Mostly-functional behavior in Java programs

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Motivation

We'd like to do aggressive code transformations, specification checking and analysis of large object-oriented programs.

The problem

Java programs are difficult to analyze, transform, and reason about (in part) due to mutable state.

Our contribution

Type-and-effect system and type-based analysis

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Initialization effects

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Type-and-effect system and type-based analysis

Initialization effects

Quiescing field inference

Our contribution

Type-and-effect system and type-based analysis

Initialization effects	Quiescing field inference	Degrees of method purity

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Surprising result: substantial *mostly-functional behavior* in Java!

Forecast

- A simple object-oriented effects system
- Initializers and initialization effects
- Final fields and eventual immutability
- Inferring quiescing fields
- Evaluating quiescing field inference

Effect systems: motivation

```
// method1: List<T> → int
int method1(List<T> l) {
  return l.size();
}
```

```
// method2: List<T> → int
int method2(List<T> l) {
  int i = 0;
  while (! l.isEmpty() ) {
    l.remove(0);  i++;
  }
  return i;
}
```

Effect systems: motivation

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// method1: List<T> → int
int method1(List<T> l) {
  return l.size();
}
```

READS state of *l*

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}
```

Type systems: "what?"

Effect systems: "how?"

Effect systems: motivation

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int method1(List<T> l) {
  return l.size();
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READS state of *l*

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  }
  return i;
}
```

"How" consists of an *effect* (READ or WRITE) in some *region*.

Object-oriented effect systems

- Classic effect systems typically feature lexically-scoped regions
- *Object-oriented effect systems* better support classes, fields, &c.
- See Greenhouse & Boyland (ECOOP 99) or Bierman & Parkinson (WOOD 03)

Inferring effects for bytecodes

$l = l_h.\nu$

$l_h.\nu = l$

method invocations

Inferring effects for bytecodes

$$l = l_h.v$$

Inferring effects for bytecodes

$$\frac{\mathsf{load}(s, l, l_h, \kappa.\nu) \qquad \mathsf{rpt}(l_h, \rho)}{\varphi(s) \sqsupseteq \textsc{read} : \{\langle \rho, \kappa.\nu \rangle\}\rangle} \textsc{Read}$$

Inferring effects for bytecodes

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Regions we consider: ρ_{this}, $\rho_{0..n}$, and $\top$.

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$l_h.\nu = l$

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Inferring effects for bytecodes

$$\frac{\text{load}(s, l, l_h, \kappa.\nu) \qquad \text{rpt}(l_h, \rho)}{\varphi(s) \sqsupseteq \textsc{read} : \{\langle \rho, \kappa.\nu \rangle\}\}\rangle} \; \textsc{read}$$

$$\frac{\text{store}(s, l_h, \kappa.\nu, l) \qquad \text{rpt}(l_h, \rho)}{\varphi(s) \sqsupseteq \textsc{write} : \{\langle \rho, \kappa.\nu \rangle\}\}\rangle} \; \textsc{write}$$

Regions we consider: ρ_{this}, $\rho_{0..n}$, and $\top$.

Inferring effects for bytecodes

$$\frac{\overset{\textsc{read}}{\mathsf{load}(s, l, l_h, \kappa.\nu) \qquad \mathsf{rpt}(l_h, \rho)}}{\varphi(s) \sqsupseteq \textsc{read} : \{\langle \rho, \kappa.\nu \rangle\}\rangle}$$

$$\frac{\overset{\textsc{write}}{\mathsf{store}(s, l_h, \kappa.\nu, l) \qquad \mathsf{rpt}(l_h, \rho)}}{\varphi(s) \sqsupseteq \textsc{write} : \{\langle \rho, \kappa.\nu \rangle\}\rangle}$$

method invocations

Regions we consider: ρ_{this}, $\rho_{0..n}$, and $\top$.

Inferring effects for bytecodes

$$\textsc{Read}\quad \frac{\mathsf{load}(s, l, l_h, \kappa.\nu) \qquad \mathsf{rpt}(l_h, \rho)}{\varphi(s) \sqsupseteq \textsc{read} : \{\langle \rho, \kappa.\nu \rangle\}\rangle}$$

$$\textsc{Write}\quad \frac{\mathsf{store}(s, l_h, \kappa.\nu, l) \qquad \mathsf{rpt}(l_h, \rho)}{\varphi(s) \sqsupseteq \textsc{write} : \{\langle \rho, \kappa.\nu \rangle\}\rangle}$$

$$\textsc{Summary}\quad \frac{s_0, \cdots, s_n \in m}{\varphi(m) \sqsupseteq \varphi(s_0) \sqcup \cdots \sqcup \varphi(s_n)}$$

$$\textsc{Call}\quad \frac{s \rightarrow m'}{\varphi(s) \sqsupseteq \mathsf{pmap}(s, \varphi(m'))}$$

Regions we consider: ρ_{this}, $\rho_{0..n}$, and $\top$.

Extending the simple system

Type-and-effect system and type-based analysis

Initialization effects

Quiescing field inference

Degrees of method purity

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Motivating initialization effects

```
class IntBox {
  private int i;
  IntBox(int j) {
    this.i = j;
  }

  int get() {
    return i;
  }
}
```

Motivating initialization effects

class IntBox {
  private int *i*;
  IntBox(**int** *j*) {
    this.*i* = *j*;   **writes** IntBox.i to **this**
  }

  int get() {
    return *i*;   **reads** IntBox.i from **this**
  }
}

Motivating initialization effects

```
class IntBox {
  private int i;
  IntBox(int j) {
    this.i = j;
  }

  int get() {
    return i;
  }
}
```

writes IntBox.i to **this**

These two effects cannot interfere!

reads IntBox.i from **this**

Motivating initialization effects

class IntBox {
  private int *i*;
  IntBox(**int** *j*) {
    this.*i* = *j*;
  }

  int get() {
    return *i*;
  }
}

initializes IntBox.i of **this**

These two effects cannot interfere!

reads IntBox.i from **this**

Motivating initialization effects

```
class IntBox {
  private int i;
  IntBox(int j) {
    this.i = j;
  }

  int get() {
    return i;
  }
}
```

```
IntBox factory(int j) {
  IntBox r =
    new IntBox(j);
  return r;
}
```

Motivating initialization effects

```
class IntBox {
  private int i;
  IntBox(int j) {
    this.i = j;
  }

  int get() {
    return i;
  }
}
```

```
IntBox factory(int j) {
  IntBox r =
    new IntBox(j);
  return r;
}
```

"Pure" methods can modify newly-allocated objects (Leavens et al.; Rugina and Cherem)

Defining initialization effects

```
class IntBox {
  private int i;
  IntBox(int j) {
    this.i = j;
  }

  int get() {
    return i;
  }
}
```

initializes IntBox.i field of **this**

Defining initialization effects

```
class IntBox {
  private int i;
  IntBox(int j) {
    this.i = j;
  }

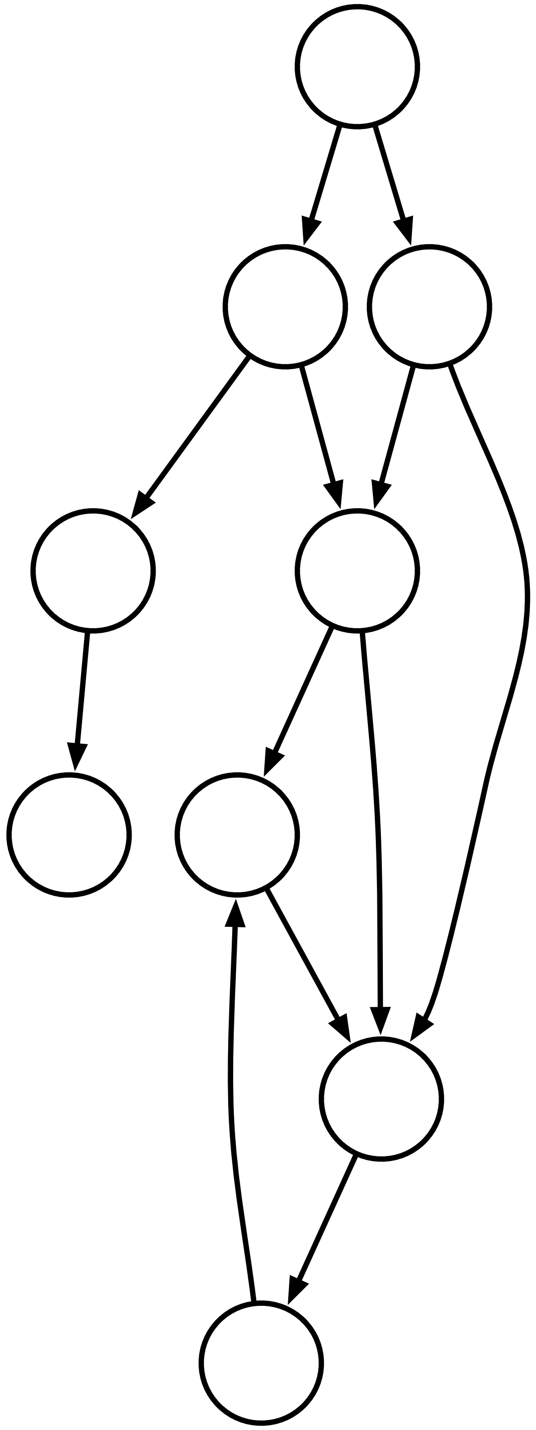
  int get() {
    return i;
  }
}
```

An *initialization effect* is a WRITE to the state of an object during its creation.

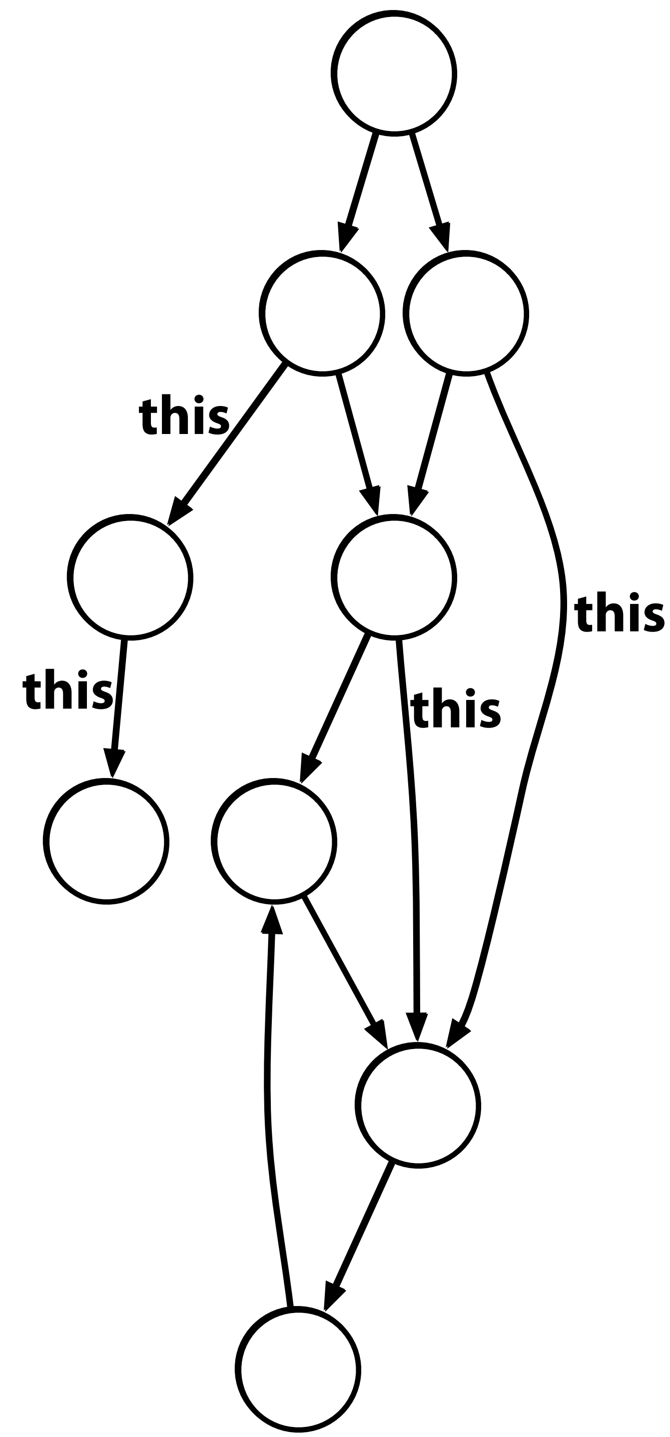
An *initializer* is a method that executes on an object during the dynamic lifetime of its constructor.

Inferring initializer methods

Inferring initializer methods

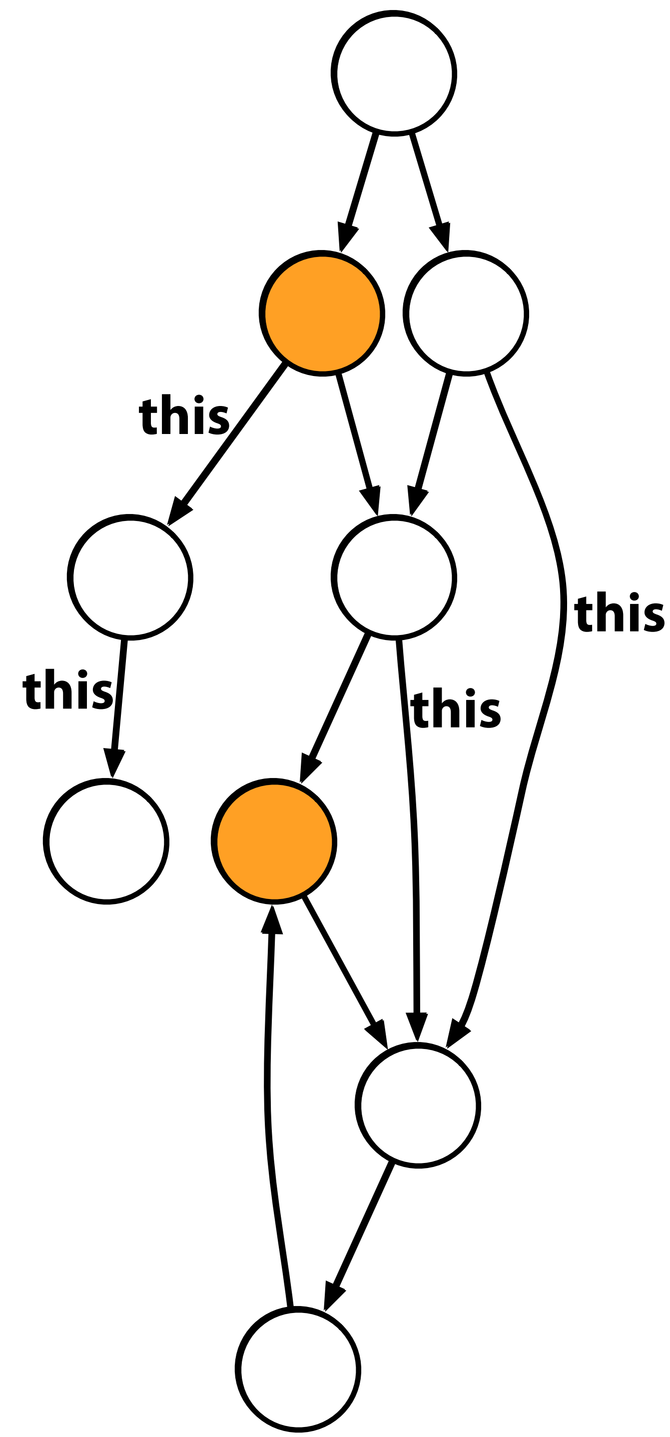


Inferring initializer methods



Inferring initializer methods

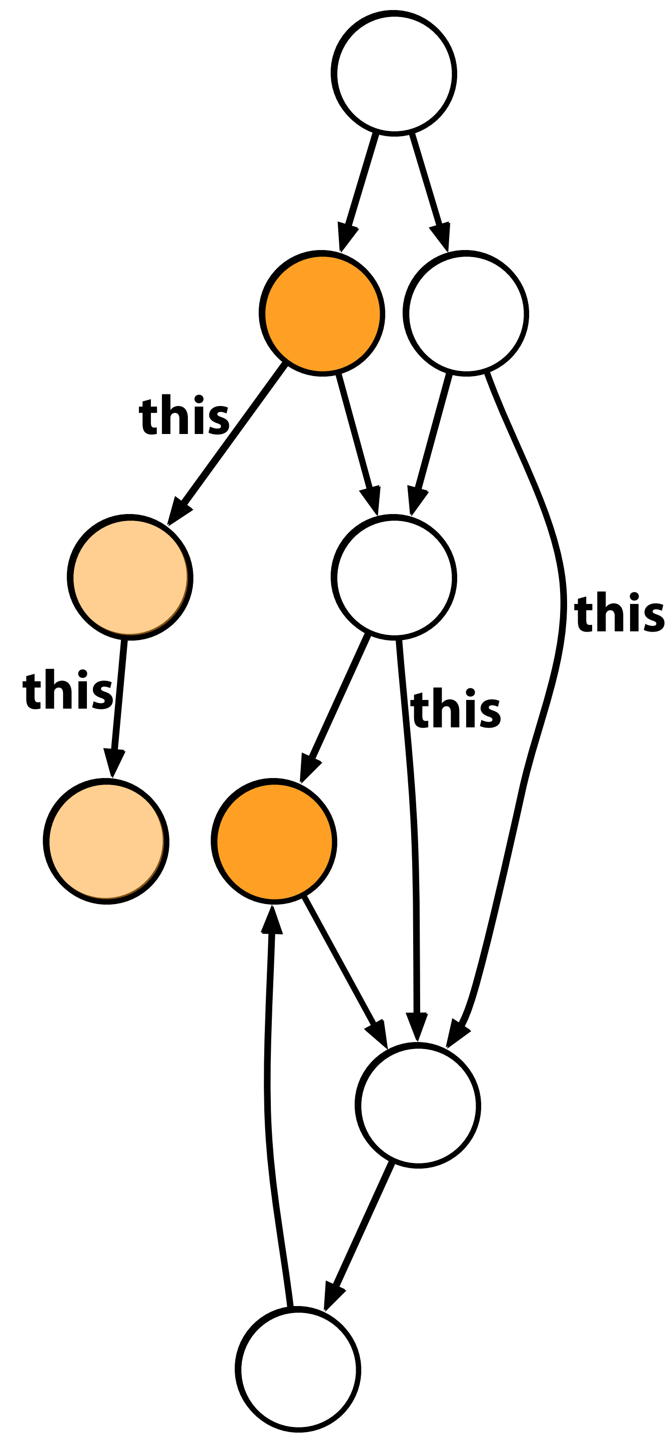
A constructor is an initializer on its receiver object.



Inferring initializer methods

A constructor is an initializer on its receiver object.

A method that is *only* invoked via this-edges from an initializer is also an initializer on its receiver object.



Inferring initialization effects

Initialization effects are writes to fields of this that occur within an initializer.

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Final fields

```
class IntBox {
  private int i;
  IntBox(int j) {
    this.i = j;
  }

  int get() {
    return i;
  }
}
```

Final fields

```
class IntBox {
  private final int i;
  IntBox(int j) {
    this.i = j;
  }

  int get() {
    return i;
  }
}
```

Final fields

```
class IntBox {
  private final int i;        i is a run-time constant
  IntBox(int j) {
    this.i = j;
  }

  int get() {
    return i;
  }
}
```

Final fields

```
class IntBox {
  private final int i;
  IntBox(int j) {
    this.i = j;
  }

  int get() {
    return i;
  }
}
```

Final fields

```
class IntBox {
  private final int i;
  IntBox(int j) {
    init(i);
  }

  int get() {
    return i;
  }
```

```
  private void init(int j) {
    this.i = j;
  }
}
```

Final fields

```
class IntBox {
  private final int i;
  IntBox(int j) {
    init(i);
  }

  int get() {
    return i;
  }

  private void init(int j) {
    this.i = j;
  }
}
```

Final fields *must be* assigned exactly once on every path through each constructor and *may only be* assigned in the constructor.

Final fields and immutability

- Java definition of **final** is restrictive, designed for simple verification
- Many fields that represent run-time constants are not declared **final**
- Several groups have developed analyses to find such fields

One example: stationary fields

- Unkel and Lam (2008): *stationary fields* are never written after they are read
- About 50% of fields in open-source Java programs can be inferred stationary; a much smaller percentage are **final**
- Their analysis is based on flow- and context-sensitive points-to analysis

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Quiescing fields

- A field is *quiescing* if it is *initialized* but never *written*; all final fields are quiescing
- Inference algorithm for these is straightforward: consider only fields that aren't implicated in a WRITE effect

Comparing kinds of fields

- All final fields are quiescing fields
- Some quiescing fields are not stationary
- Some stationary fields are not quiescing
- The inference algorithm for quiescing fields runs in seconds on substantial Java programs

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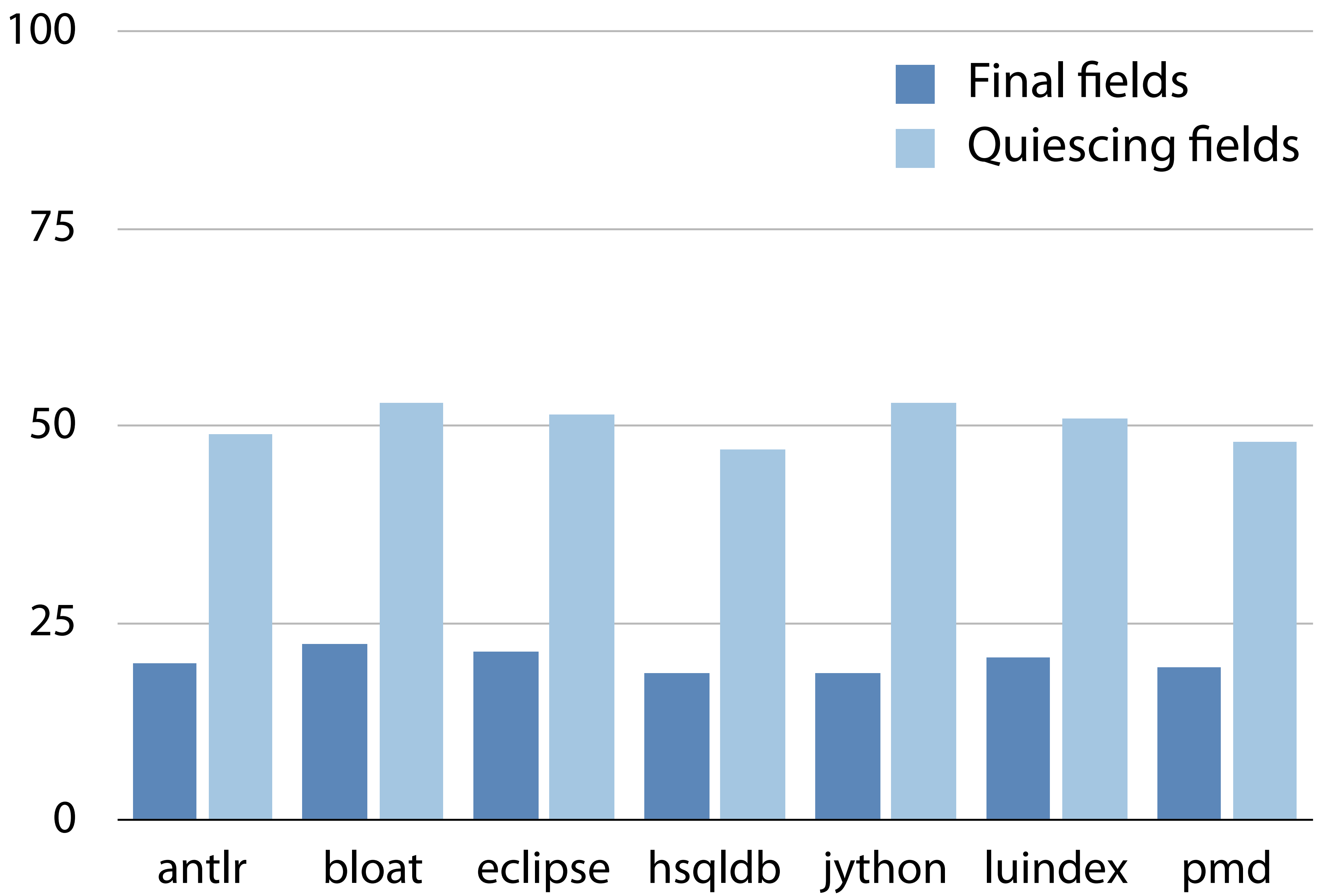
Evaluation

- Medium-sized Java programs from the DaCapo benchmark suite
- Soot and DIMPLE for bytecode analysis, performed on workstation hardware
- Executed benchmarks under instrumented Jikes RVM

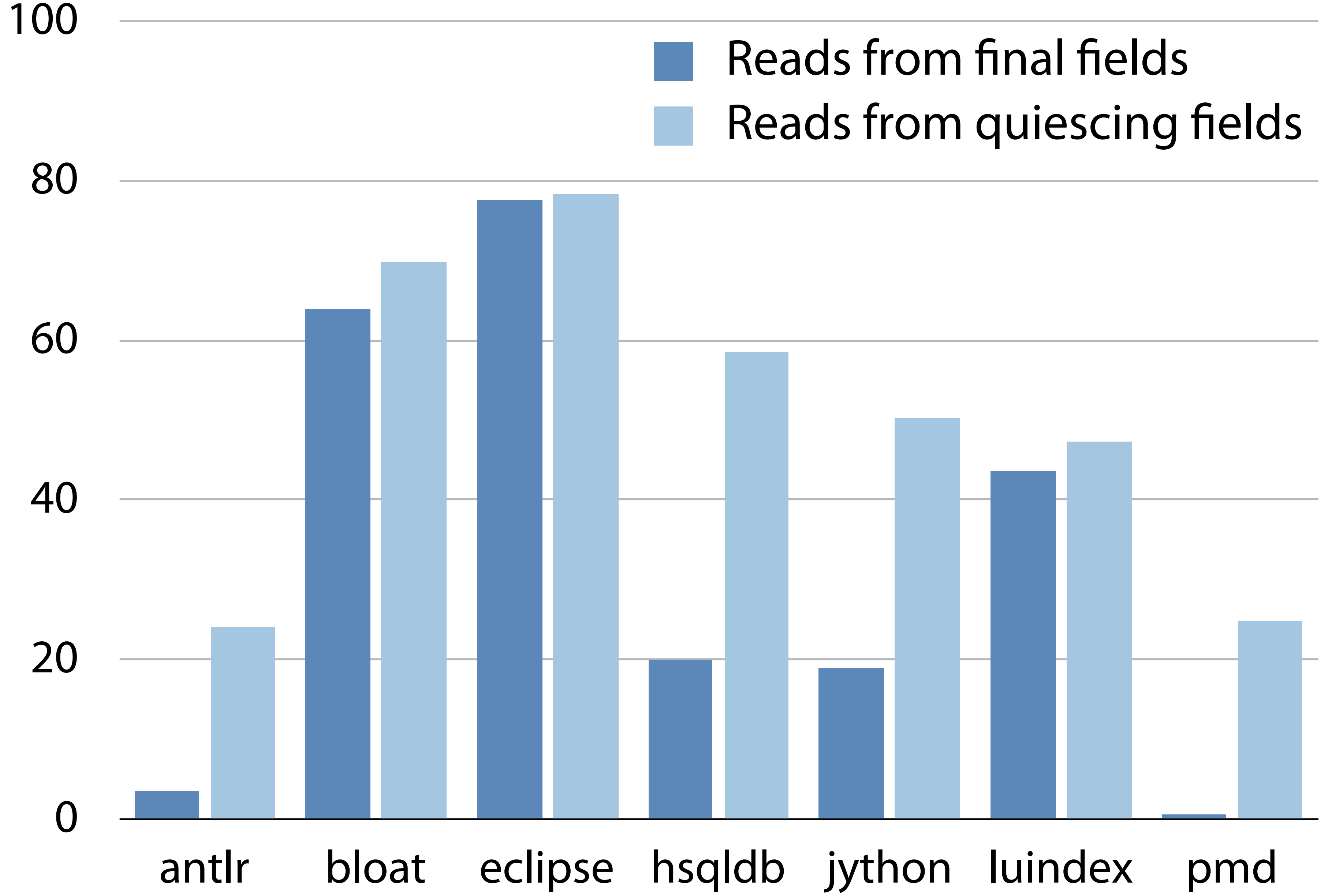
Benchmarks

	statements	classes	fields	methods
antlr	1.39 M	3729	14082	37209
bloat	1.41 M	3827	14524	33609
eclipse	1.38 M	3895	15161	33408
hsqldb	1.59 M	4190	17566	38504
jython	1.45 M	4058	14737	35604
luindex	1.35 M	3903	14511	32759
pmd	1.51 M	4265	15489	36393

Static prevalence of final and quiescing fields



Final and quiescing fields as a percentage of all dynamic reads



Conclusion

- Three novel features improve the precision of type-and-effect systems
- A significant portion of Java field reads are from fields with unchanging values
- It is possible to efficiently infer quiescing fields with type-based analyses

Thanks!

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