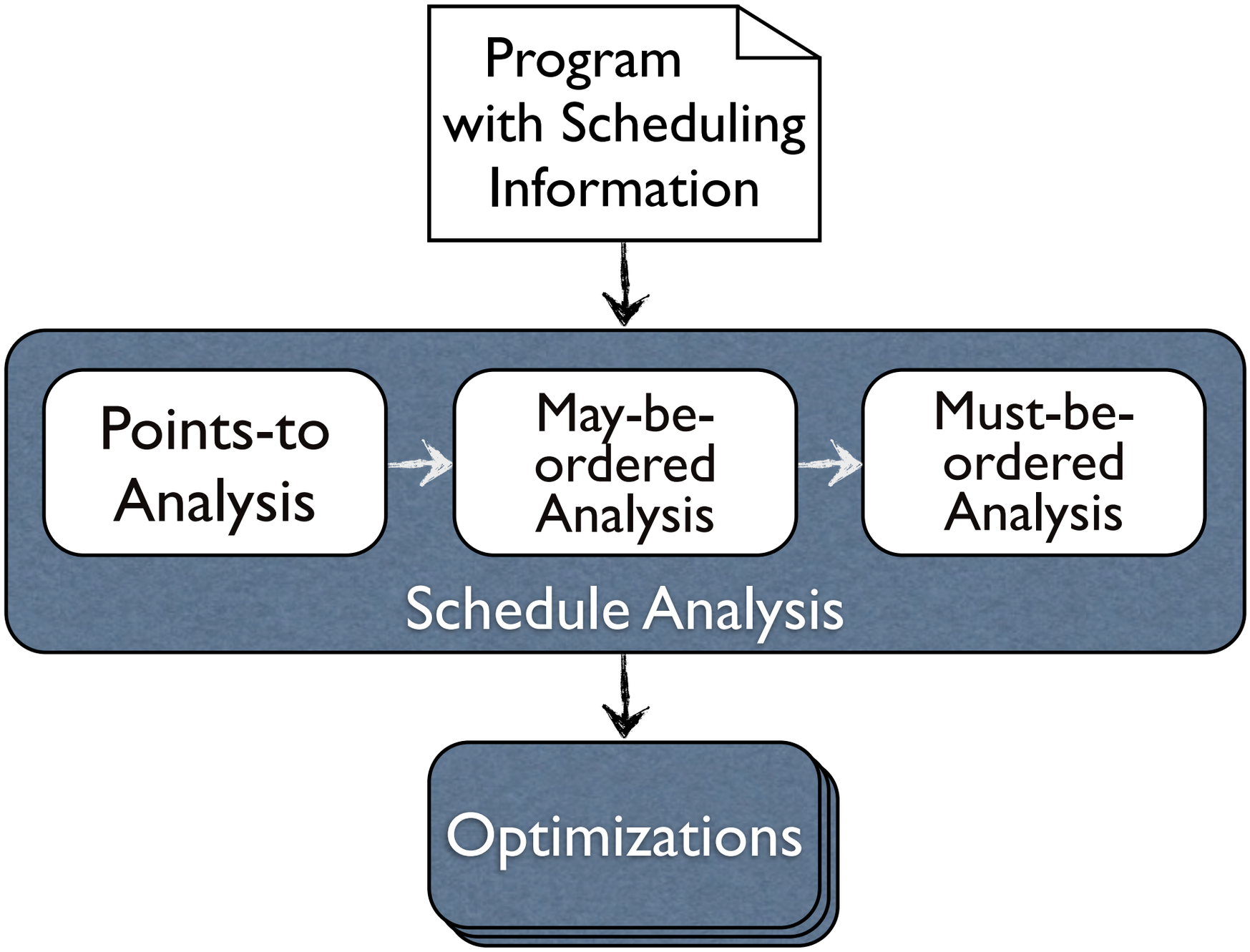

Points-to Analysis

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

Points-to Analysis

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task doThings() {
  Activation a = schedule A();
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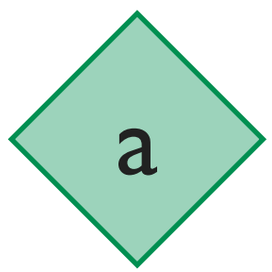

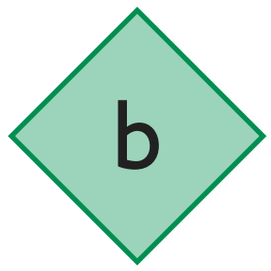

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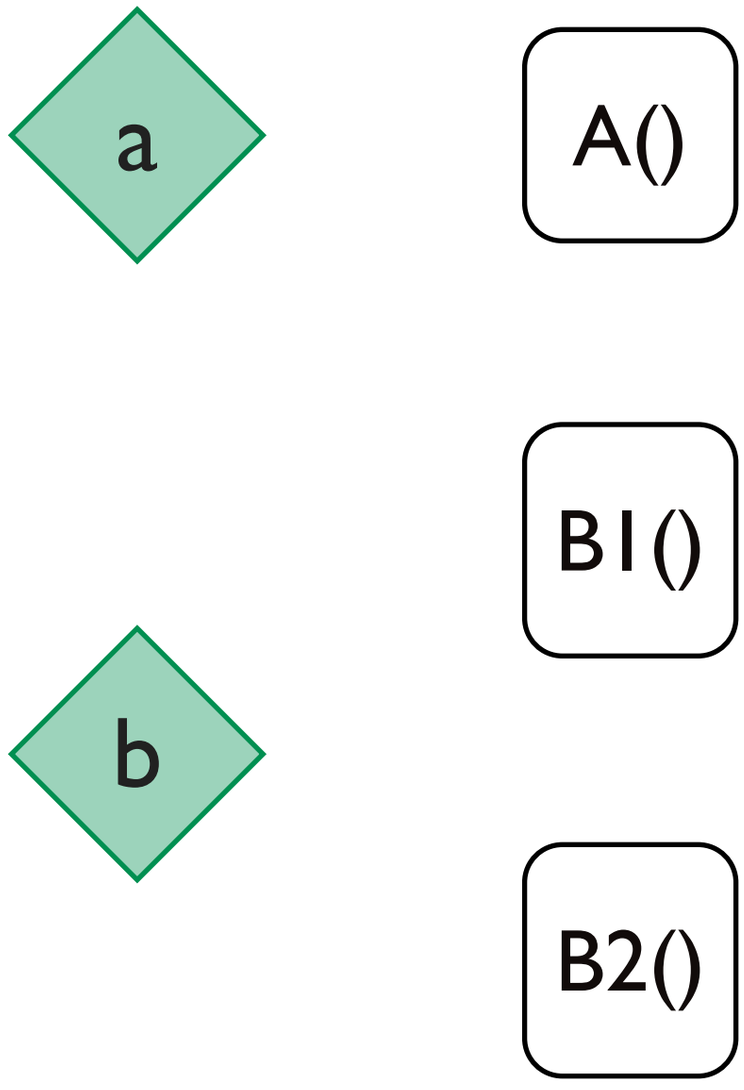

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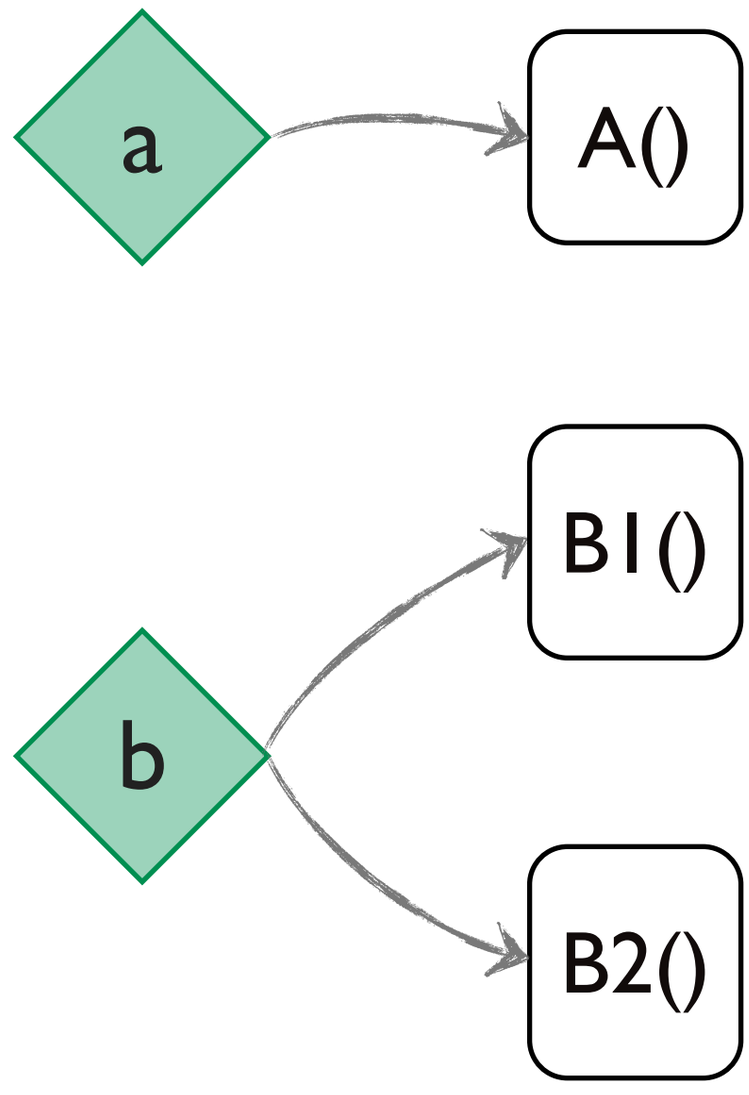

May-be-ordered Analysis

- Analyze happens-before relationships
  - Implicit creation edges
  - Explicit arrow statements
- Compute read/write sets for each activation

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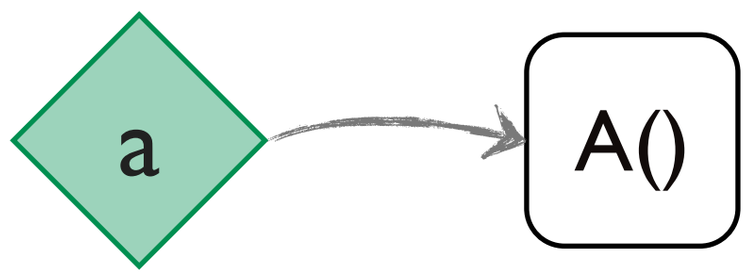

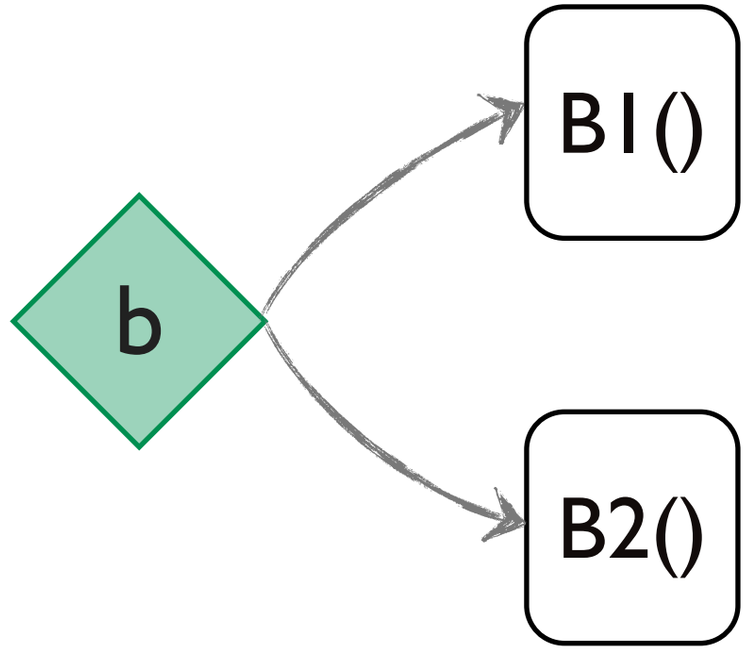

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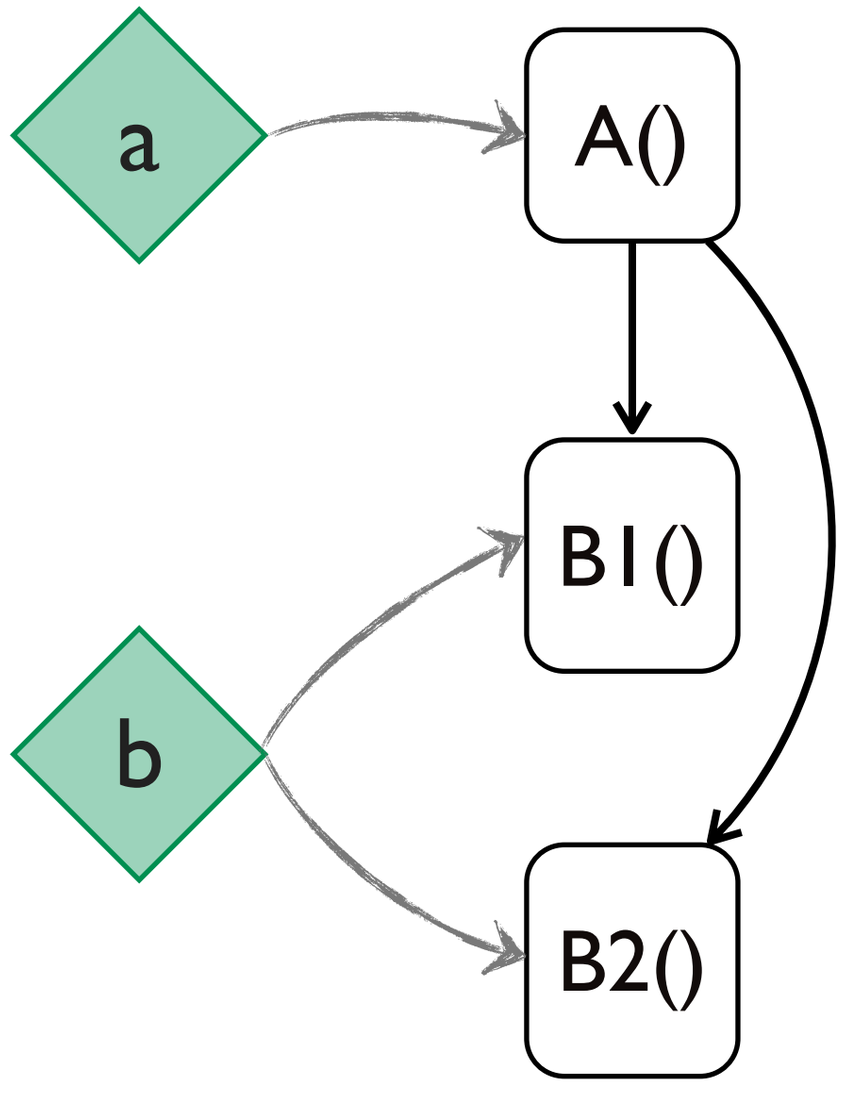

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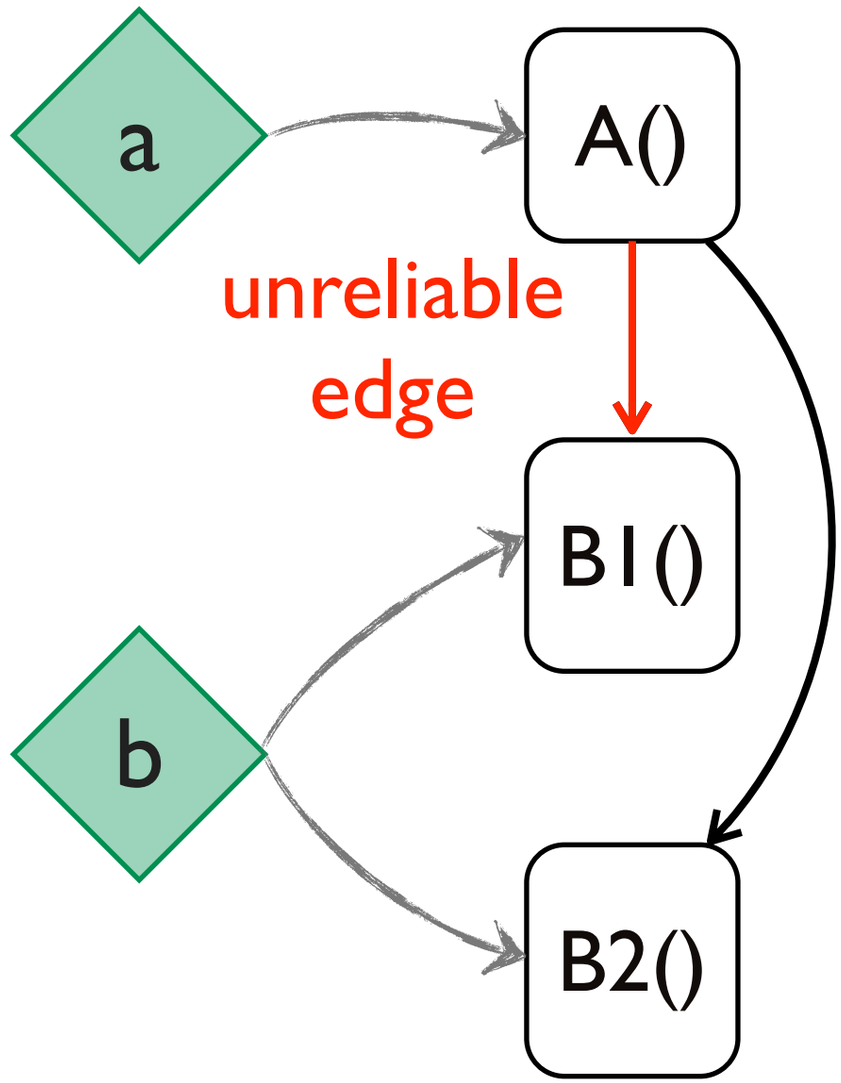

Conservative Approximation

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- May-be-ordered Analysis:
  - over-approximates happens-before edges
  - under-approximates parallelism

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➡ But: want to know if two activations *must* be ordered

Must-be-ordered Analysis

Must-be ⊆ Reality ⊆ May-be

in # of happens-before edges

Question: how to get from may-be ordered to must-be ordered?

Must-be-ordered Analysis

Must-be-ordered Analysis

- *Trivial* **solution: remove *all* edges**

Must-be-ordered Analysis

- *Trivial* **solution: remove *all* edges**
- *Current* **solution: filter out edges**
  - No conditional edges
  - Only edges with single source and target objects
  - Analyze simple loops, but no recursion

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Concurrency Control Mechanisms

- Two common concurrency control mechanisms for shared-memory models:
  - *Locks* **with synchronized blocks**
    - ➡ **Synchronization removal optimization**
  - *Software Transactional Memory* **(STM)**
    - ➡ **Reducing strong atomicity overhead**

Strong Atomicity

- In a strong atomic model, every memory access must be treated *as if* it occurred inside a transaction
- e.g., a write `x.f = 3;` outside a transaction is equivalent to:

```
atomic { x.f = 3; }
```

- Without optimization:
  - Overhead on every single read/write outside a transaction

Reducing Strong Atomicity Overhead

- A read/write *outside a* transaction requires a memory barrier if:
  - any transaction may access same object
  - it may access it concurrently
- Otherwise, we can remove the memory barrier

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```
requiresReadBarrier(readBC) :-
    readOutsideTransaction(readBC),
    writeInsideTransaction(writeBC),
    mayInterfere(readBC, writeBC).
```

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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

Concluding Remarks

- Exposing scheduling constraints to compiler enables static analysis of runtime schedules
- →-statements increase optimization potential
- Schedule analysis factors out common aspects of optimizations
  - Integration into single optimizing compiler
  - E.g., locking and STM in same program

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  - Simplifies optimization implementations
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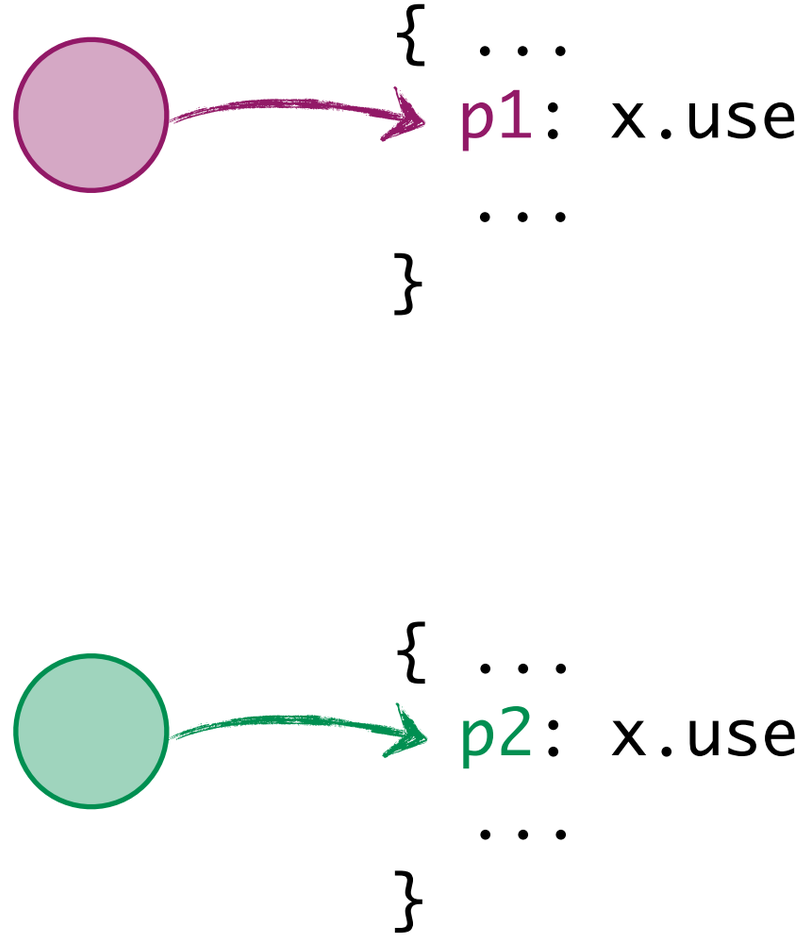

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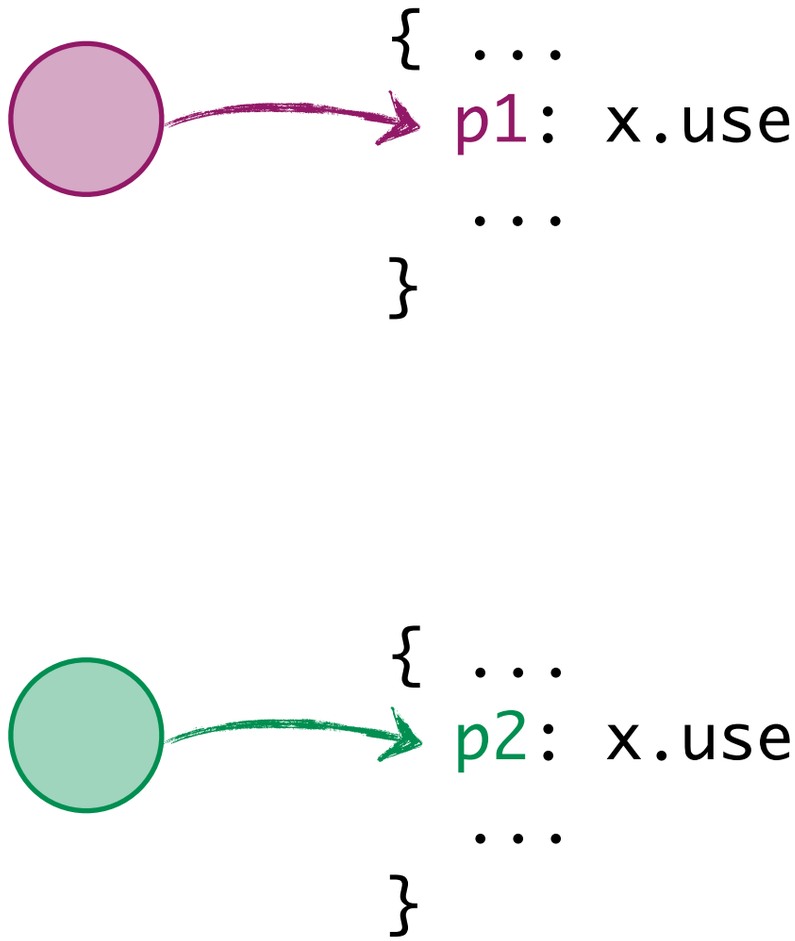
mayInterfere(p1, p2) :-
    execute(act1, p1),
    execute(act2, p2),
```



Generic Optimization Question

May a memory access at program point p1 interfere with a memory access at program point p2?

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mayInterfere(p1, p2) :-
    execute(act1, p1),
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```

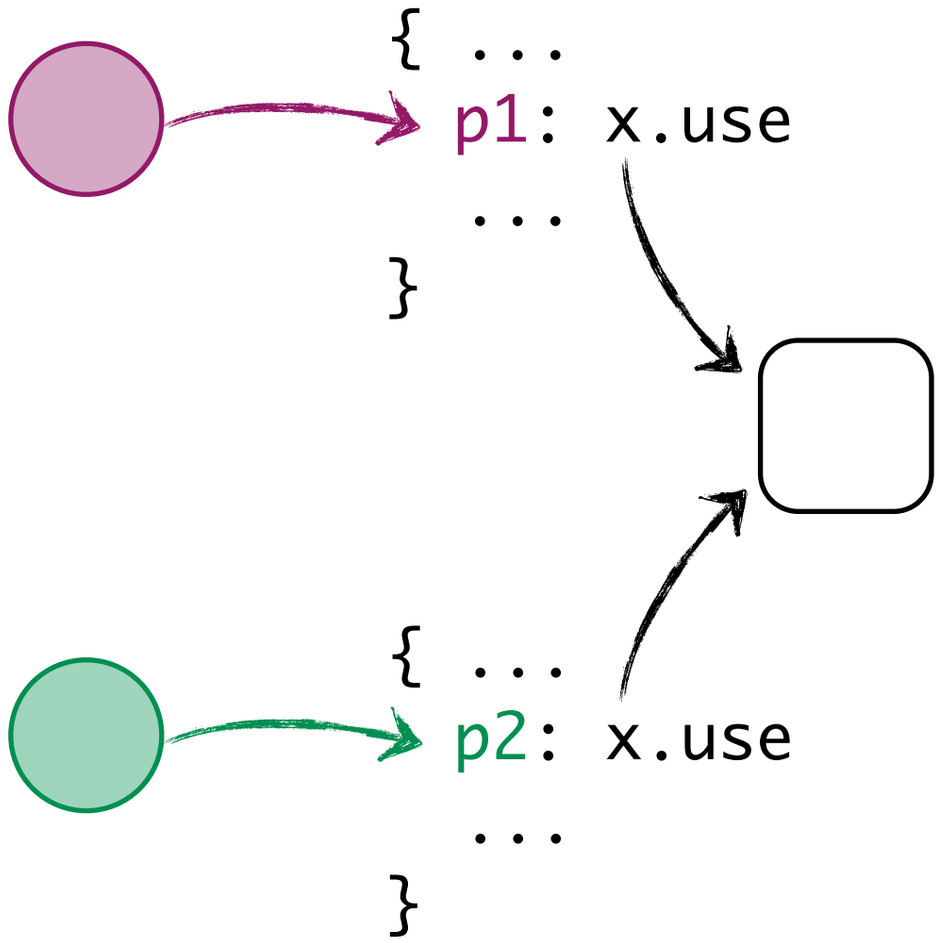

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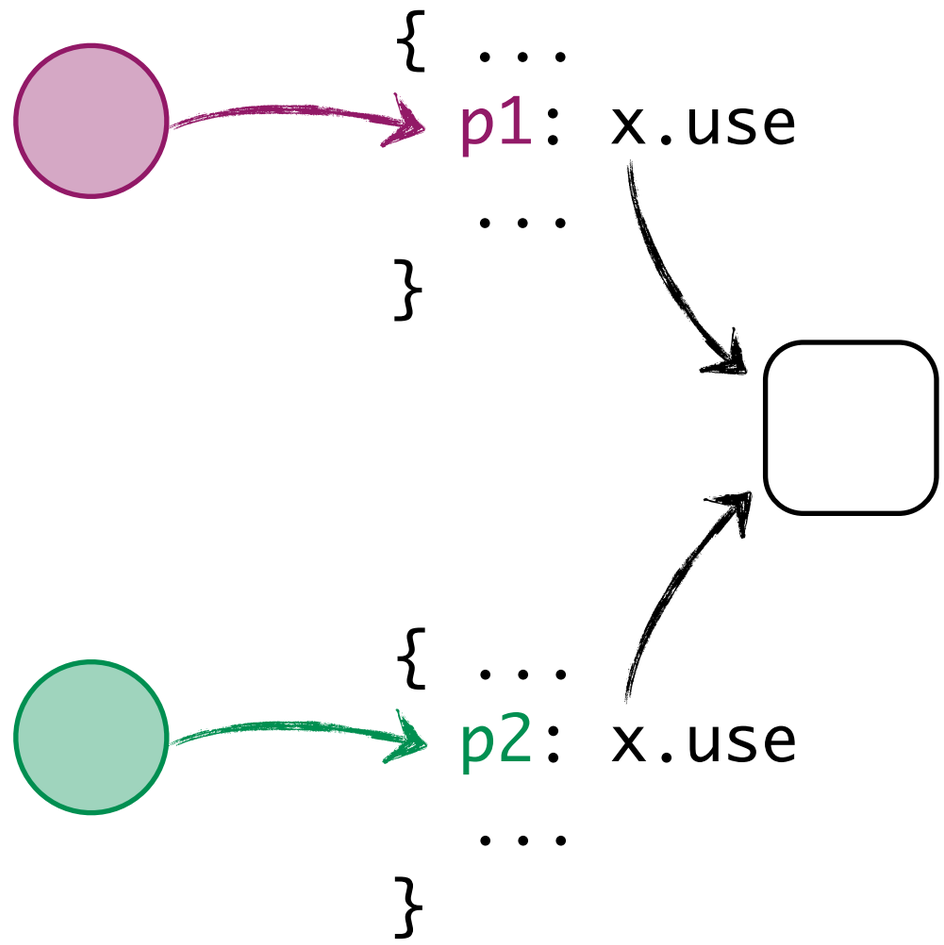

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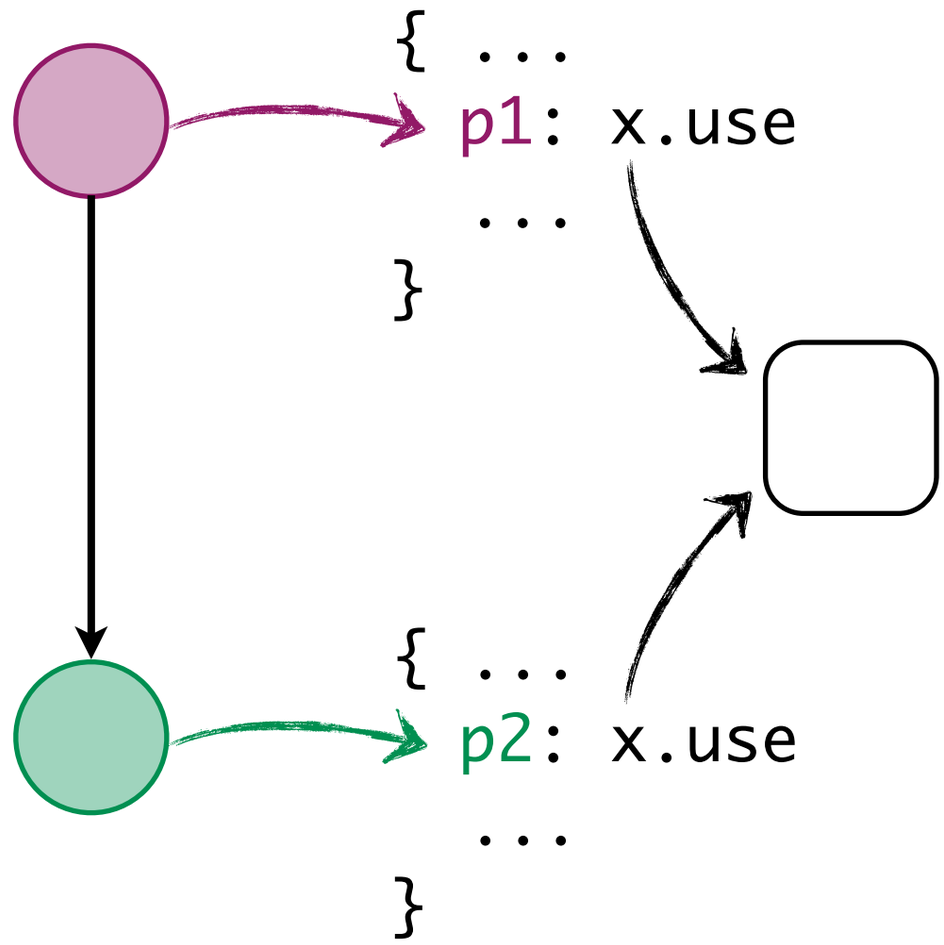

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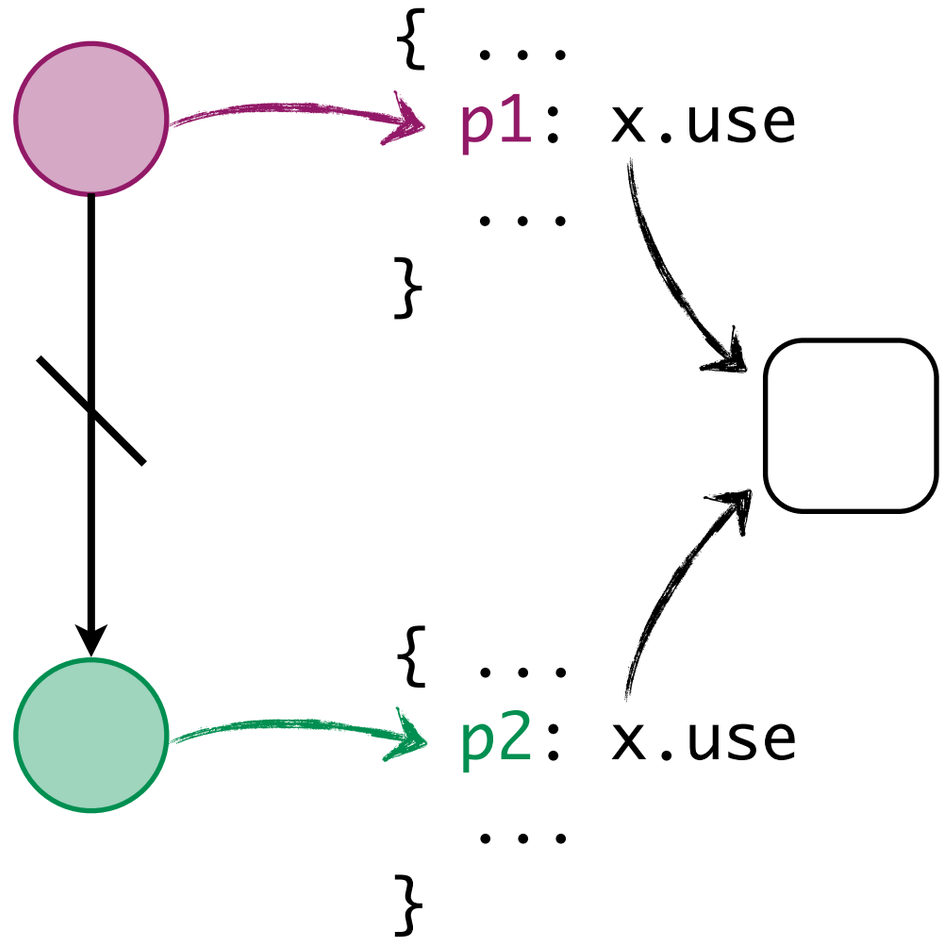
```
mayInterfere(p1, p2) :-
    execute(act1, p1),
    execute(act2, p2),
    access(p1, obj),
    access(p2, obj),
    !ordered(act1, act2).
```

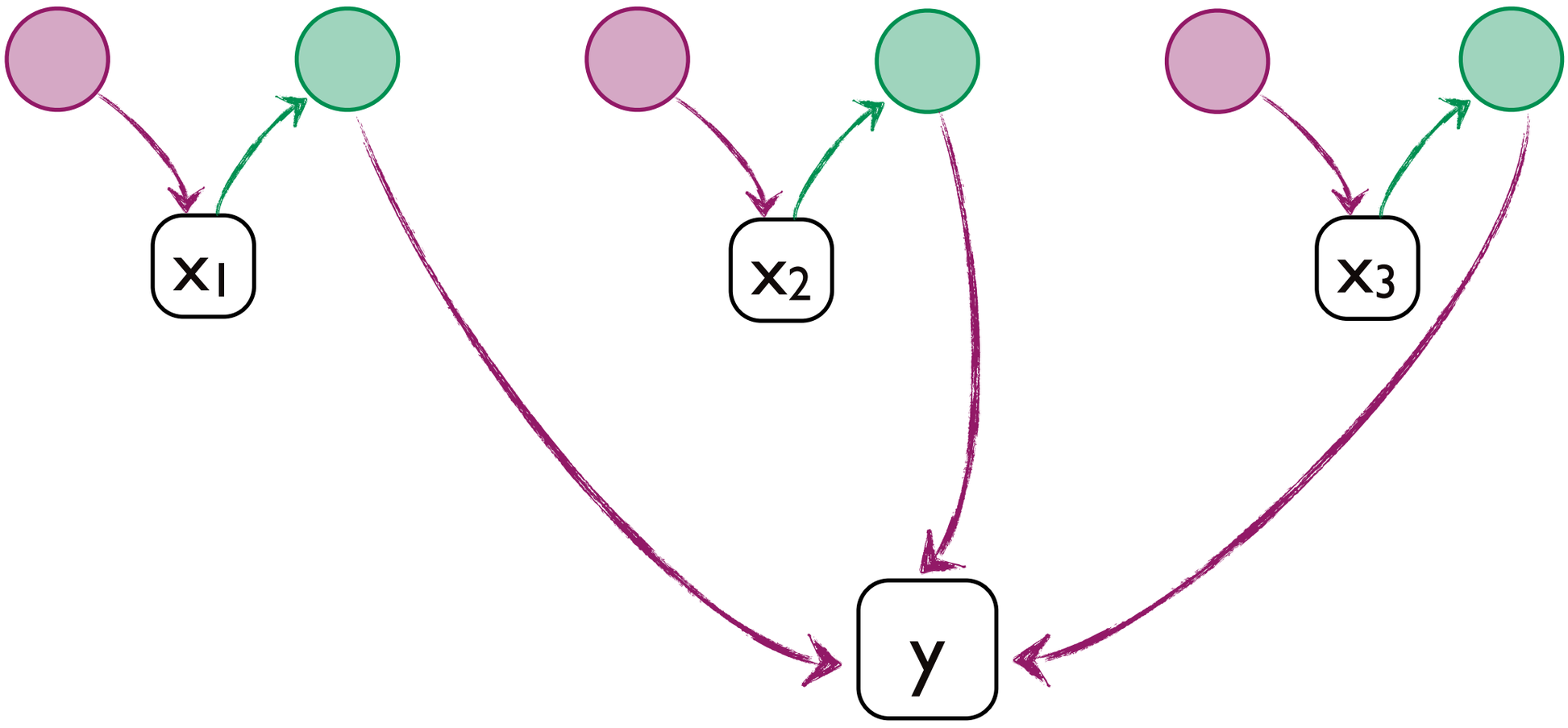


Next Steps

- Identify and analyze special cases/patterns. E.g.:
  - relative ordering of program phases
  - primitive recursion
  - nested loops
- Performance evaluation

Example

- Do we need to synchronize?



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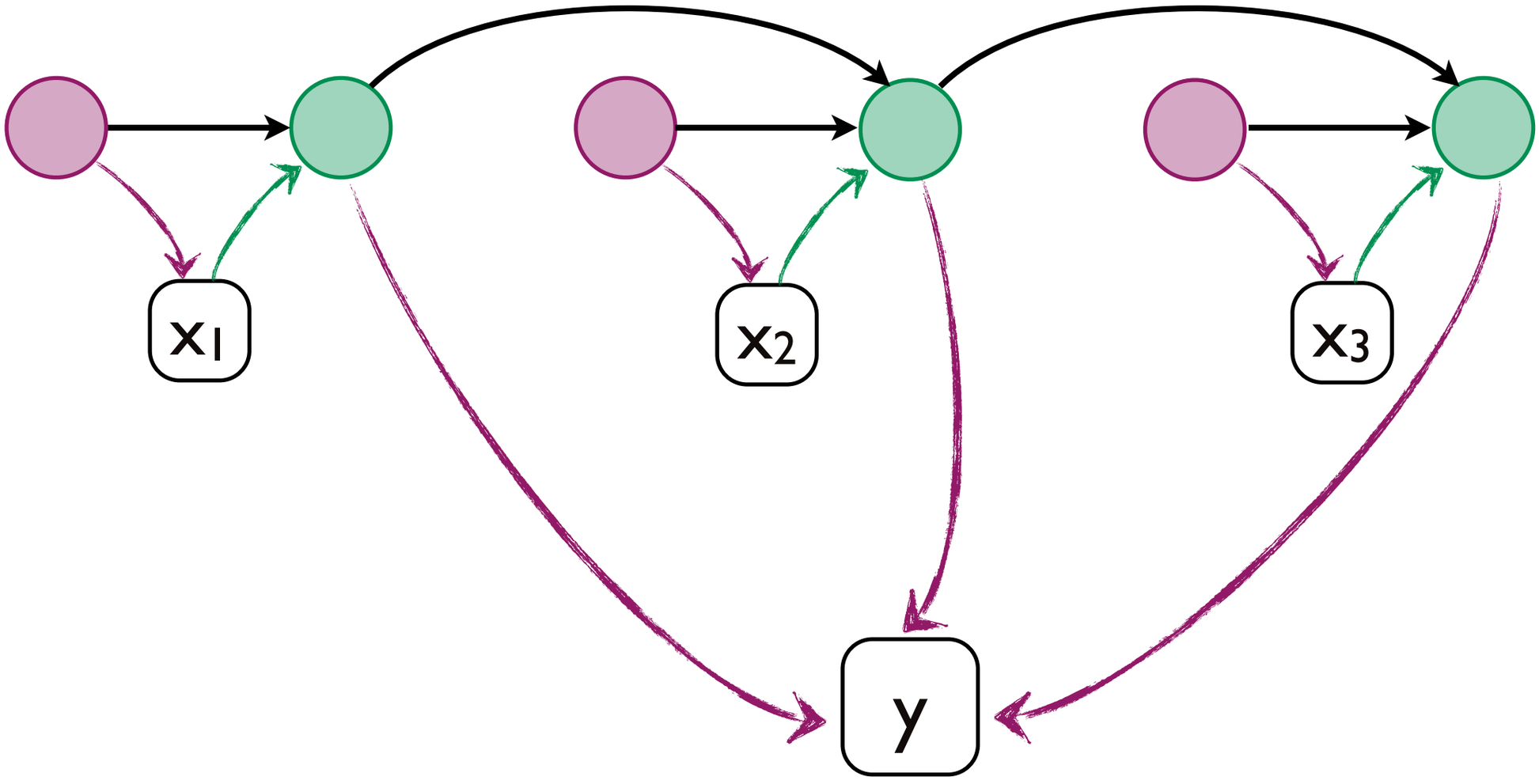

A Note on Notation

- Datalog: formal and executable specification language
- Efficient implementations scale to large real-world program analyses (Whaley&Lam, bddbddb)

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trans(x, y2) :- trans(x, y1), edge(y1, y2).
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- Example:

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trans(x, y2) :- trans(x, y1), edge(y1, y2).
```

- Maps naturally to inference rules:

$$\frac{\texttt{edge}(x, y)}{\texttt{trans}(x, y)} \qquad \frac{\texttt{trans}(x, y1)\ \ \texttt{edge}(y1, y2)}{\texttt{trans}(x, y2)}$$

Concluding Remarks

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  - Threads, fork/join, intervals, ...
  - ... can be intermixed in the same program

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- Synergistic effects between optimizations:
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- Optimizations directly profit from improvements of the schedule analysis

Synchronization Removal

- A monitor enter bytecode is required if parallel activations may try to lock the same object
- Otherwise, it can be removed

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```
requiredMonitorEnter(enterBC1) :-
   isMonitorEnter(enterBC1),
   isMonitorEnter(enterBC2),
   mayInterfere(enterBC1, enterBC2).
```

Pre-processing

- Compute domains and extract static program facts
- Examples:

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```
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```

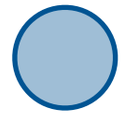
```
arrow(lhs:Var, rhs:Var)

schedule(lhs:Var, s:Sig, act:Obj)
```

May-be-ordered Analysis

- Compute read/write sets

```
reads(act:Obj, obj:Obj) :-
    execute(act, bc),
    load(bc, v, _, _),
    variablePT(v, obj).
```



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class MyClass {

  ...

  task doCompute(Vector in) {

    Activation last = now;

    for(Object o : in) {

      Activation map = sched this.doMap(o);

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      map → write;

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    }

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```

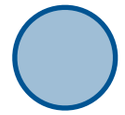

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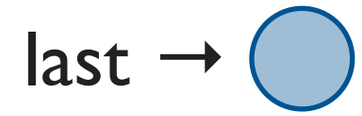


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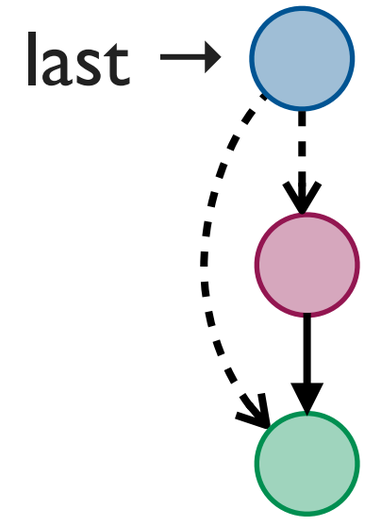

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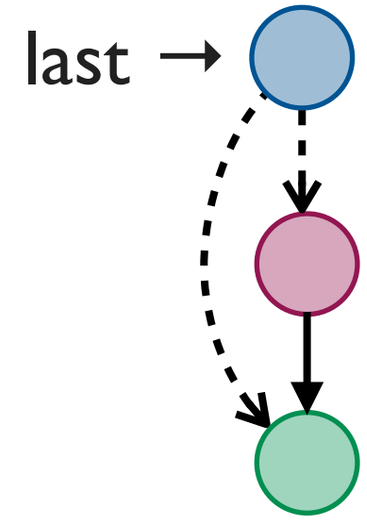

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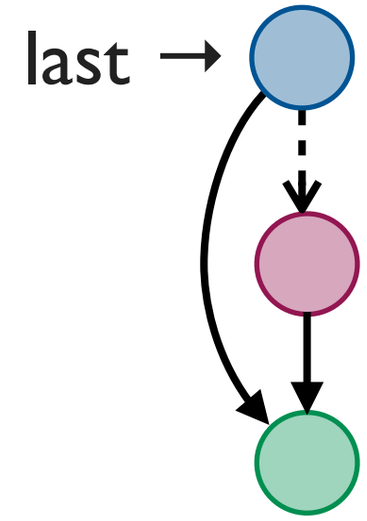

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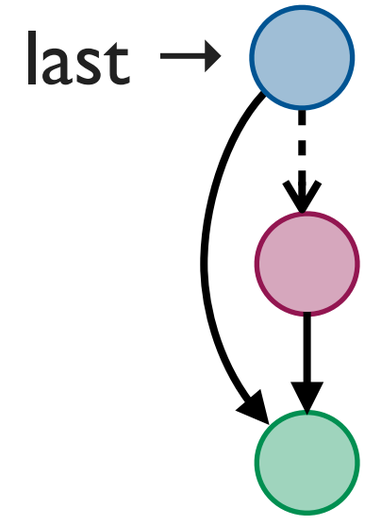

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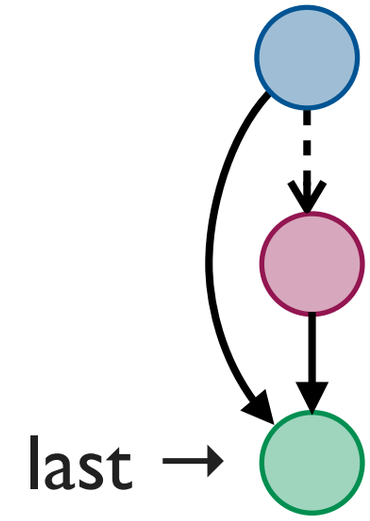

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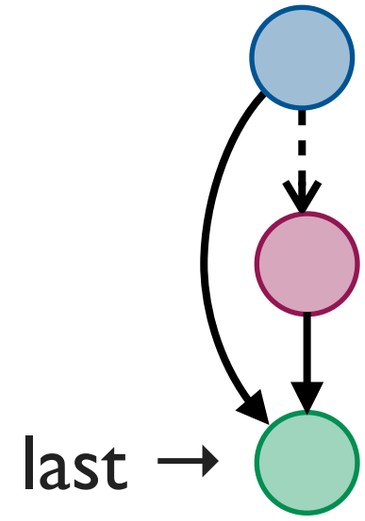

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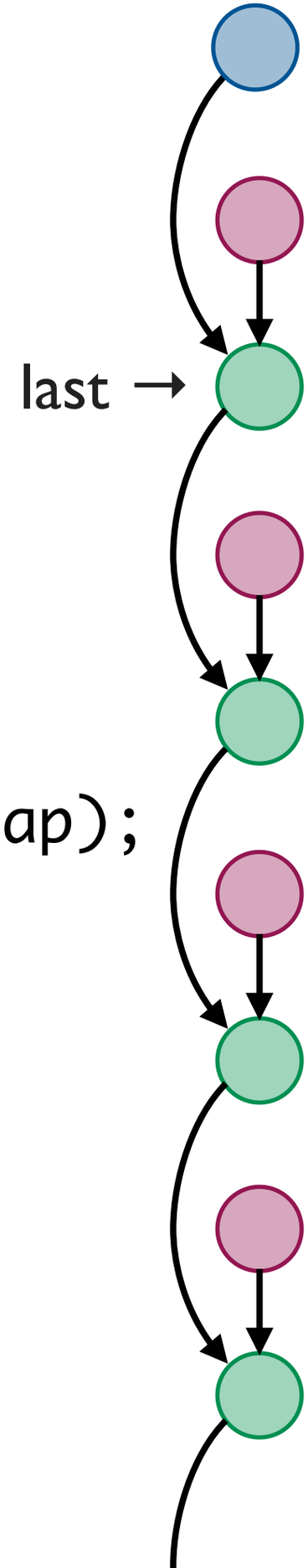

Other Optimizations

- Dependence reduction
- Removing lock-guards in intervals
- Removing happens-before assertions in intervals
- More?