Frequency-Aware Escape Analysis

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2025-10-20

Outline

Control-Flow Sensitivity

Frequency-Aware Escape Analysis

Example

Challenges

Control-Flow Sensitivity

Frequency-Aware Escape Analysis

Example

Challenges

What Does “Control-Flow Sensitive” Really Mean?

Escape partiality?

```
1  Foo foo = new Foo();
2  if (...) {
3      return null;
4  } else {
5      return foo;
6  }
```


Escape partiality?

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```

- Without: `foo` escapes

Escape partiality?

```
1  Foo foo = new Foo();
2  if (...) {
3      return null;
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```

- Without: `foo` escapes
- With: `foo` escapes **at line 5**

Allocation Sinkability?

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1  Foo foo = new Foo();
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```

- Without: allocation is fixed
- With: allocation can be sunk

Scalar Replacement Across Merges?

```
1
2   if (...) {
3       dog = new Dog();
4       dog.age = 25;
5   } else {
6       if (...) {
7           dog = new Dog();
8           dog.age = 12;
9       } else {
10          dog = new Dog();
11          dog.age = 3;
12      }
13      dog.name = ”Bobby”;
14  }
15  return dog.name;
```


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```

- Without: two-level allocation merges, cannot scalar replace
- With: can scalar replace through arbitrary allocation merges

Scalar Replacement Across Merges?

```
1   String dogName;
2   if (...) {
3
4
5   } else {
6       dogName = ”Bobby”;
7
8
9
10
11
12
13
14  }
15  return dogName;
```

- Without: two-level allocation merges, cannot scalar replace
- With: can scalar replace through arbitrary allocation merges

Tracing of Changes in Object Connectivity?

```
1  Foo foo = new Foo();
2  Bar bar = new Bar();
3  foo.a = bar;
4  ...
5  foo.a = null;
6  return foo;
```


Tracing of Changes in Object Connectivity?

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1  Foo foo = new Foo();
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- Without: both `foo` and `bar` escape

Tracing of Changes in Object Connectivity?

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2  Bar bar = new Bar();
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```

- Without: both `foo` and `bar` escape
- With: only `foo` escapes

Control-Flow Sensitivity

Frequency-Aware Escape Analysis

Example

Challenges

Frequency-Aware Escape Analysis

- Goal: leverage the most profitable features of “classic” partial EA

Freque

Partial Escape Analysis and Scalar Replacement for Java

► G

DISSERTATION

submitted in partial fulfillment of the requirements
for the academic degree

Doktor der technischen Wissenschaften

in the Doctoral Program in Engineering Sciences

Submitted by

Dipl.-Ing. Lukas Stadler

Frequency-Aware Escape Analysis

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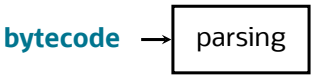
- Features
  - partial escape analysis
  - allocation sinking
  - allocation merge-agnostic
- Key design decision: assume static (conservative) object connectivity
  - theoretical analysis precision loss but seemingly low practical impact
  - not overall worse, this simplification has significant benefits (more later)

Frequency-Aware Escape Analysis: Architecture



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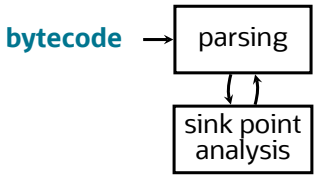

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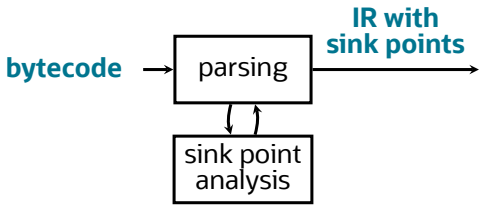

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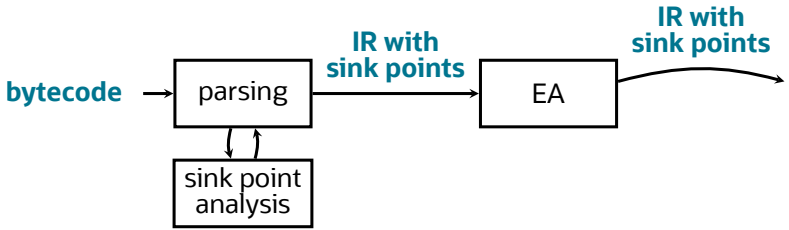

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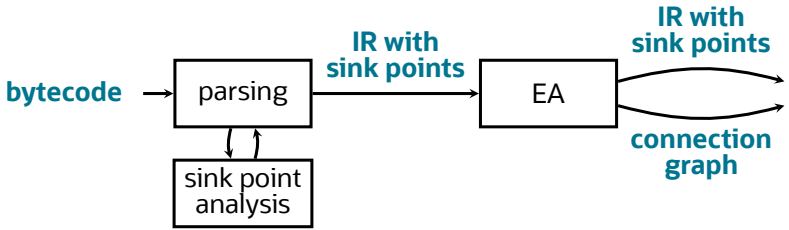

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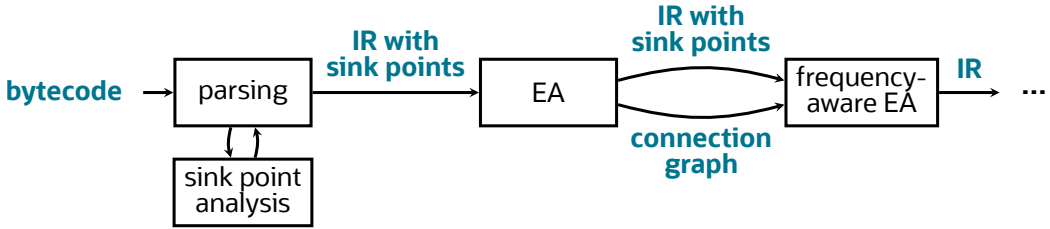

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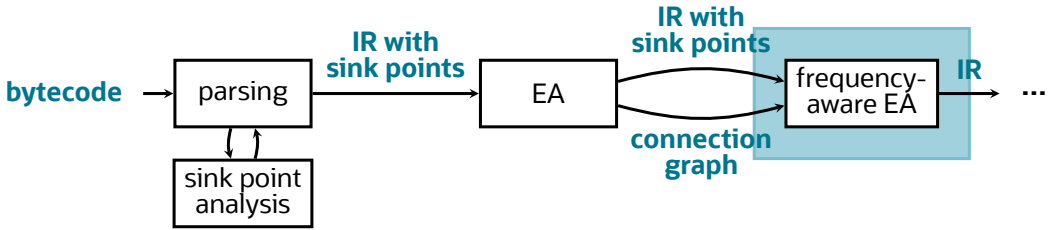

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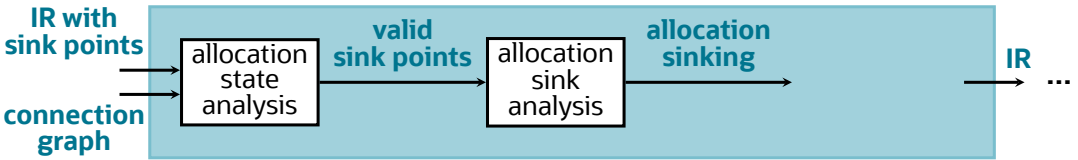

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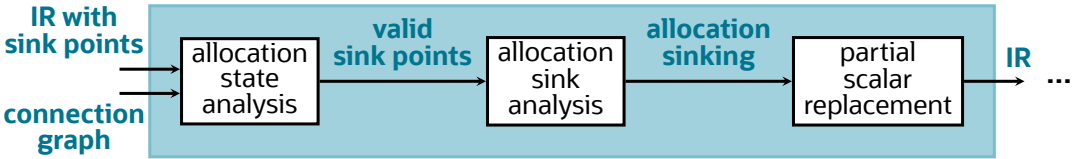

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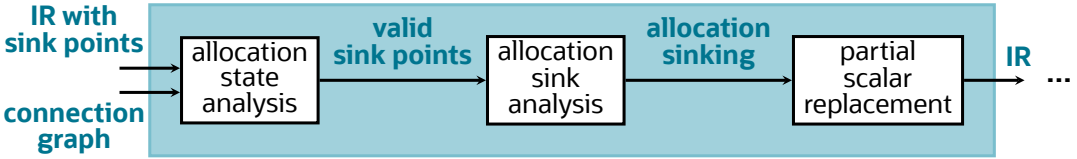

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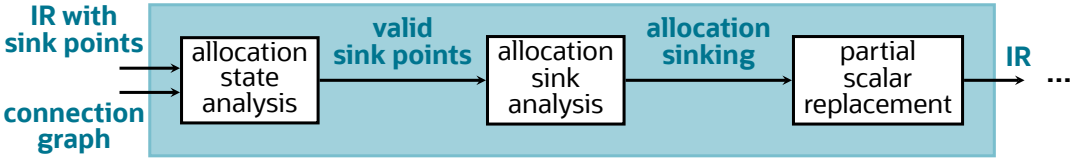

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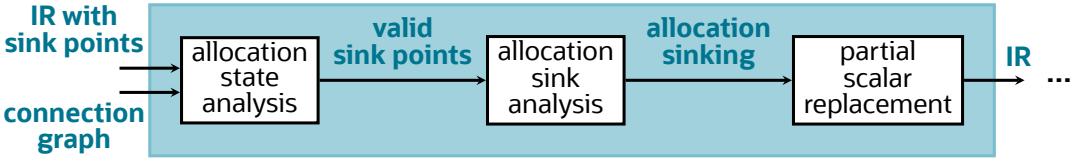

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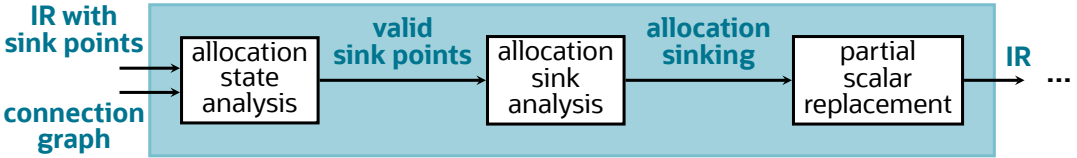

- Important difference with Stadler: decoupled analysis and transformation
  - less local and greedy, potentially better decisions
  - more modular and maintainable
  - enabled by static object connectivity model

Control-Flow Sensitivity

Frequency-Aware Escape Analysis

Example

Challenges

Example

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1   static void run(int dogLifeStage) {
2       Dog dog;
3       if (dogLifeStage == 2) {
4           dog = new Dog();
5           dog.age = 25;
6       } else {
7           if (dogLifeStage == 1) {
8               dog = new Dog();
9               dog.age = 12;
10          } else {
11              dog = new Dog();
12              dog.age = 3;
13          }
14          // dog <- phi (...)
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16          dog.name = ”Bobby”;
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20      Person person = new Person();
21      person.pet = dog;
22      if (dogLifeStage < 2) {
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After Sink Point Analysis

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After EA (Input to Frequency-Aware EA)

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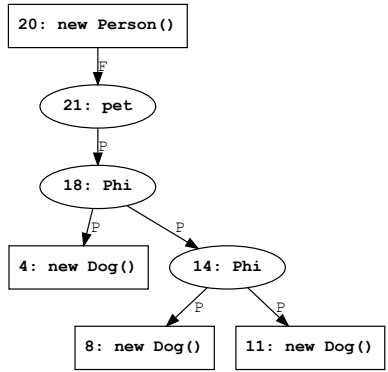

Allocation State Analysis: Assigning Allocations to Escape Sites

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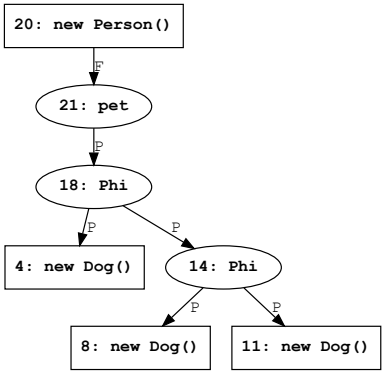

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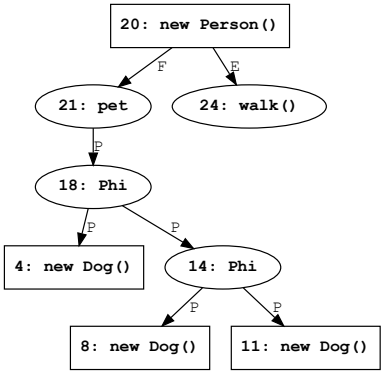

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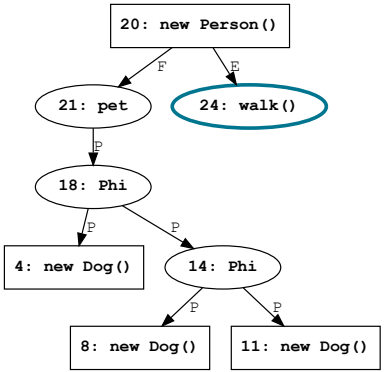

escaping-allocations(24) =

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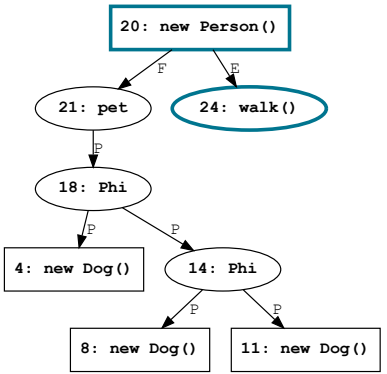

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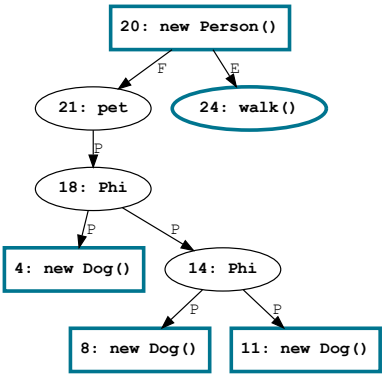

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Allocation State Analysis: Projecting a CFG

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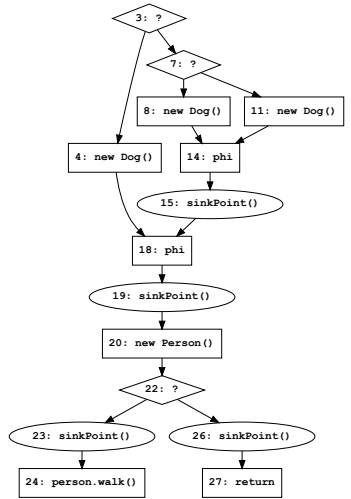

Allocation State Analysis: Propagating Virtual State

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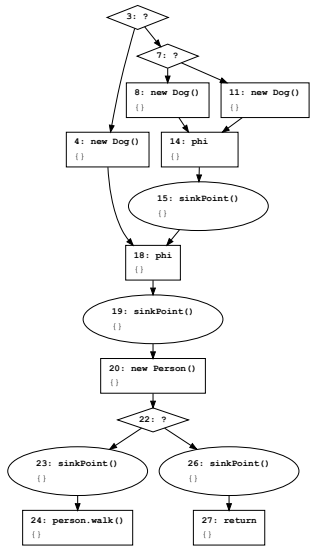

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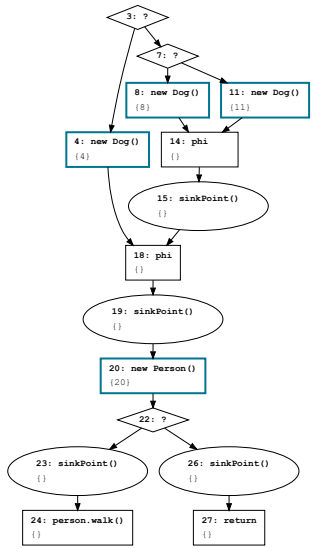

Allocation State Analysis: Propagating Virtual State

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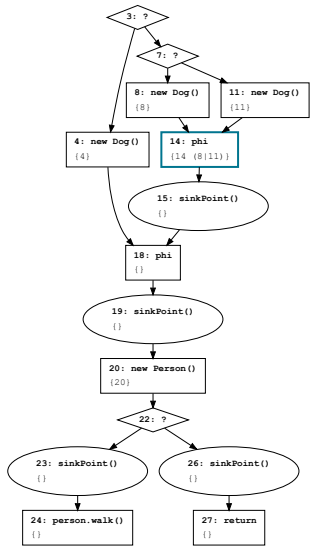

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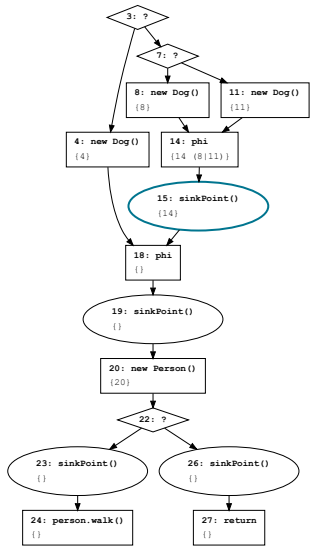

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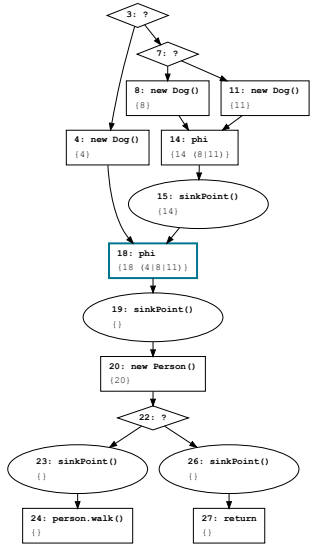

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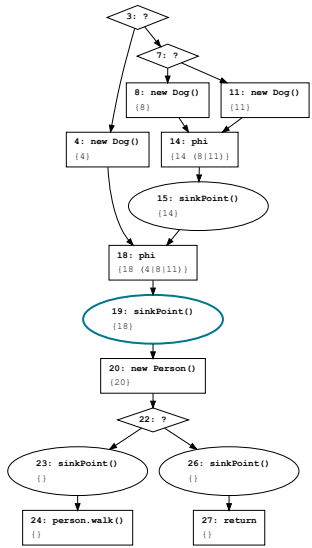

Allocation State Analysis: Propagating Virtual State

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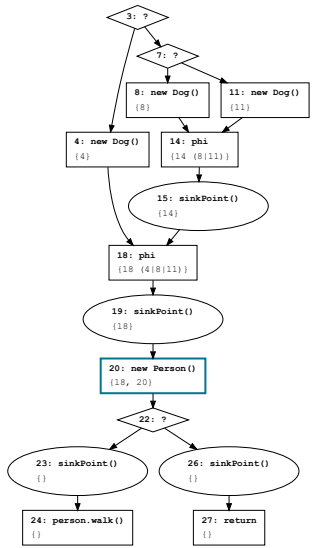

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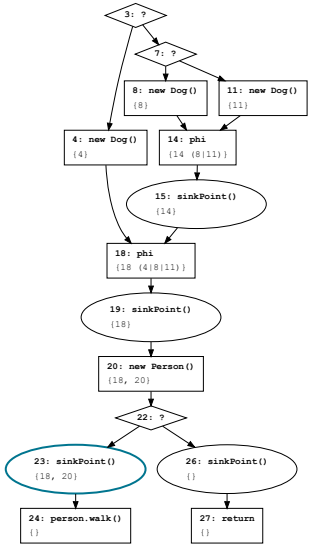

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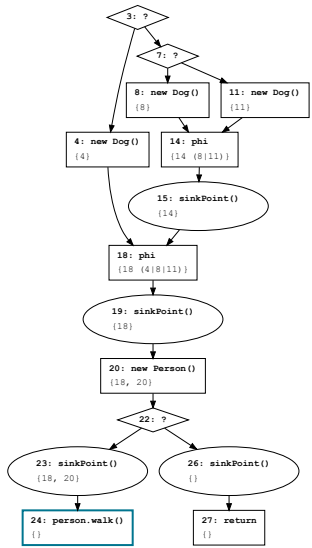

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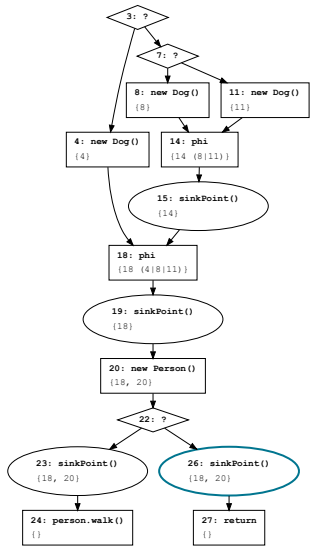

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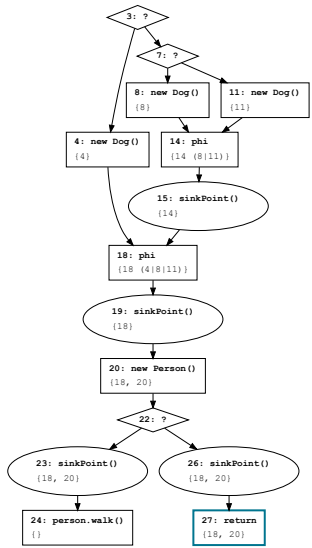

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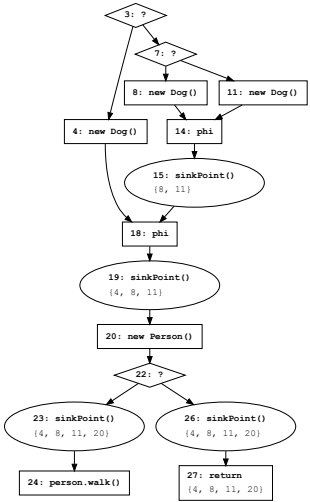

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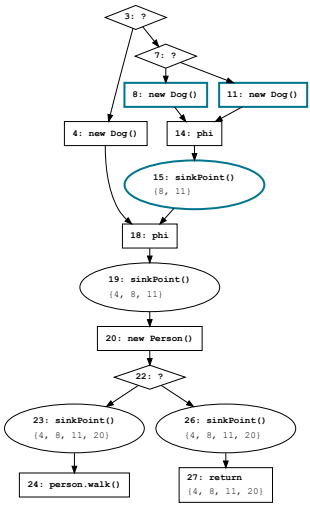

- $\{8, 11\}$ can be sunk to 15

Allocation State Analysis: Result

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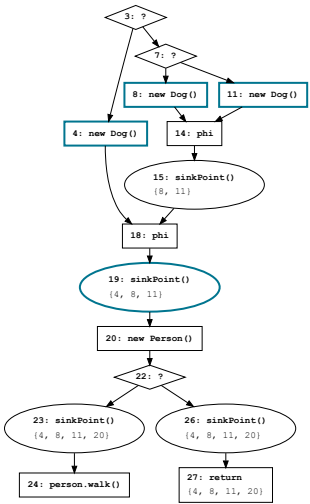

- $\{8, 11\}$ can be sunk to 15
- $\{4, 8, 11\}$ can be sunk to 19

Allocation State Analysis: Result

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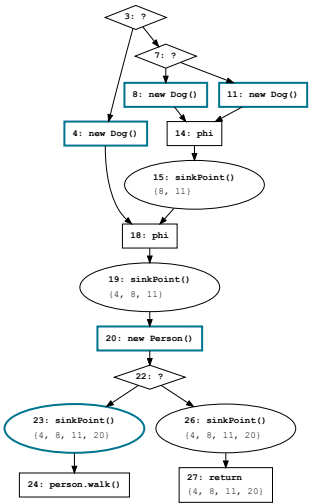

- $\{8, 11\}$ can be sunk to 15
- $\{4, 8, 11\}$ can be sunk to 19
- $\{4, 8, 11, 20\}$ can be sunk to 23

Allocation State Analysis: Result

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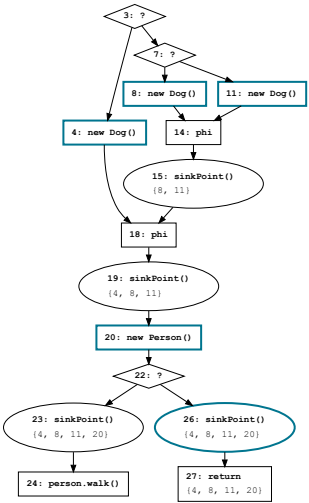

- $\{8, 11\}$ can be sunk to 15
- $\{4, 8, 11\}$ can be sunk to 19
- $\{4, 8, 11, 20\}$ can be sunk to 23
- $\{4, 8, 11, 20\}$ can be sunk to 26

Allocation State Analysis: Result

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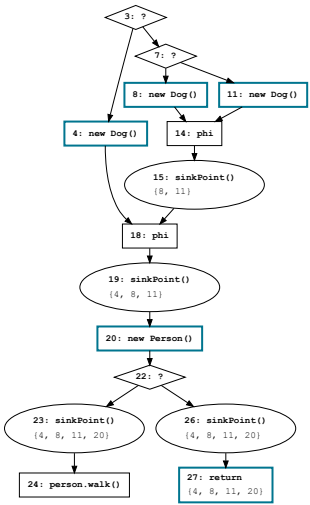
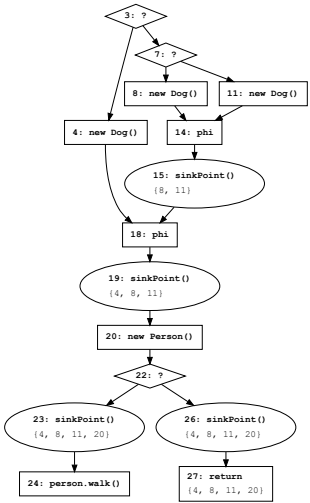


- $\{8, 11\}$ can be sunk to 15
- $\{4, 8, 11\}$ can be sunk to 19
- $\{4, 8, 11, 20\}$ can be sunk to 23
- $\{4, 8, 11, 20\}$ can be sunk to 26
- $\{4, 8, 11, 20\}$ can be sunk **below** 27

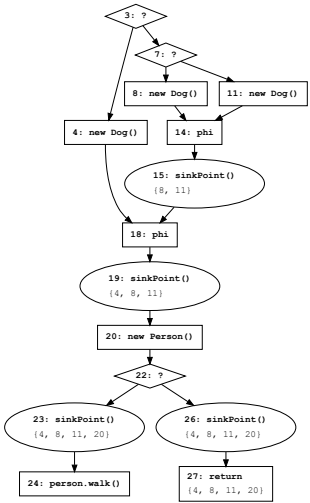
Allocation Sink Analysis: Feasible Sinkings

- Given
  - a projected CFG



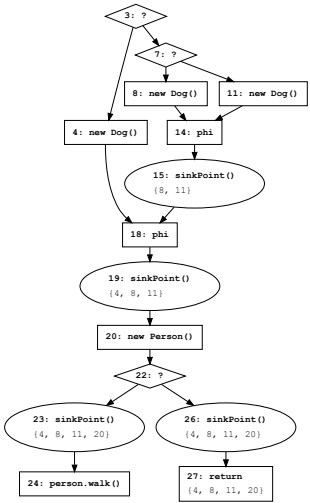
Allocation Sink Analysis: Feasible Sinkings

- Given
  - a projected CFG
  - a set of valid sink points for each allocation



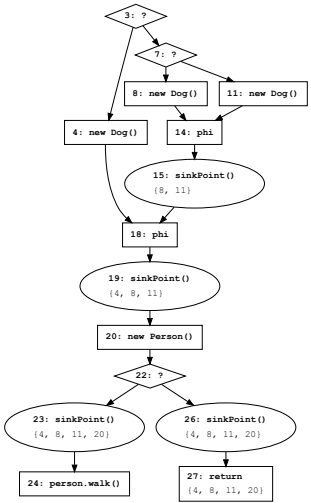
Allocation Sink Analysis: Feasible Sinkings

- Given
  - a projected CFG
  - a set of valid sink points for each allocation
- Find a minimum-cost “sinking” of all allocations



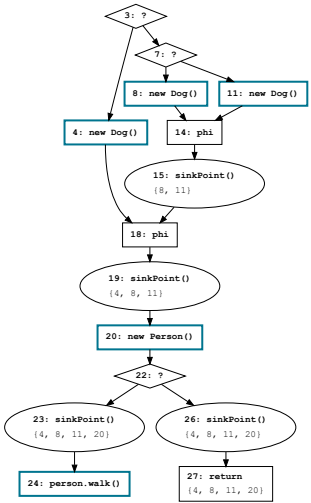
Allocation Sink Analysis: Feasible Sinkings

- Given
  - a projected CFG
  - a set of valid sink points for each allocation
- Find a minimum-cost “sinking” of all allocations
- Subject to:
  - allocations dominate their escape points



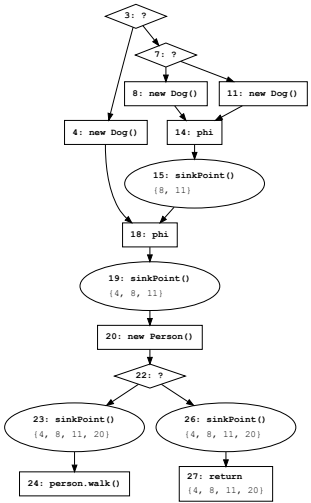
Allocation Sink Analysis: Feasible Sinkings

- Given
  - a projected CFG
  - a set of valid sink points for each allocation
- Find a minimum-cost “sinking” of all allocations
- Subject to:
  - allocations dominate their escape points
    $\{4, 8, 11, 20\}$ dominate 24



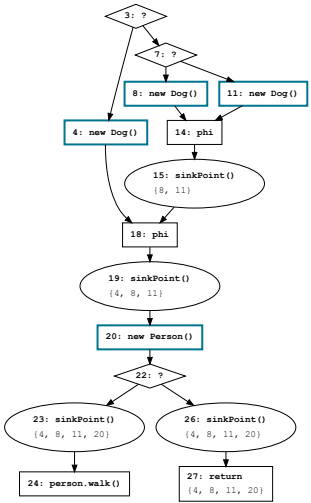
Allocation Sink Analysis: Feasible Sinkings

- Given
  - a projected CFG
  - a set of valid sink points for each allocation
- Find a minimum-cost “sinking” of all allocations
- Subject to:
  - allocations dominate their escape points
    $\{4, 8, 11, 20\}$ dominate 24
  - allocations are dominated by their dependencies



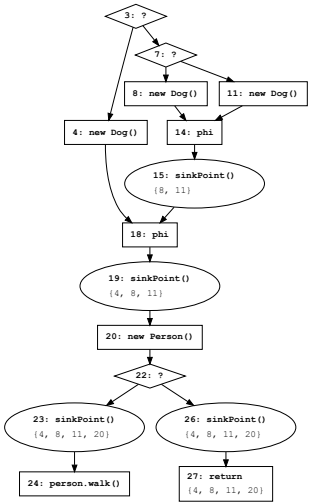
Allocation Sink Analysis: Feasible Sinkings

- Given
  - a projected CFG
  - a set of valid sink points for each allocation
- Find a minimum-cost “sinking” of all allocations
- Subject to:
  - allocations dominate their escape points
    $\{4, 8, 11, 20\}$ dominate 24
  - allocations are dominated by their dependencies
    $\{20\}$ is dominated by $\{4, 8, 11\}$



Allocation Sink Analysis: Feasible Sinkings

- Given
  - a projected CFG
  - a set of valid sink points for each allocation
- Find a minimum-cost “sinking” of all allocations
- Subject to:
  - allocations dominate their escape points
    $\{4, 8, 11, 20\}$ dominate 24
  - allocations are dominated by their dependencies
    $\{20\}$ is dominated by $\{4, 8, 11\}$
  - ϕ-related allocations are sunk and merged together



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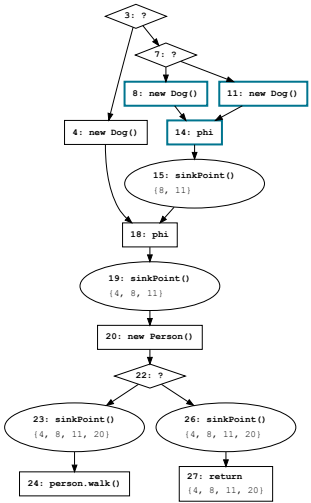
  - allocations are dominated by their dependencies
    $\{20\}$ is dominated by $\{4, 8, 11\}$
  - ϕ-related allocations are sunk and merged together
    if 8 is sunk below 14, so is 11 (and vice versa)



Allocation Sink Analysis: Feasible Sinkings

- Given
  - a projected CFG
  - a set of valid sink points for each allocation
- Find a minimum-cost "sinking" of all allocations
- Subject to:
  - allocations dominate their escape points
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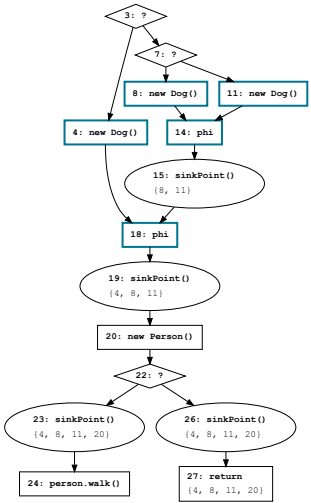

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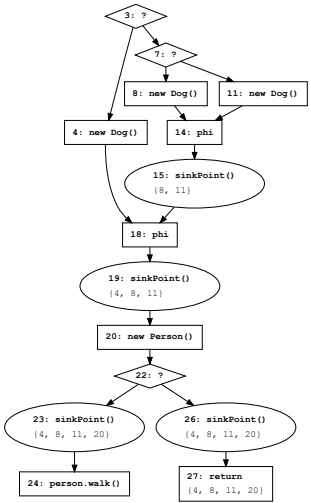

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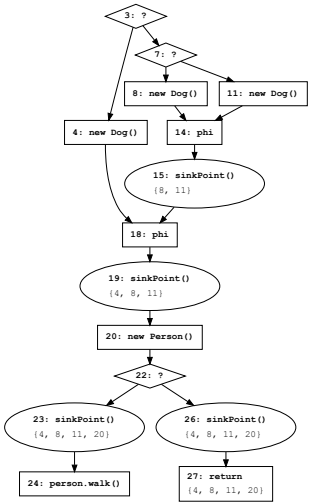

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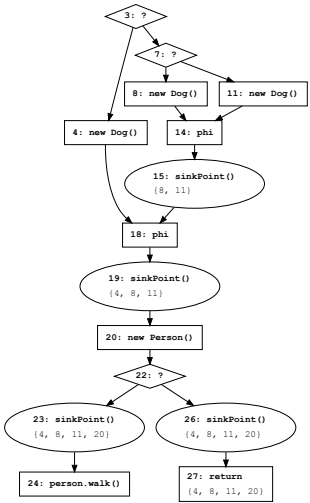

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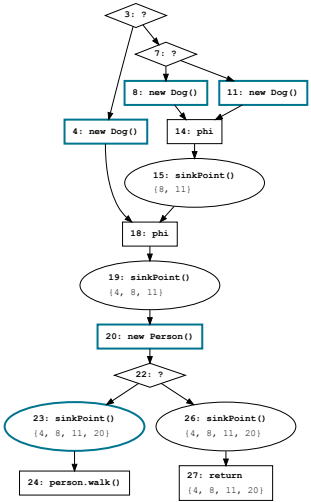

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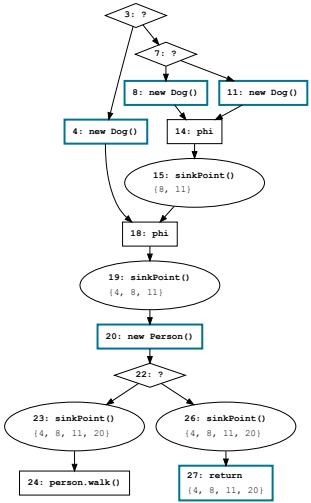

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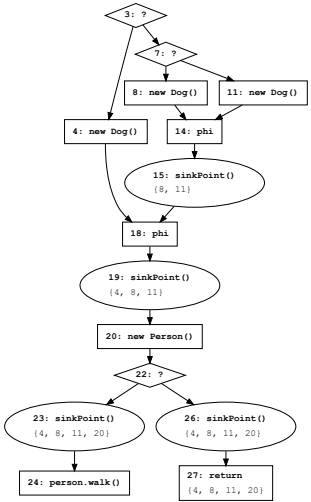

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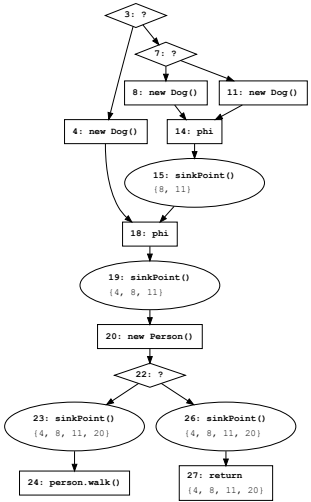

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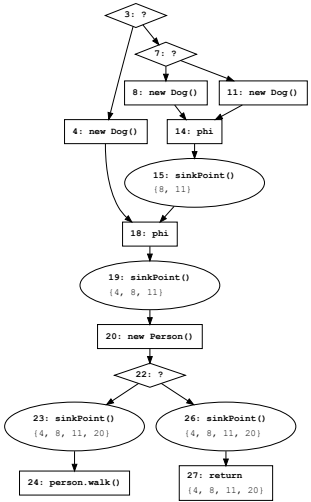

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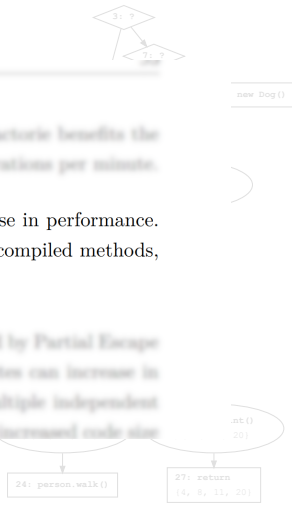
in performance, with many being above 10%. ScalaDaCapo factorie benefits the most in terms of performance, with a 33% improvement in iterations per minute.

Notably, the DaCapo jython benchmark shows a 2.1% decrease in performance. Partial Escape Analysis can in rare cases increase the size of compiled methods, which has a negative influence on this benchmark.

While there will never be more dynamic allocations in code optimized by Partial Escape Analysis than in the unoptimized code, the number of allocation sites can increase in some cases, e.g., when the same virtual object is materialized in multiple independent branches. Benchmarks that are sensitive to this may suffer from the increased code size



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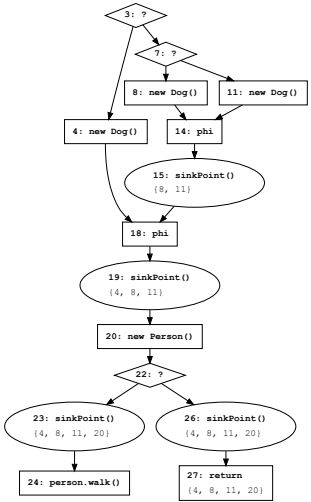

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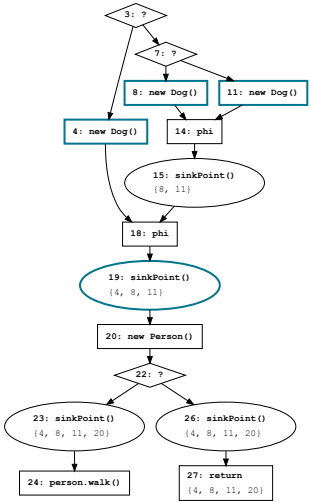

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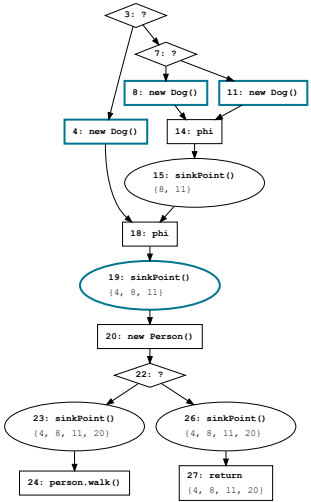

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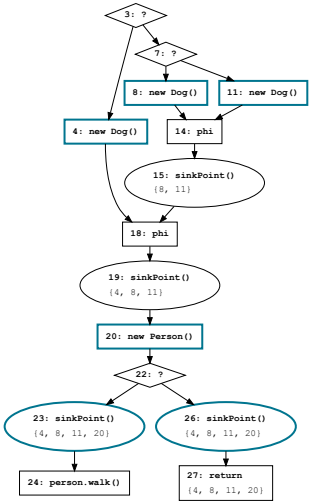

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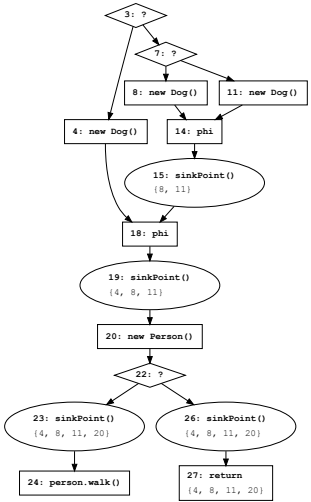

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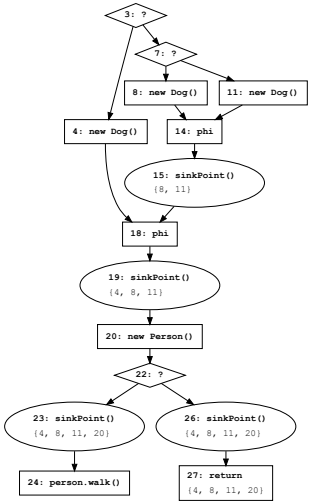

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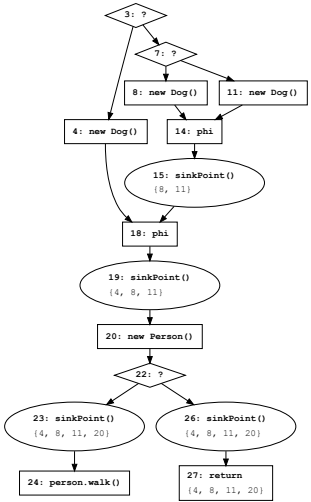
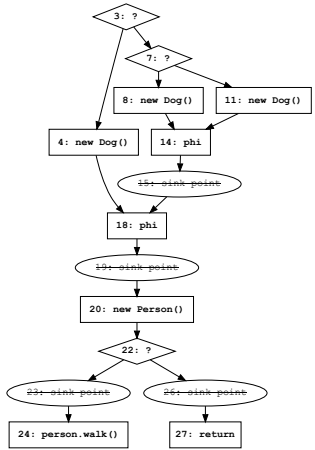
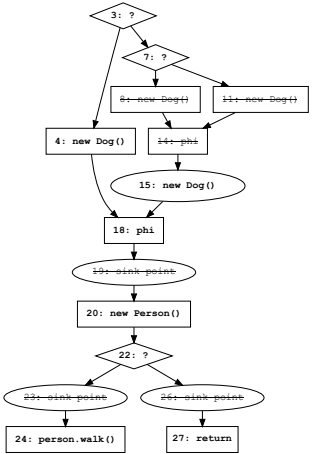


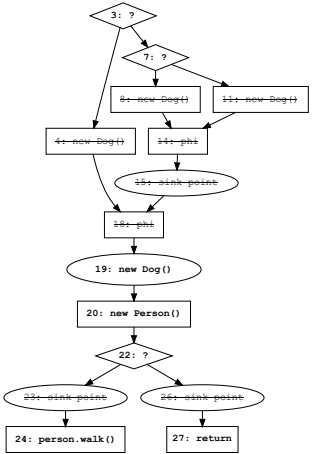
Allocation Sink Analysis: Sinking A (Original)



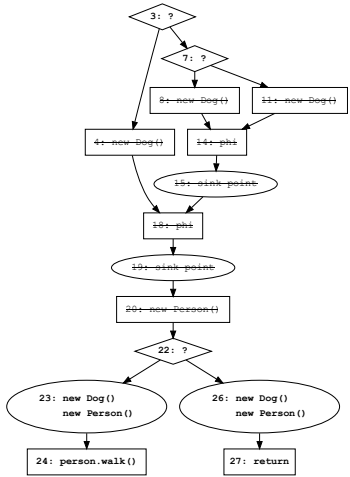
Allocation Sink Analysis: Sinking B (Better Code Size)



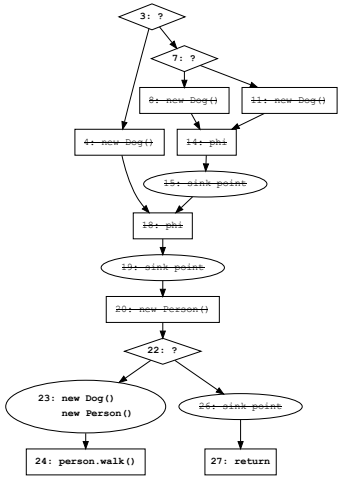
Allocation Sink Analysis: Sinking C (Even Better Code Size)



Allocation Sink Analysis: Sinking D (As Bad as Original)



Allocation Sink Analysis: Sinking E (Best)



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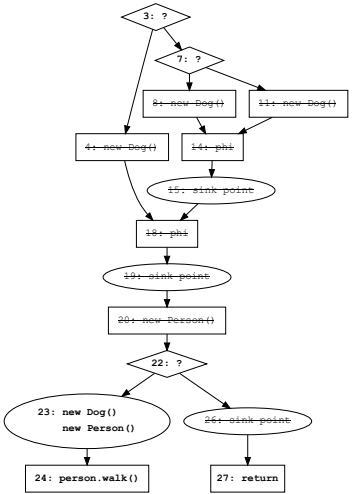
Partial Scalar Replacement: Output for Sinking E

```
static void run(int dogLifeStage) {
    Dog dog;
    if (dogLifeStage == 2) {
        dog = new Dog();
        dog.age = 25;
    } else {
        if (dogLifeStage == 1) {
            dog = new Dog();
            dog.age = 12;
        } else {
            dog = new Dog();
            dog.age = 3;
        }
        dog.name = ”Bobby”;
    }
    Person person = new Person();
    person.pet = dog;
    if (dogLifeStage < 2) {
        person.walk();
    }
}
```




```
static void run(int dogLifeStage) {
    int age;
    String name;
    if (dogLifeStage == 2) {
      age = 25;
      name = null;
    } else {
        if (dogLifeStage == 1) {
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        } else {
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        }
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    }
    if (dogLifeStage < 2) {
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        dog.age = age;
        dog.name = name;
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        person.pet = dog;
        person.walk();
    }
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Control-Flow Sensitivity

Frequency-Aware Escape Analysis

Example

Challenges

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3      ...
4      sinkPoint();
5      ...
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- More generally, can we always project the CFG we need from C2’s IR?

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  - due to allocation merge limitation
- Might have to implement independently

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- Heuristic (e.g. frequency estimation)
- Compilation time
- …

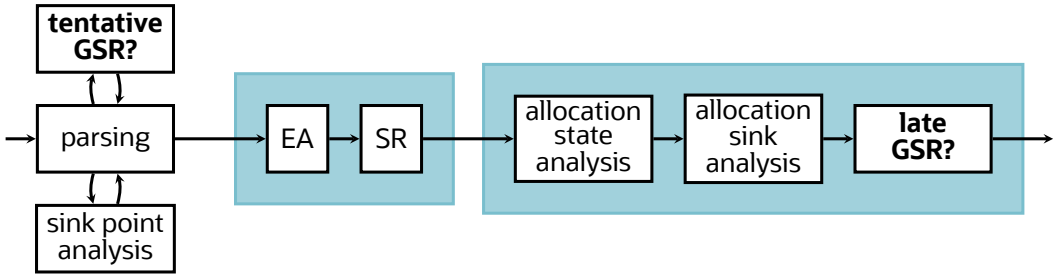
Plan and Status

- ✓ Study literature
- ✓ Study C2 implementation
- ✓ Study opportunities in benchmarks
- ► Gather tests and micro-benchmarks
- ► Prototype general (partial, merge-agnostic) SR (highest uncertainty)

  Apply general SR to current EA (intermediate contribution)

  Implement rest of frequency-aware escape analysis

Plan and Status: Tentative vs. Late General SR



- Tentative GSR: construct dual (heap/scalar) representation during parsing
- Late GSR: infer scalar representation on-demand, after escape analysis

