A Dynamic Evaluation of the Precision of Static Heap Abstractions

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Introduction

Broad goal: verify correctness properties of software

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Motivating domain: multi-threaded programs (race and deadlock detection)

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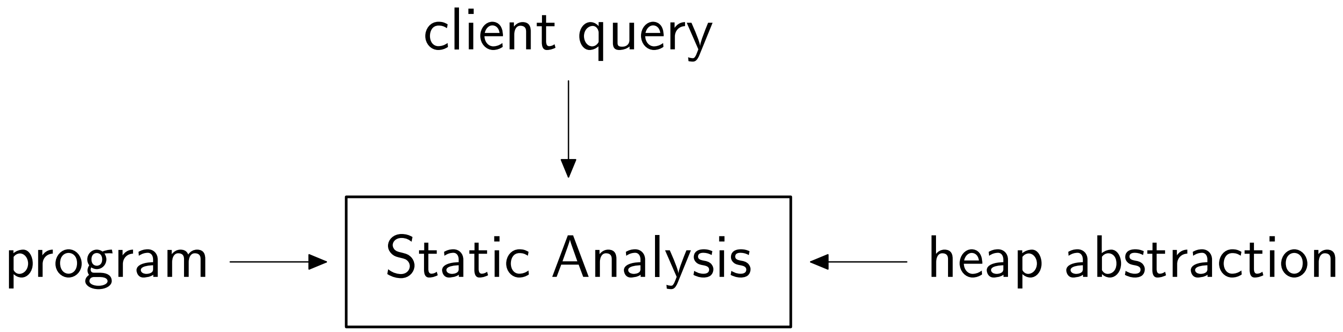

client query

program

Static Analysis

heap abstraction

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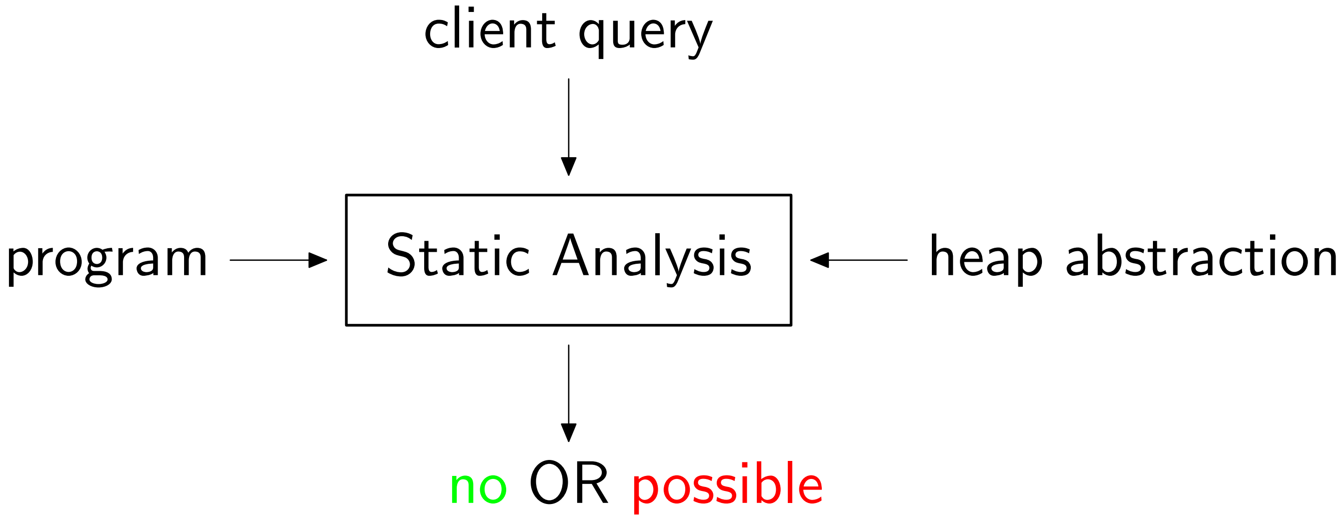

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(false positives ⇒ imprecision!)

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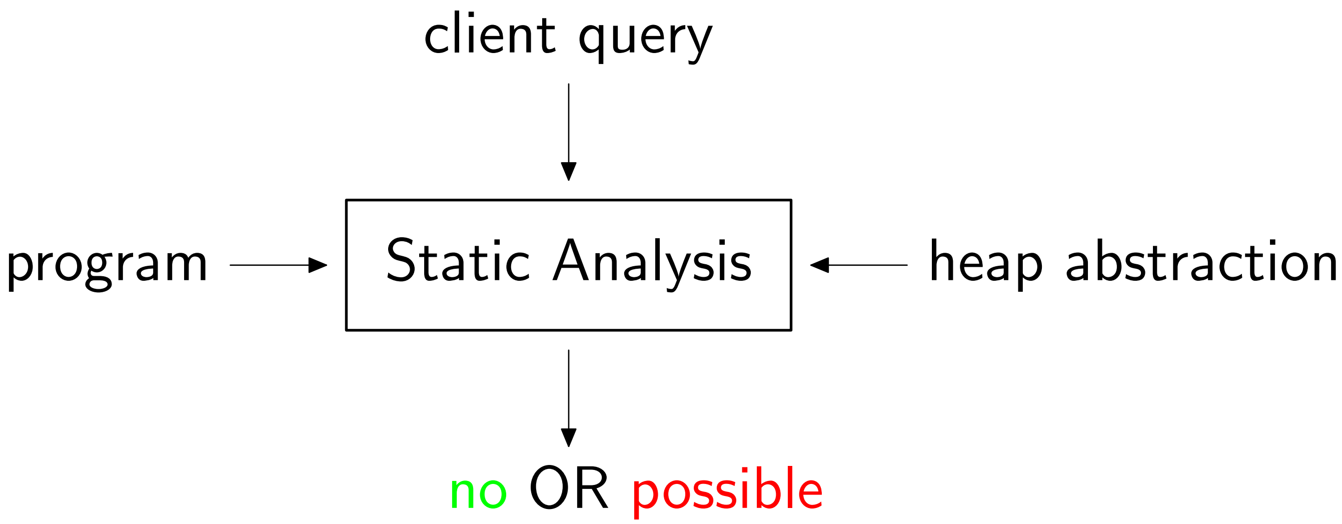

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Heap abstraction affects **precision** and **scalabilty**

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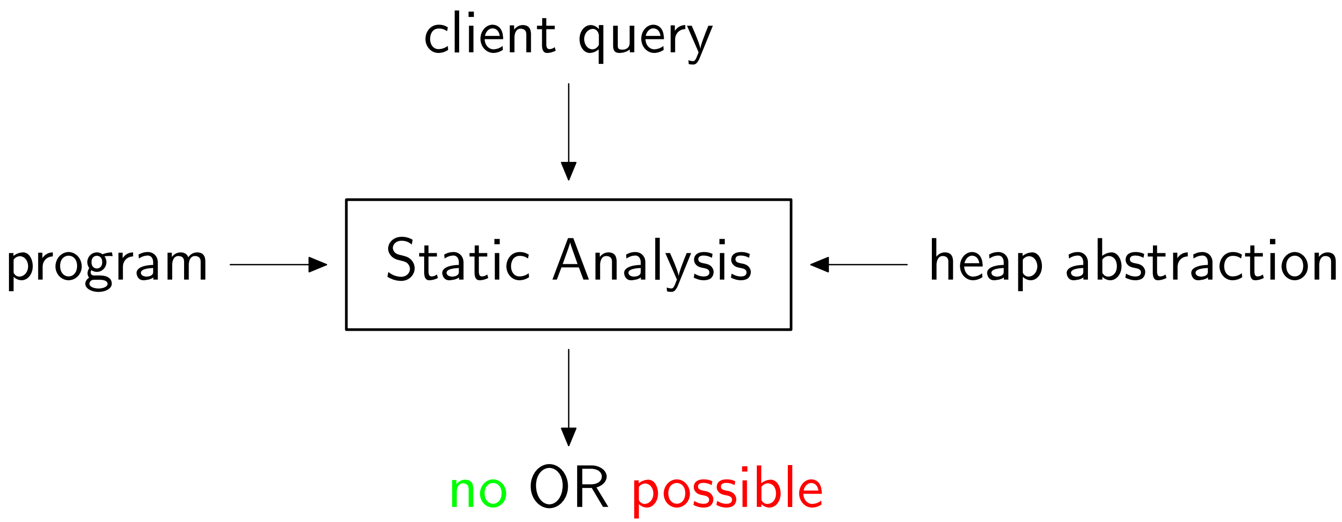

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Static Analysis

heap abstraction

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Heap abstraction affects **precision** and **scalabilty**

Question: what heap abstractions should one use?

Example client: THREADESCAPE

Query: Does a variable point to a thread-escaping object at a program point?

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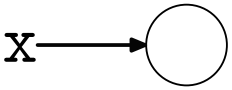

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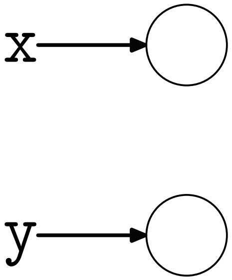

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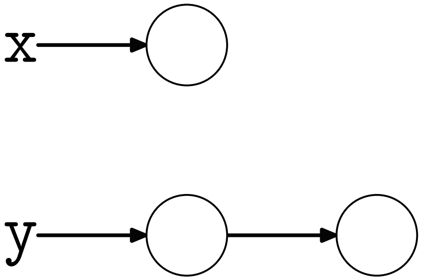

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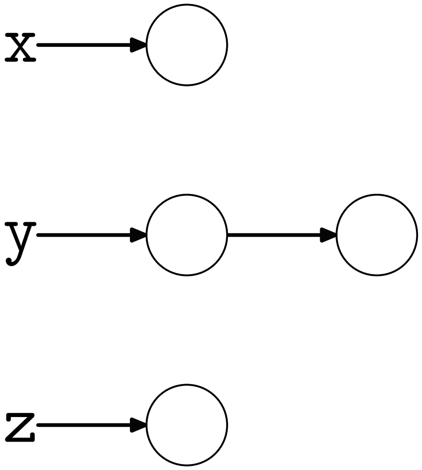

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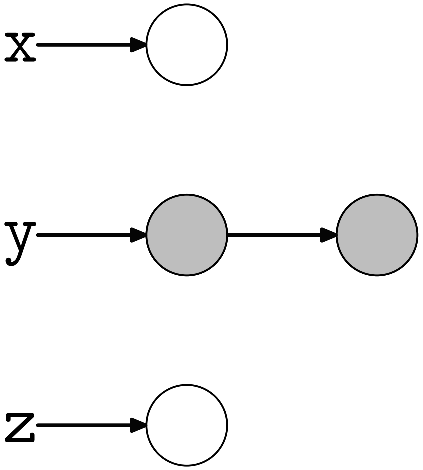

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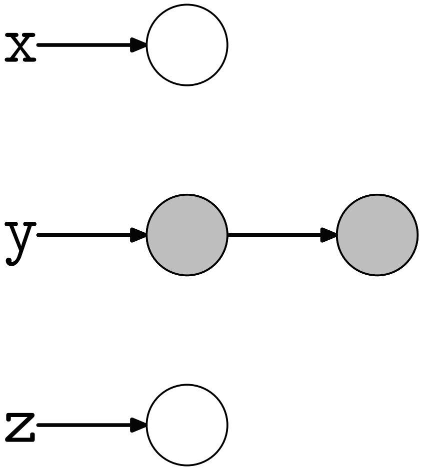

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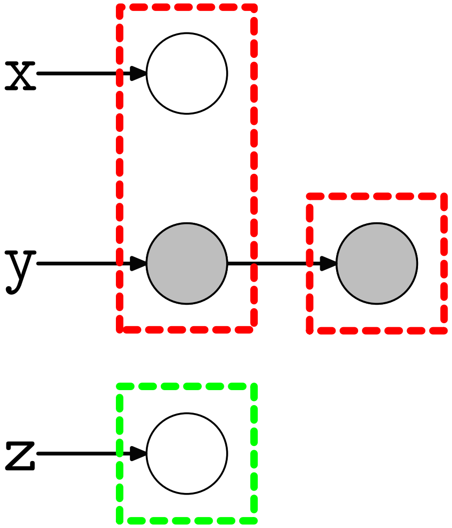

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abstract answer	yes	yes	no

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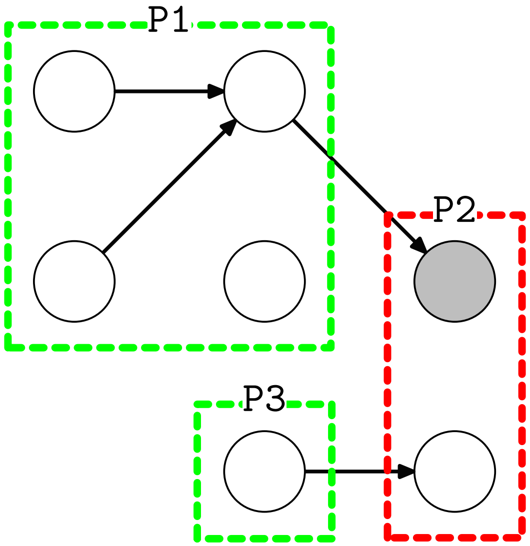

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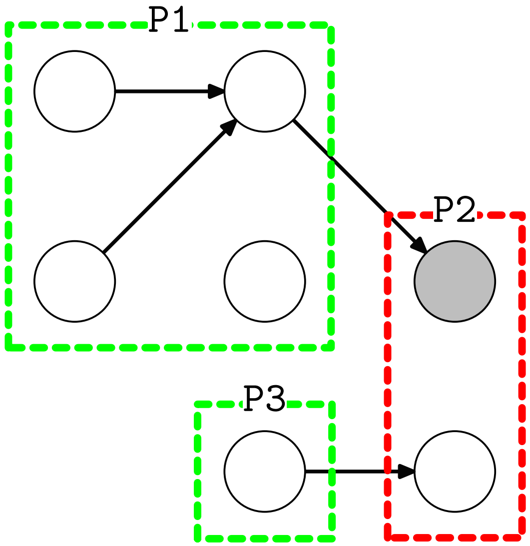

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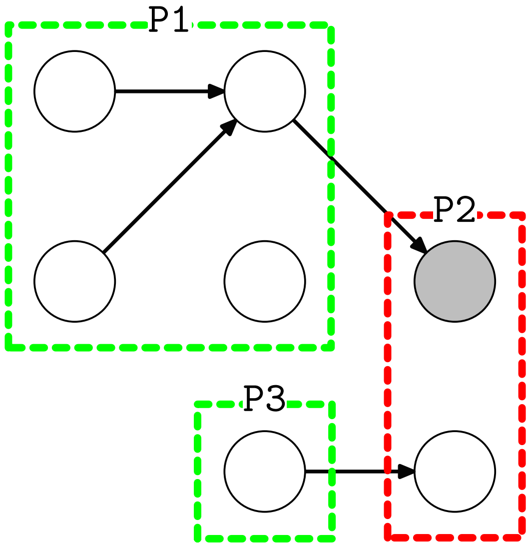

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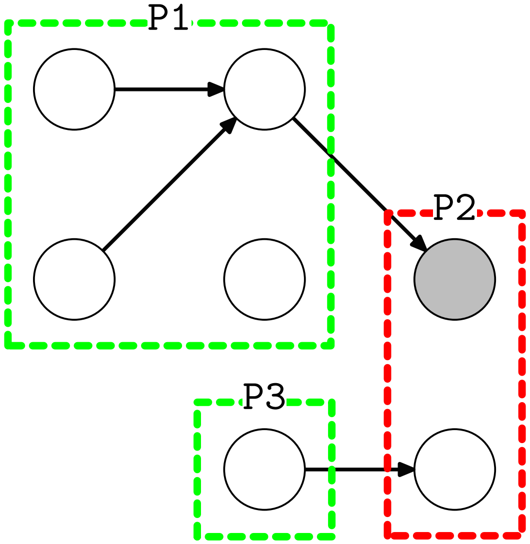

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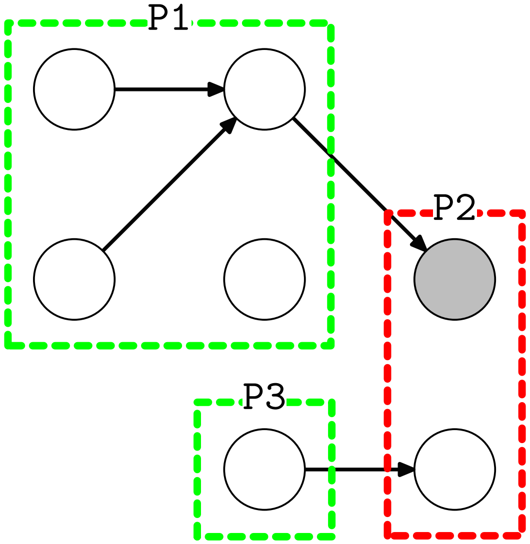

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Example:

$$\alpha(o) = \langle \text{alloc-site}(o), \text{other-information}(o) \rangle$$

The heap abstraction landscape

Tradeoff:

imprecise, fast
(e.g., 0-CFA)
↔
precise, slow
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Object recency
Heap connectivity
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Many dimensions:

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Question: how can we explore all these abstractions **cheaply**?

Main idea

Goal: get an idea of the utility of these abstractions
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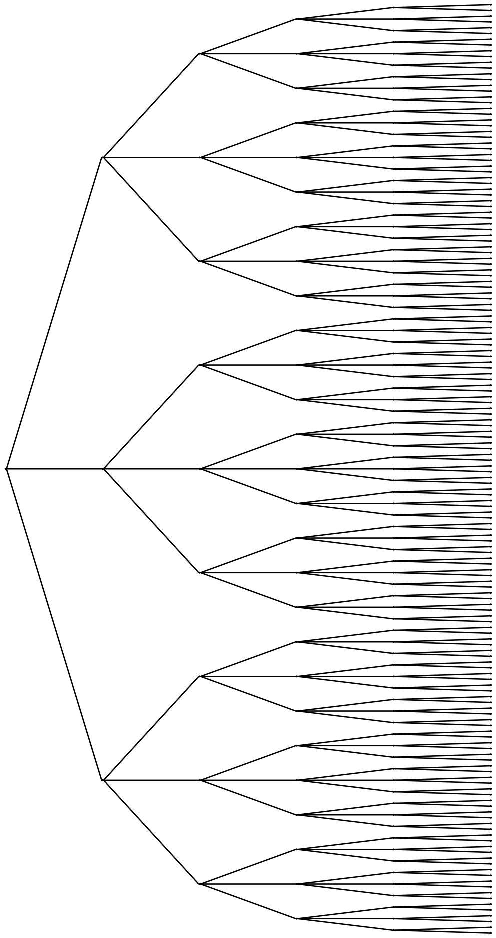

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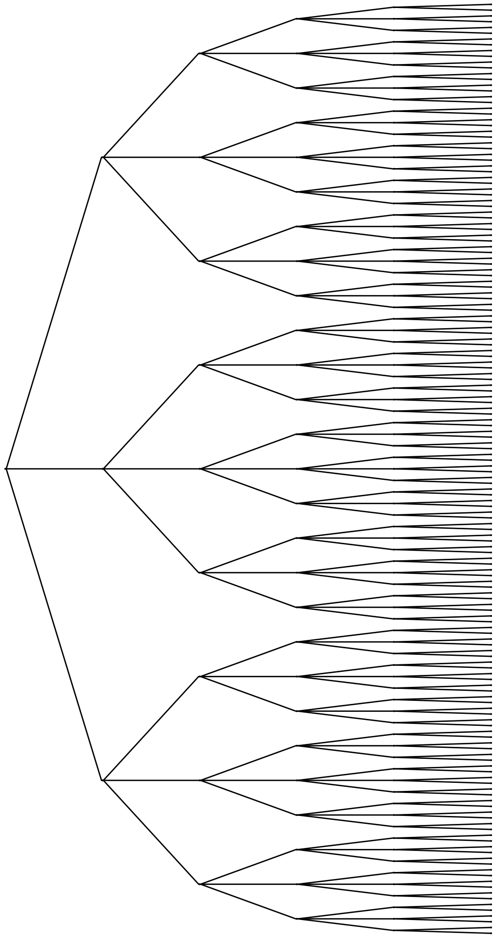

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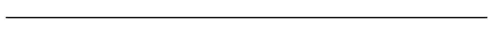

Dynamic: one trace (cheap)

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1. Run program dynamically with instrumentation

Concrete trace: ω_1 ω_2 ω_3 ω_4 ω_5

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Abstract trace:	ω_1^α	ω_2^α	ω_3^α	ω_4^α	ω_5^α

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Abstract query answer:	no	yes	no	yes	no

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Query is true ⇔ true on any state in trace

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$\Rightarrow$ performing the most precise analysis using a given heap abstraction α

$\Rightarrow$ provides **upper bound** on precision of any static analysis using α

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- Abstractions: augment allocation sites with more context
  - call stack
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Abstraction: call stack [Shivers, 1988]

Common pattern: factory constructor methods

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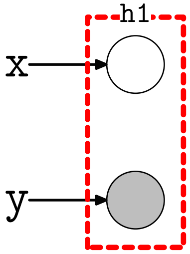

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✗ Allocation sites are too weak

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$$\text{call-stack-during-allocation-of}(o)[1..k]$$

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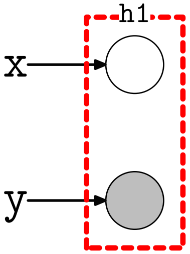

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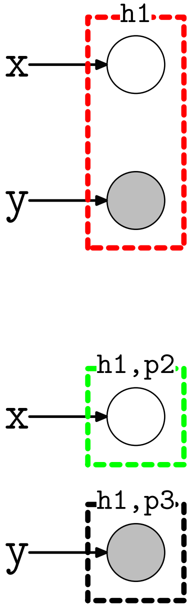

$\textsc{Alloc}$

$\textsc{Alloc}_{k=1}$

- ✗ Allocation sites are too weak
- ✓ Adding one level of calling context is sufficient

Abstraction: object recency [Balakrishnan & Reps, 2006]

Common pattern: server programs construct data, release to new thread

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    while (*) {
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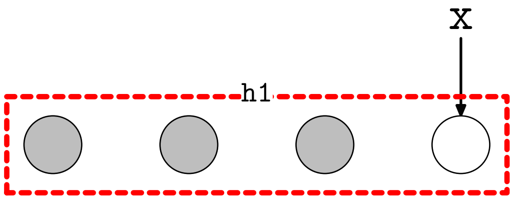

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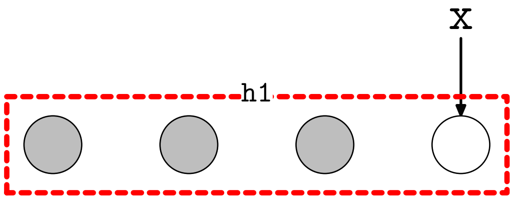

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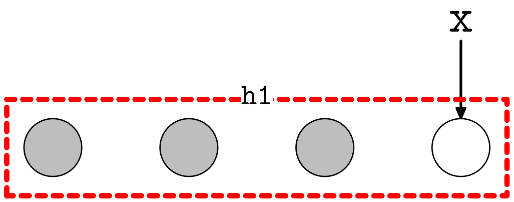

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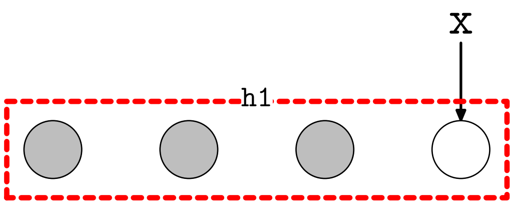

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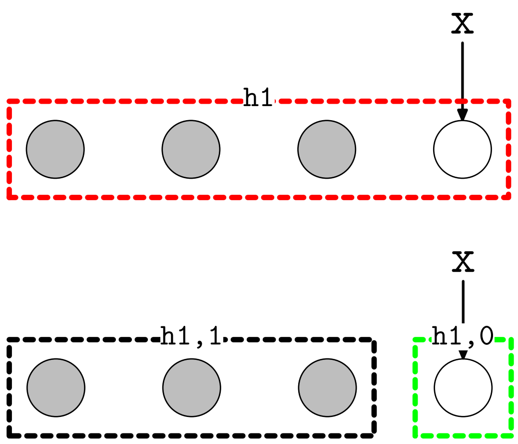

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✓ Recency makes the proper distinctions

Abstraction: heap connectivity [Sagiv et al., 2002]

Common pattern: build linked list data structures

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    spawn s
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    y = x
    while (*) {
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      if (x.f == y)
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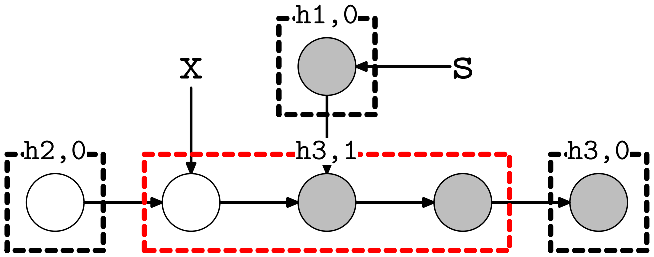

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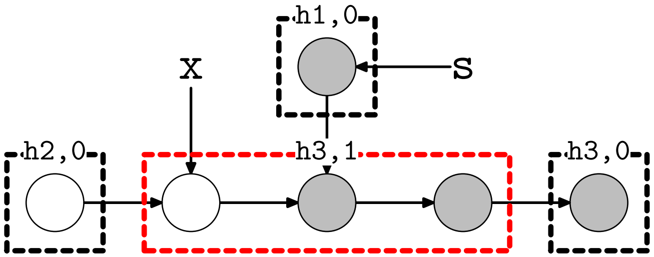

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$\textsc{ReachFrom}_k$: set of alloc. sites reaching $\textsc{Alloc}_k(o)$

$\textsc{PointedToBy}_k$: set of alloc. sites reaching $\textsc{Alloc}_k(o)$ in 1 step

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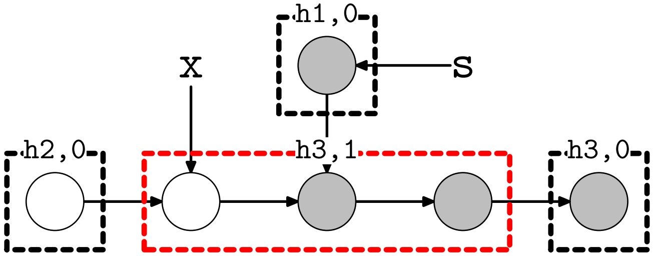


$\textsc{Recency}^{r=\infty}$

✗ No amount of recency helps

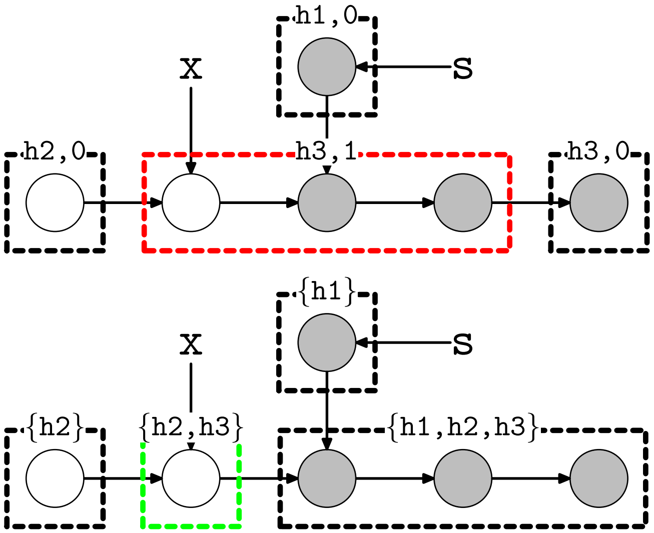
Abstraction: heap connectivity [Sagiv et al., 2002]

$\textsc{ReachFrom}_k$: set of alloc. sites reaching $\textsc{Alloc}_k(o)$

$\textsc{PointedToBy}_k$: set of alloc. sites reaching $\textsc{Alloc}_k(o)$ in 1 step

Common pattern: build linked list data structures

```
h1: s = new
    spawn s
h2: x = new
    y = x
    while (*) {
h3:   z = new
      y.f = z
      if (x.f == y)
        s.f = z
      y = z
    }
    x = x.f
p1: ... x ...
```



$\textsc{Recency}^{r=\infty}$

$\textsc{ReachFrom}_{k=0}$

- ✗ No amount of recency helps
- ✓ Reachability makes proper distinctions

Clients

THREADESCAPE: Does variable v

point to an object potentially reachable from another thread?

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NonStationaryField: for a field f, does there exist an object o such that
$o.f$ is written to after $o.f$ is read from?
(generalization of `final` in Java from [Unkel & Lam, 2008])

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Motivated by race and deadlock detection.

Benchmarks

9 Java programs from the DaCapo benchmark suite (version 9.12):

`antlr`	A parser generator and translator generator
`avrora`	A simulation and analysis framework for AVR microcontrollers
`batik`	A Scalable Vector Graphics (SVG) toolkit
`fop`	An output-independent print formatter
`hsqldb`	An SQL relational-database engine
`luindex`	A text indexing tool
`lusearch`	A text search tool
`pmd`	A source-code analyzer
`xalan`	An XSLT processor for transforming XML

290–1357 classes, 1.7K–6.8K methods, 133K–512K bytecodes, 5–46 threads

Experiments

Precision:

$$0\% \leq \frac{\text{number of queries } q \text{ such that } q \text{ is true (concrete)}}{\text{number of queries } q \text{ such that } q^{\alpha} \text{ is true (abstract)}} \leq 100\%$$

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Questions:

- What abstraction works best for a given client?
- What is the effect of the k in k-CFA?
- What is the effect of the recency depth r?
- How scalable are the high-precision abstractions?

General results: THREADESCAPE

benchmark	ALLOC	$\text{ALLOC}_{k=5}$	RECENCY	REACHFROM
`antlr`	48.6	85.0	81.0	**100.0**
`avrora`	54.7	62.3	69.2	**77.8**
`batik`	13.5	15.1	**20.9**	**20.6**
`fop`	36.3	**99.3**	42.8	41.3
`hsqldb`	62.6	69.0	**94.3**	?
`luindex`	6.3	**97.2**	6.8	6.8
`lusearch`	14.3	**90.0**	19.0	19.6
`pmd`	12.4	**87.1**	14.9	14.6
`xalan`	64.0	**78.9**	**78.7**	76.6
average	34.8	**76.0**	47.5	44.7

Main points:

- ALLOC can be very imprecise
- $\text{ALLOC}_{k=5}$ works best most of the time

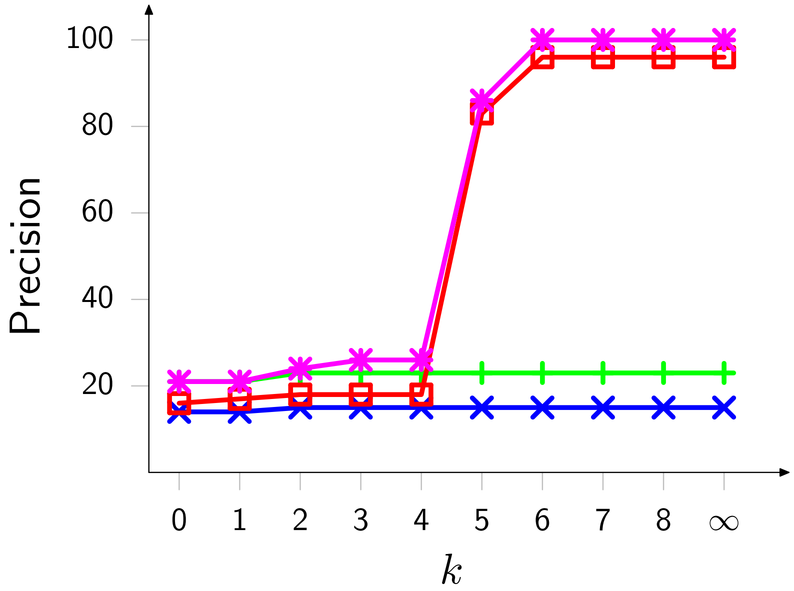
General results: NonStationaryField

benchmark	Alloc	$\text{Alloc}_{k=5}$	Recency	ReachFrom
`antlr`	59.1	60.1	**91.0**	78.3
`avrora`	33.2	33.6	**93.6**	77.2
`batik`	35.8	36.1	**99.5**	65.3
`fop`	42.0	44.9	**90.9**	68.2
`hsqldb`	45.4	49.5	**94.6**	?
`luindex`	78.0	84.2	**94.8**	**94.8**
`lusearch`	38.2	38.2	**64.9**	56.5
`pmd`	37.8	39.9	**96.4**	69.4
`xalan`	44.0	44.5	**90.4**	74.2
average	45.9	47.9	**90.7**	73.0

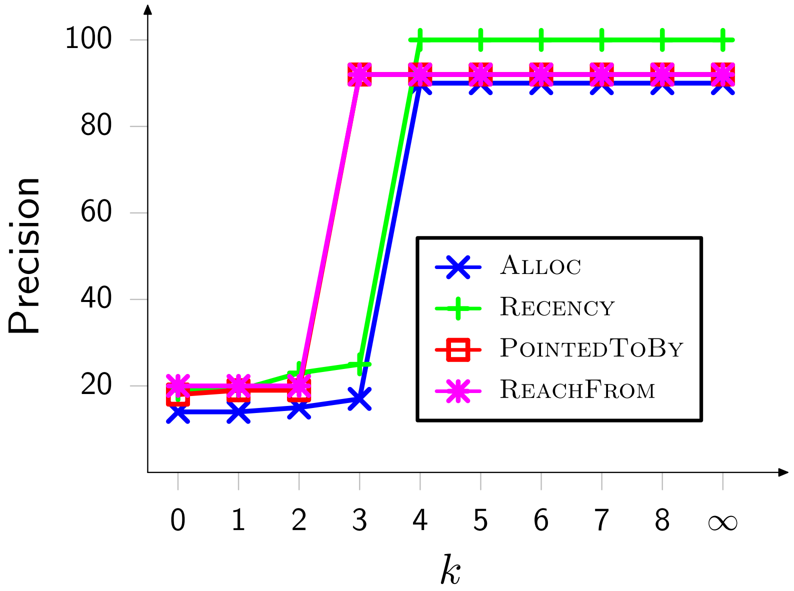
Main points:

- Call stack useless, reachability helps a bit
- Recency offers huge improvement: captures temporal properties

Effect of call stack depth k



(a) (ThreadEscape, `batik`)



(b) (ThreadEscape, `lusearch`)

Main points:

- Phase transition: sharp increase in precision beyond $k \approx 5$
- Synergy of information: ReachFrom requires high k to be precise

Effect of recency depth

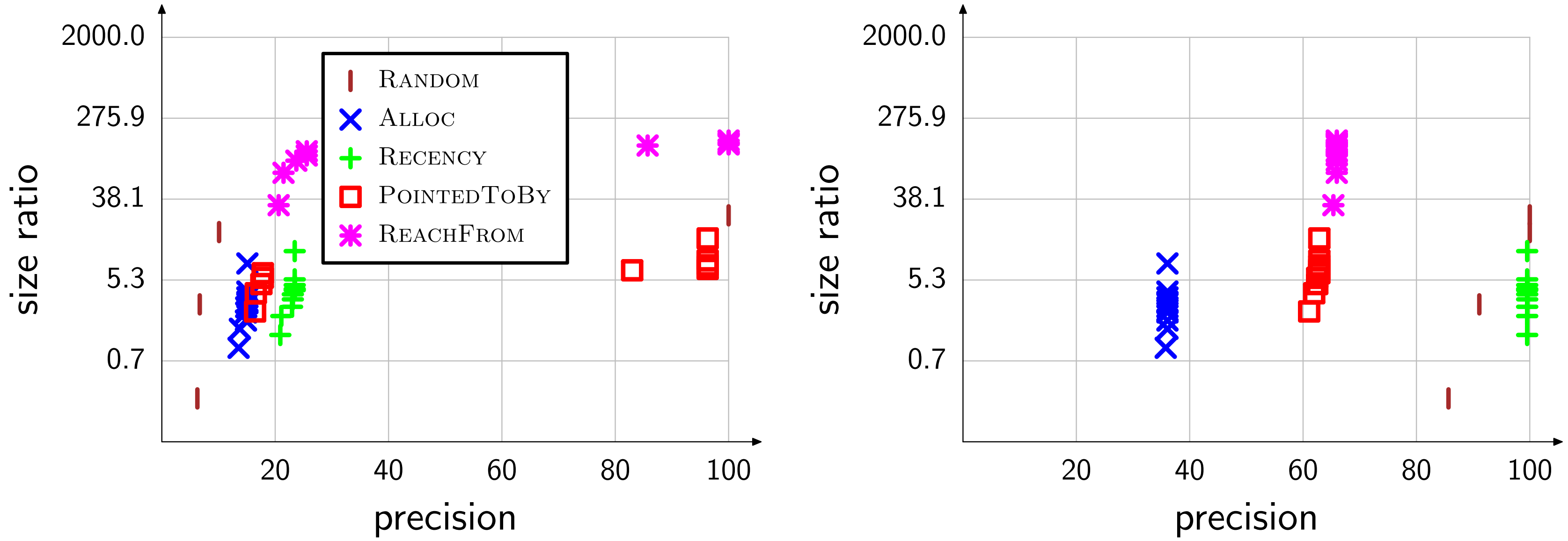
THREADESCAPE on `batik`:

	$r = 0$	$r = 1$	$r = 2$	$r = 3$	$r = 4$	$r = 5$
$k = 0$	13.5	20.9	21.4	**22.1**	**22.5**	**22.6**
$k = \infty$	15.1	23.4	**99.0**	**99.0**	**99.0**	**99.0**

Main points:

- Increasing recency depth beyond 1 helps, but maxes out quickly
- Synergy of information: need both large k and large r for success

Tradeoff between precision and size



(a) (ThreadEscape, `batik`) (b) (NonStationaryField, `batik`)

Main points:

- Reachability is quite expensive, Recency is cheap
- Random is surprisingly effective on NonStationaryField, but Recency is better

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- Goal: determine good heap abstractions to use in static analysis
- Dynamic analysis enables us to quickly explore many heap abstractions
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- Hopefully will serve as a useful guide for developers of static analyses

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Thank you!