Exploiting Task-Order Information in Optimizing Compilers for Parallel Programs

Christoph Angerer

Motivation

- Parallel programming becomes increasingly mainstream
- Influences models, languages, runtime libraries
- Added support for:
  - Controlling access to shared data
  - Controlling parallel program flow

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Can a compiler exploit information about the execution-order of tasks?

Example

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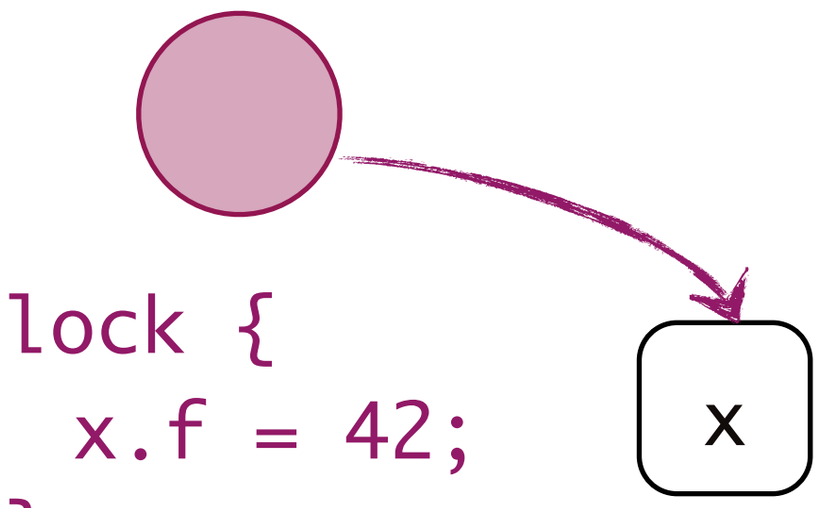
task A



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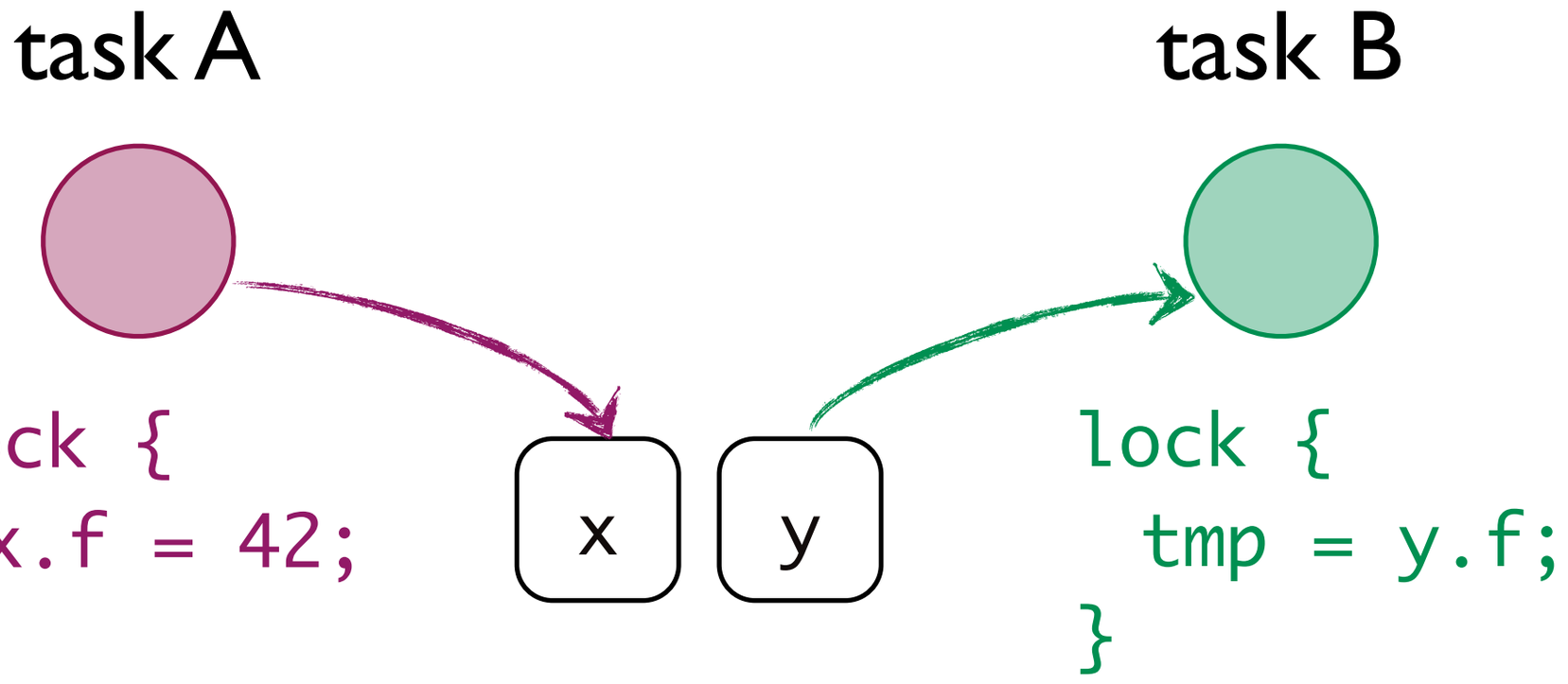

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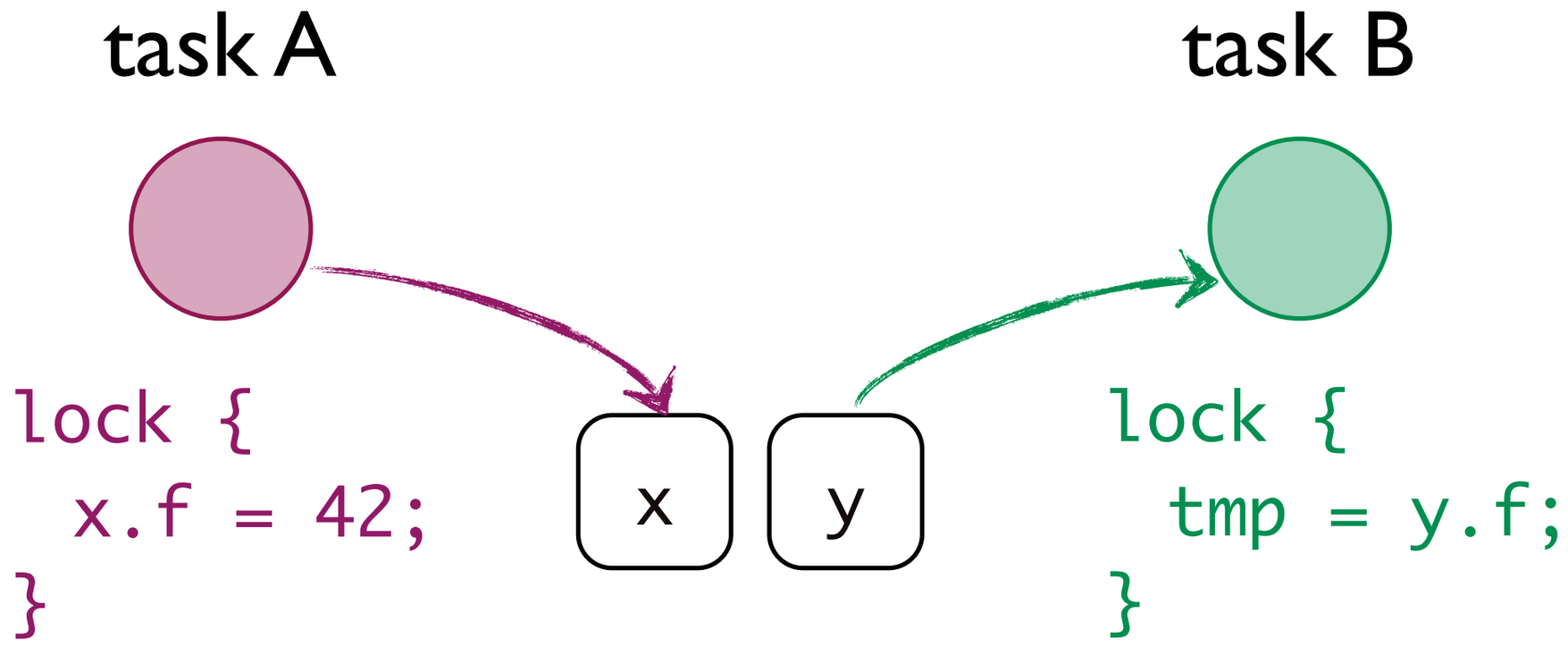

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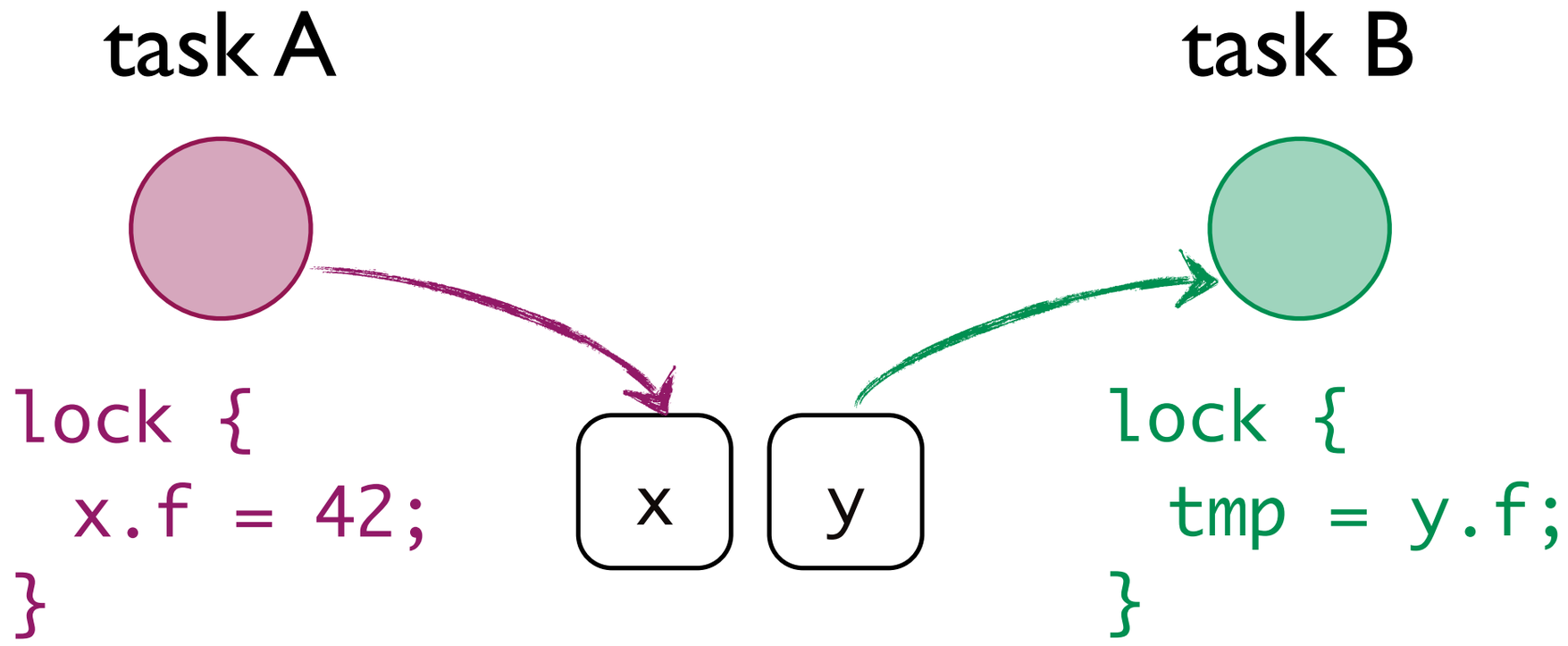

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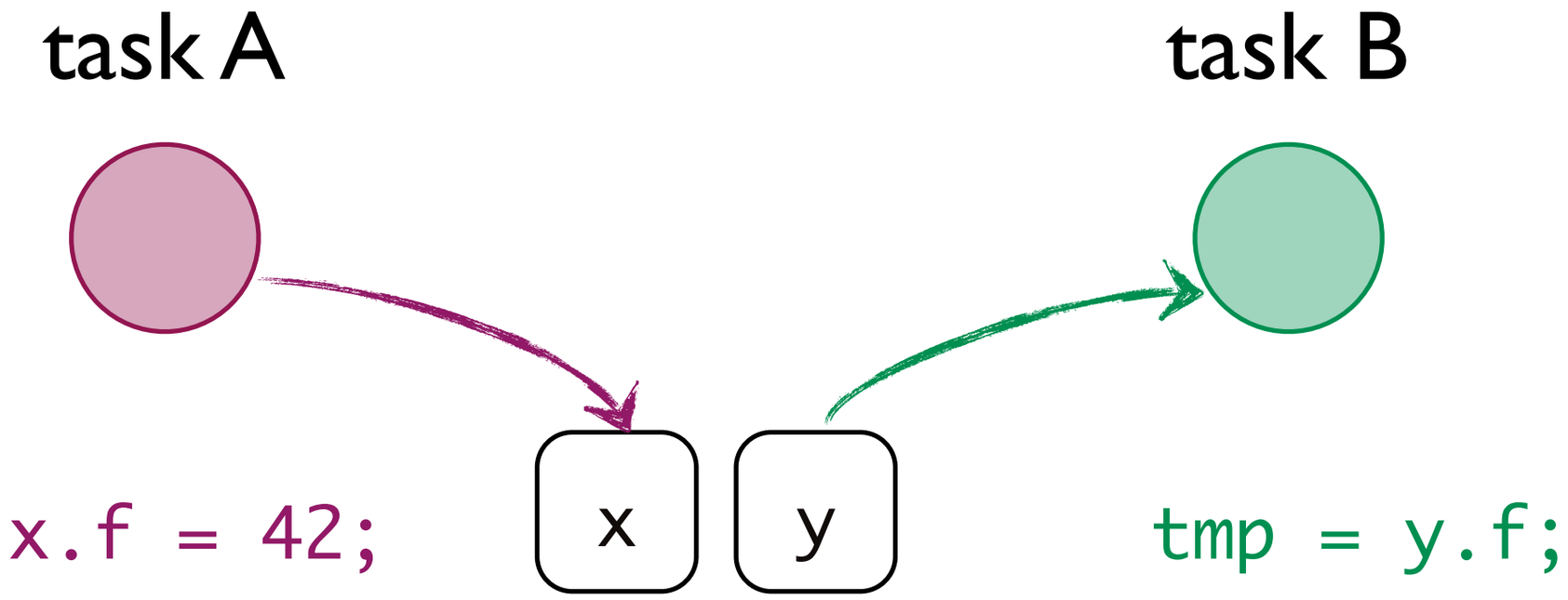

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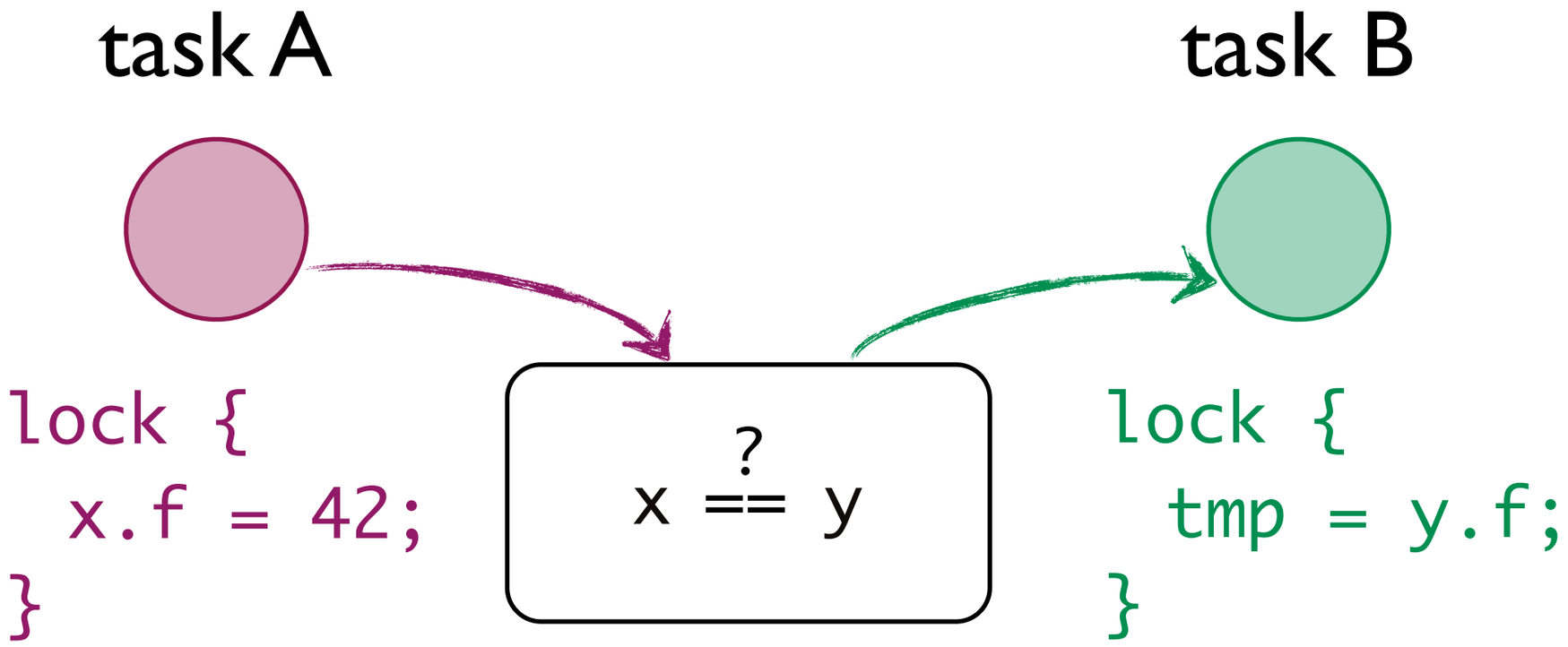

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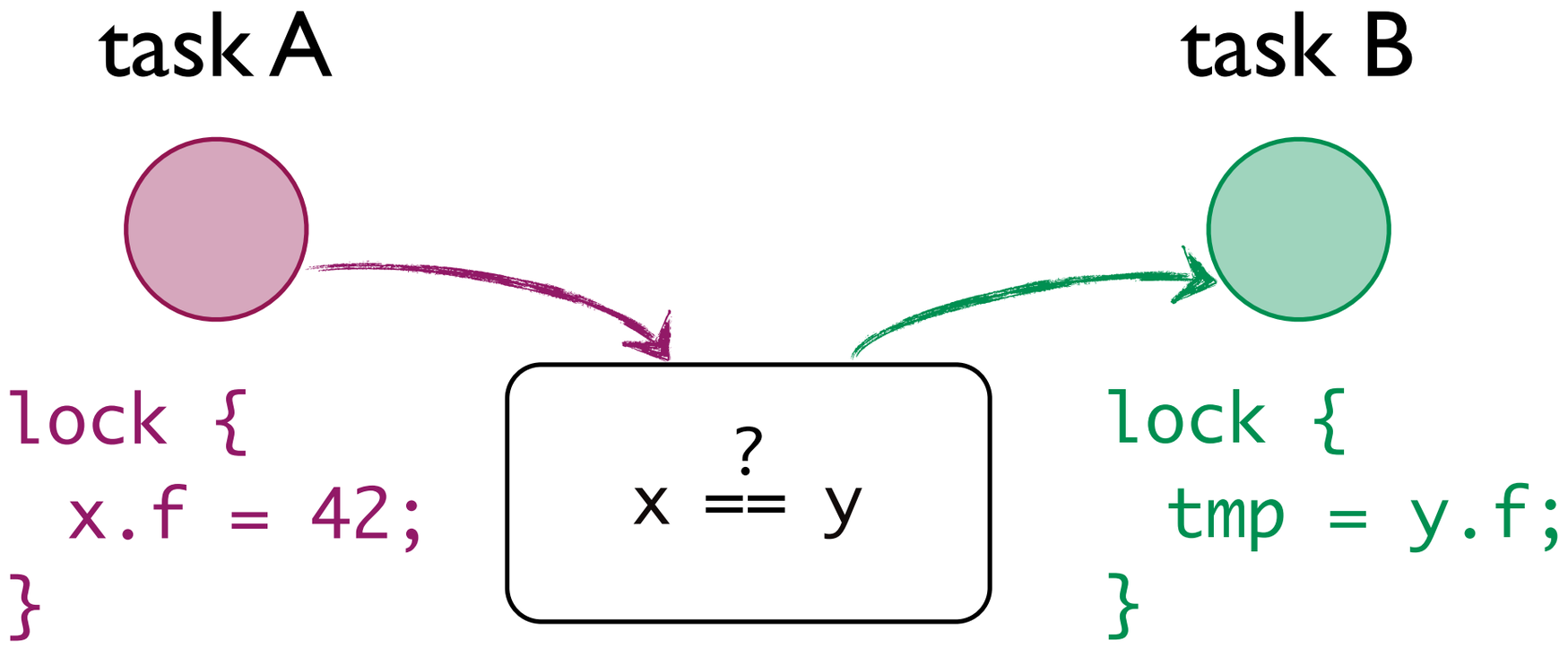

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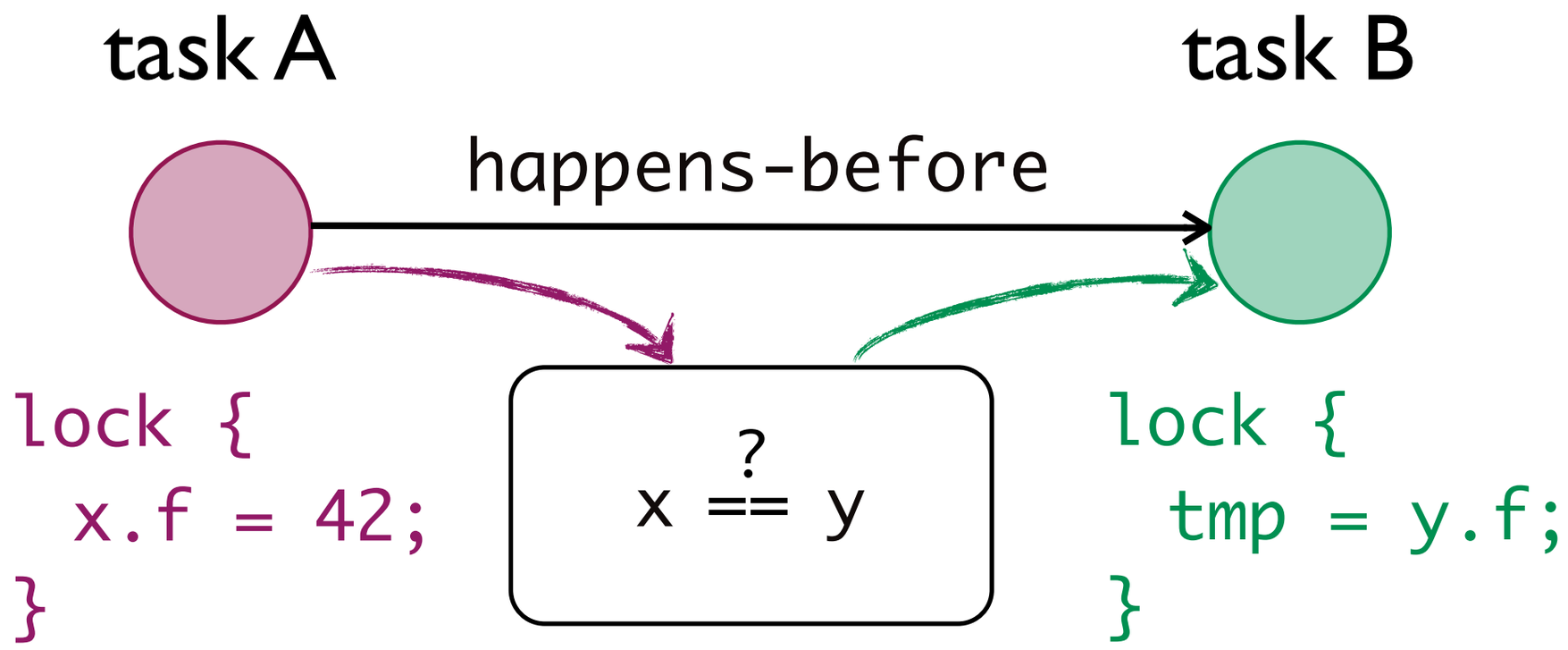

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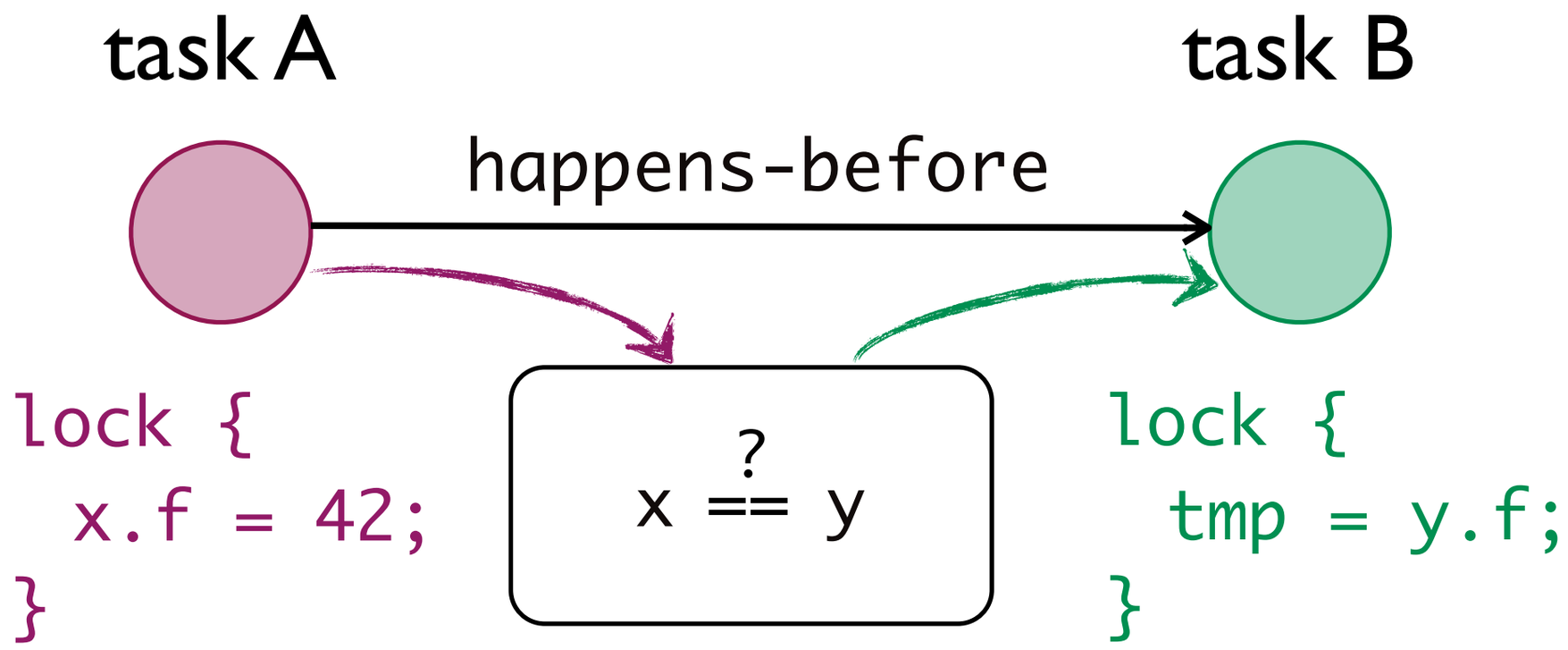

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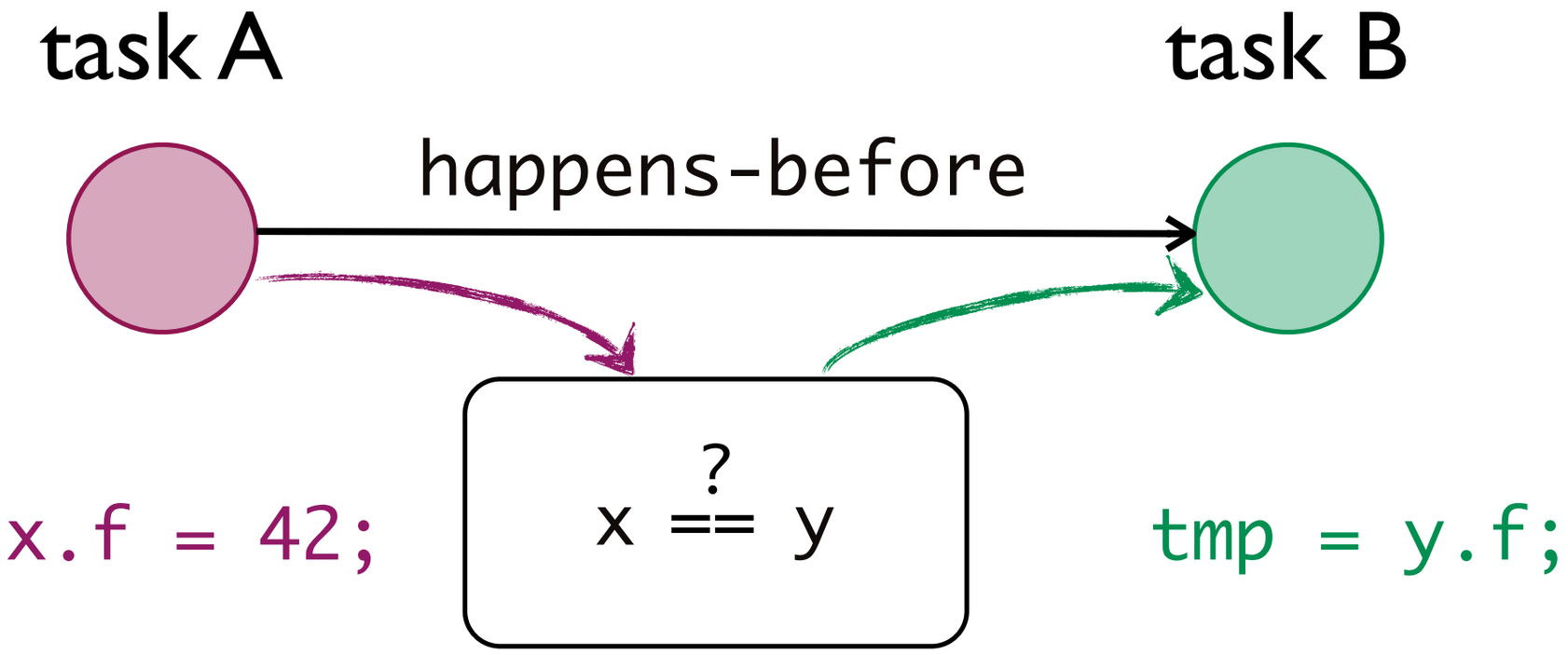

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☑ Ordered memory access

Thesis Statement

"Effective optimizations for shared-memory parallel programs need task-order information."

Contributions

- Programming model with explicit task-ordering constraints
- Schedule analysis to extract task-order information
- Evaluation of compiler optimizations that use task-order information

Outline

- Motivation
- Task Model
- Schedule Analysis
- Two Case Studies
- Conclusion

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  - Not much previous work here

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Task tA = Task.StartNew(/*A*/);

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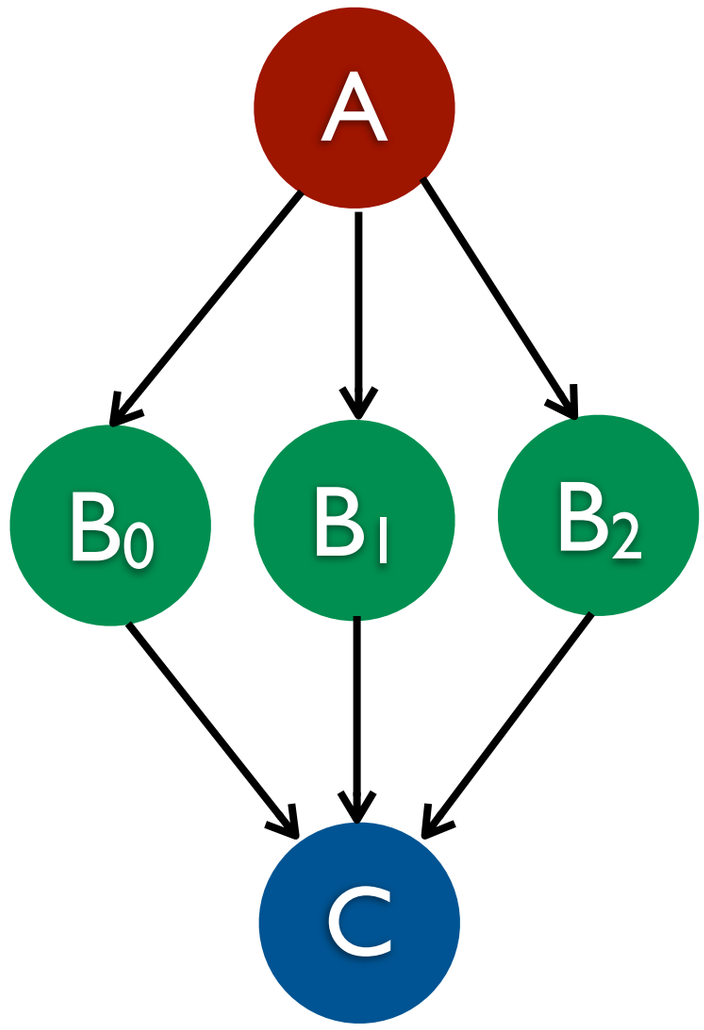

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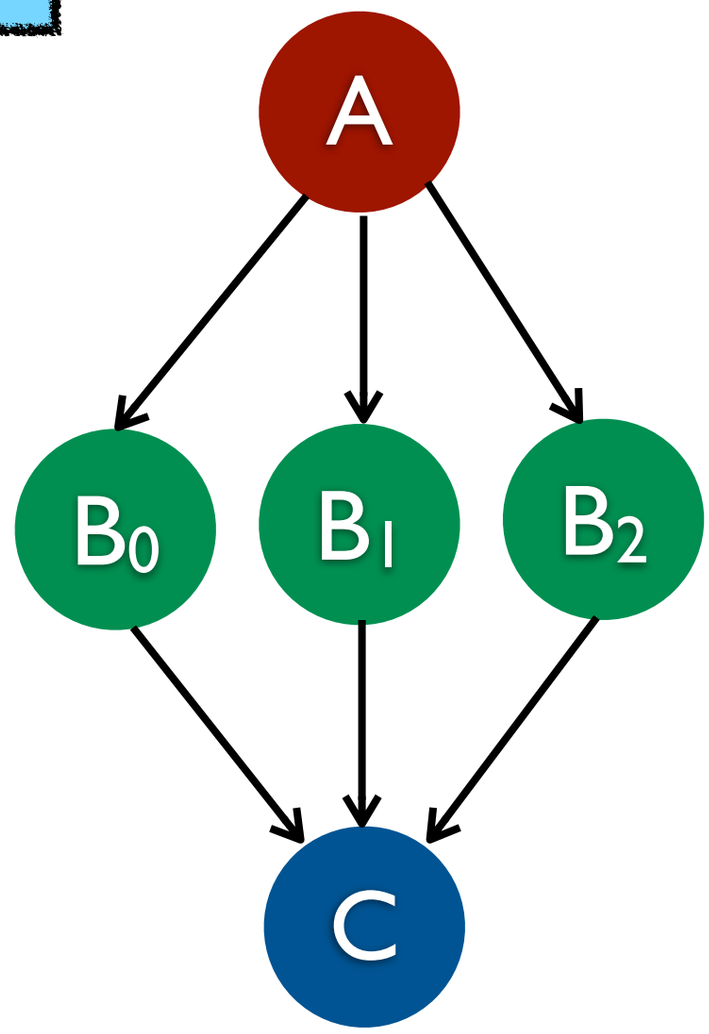

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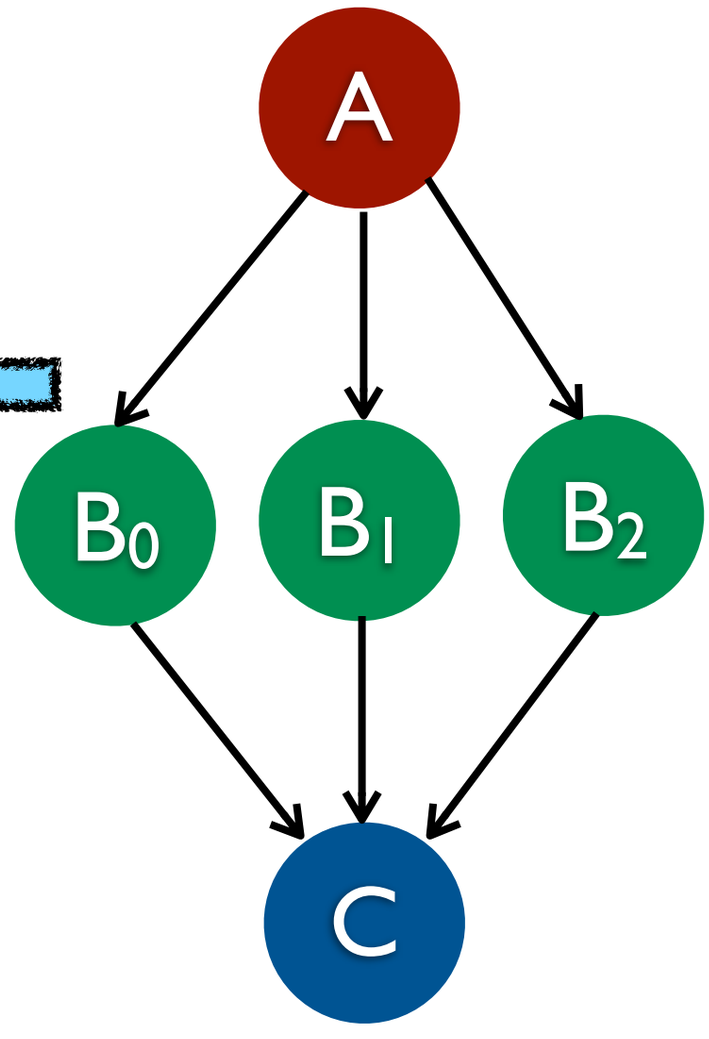

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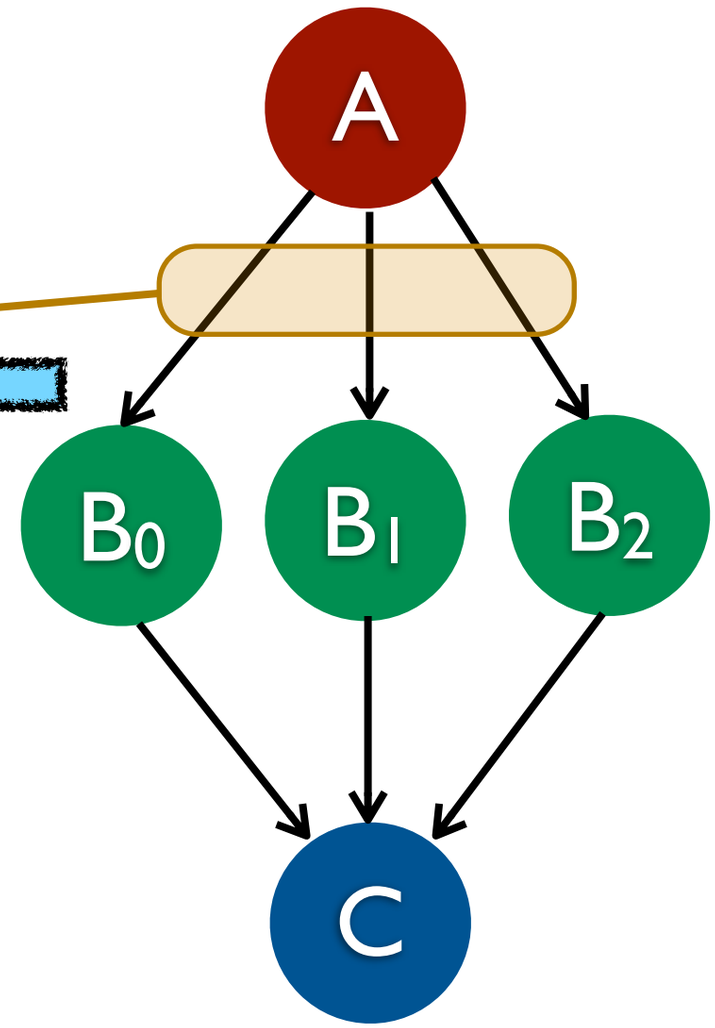

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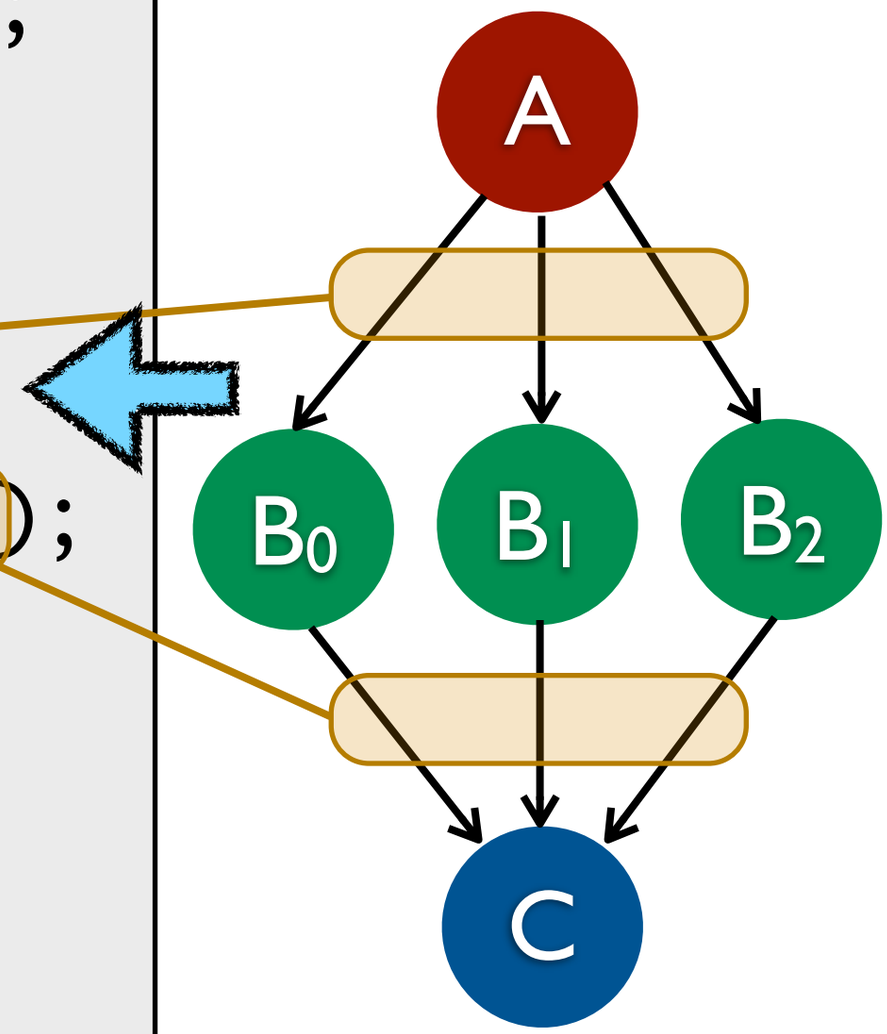

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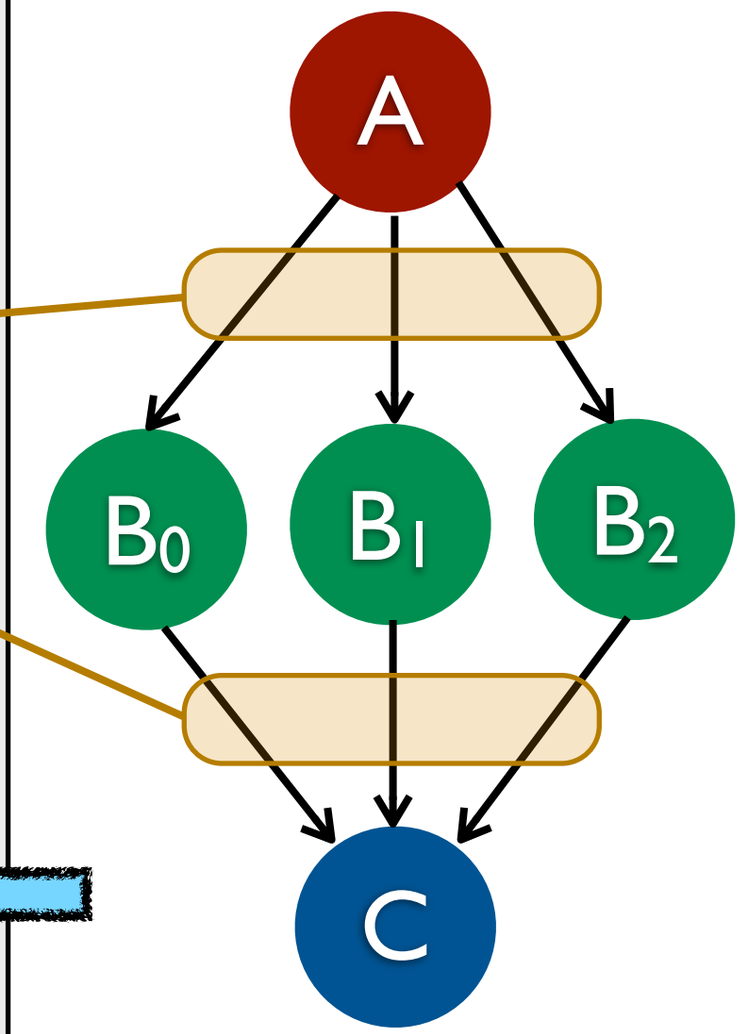

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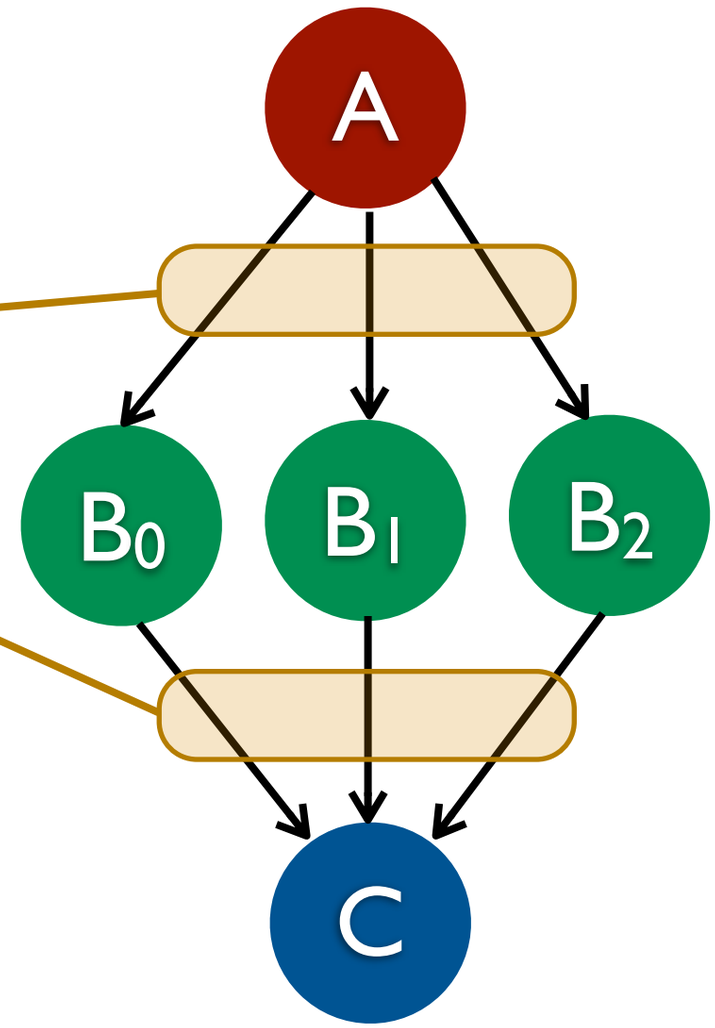

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Abstraction:

Tasks with explicit happens-before relationships

Our Model: Explicit Scheduling

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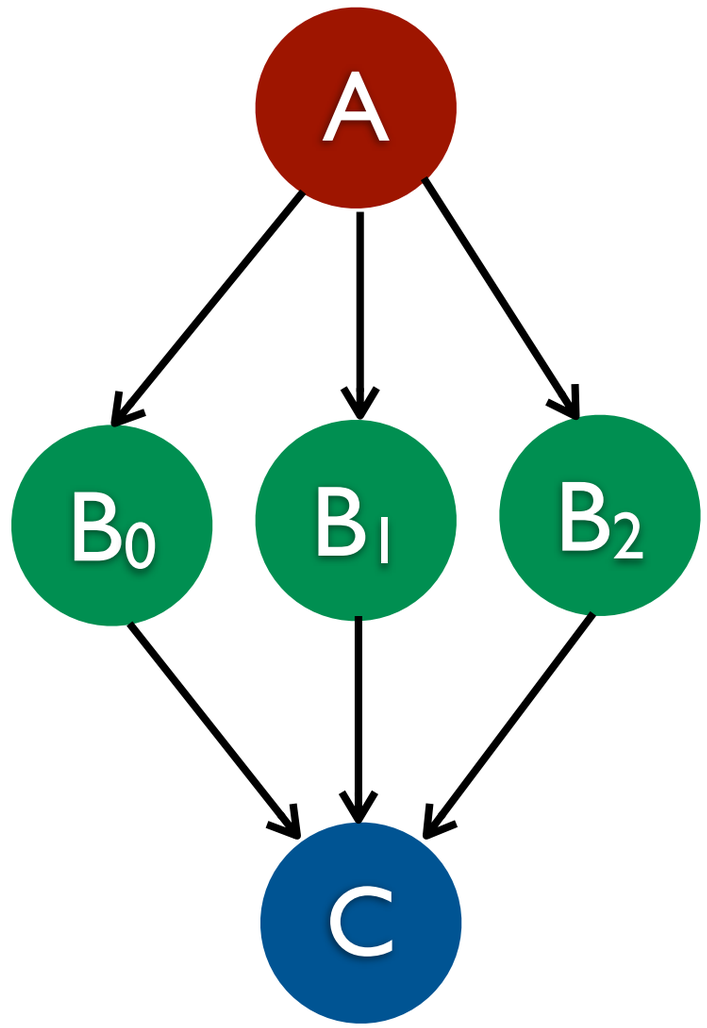

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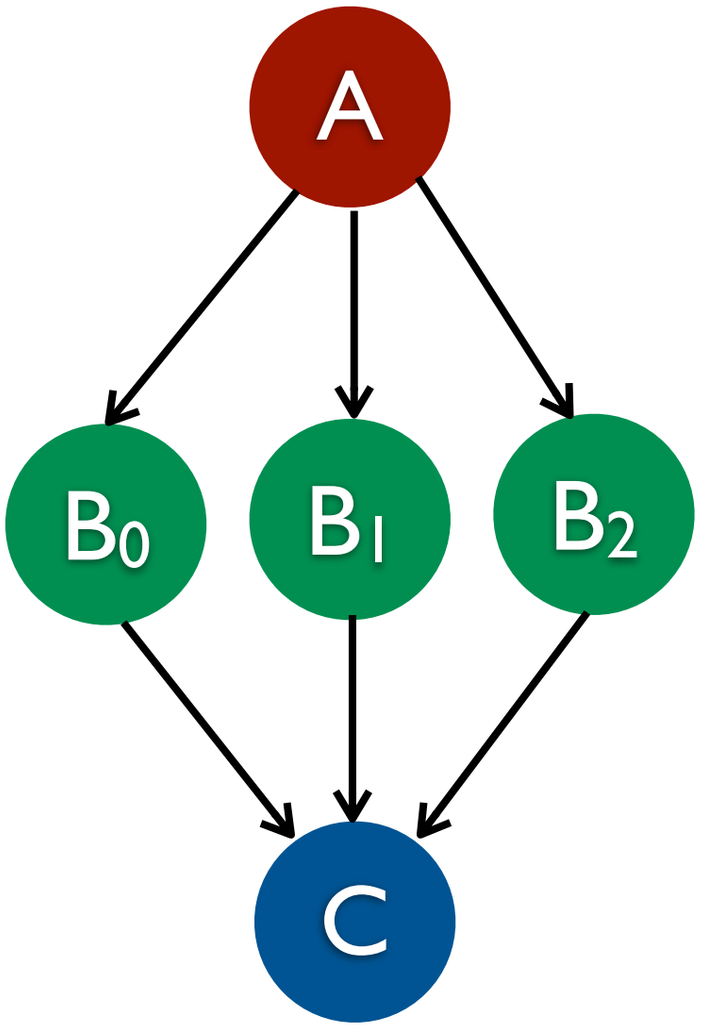

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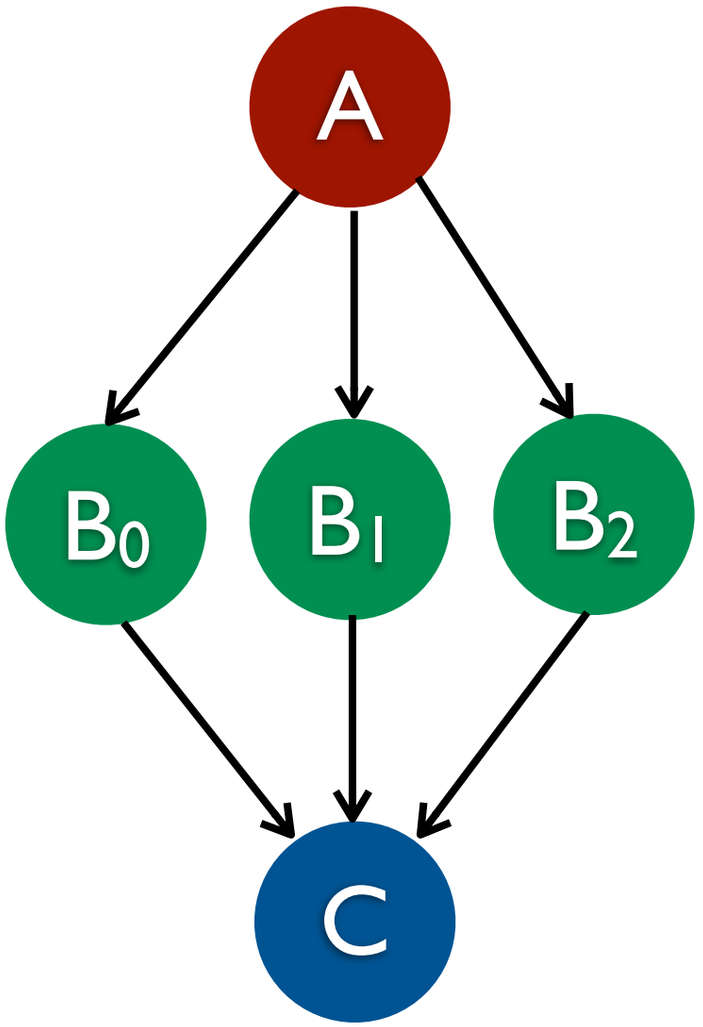

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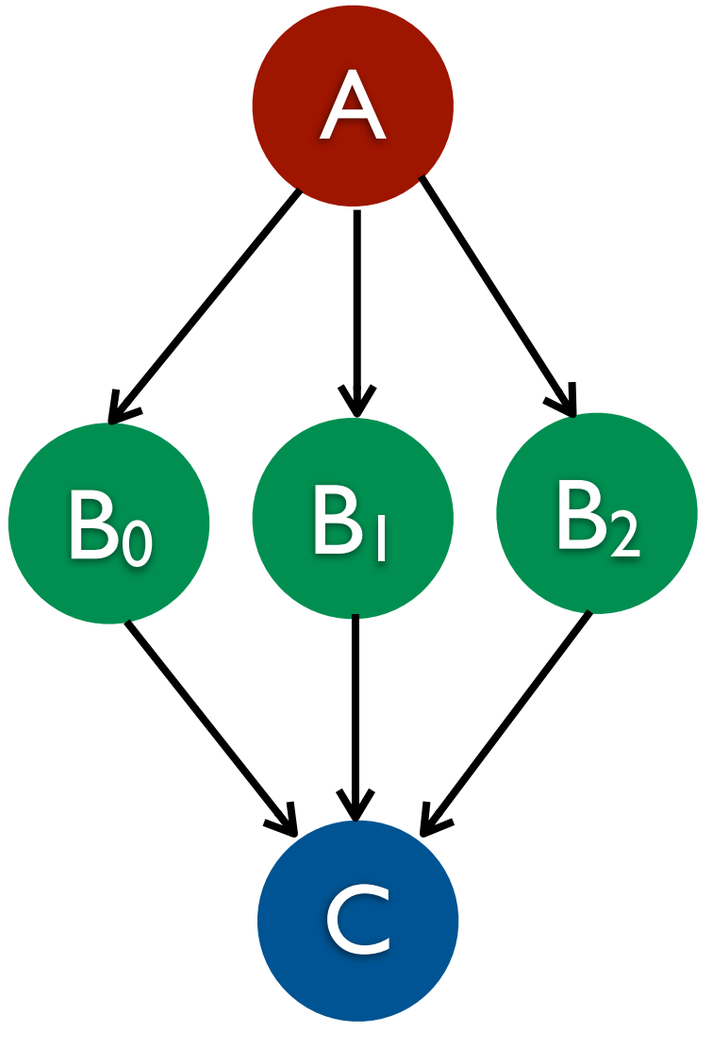

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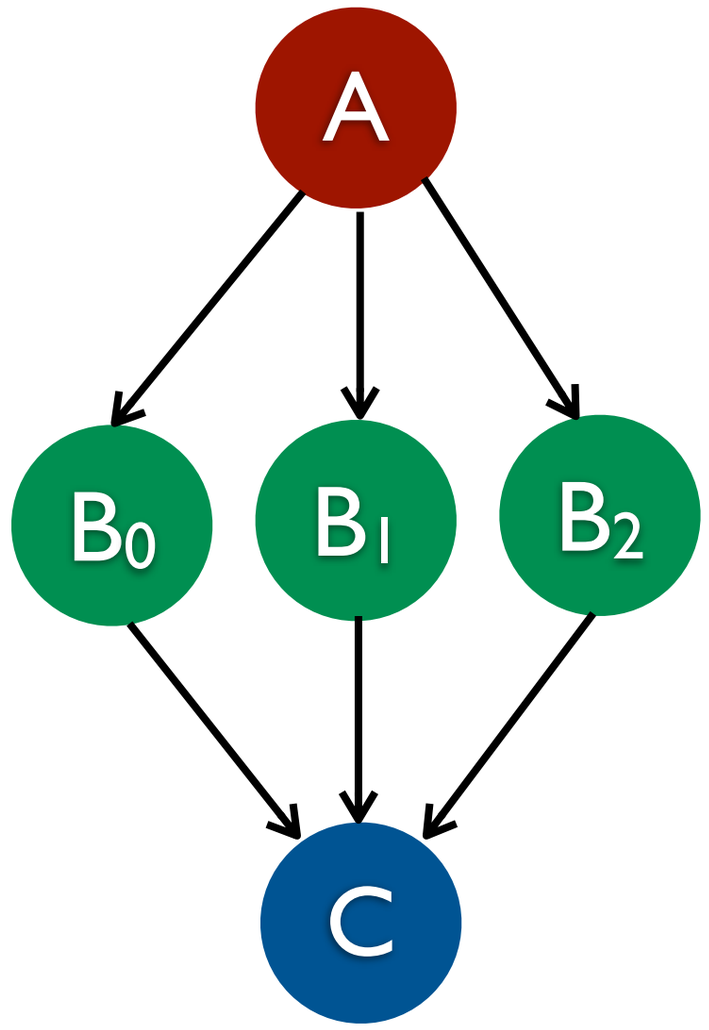

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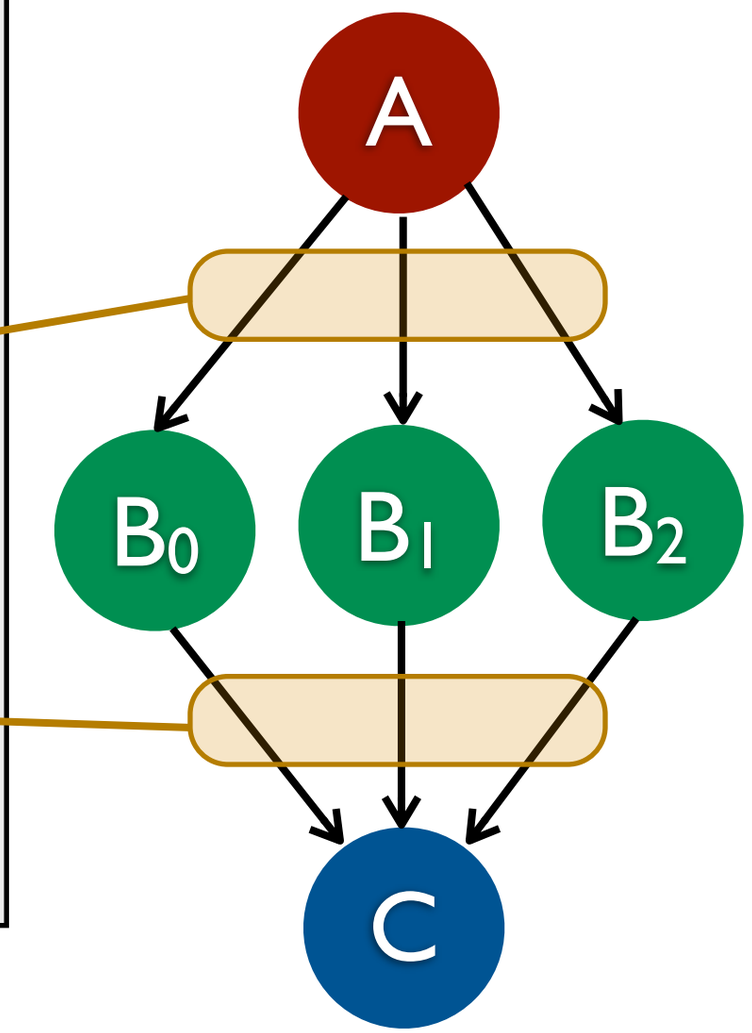

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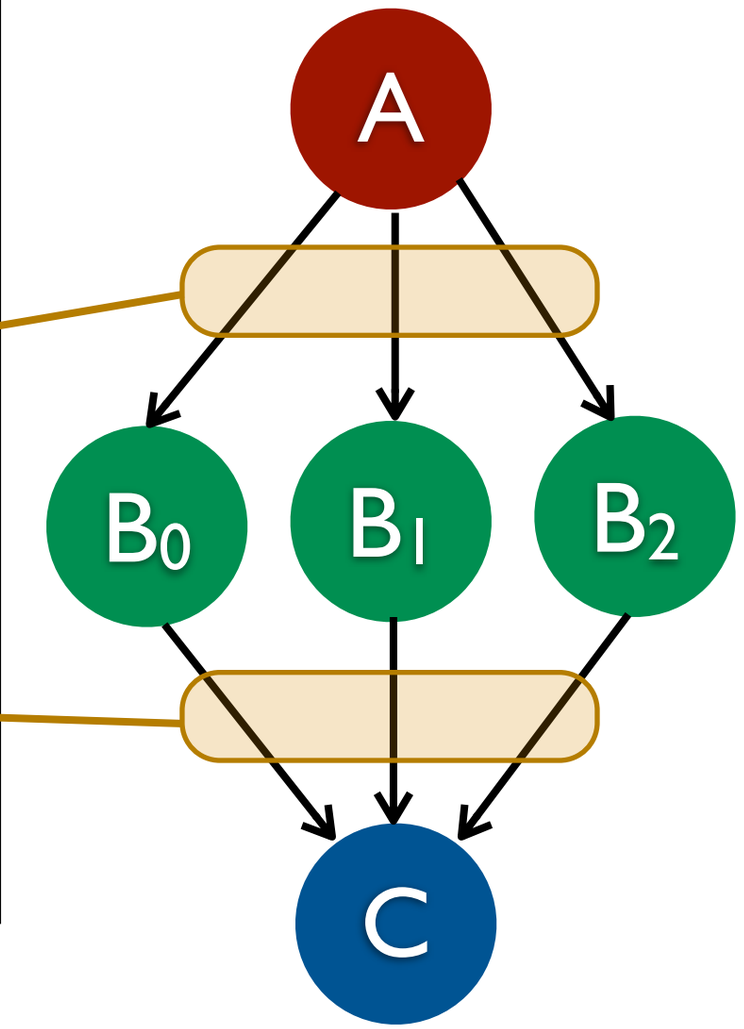

General enough to express threads, fork/join, thread libraries, ...

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- Motivation
- Task Model
- Schedule Analysis
- Two Case Studies
- Conclusion

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2. Until fixed-point reached:

   Find tasks that may be created without ordering

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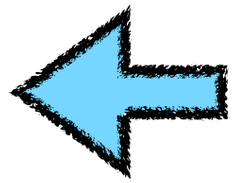

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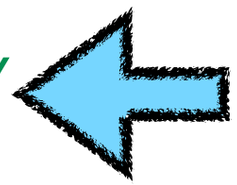

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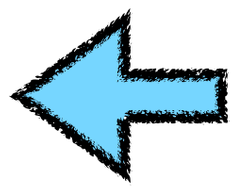

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2: Find Unordered Tasks

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2: Find Unordered Tasks

- Key insight:
  - We look for unordered-ness, not ordered-ness
- Unordered-ness is monotonic!

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Ordered-ness:

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Unordered-ness:

for T1: B ‖ B

for T2: A ‖ B

monotonic

Summary Schedule Analysis

- Static bytecode analysis
- Computes relation:
  `mayBeParallel(task1, task2)`
- If `!mayBeParallel(task1, task2)` then `task1` and `task2` are guaranteed to be ordered

Outline

- Motivation
- Task Model
- Schedule Analysis
- Two Case Studies
  - Sequentially Consistent Java
  - Dynamic Fractional Permissions
- Conclusion

Sequential Consistency

- Easy-to-understand memory model
- Conceptually:
  - All memory accesses are visible immediately
  - All tasks agree on same legal sequential history of memory events
  - No instruction re-ordering

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- Conceptually:
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  - All tasks agree on same legal sequential history of memory events
  - No instruction re-ordering

Inefficient without optimizations!

SC Example

Initially, x == y == 0

Task 1	Task 2
1: r1 = x;	3: r2 = y;
2: y = 2;	4: x = 1;

Is r1 == 1 AND r2 == 2 possible?

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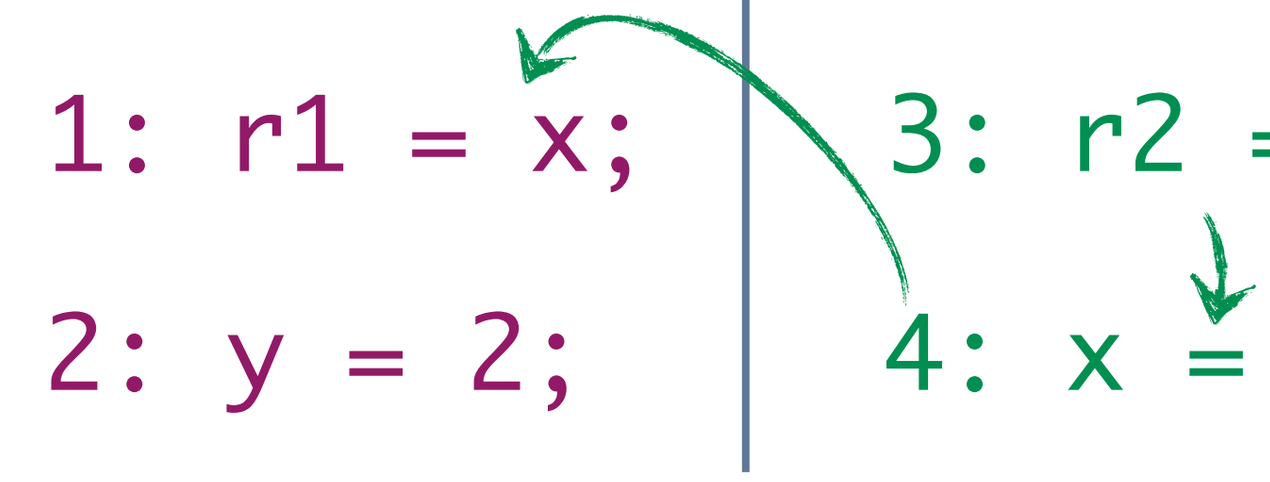

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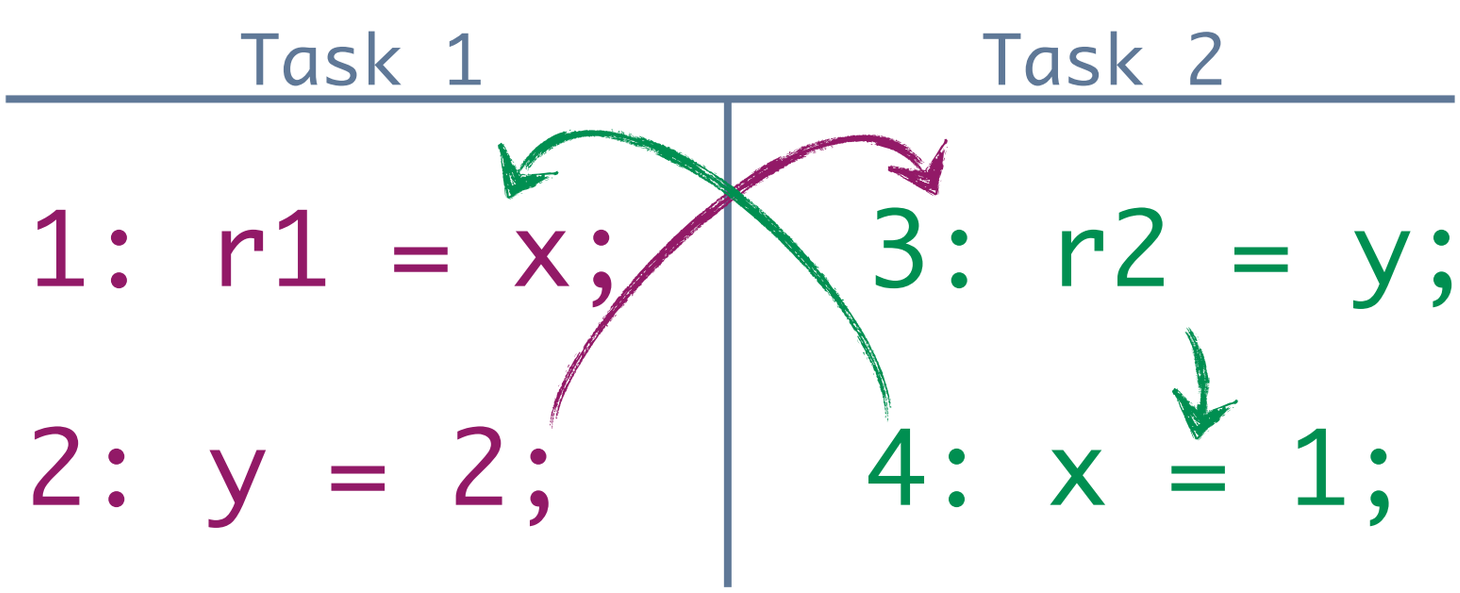

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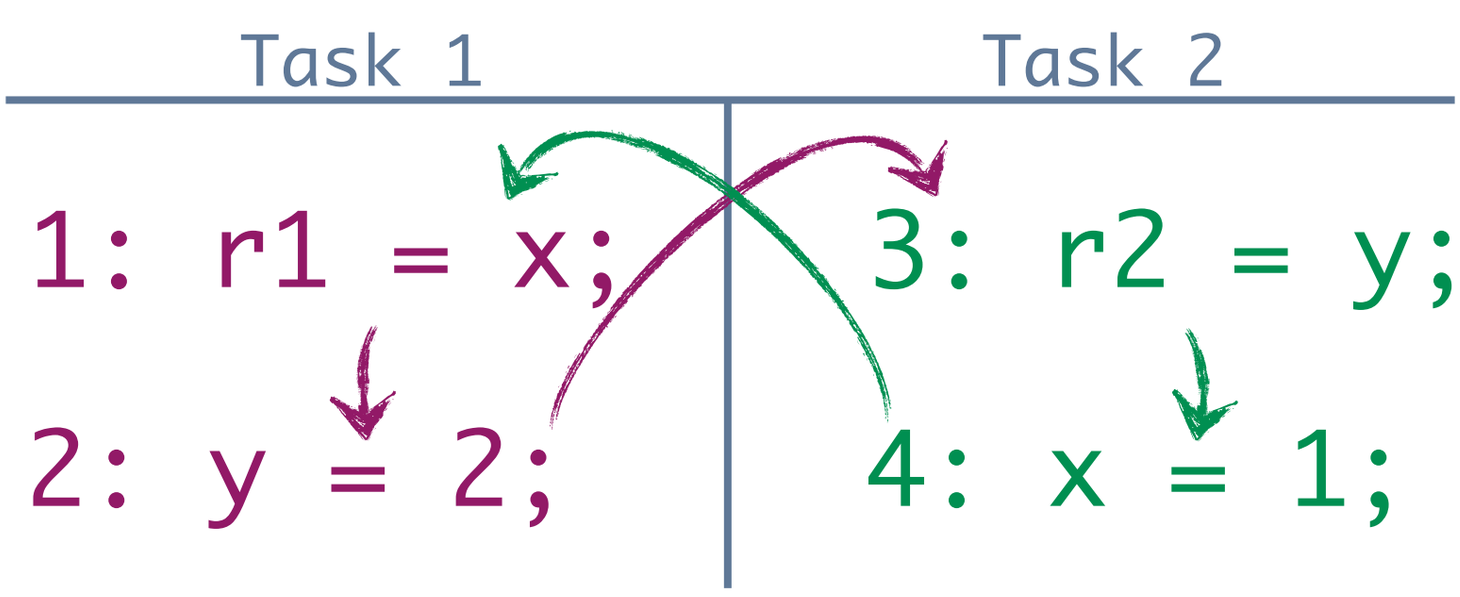

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SC Example

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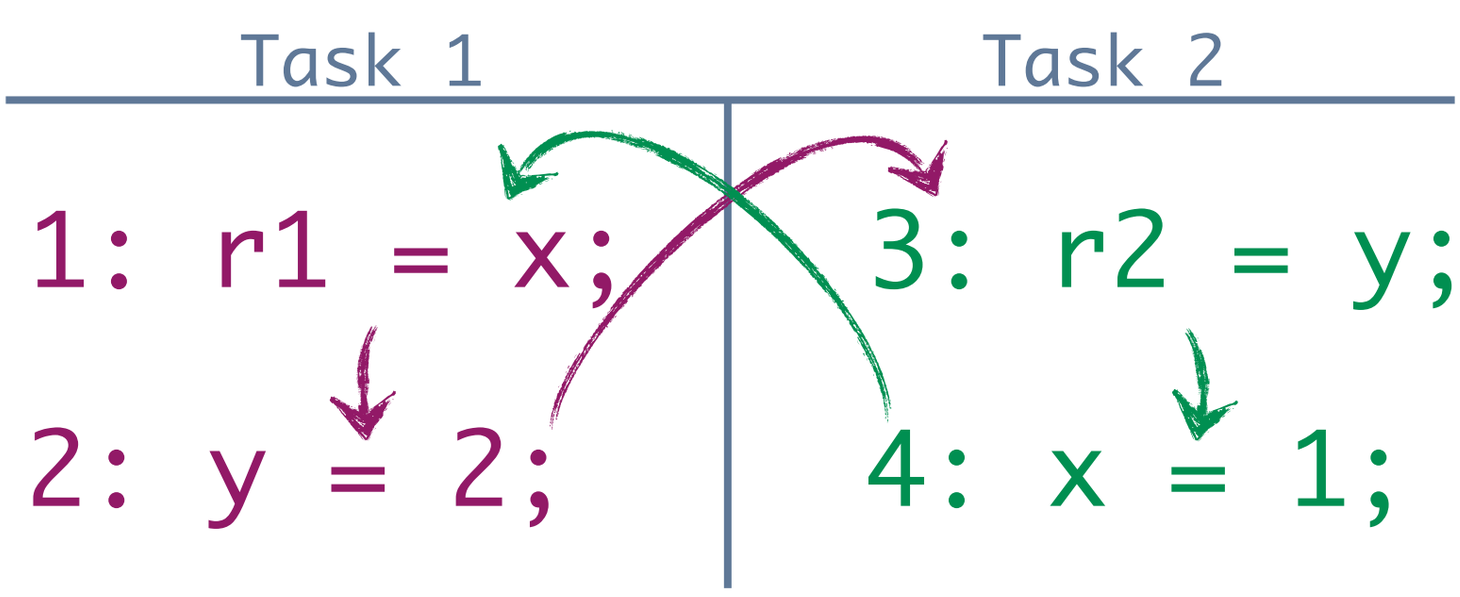

Is r1 == 1 AND r2 == 2 possible?

No, if "sequentially consistent"

SC Example

Initially, x == y == 0

Task 1	Task 2
2: y = 2;	4: x = 1;
1: r1 = x;	3: r2 = y;

Is r1 == 1 AND r2 == 2 possible?

Yes, if the compiler reorders
1,2 and/or 3,4

Sequentially Consistent Java

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  - Guard every memory access with barriers (fields and array elements)

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Sequentially Consistent Java

- Simple model:
  - Guard every memory access with barriers (fields and array elements)
- Drawbacks:
  - Barriers introduce overhead
  - Prevents many standard optimizations
- Optimize to re-gain performance:
  - Remove barriers where not needed
  - Different objects ∨ ordered tasks

Evaluation Setup

- Intel Core 2 Duo, 2.8 GHz, 4Gb RAM

  ⇒2 Java Threads

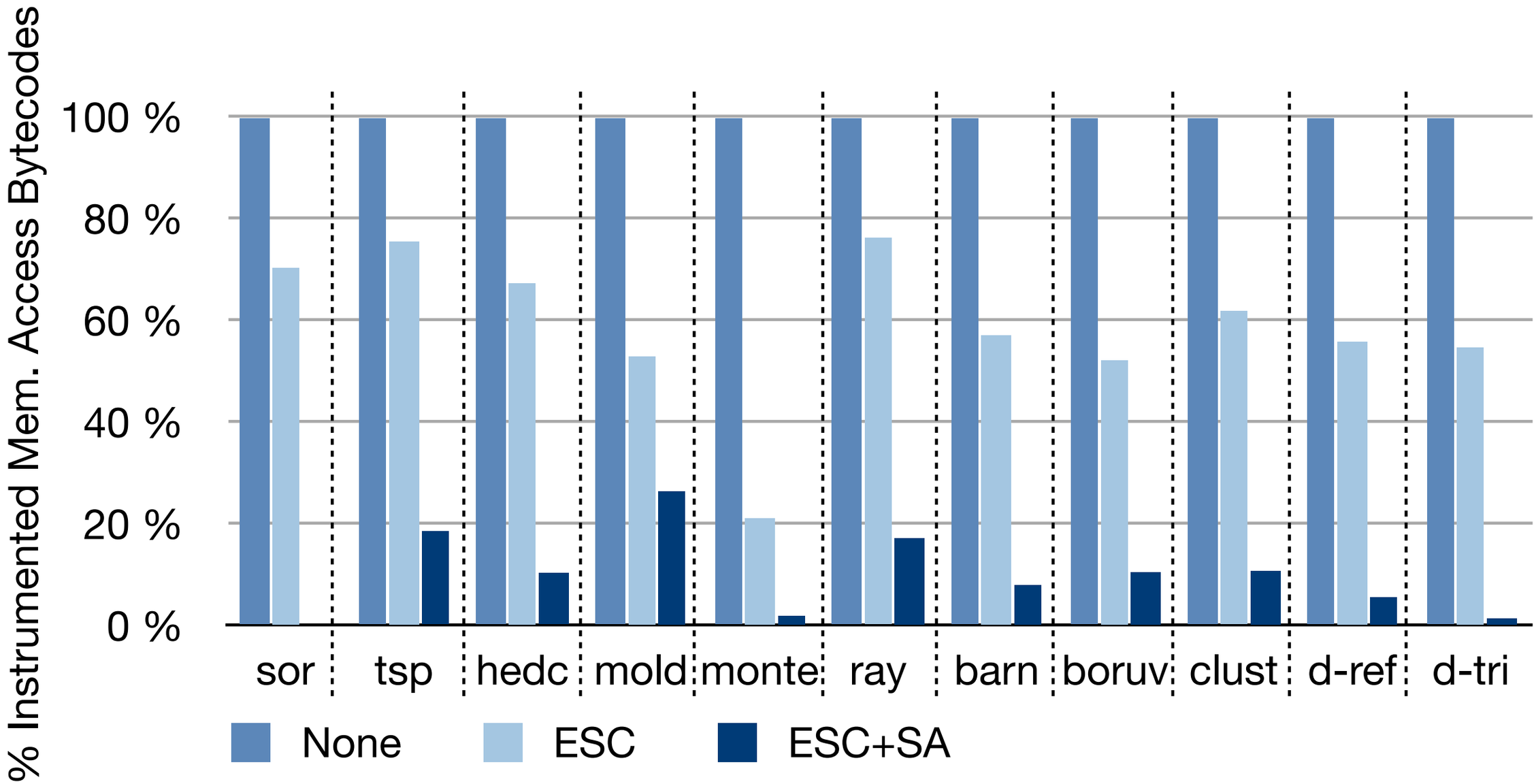
- Java 1.6.0 (Mac)

- Benchmarks
  - Java Grande: numeric apps
  - Erco Benchmarks: OO-style parallelism
  - Lonestar: larger applications, irregular behavior

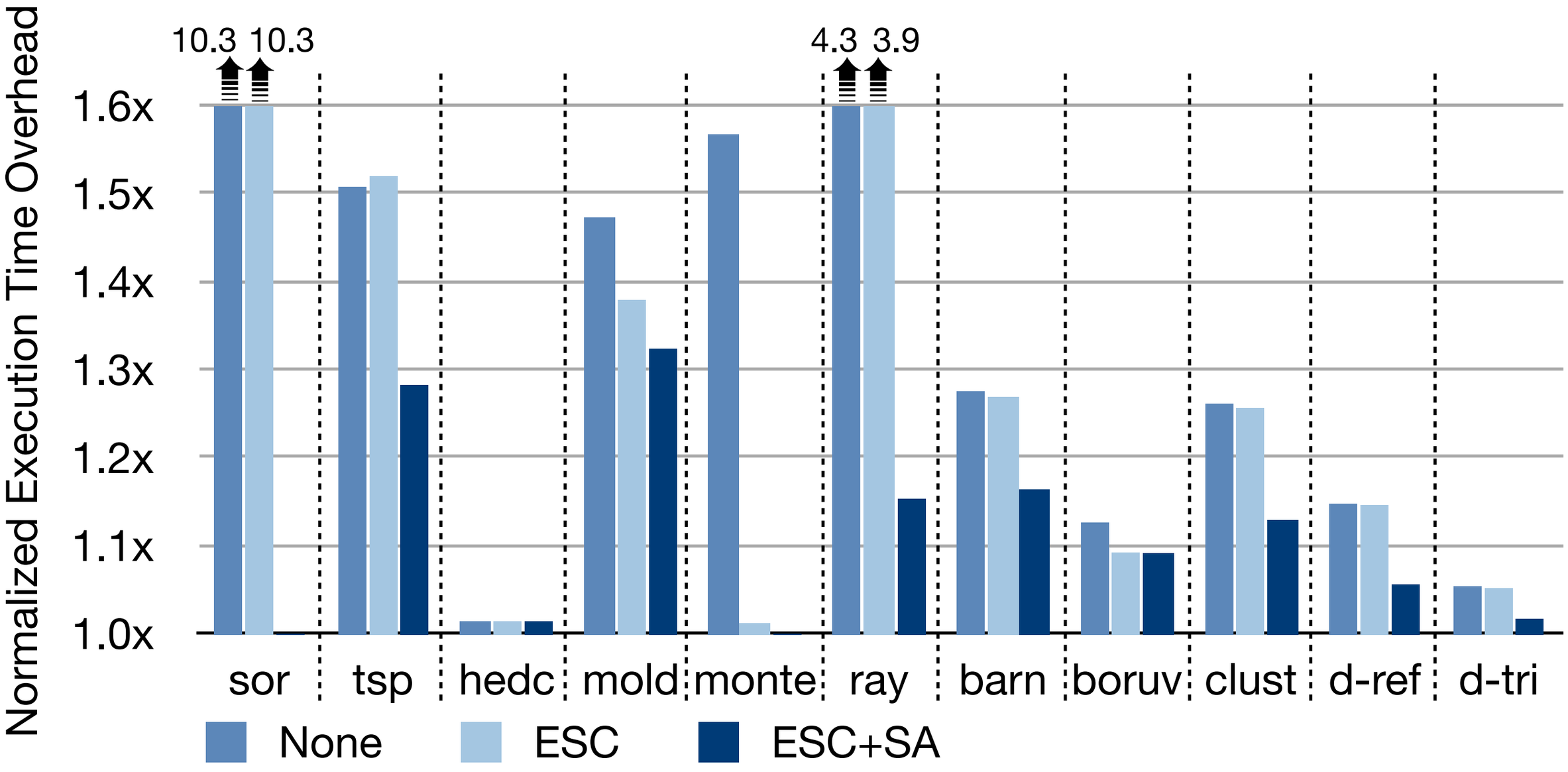
Configurations

- Relaxed memory model, programmer-provided SC (`Baseline`)
- SC, no optimizations (None)
- SC, escape analysis (ESC)
- SC, schedule analysis + escape analysis (SA+ESC)

Instrumentation Overhead



Execution Time



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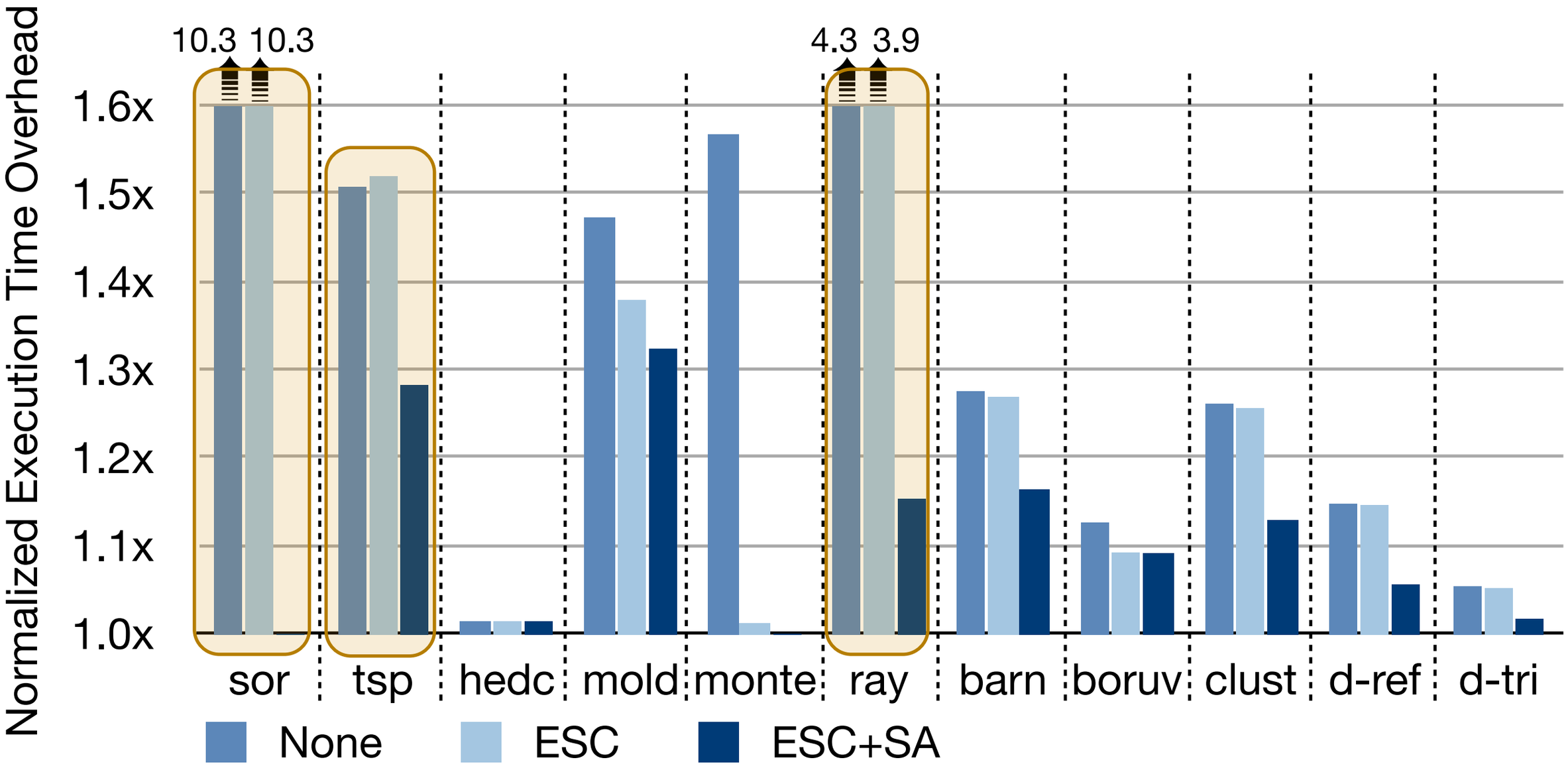

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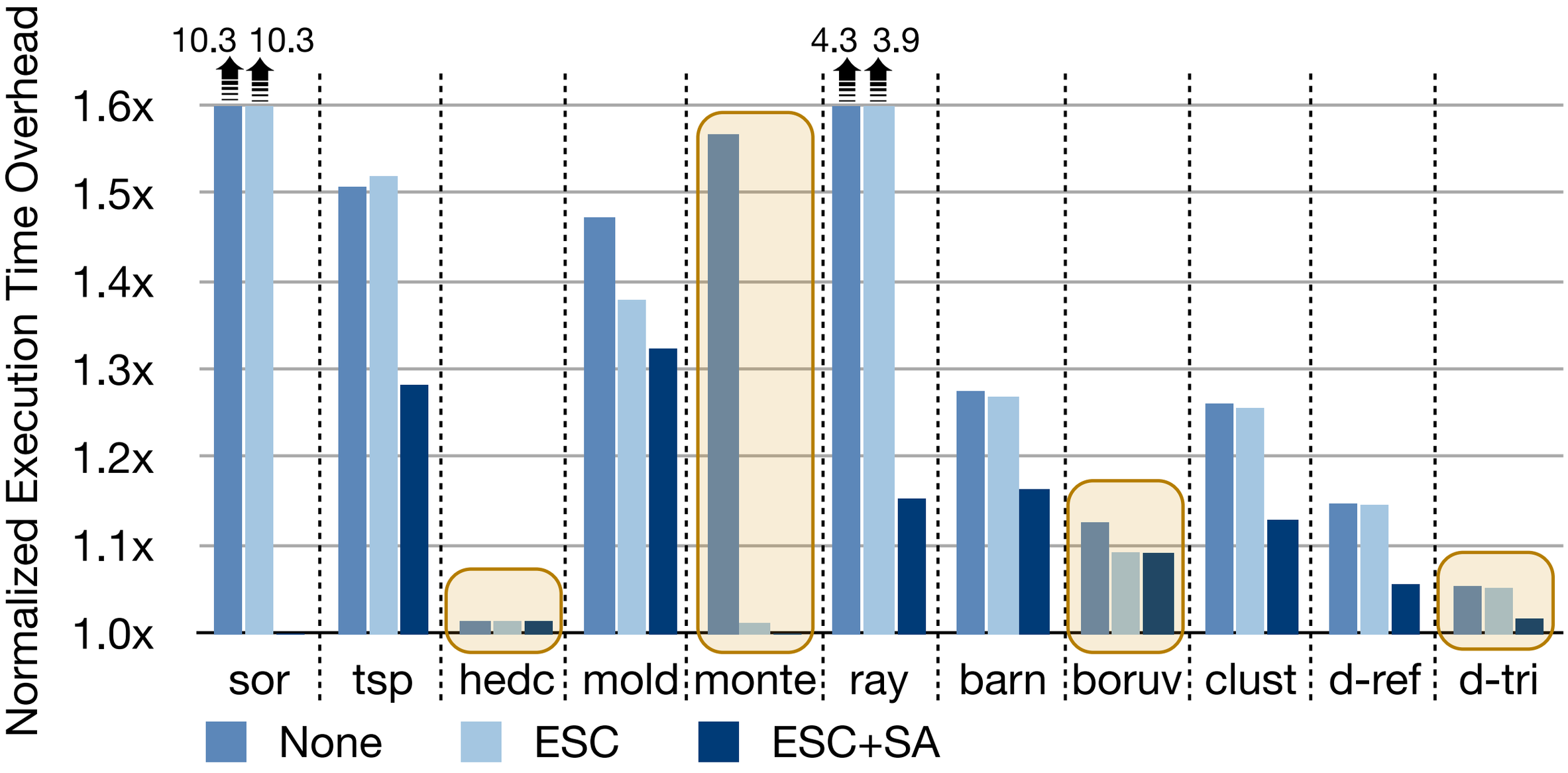

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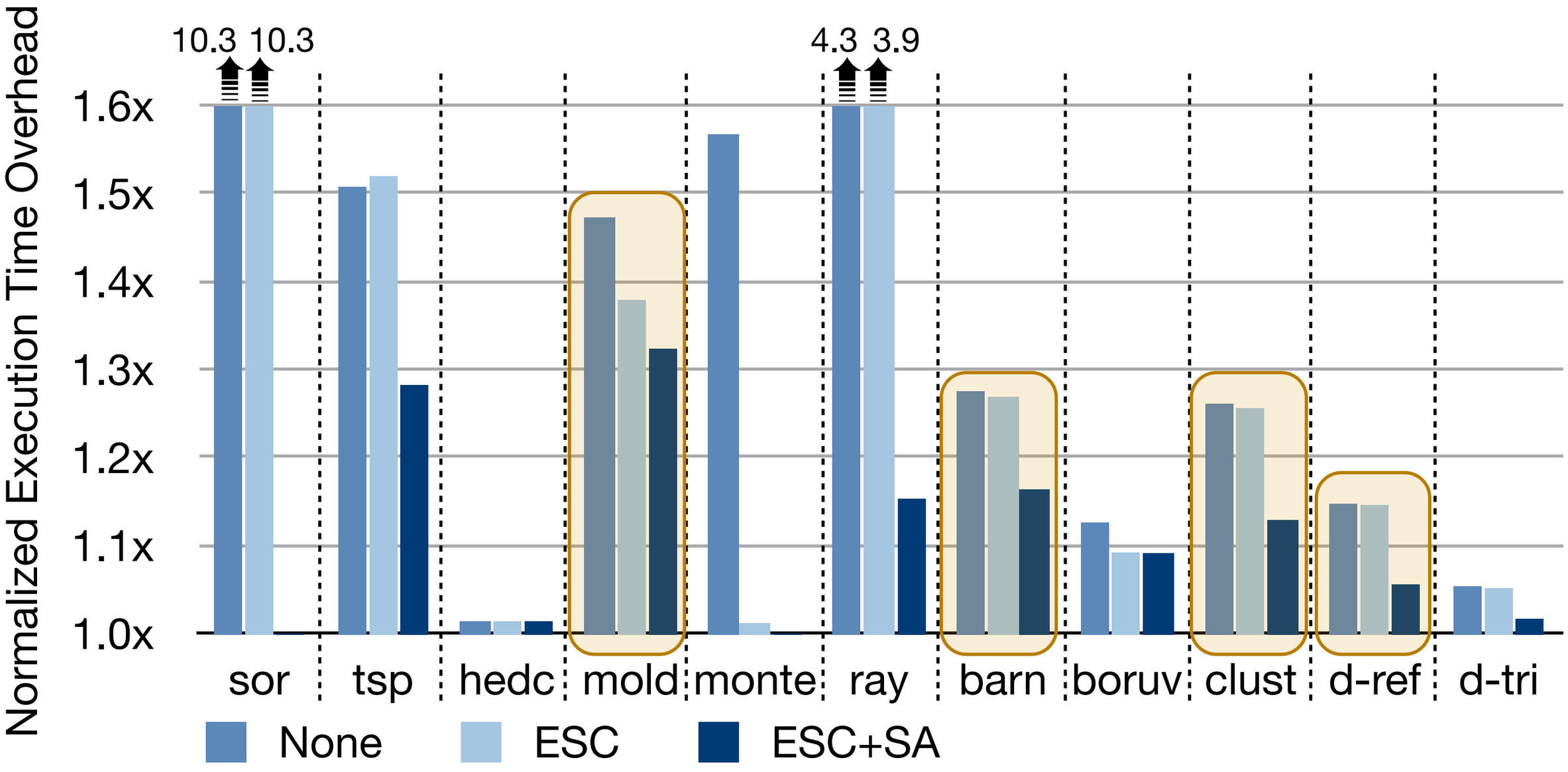

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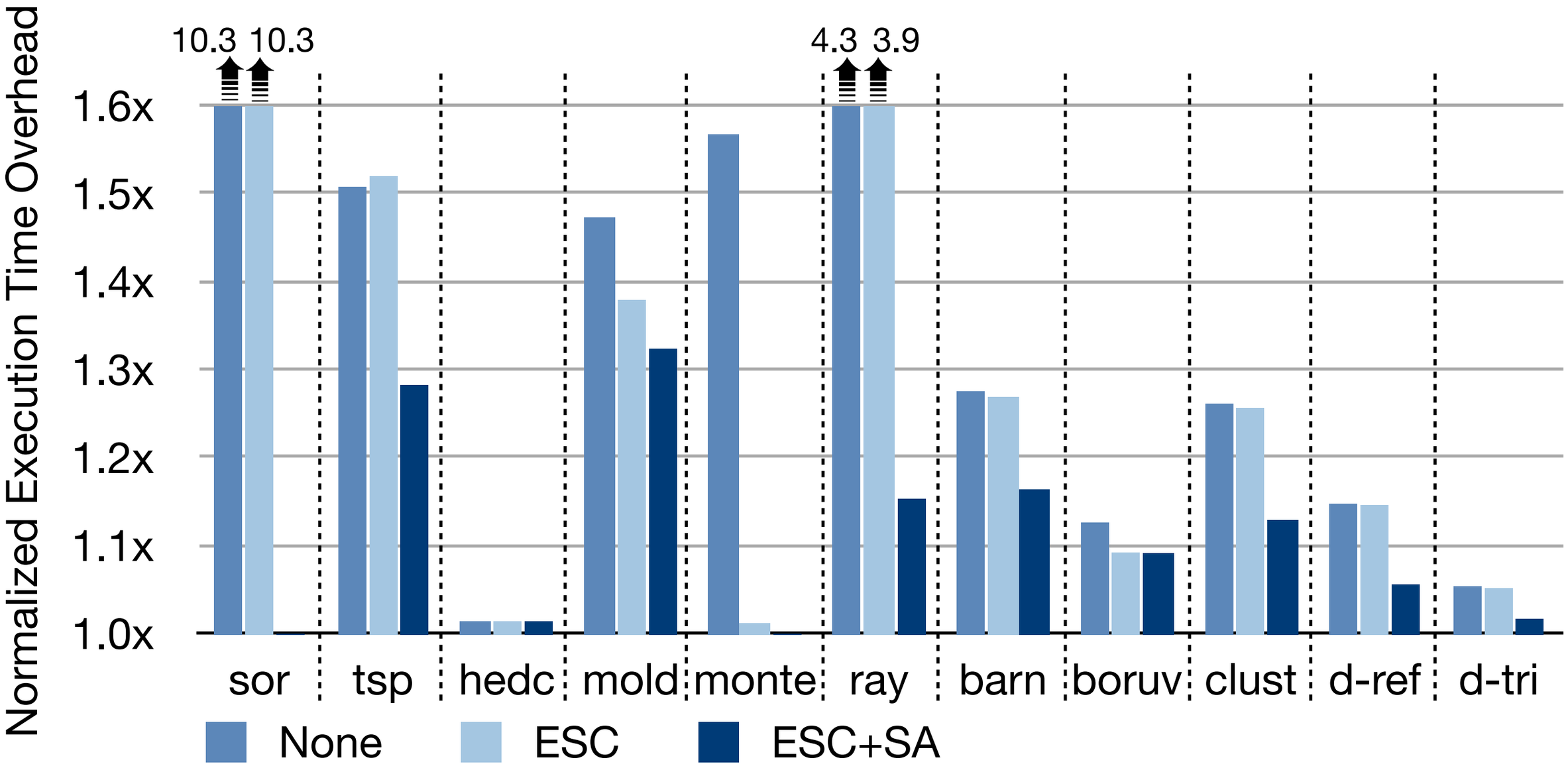

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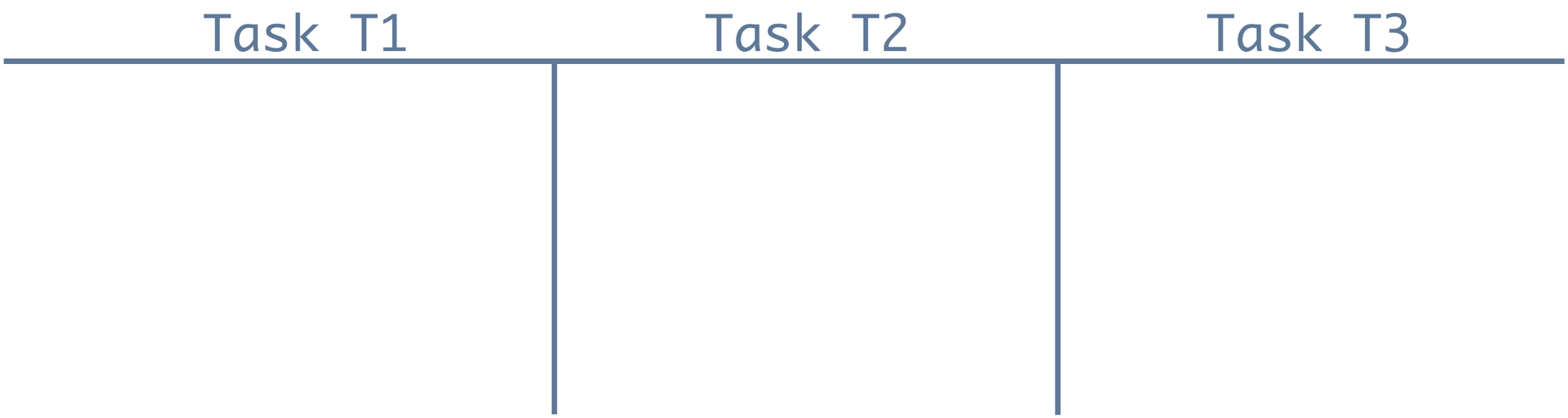
Dynamic Fractional Permissions

- Dynamic version of static data-race detection framework [Boyland 2003]
- Programmer manages access permissions:
  - Every object o has associated access control list
  - `Task T ∈ ACL(o) ⇒ read access`
  - `Task T only task in ACL(o) ⇒ write access`
- Compiler inserts permission checks

Permission Operations



Permission Operations

Task T1	Task T2	Task T3
`x = new Obj();`		

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ACL(x): {T1}

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Permissions:	T1	T2	T3
Can read x:	✓	✗	✗
Can write x:	✓	✗	✗

Permission Operations

Task T1	Task T2	Task T3
`x = new Obj();` `x.Add(T2);`		

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ACL(x): {T1, T2}

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Permission Operations

Task T1	Task T2	Task T3

`x = new Obj();`
`x.Add(T2);`
`x.Yield(T3);`		

ACL(x): {T1, T2}

Permission Operations

Task T1	Task T2	Task T3

`x = new Obj();`
`x.Add(T2);`
`x.Yield(T3);`		

ACL(x): {T3, T2}

Permission Operations

Task T1	Task T2	Task T3

`x = new Obj();`
`x.Add(T2);`
`x.Yield(T3);`		

ACL(x): {T3, T2}

Permissions:	T1	T2	T3
Can read x:	✗	✓	✓
Can write x:	✗	✗	✗

Permission Operations

Task T1	Task T2	Task T3

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`x.Yield(T3);`
	`x.Yield(T3);`	

ACL(x): {T3, T2}

Permission Operations

Task T1	Task T2	Task T3

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`x.Add(T2);`
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ACL(x): {T3}

Permission Operations

Task T1	Task T2	Task T3

`x = new Obj();`
`x.Add(T2);`
`x.Yield(T3);`
	`x.Yield(T3);`	

ACL(x): {T3}

Permissions:	T1	T2	T3
Can read x:	✗	✗	✓
Can write x:	✗	✗	✓

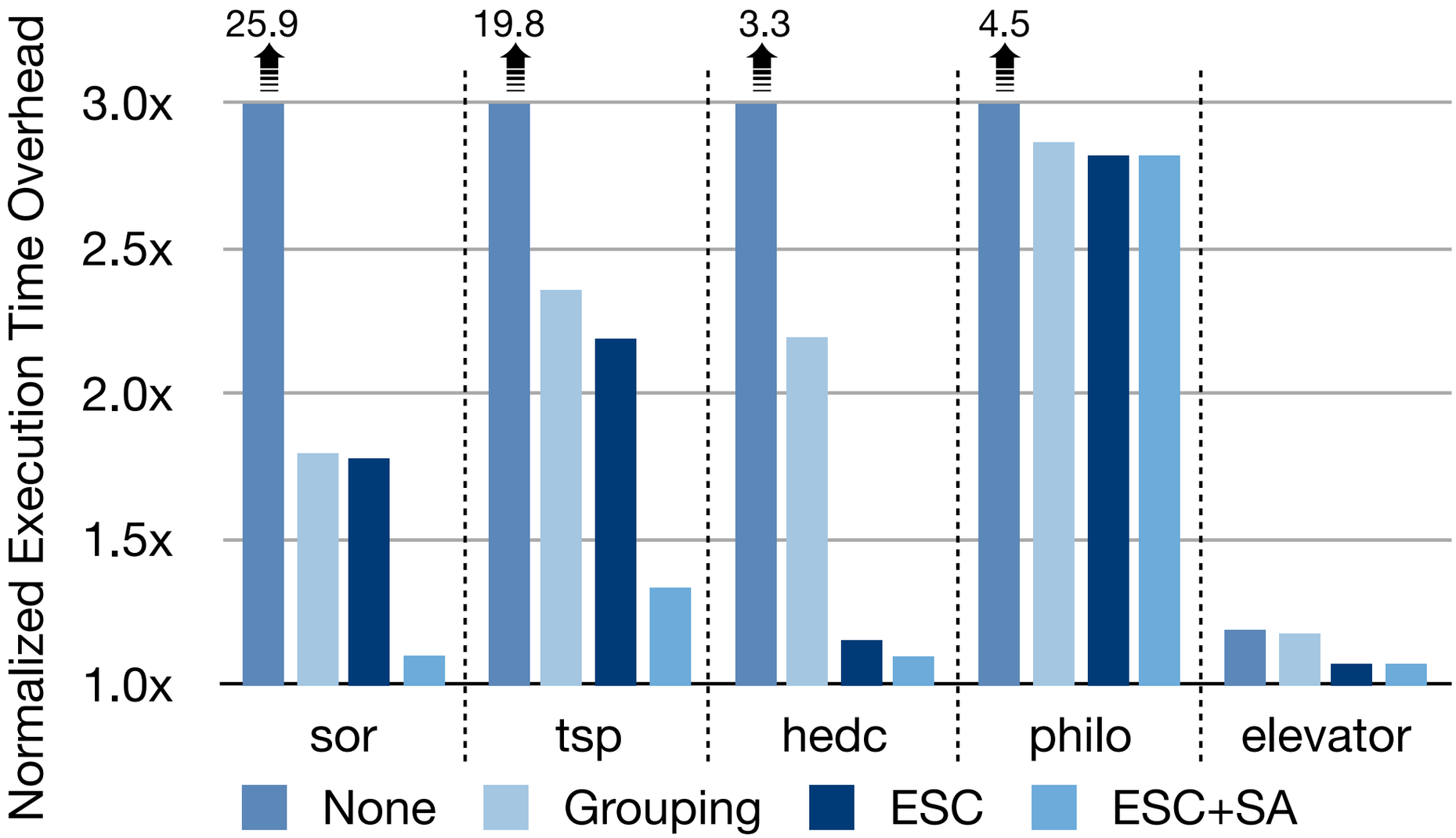
Optimizations

- Group redundant permission checks (method-local)
- Remove `new`, `Add`, and `Yield` operations for task-local objects
- Reduce number of inserted permission checks

Configurations

- No permission system (`Baseline`)
- No optimizations, permission checks on all accesses (None)
- Grouping of redundant permission checks (Group)
- Escape analysis (ESC)
- Schedule analysis + escape analysis (SA+ESC)

Execution Time



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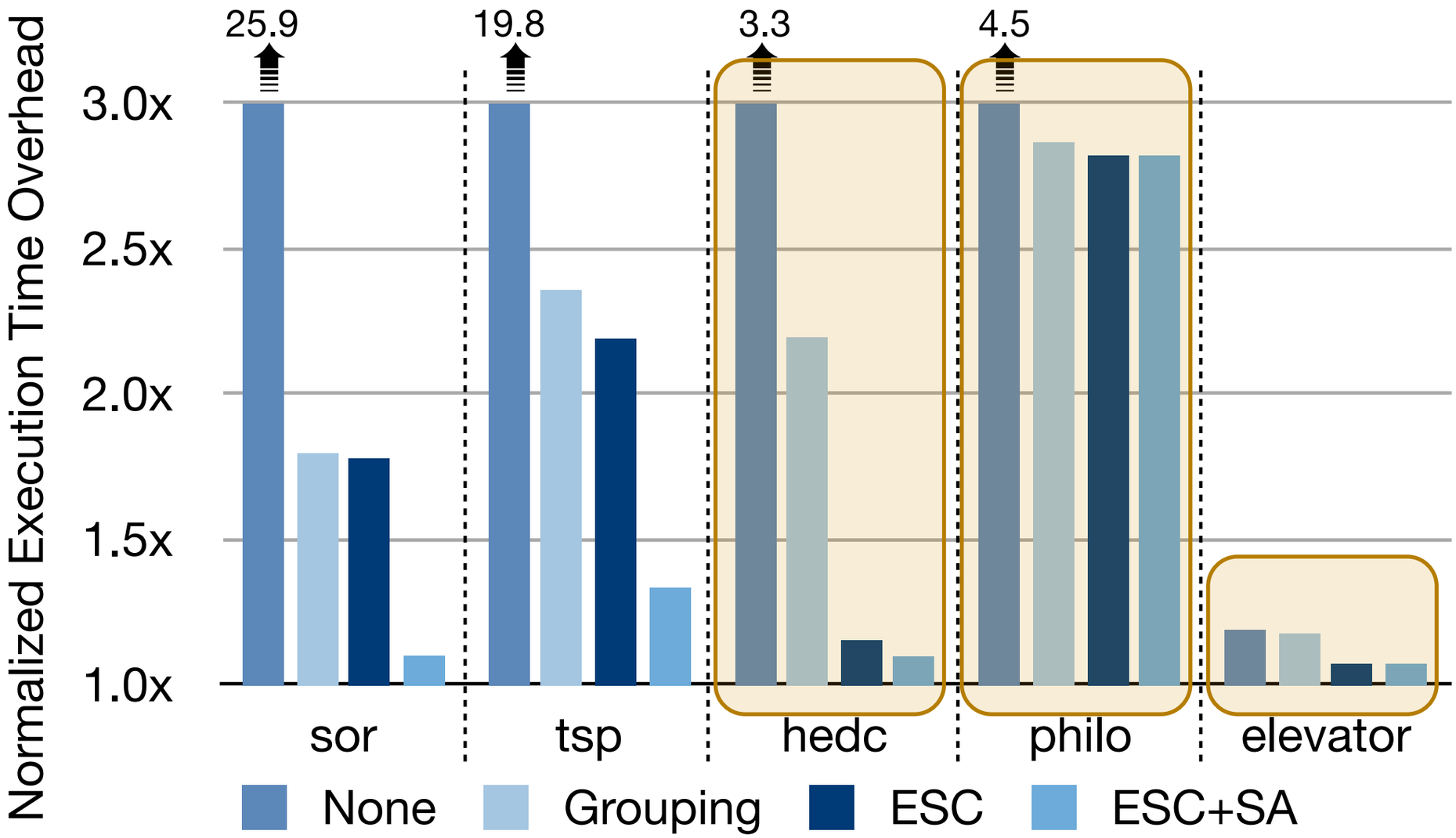

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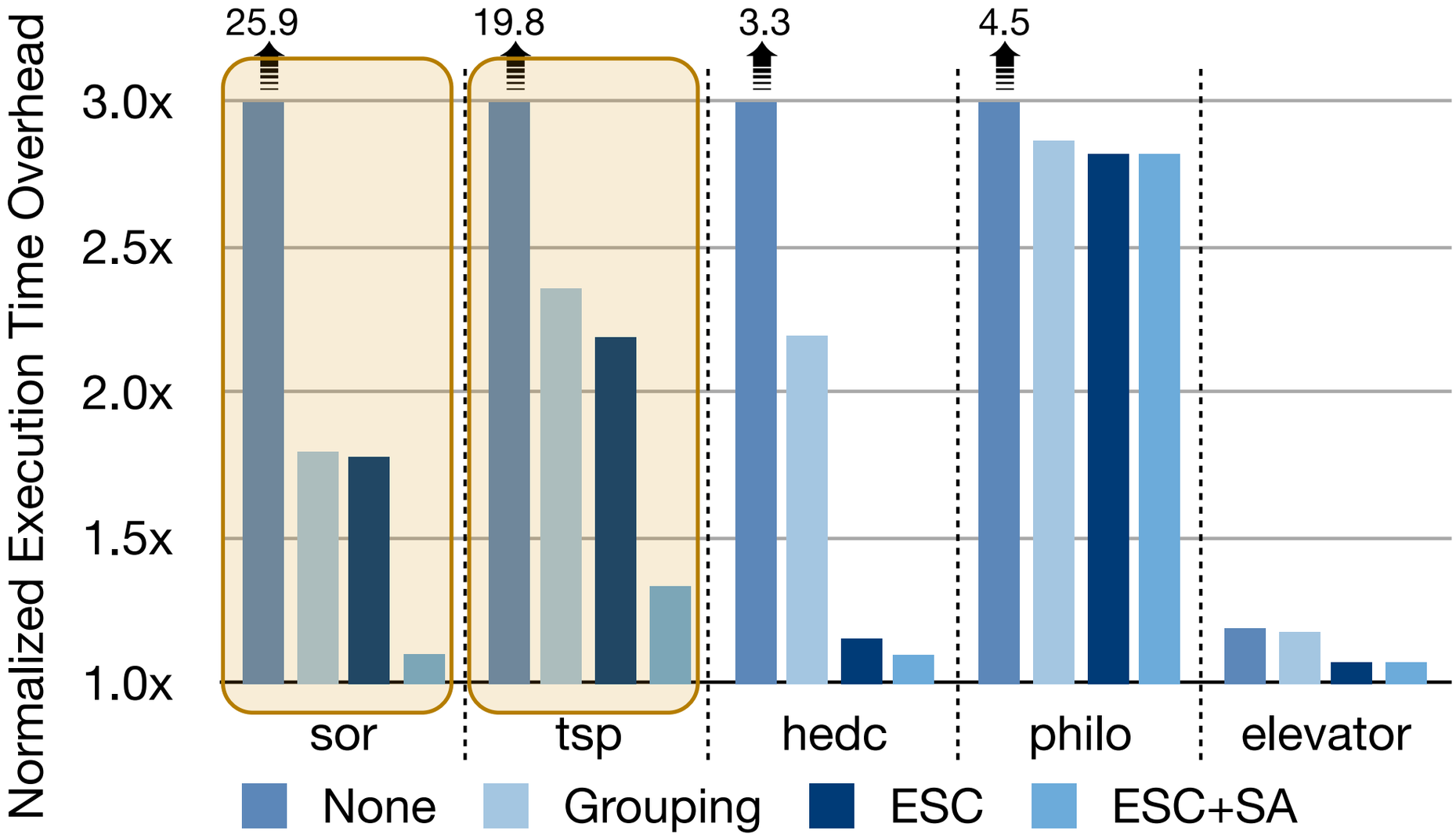

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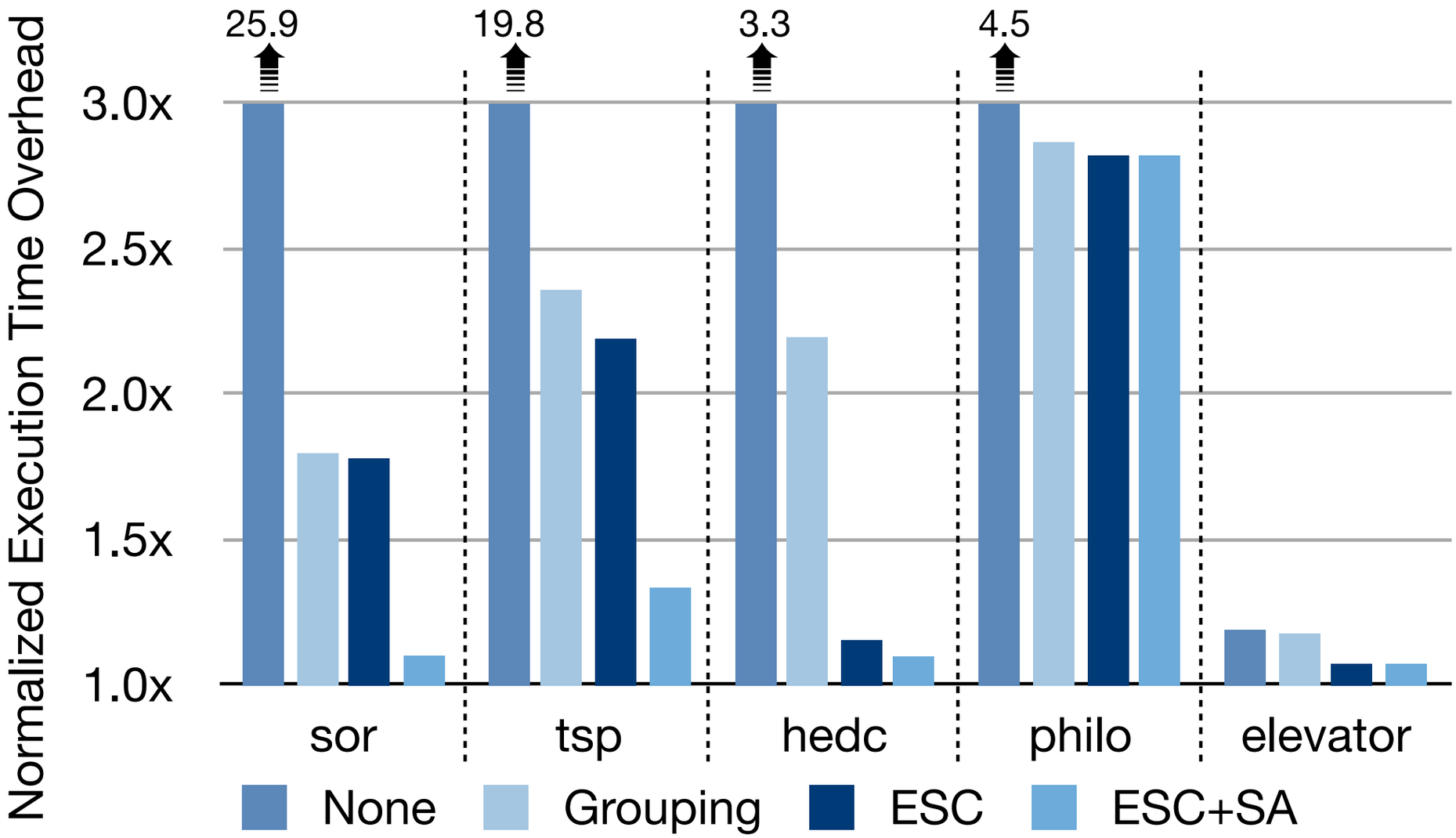


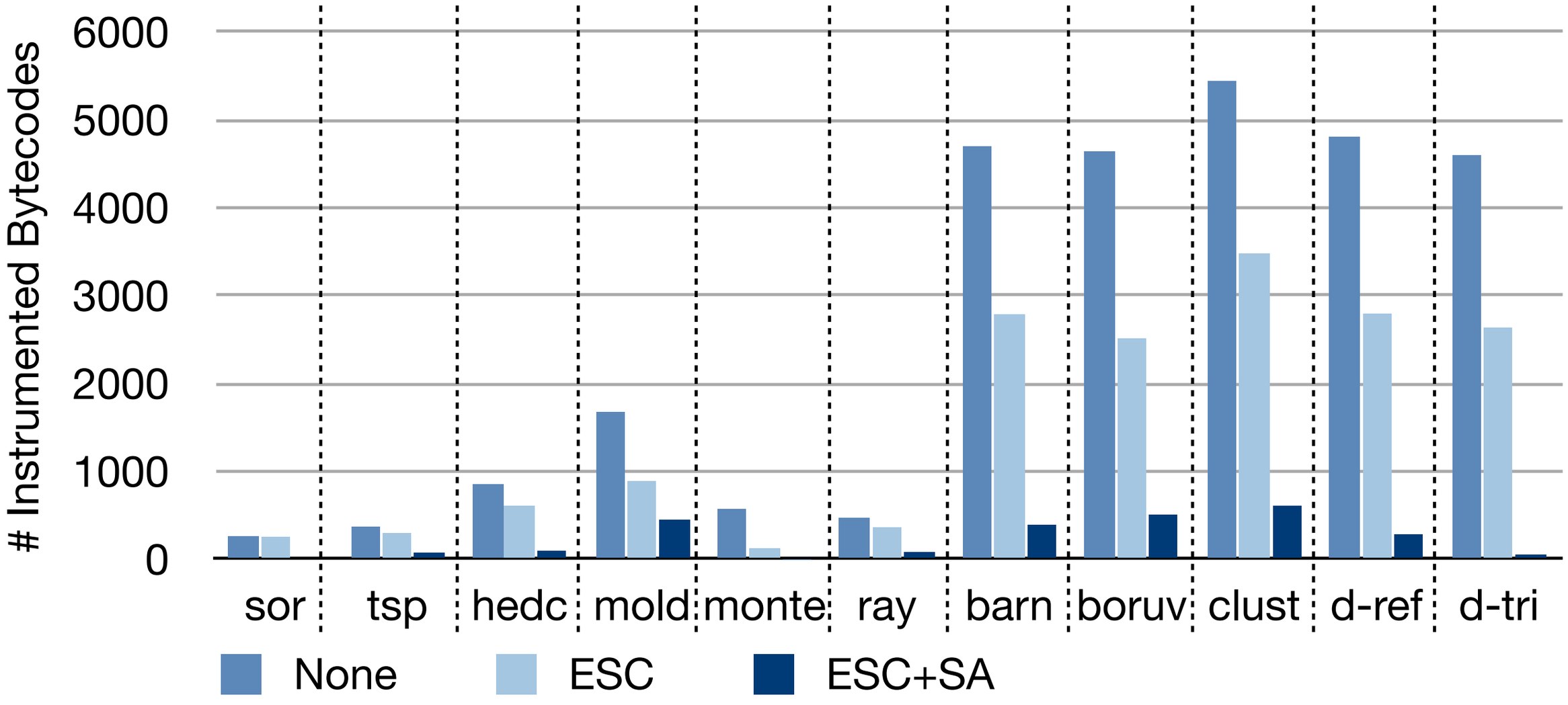
Conclusion

- Compilers for shared-memory parallel programs can exploit task-order information
- Schedule analysis:
  - can extract task-order information from real-world programs
  - provides basis for effective optimizations

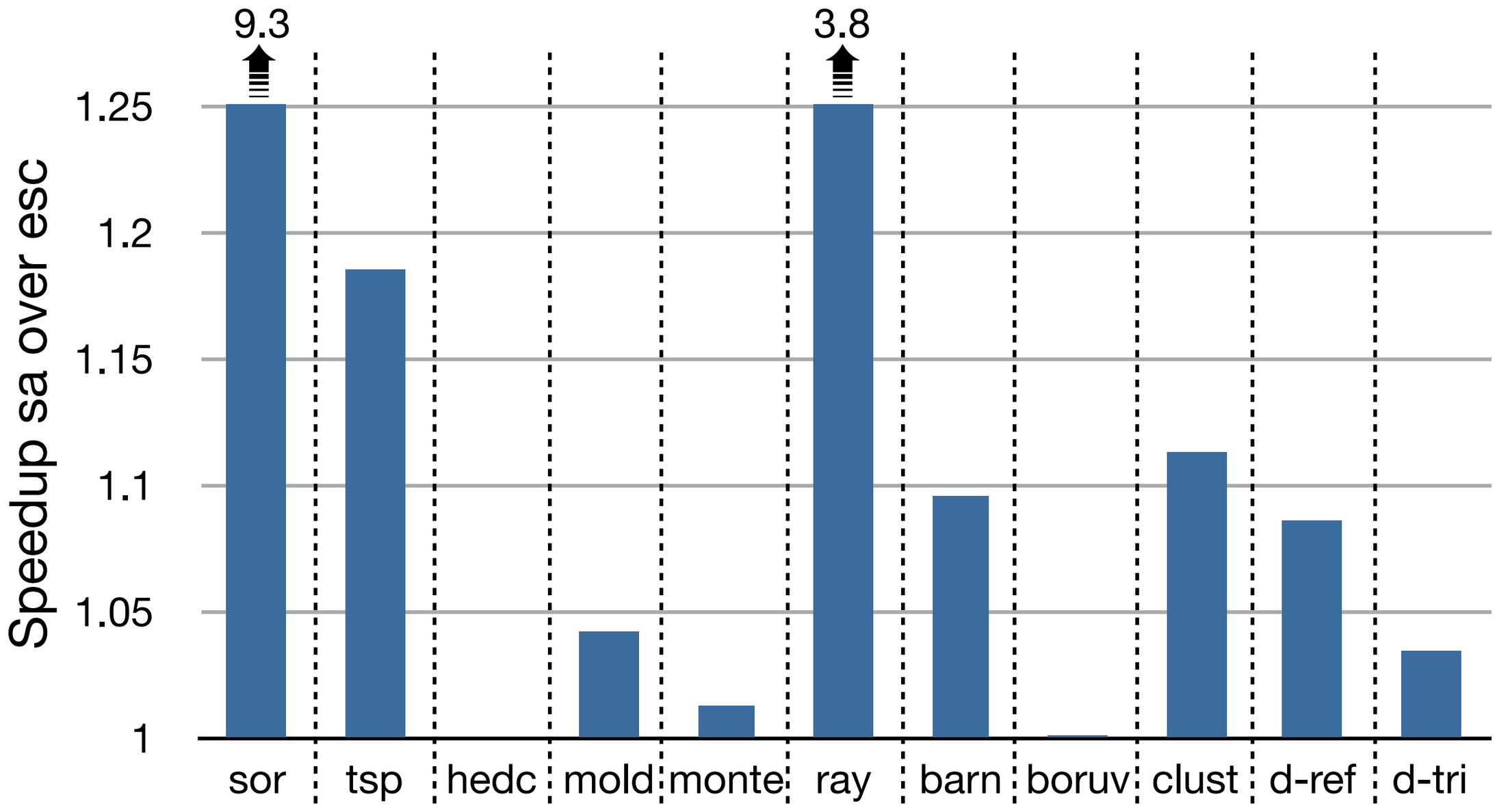
Implementation

- Bytecode-to-bytecode translation with `getVolatile()` and `putVolatile()` intrinsics
- Analyzes bytecode in SSA form
- Wala framework for analysis,
- Javassist for code generation

Instrumentation Overhead



Speedup SA+ESC over ESC



Related Work

- **Compiler techniques for high performance sequentially consistent java programs.** Z. Sura et al, PPoPP'05

- **A case for an SC-preserving compiler.** D. Marino et al, PLDI'11

- **Efficient sequential consistency using conditional fences.** C. Lin, V Nagarajan, R. Gupta, PACT'10

- **BulkCompiler: high-performance sequential consistency through cooperative compiler and hardware support.** W. Ahn et al, MICRO'09

- **MHP Analysis.** (Agarwal et al)

Ordering with Threads

```
/*A*/

Thread[] ts = new Thread[3];
for(int i=0; i<3; i++) {
  ts[i] = new MyThread(/*B*/);
  ts[i].start();
}
for(int i=0; i<3; i++)
  ts[i].join();

/*C*/
```

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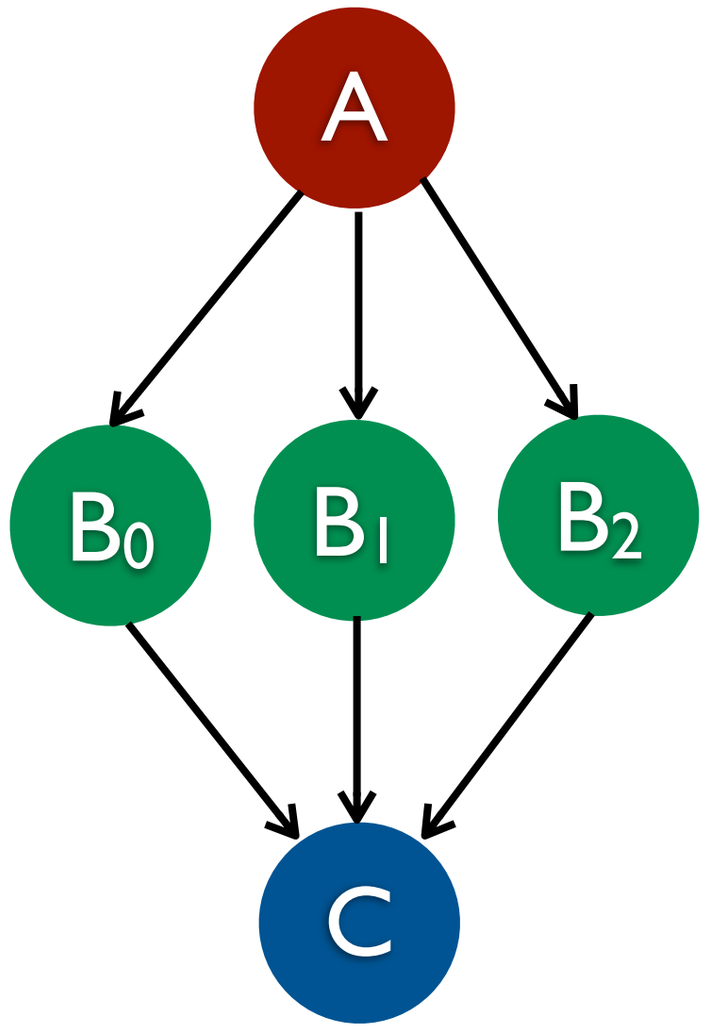

Ordering in OpenMP

```
/*A*/

//#omp parallel for
for(int i=0; i<3; i++) {
  /*B*/
}

/*C*/
```

Ordering in OpenMP

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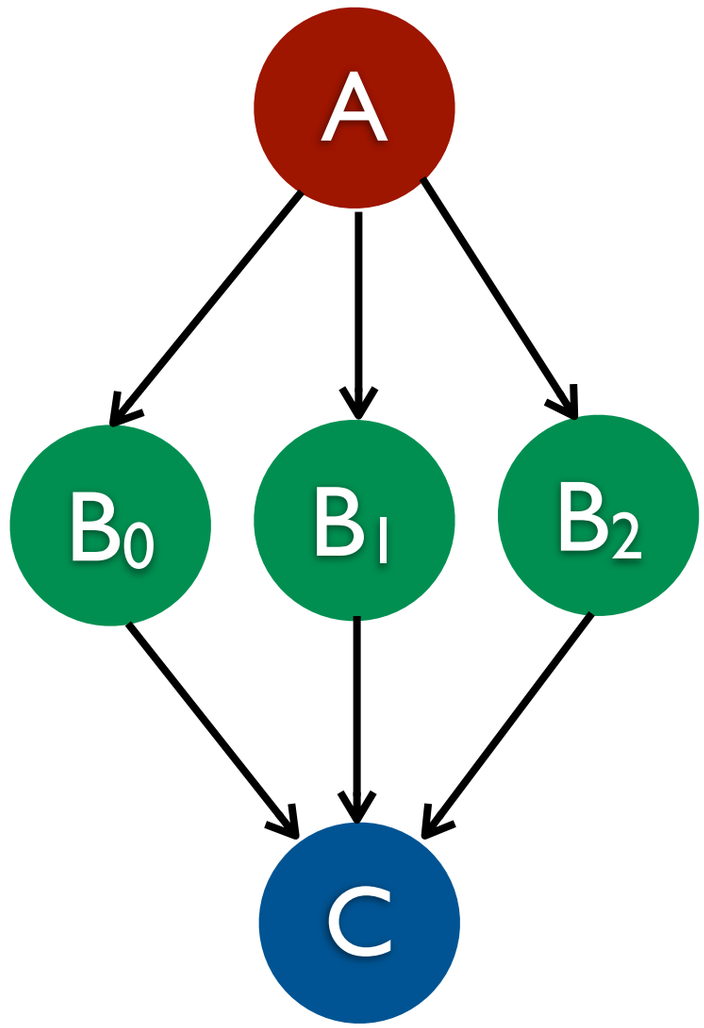

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@T1: o.CheckRead()        ⇒ true iff T1 ∈ ACL(o)
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/*inserted by compiler*/
@T1: o.CheckRead()    ⇒ true iff T1 ∈ ACL(o)

@T1: o.CheckWrite()   ⇒ true iff ACL(o) == {T1}
```