Allocation Removal by Partial Evaluation in a Tracing JIT

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Dynamic Languages are Slow

- Interpretation overhead
- Type dispatching
- Boxing of primitive types

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- Boxing of primitive types
  - A lot of allocation of short-lived objects

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x = a + b; y = x + c
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- Use a JIT compiler
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- Use a JIT compiler
- **Add an optimization that can deal with heap operations**
- optimize short-lived objects
- remove some of the redundant type checks

Overview

1. Experimental Context

2. Proposed Optimization

3. Benchmarks

Our Experimental Context is the PyPy Project

A general environment for implementing dynamic languages

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Approach

- write an interpreter for the language in RPython
- compilable to an efficient C-based VM

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- write an interpreter for the language in RPython
- compilable to an efficient C-based VM
- (RPython is a restricted subset of Python)

PyPy Uses a Novel Tracing JIT

the feature that makes PyPy interesting:

- a meta-JIT, applicable to many languages
- needs a few source-code hints (or user annotations) in the interpreter
- JIT is a tracing JIT compiler

Tracing JITs Compile by Observing an Interpreter

- VM contains both an interpreter and the tracing JIT compiler
- JIT works by observing and logging what the interpreter does
  - for interesting, commonly executed code paths
  - produces a linear list of operations (trace)
- trace is optimized and then turned into machine code

The Advantages of Tracing JITs

- Traces are interesting linear pieces of code
- most of the time correspond to loops
- everything called in the trace is inlined
- can perform good optimizations on the trace
- rarer paths run by the interpreter

Example Trace

Trace of `x = a + b; y = x + c`:

```
guard_class(a, Integer)
guard_class(b, Integer)
i1 = get(a, intval)
i2 = get(b, intval)
i3 = int_add(i1, i2)
x = new(Integer)
set(x, intval, i3)
```

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```

Optimized Example Trace

Trace of `x = a + b; y = x + c`:

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Contribution of our Paper

- a simple, efficient and effective optimization of heap operations in a trace
- using online partial evaluation
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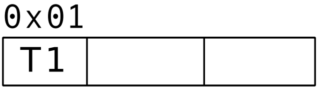
Ingredients

- a slightly simplified model for objects on the heap
- operational semantics of trace operations that manipulate the heap
- optimization rules for those operations, following the operational semantics

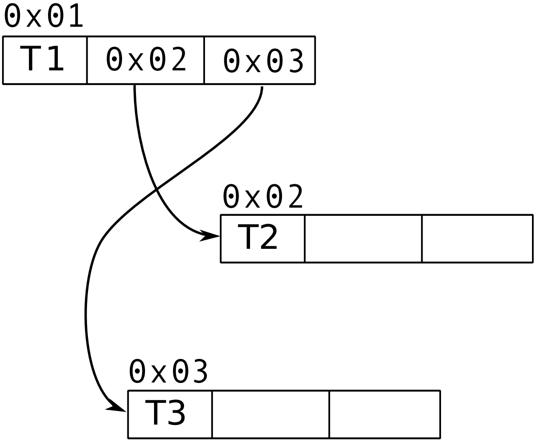
Heap Model



0x01

T1

Heap Model



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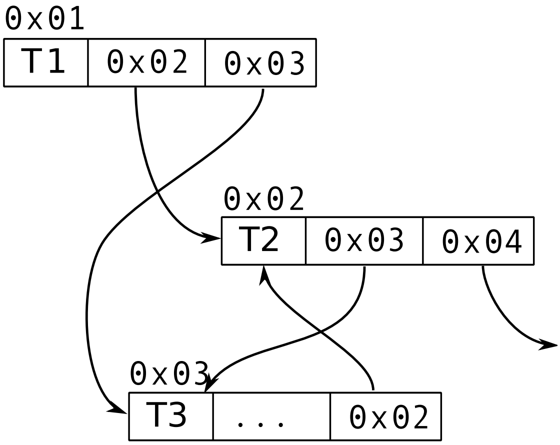
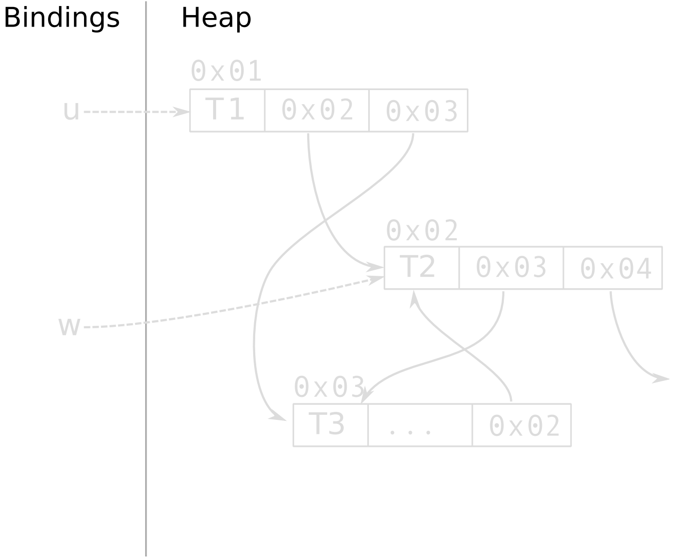


Operations Manipulating Heap Objects

- `v = new(T)` makes a new object
- `u = get(w, F)` reads a field out of an object
- `set(v, F, w)` writes a field of an object
- `guard(v, T)` checks the type of an object

Operations: New

v=new(T4)



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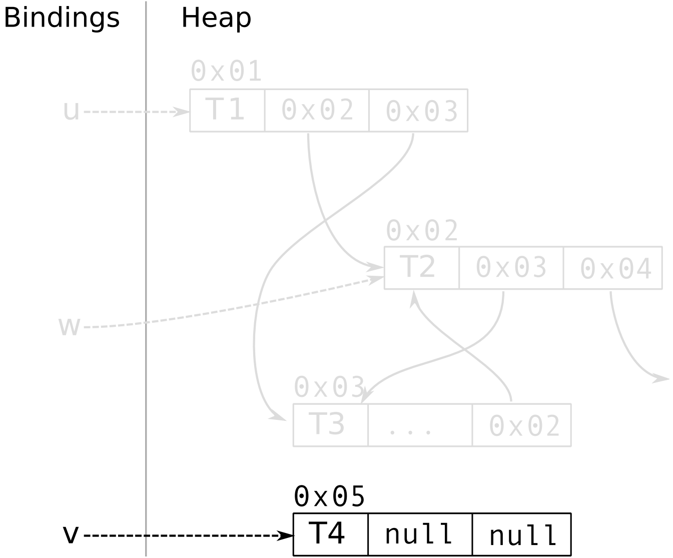
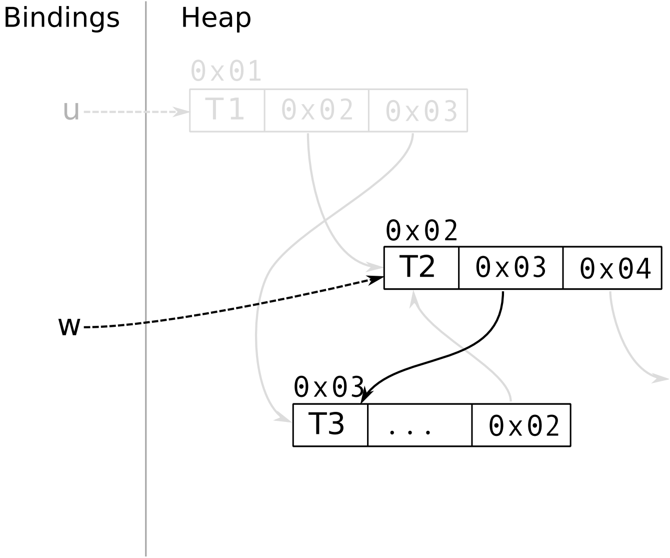


Operations: Get

v=get(w, L)



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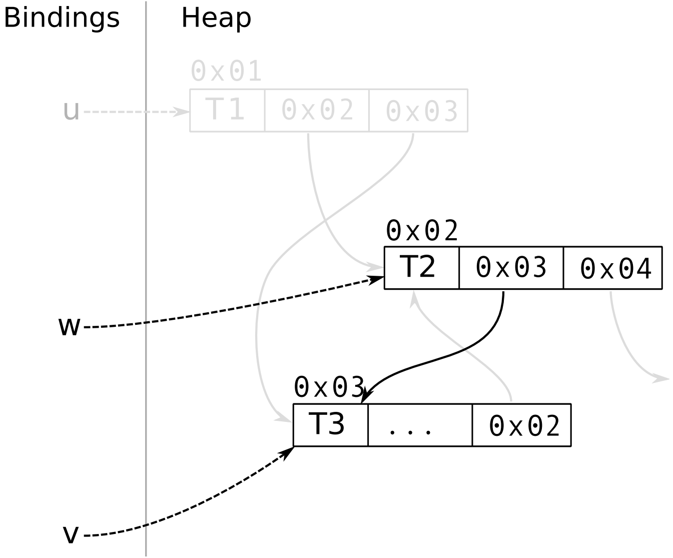
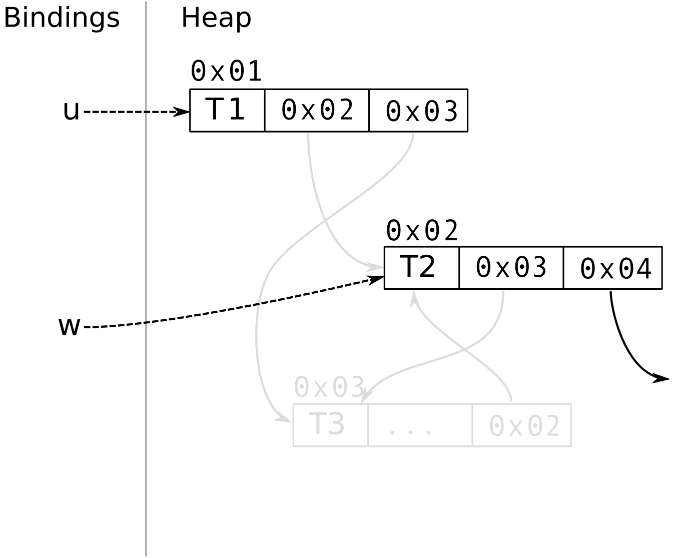


Operations: Set

set(w, R, u)



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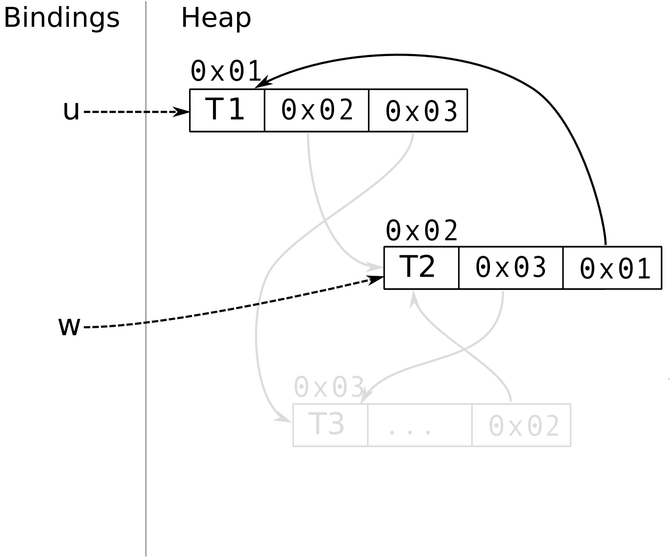

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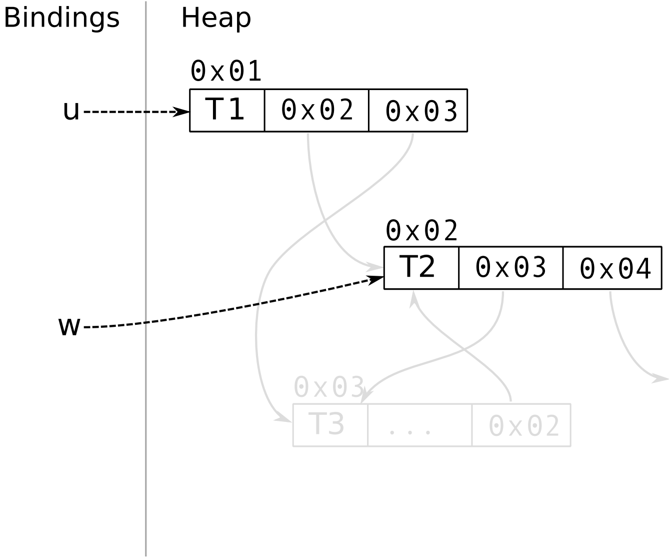

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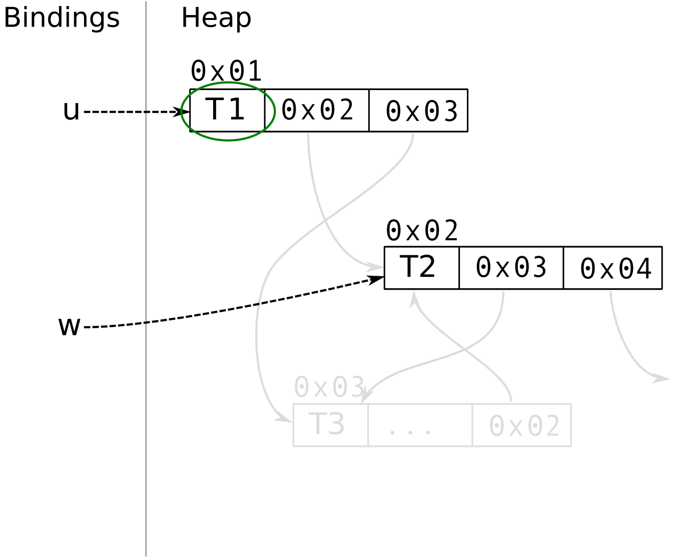

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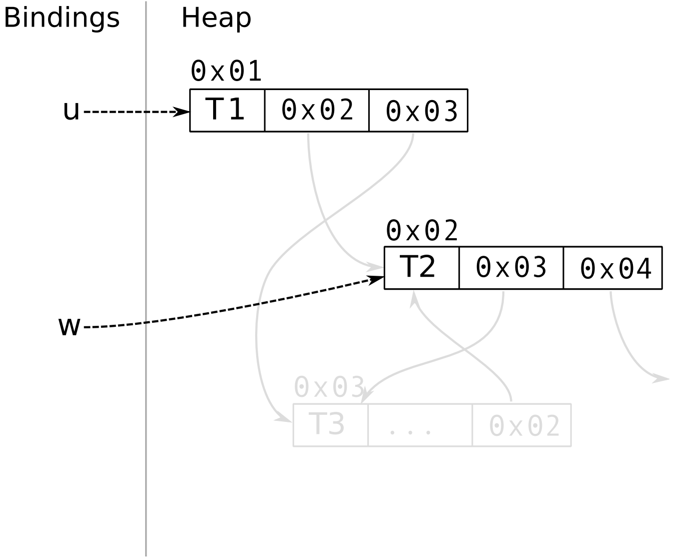

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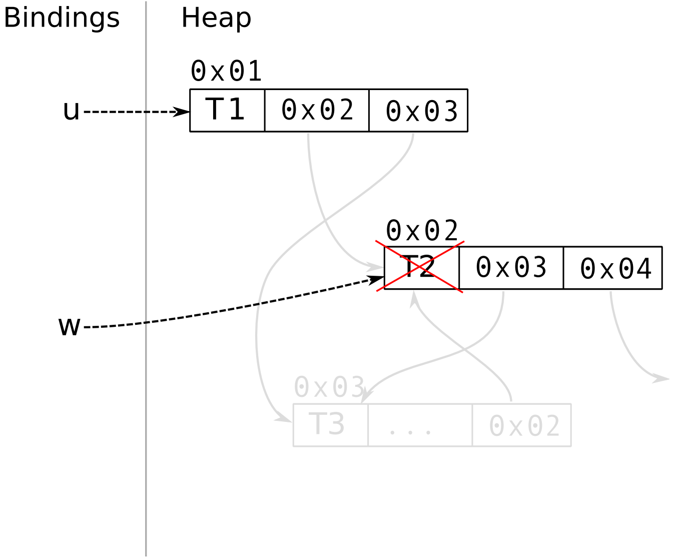

Optimization by Online Partial Evaluation

- Trace is optimized using online partial evaluation
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- static heap contains objects that are allocated within the trace
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- Trace is optimized using online partial evaluation
- part of the runtime heap is modelled in the static heap
- static heap contains objects that are allocated within the trace
- (as opposed to before the trace is executed)
- operations acting on the static heap can be executed
- follows operational semantics
- all others need to be residualized
- all fairly straightforward

Optimizing New

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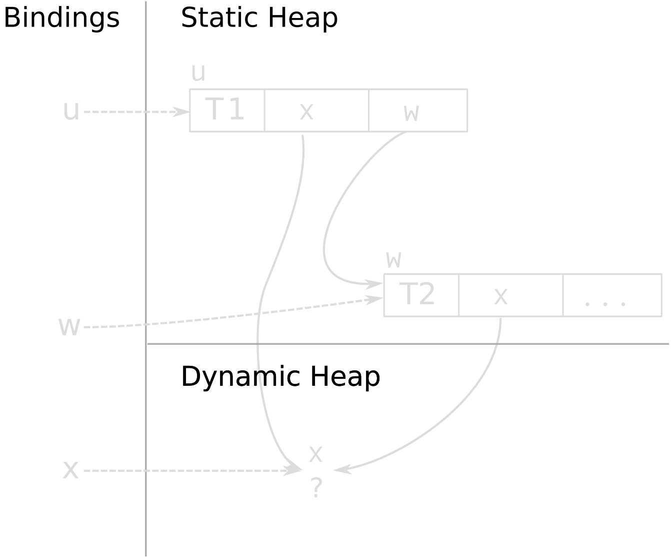

Bindings

Static Heap

Dynamic Heap

Optimizing New

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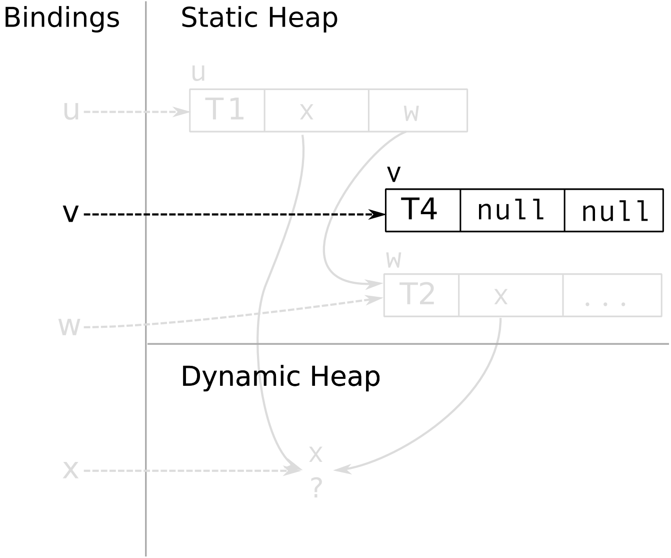


Bindings

Static Heap

u

T1	x	w

v

T4	null	null

w

T2	x	. . .

u

v

w

Dynamic Heap

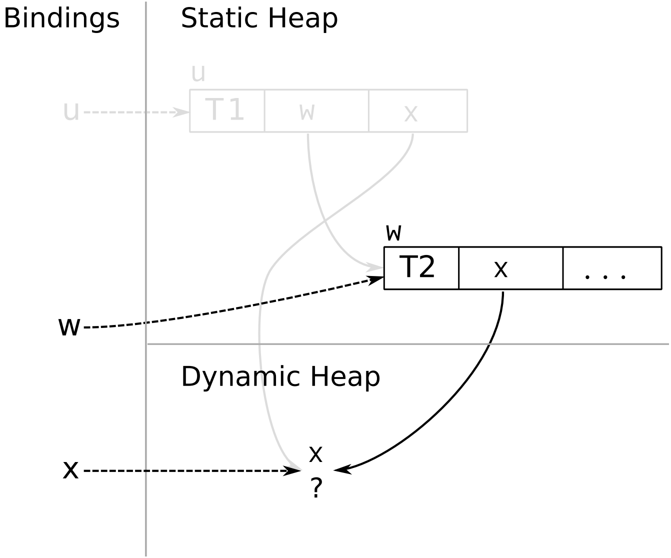
x

x

?

Optimizing Get

v=get(w, L)



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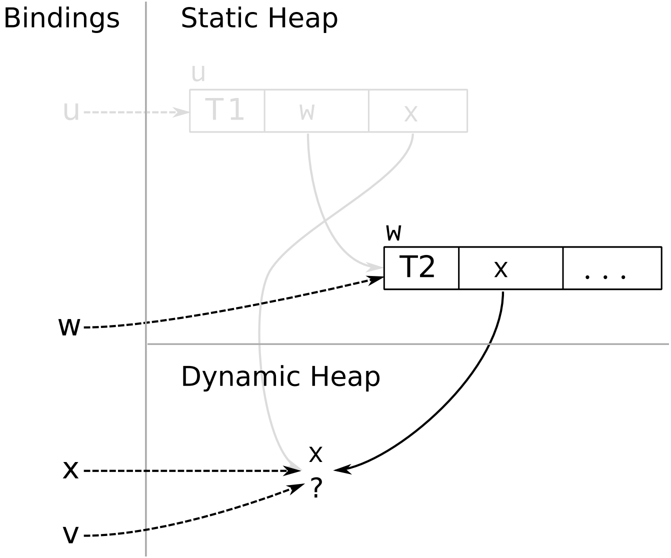
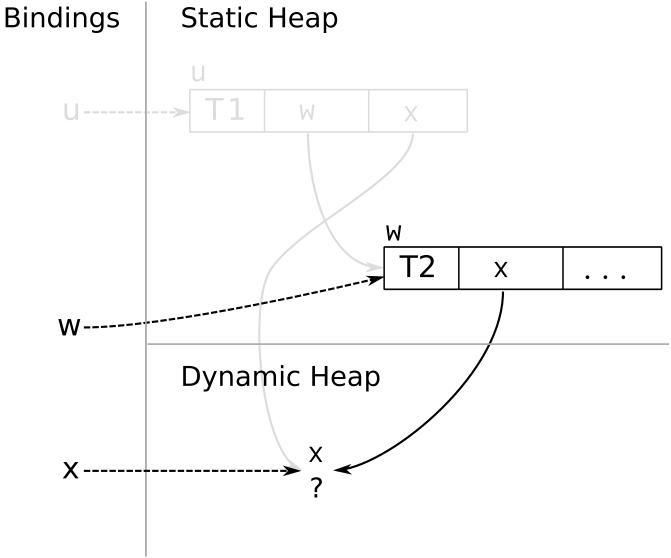


Optimizing Get

v=get(x, R)



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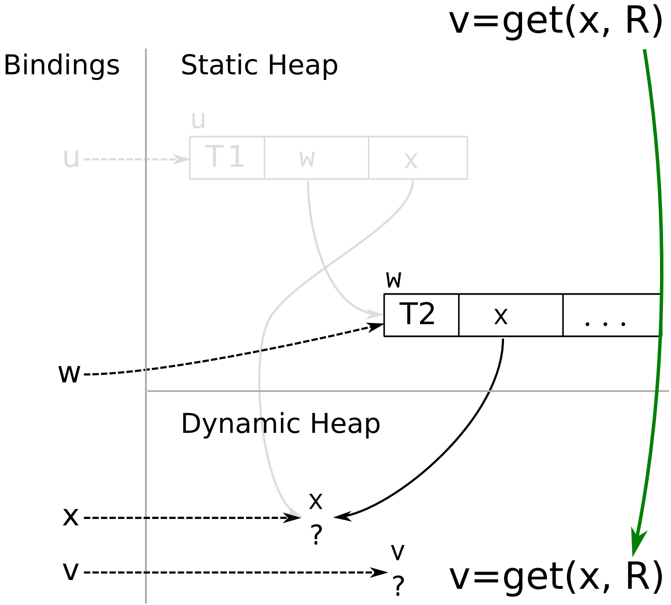

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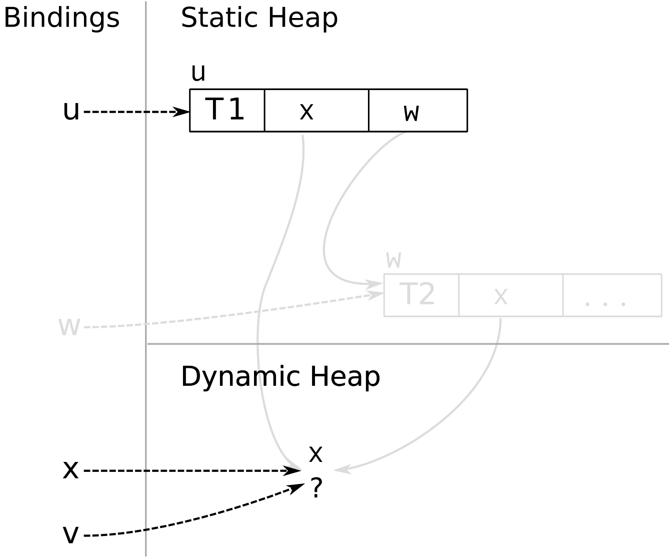
guard(u, T1)



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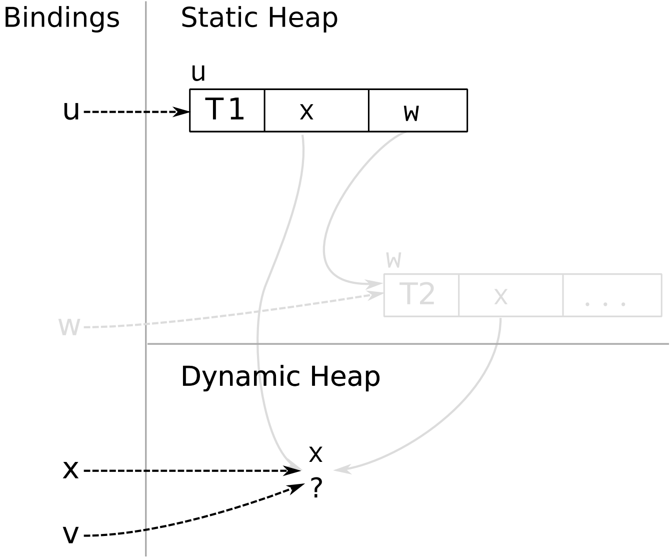

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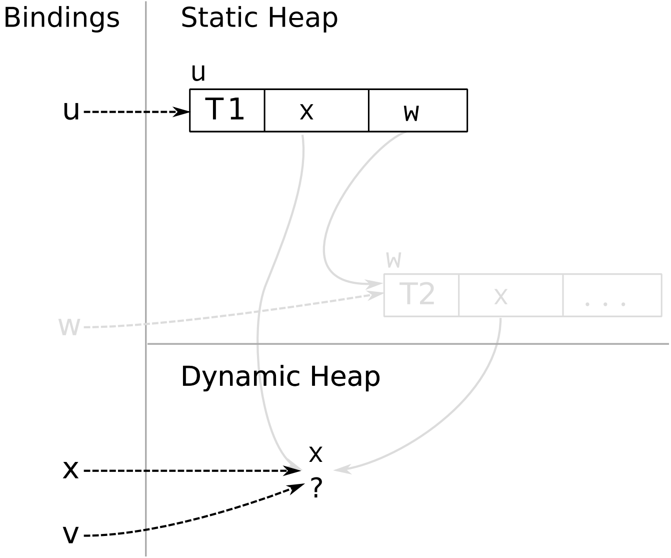

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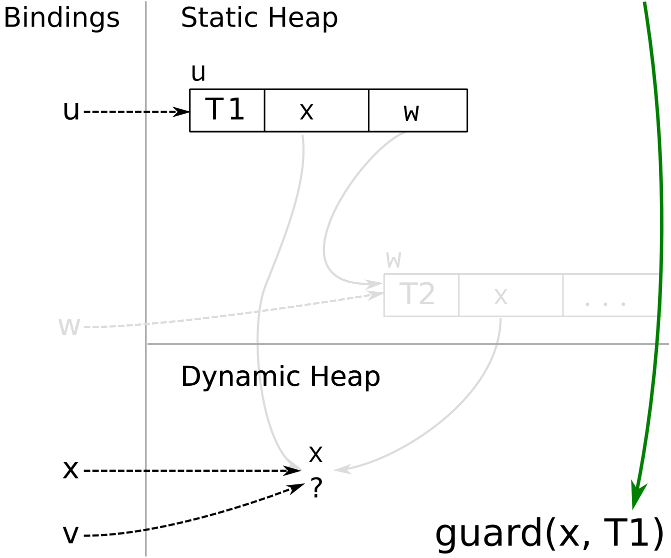
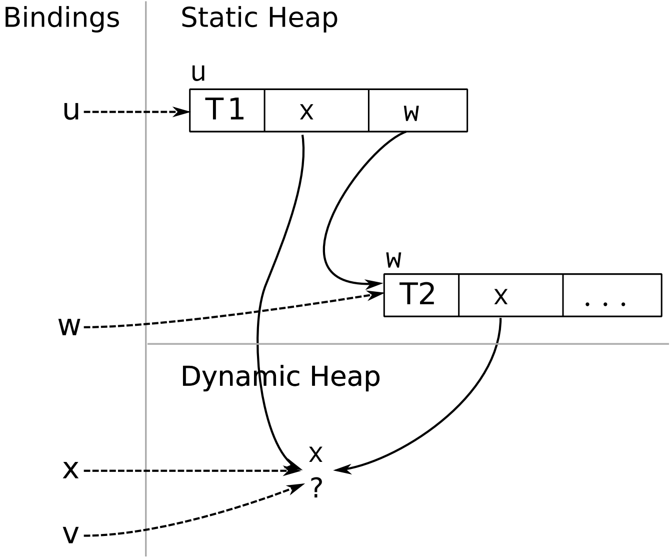


guard(x, T1)

Optimizing Set

set(u,R,v)



Bindings

Static Heap

u

T1	x	w

w

T2	x	. . .

Dynamic Heap

x

?

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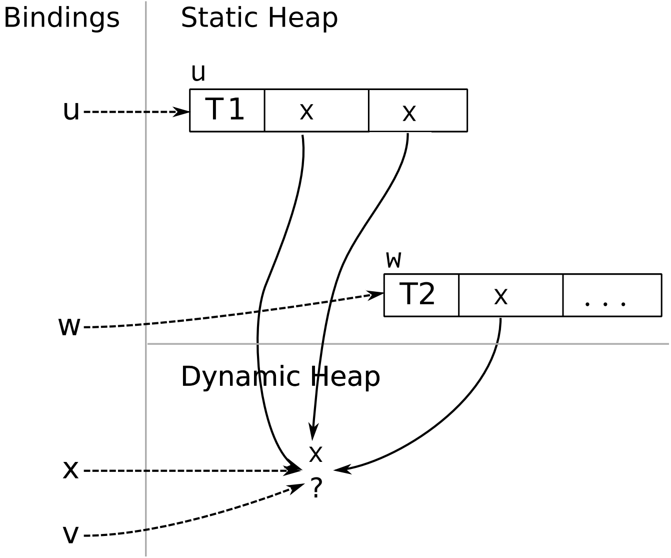

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- lose track of the static object because of possibility of aliasing
- need to lift the static object
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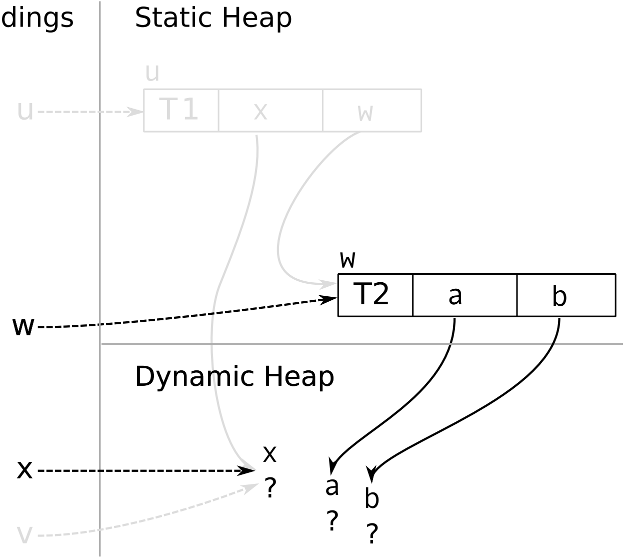
- lose track of the static object because of possibility of aliasing
- need to lift the static object
- lifting produces operations that recreate the static object
- needs to be careful due to recursive structures

Optimizing Set

set(x,R,w)



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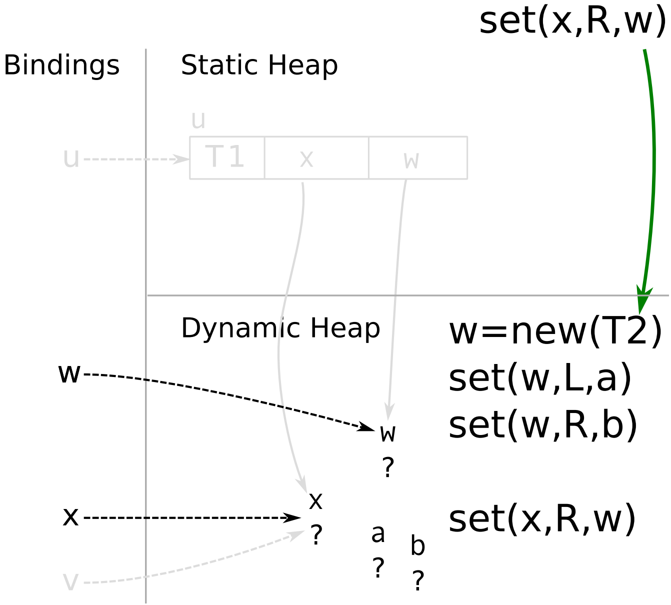

w=new(T2)
set(w,L,a)
set(w,R,b)

set(x,R,w)

Properties of the Optimization

- output trace is never longer than input trace
- runtime linear in the length of the trace

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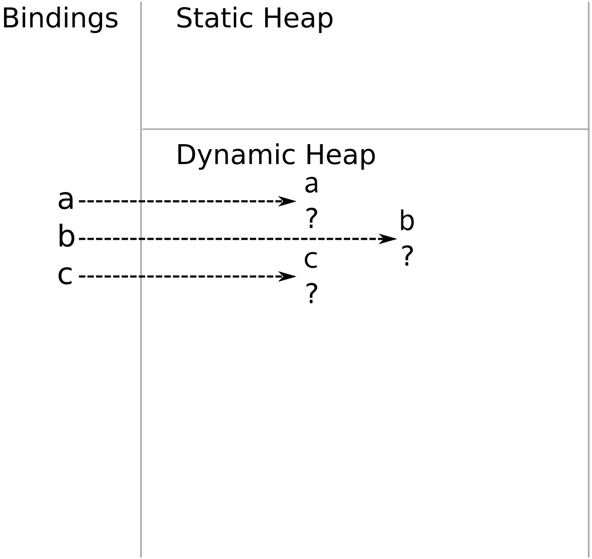
Implementation

- about 400 lines of code
- some added complexity over presentation
- objects with arbitrary numbers of fields
- array support

Optimizing the Example Trace



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guard(x, Int)
guard(c, Int)
i4 = get(x, intval)
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return(y)
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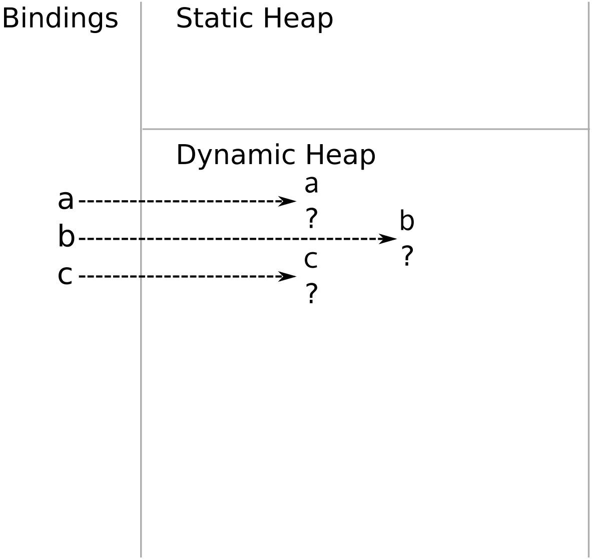

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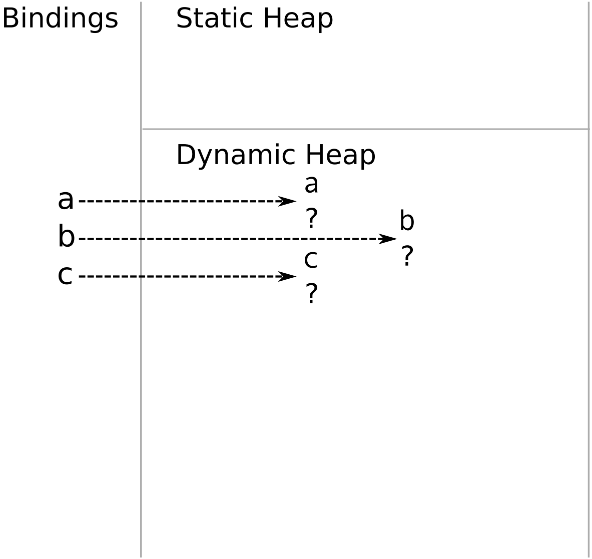

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Dynamic Heap

a

b

c

a

?

b

?

c

?

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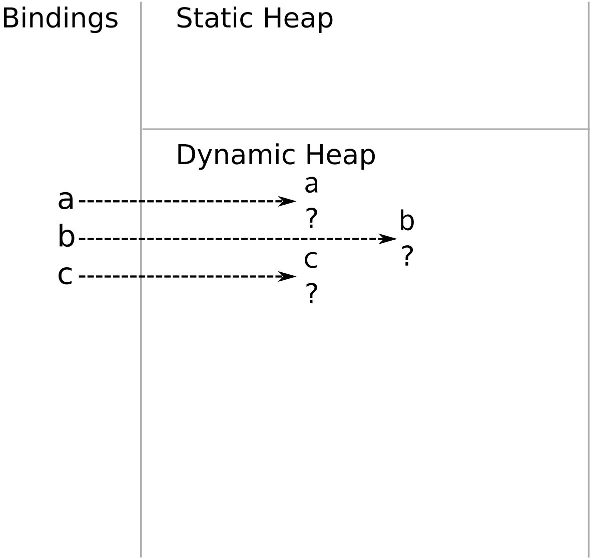

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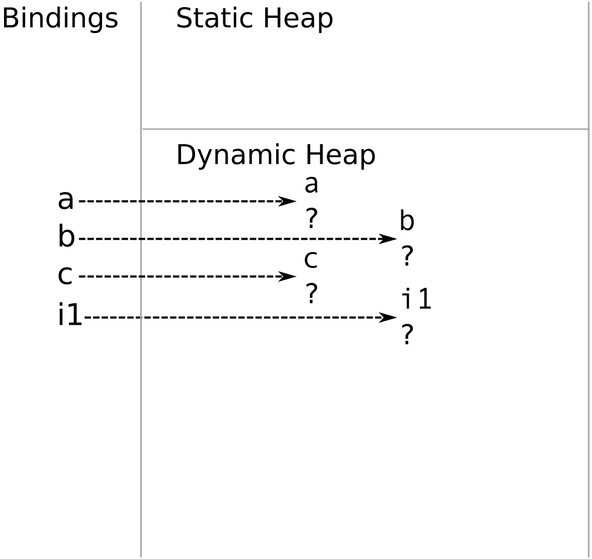

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a

b

c

i1

a
?

b
?

c
?

i 1
?

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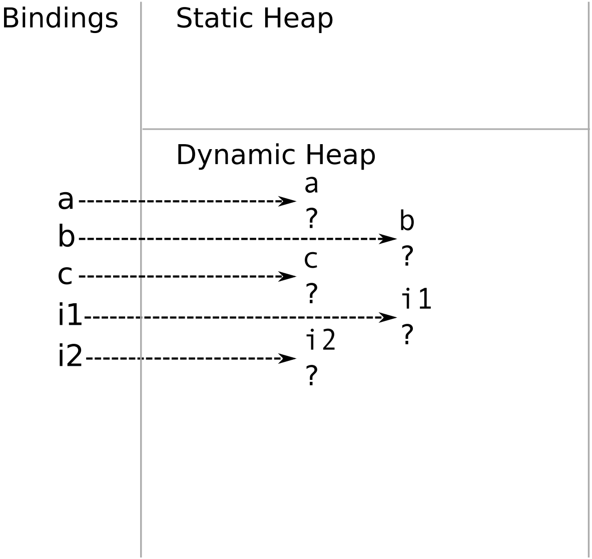

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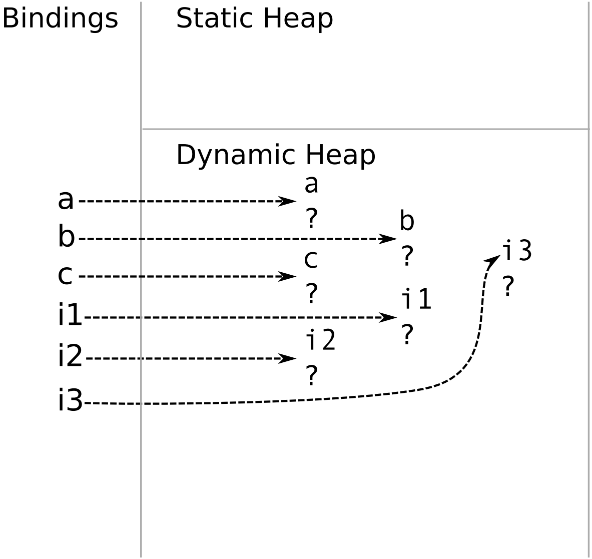

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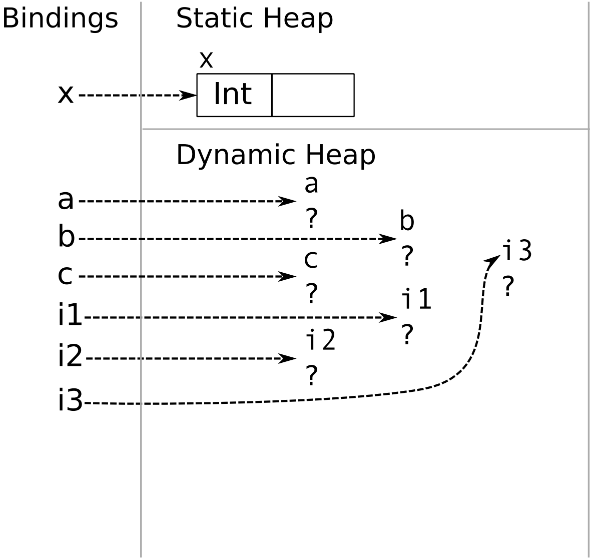

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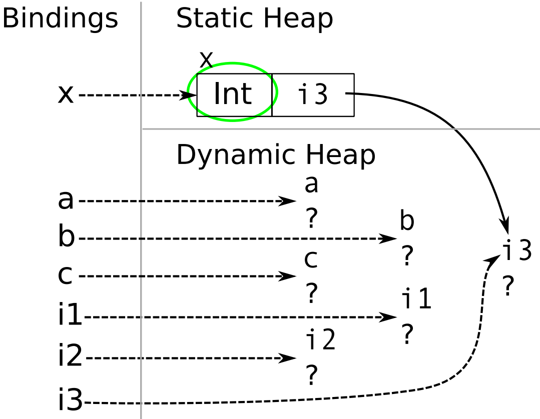
Optimizing the Example Trace



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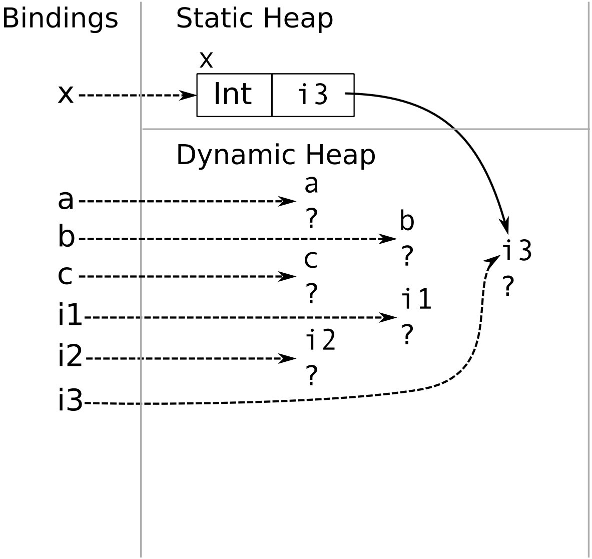

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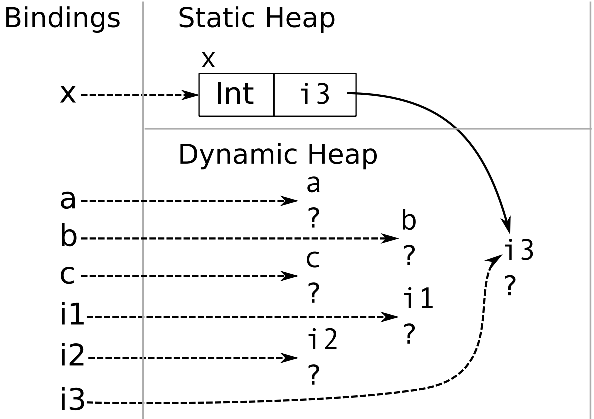

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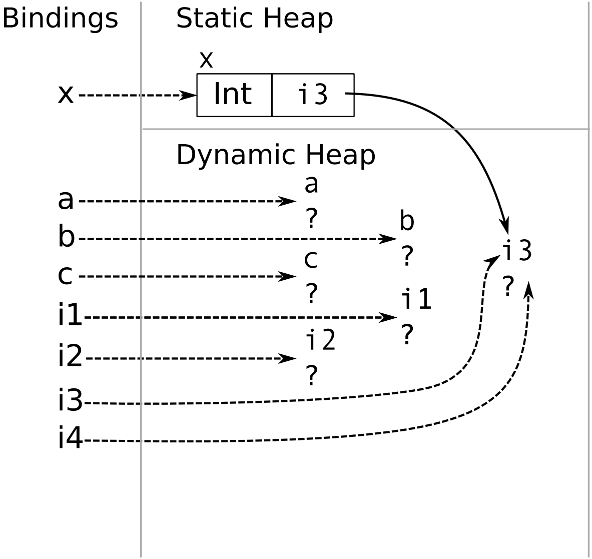

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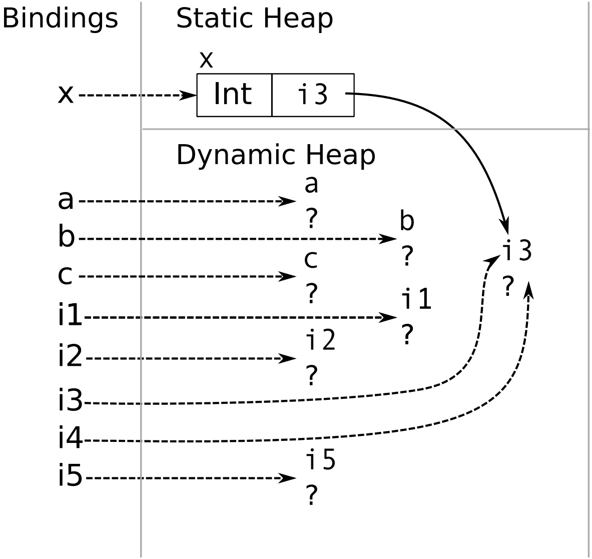

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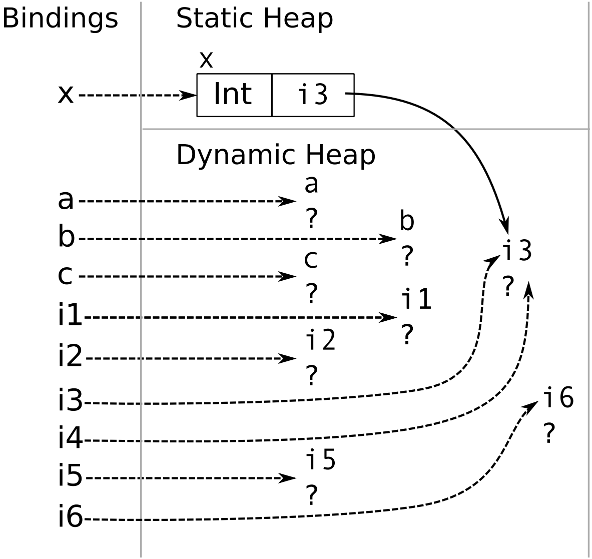

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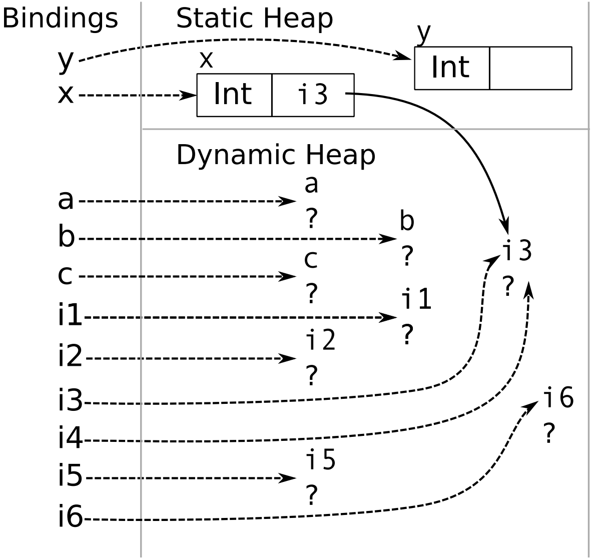

Bindings

Static Heap

y

x

x

Int

i3

y

Int

Dynamic Heap

a

b

c

i1

i2

i3

i4

i5

i6

a
?

b
?

c
?

i1
?

i2
?

i3
?

i5
?

i6
?

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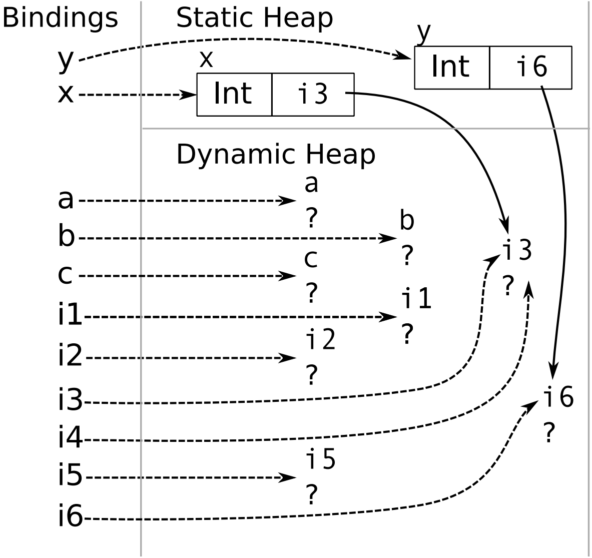

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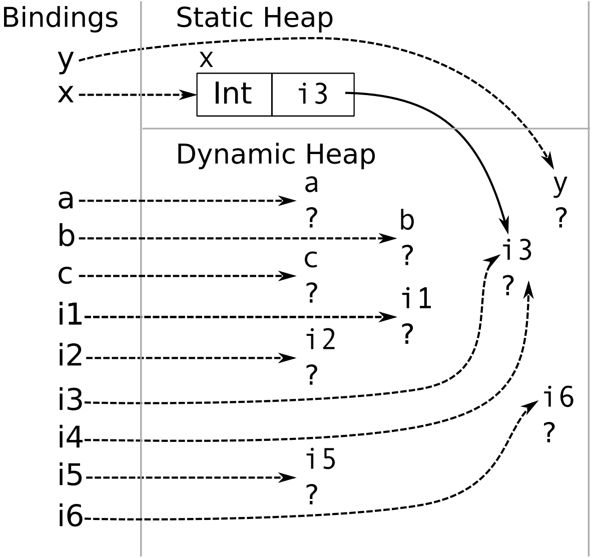

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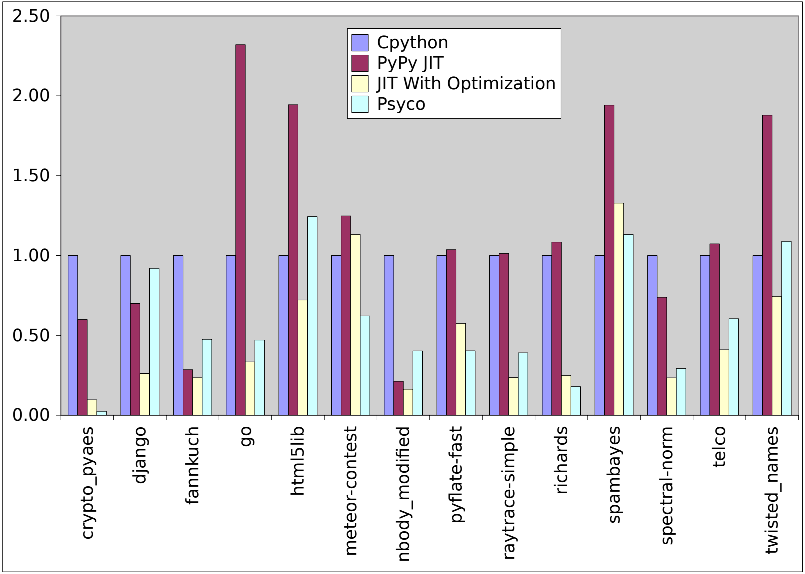
  - 93% of all `guard` operations
- Timings improve by a factor between 1.1 and 6.95
- outperforming standard Python on all benchmarks but two

Benchmark


2.50
2.00
1.50
1.00
0.50
0.00
Cpython
PyPy JIT
JIT With Optimization
Psyco
crypto_pyaes
django
fannkuch
go
html5lib
meteor-contest
nbody_modified
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richards
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Conclusion

- We propose a very simple partial-evaluation-based optimization for tracing JITs of dynamic languages that:
  - can remove a lot of allocations and type checks in practical programs.
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  - is efficient and effective.
  - has no control issues because all control decisions are made by the tracing JIT.
- We claim that this is a general strategy to get rid of control problems by simply observing the runtime behaviour of the program.

Backup Slides

What About Correctness?

- We haven't proven correctness yet
- should not be too hard
- lifting needs to be carefully handled

Comparison to Escape Analysis

- Effect very similar to escape analysis
- Escape analysis needs a complex upfront analysis
- our optimization automatically has a lot of context, due to the inlining tracing does
- our optimization can optimize operations on objects even if they escape later

Comparison to ”Dynamic Typing”/Boxing Analysis

- those optimizations work ahead of time
- don’t work for many dynamic languages, where the source simply does not contain enough information

Python Example:

```
def sum(container, initial):
    result = initial
    for element in container:
        result = result + element
    return result
```