Efficient Runtime Tracking of Allocation Sites in Java

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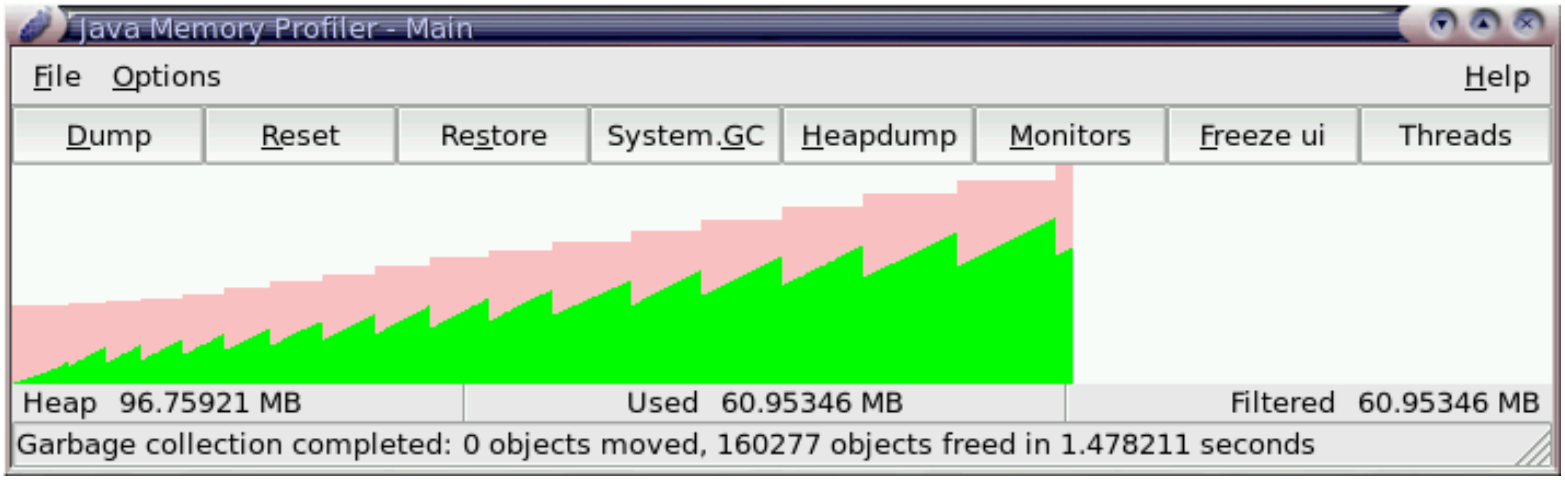
Why Do You Need Allocation Site Information?

How to fix a memory leak after two weeks of execution?

```
> java com.example.Server
started
......running for one week
......running for two weeks
server crashed due to java.lang.OutOfMemoryError!
>
```



Allocation Site Tracker Helps!

Tracker tells you where each object was allocated.

```
Bytes         Class          Allocation site
                             (Method name and bytecode index)
900,278,800   String         com.example.Property.putProperty()#191
 98,148,020   LinkedList     com.example.DataTable.putInteger()#187
 20,352,384   String         com.example.Property.prepare()#35
 ……           ……             ……
```

```
void putProperty(Element elem) {
  ……
  String attribute = new String(elem.getString());
  ……
}
```

Allocation site is a good starting point for fixing the leak.

Also, optimizations in JVM can benefit from the tracker.

Tracker Should Be Always Enabled.

- For fixing memory leaks …

```
> java com.example.Server
started
......running for one week
......running for two weeks
server crashed due to java.lang.OutOfMemoryError!
> java -enableTracker com.example.Server
started
......running for one week
......running for two weeks
```

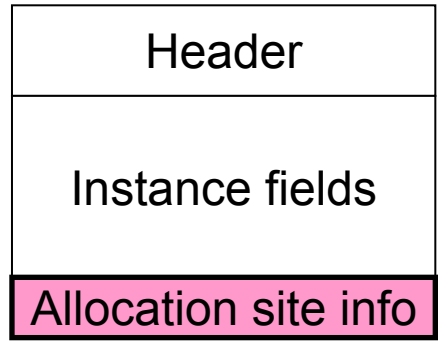
☹ should have always enabled the tracker.

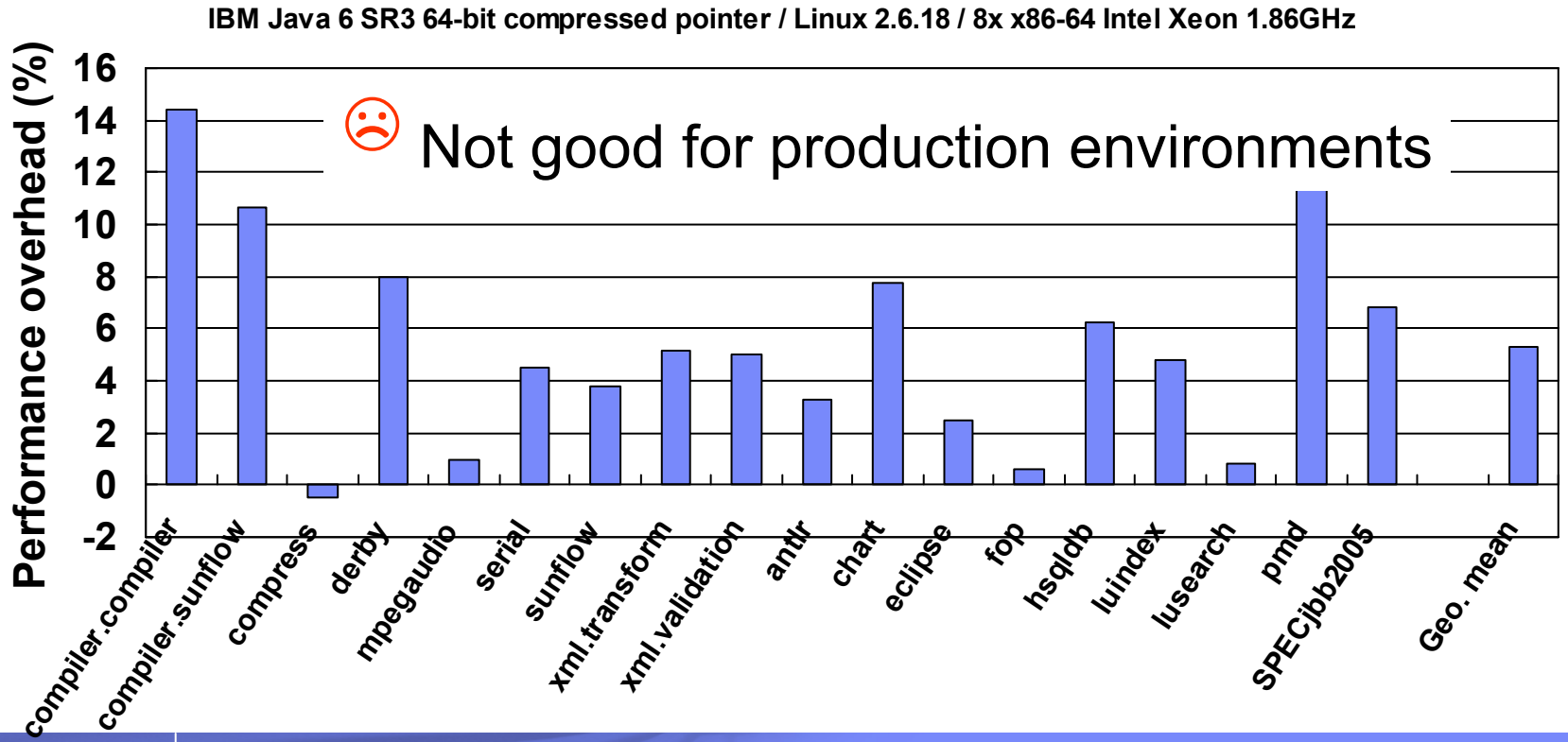
- And also for JVM optimizations ….

Challenge: Performance Overhead

- Adding allocation site information to each object hits performance [Hauswirth et al., 2004].
  - Reducing effective CPU cache size, increasing GC frequency and overhead, etc.

Java object layout

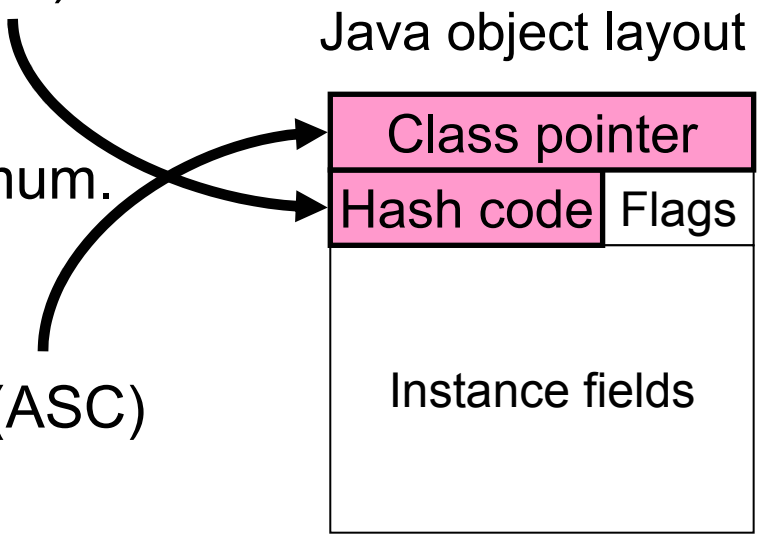




Minimal-Overhead Allocation Site Trackers

Never increase per-object space.

- Allocation-Site-as-a-Hash-code (ASH) Tracker
  - Performance overhead: ~0% on average, 1.4% at maximum.
  - Some JVMs do not always have a hash code field.
- Allocation-Site-via-a-Class-pointer (ASC) Tracker
  - Performance overhead: 1% on average, 2% at maximum.
  - Almost all JVMs have a class pointer field.

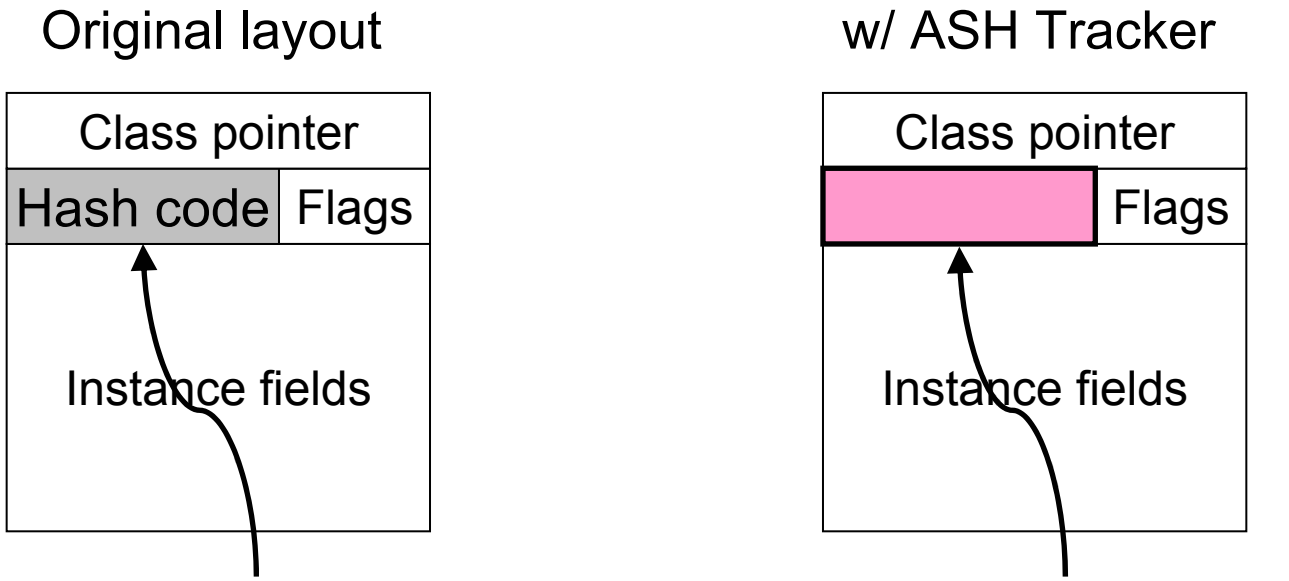


Outline

- Introduction
- ASH Tracker
- ASC Tracker
- Experiments
- Applications of ASH/ASC Trackers
- Conclusions

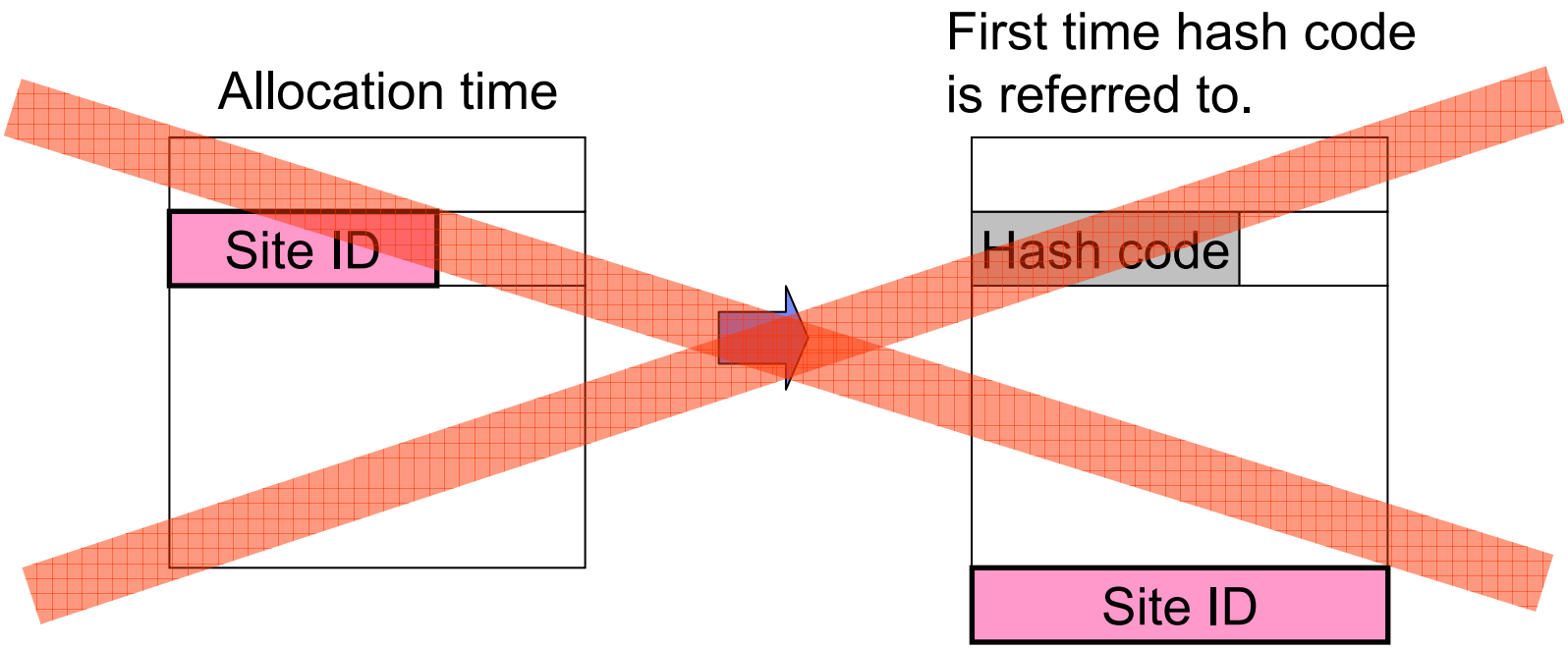
Allocation-Site-as-a-Hash-code (ASH) Tracker

- Embed an allocation-site ID into a hash code field.
  - Embed at allocation time.
- ID is a unique integer of the site.
  - Assigned by an interpreter or a JIT compiler.



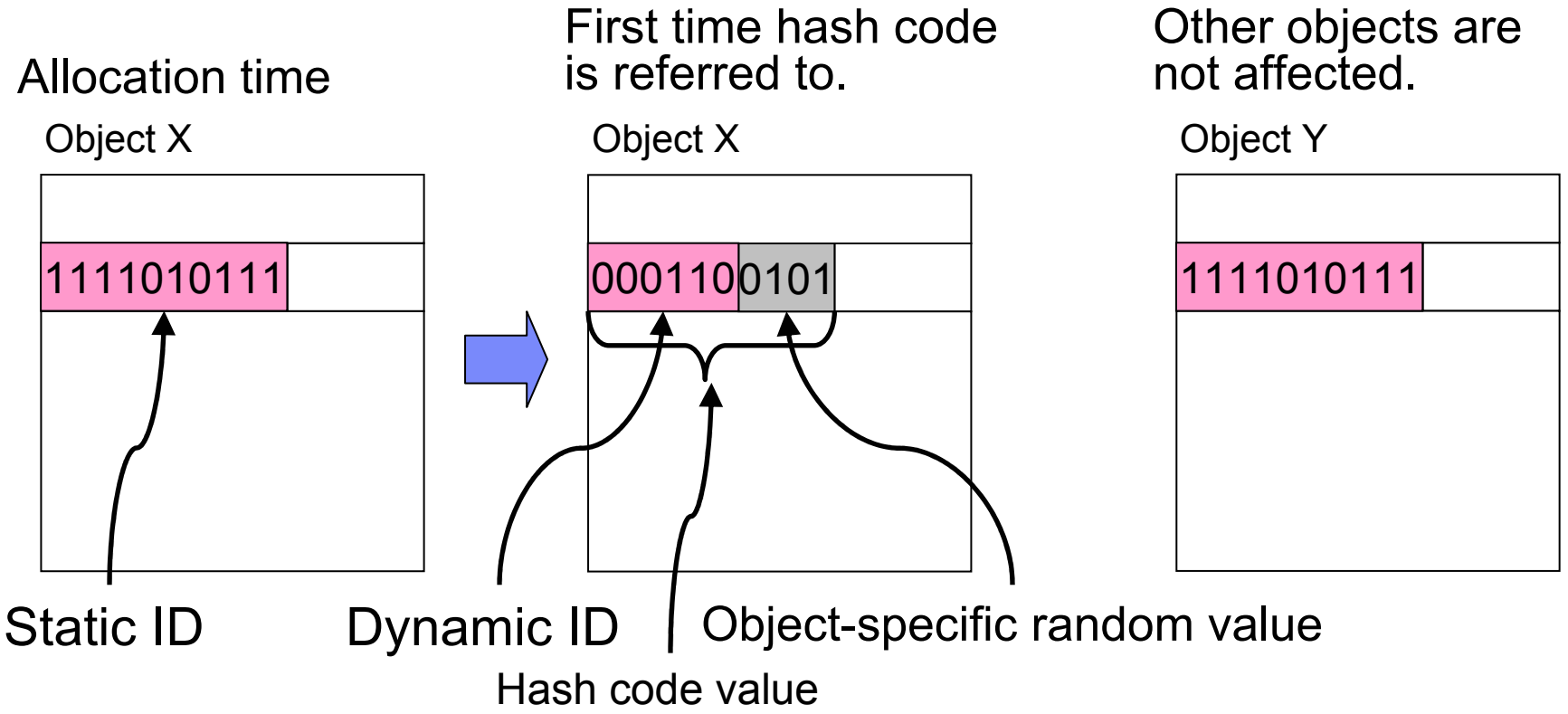
How to Deal with Hash Code Collisions?

- Hash code values should be as distinct as possible from all others [Java API Spec].
  - Collisions slow down hash-table access, for example.
- How about appending a site ID field when hash code is first referred to?
  - ☹ Some programs often refer to hash code.



Collision Avoidance without Increasing Space

- Our solution:
  - Embed a shorter *dynamic* ID and a random value.
- Hash code value = dynamic ID + random value
  - Random value helps avoid collisions.

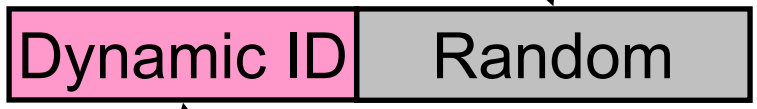


How to Deal with Hash Code Collisions? (2nd Round)

- All objects allocated at the same site have the same high-order bits in their hash code values.

Need a long random-value field to avoid collisions.

Hash code field:



Need a long ID field to track allocation sites accurately.

Variable-Length Dynamic ID

- Shorter IDs for hot allocation sites.
  - Allocate many objects.
    → Need a long random value.
  - Not so many hot allocation sites in a program.
    → Short site IDs suffice.
- Longer IDs for cold allocation sites.
  - Allocate few objects.
    → Short random values suffice.
  - Many cold allocations sites in a program.
    → Need long site IDs.

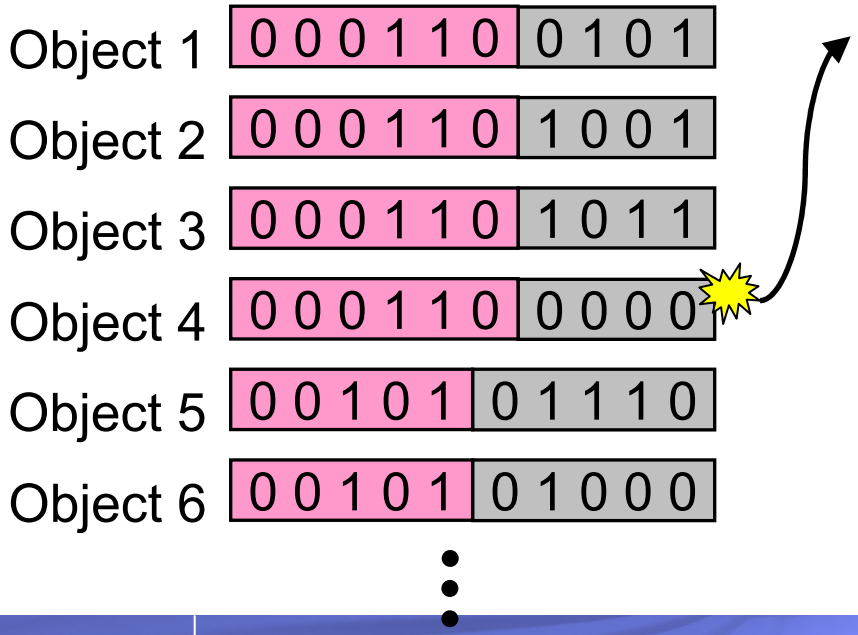
```
for (i = 0;
     i < BIG_NUMBER;
     i++) {
  obj = new Object();
  use(obj.hashCode());
}
```


```
if (error1) {
  obj = new Object();
  use(obj.hashCode());
}
...
if (error2) {
  obj = new Object();
  use(obj.hashCode());
}
```

Dynamic Shrinking of ID Field

- It is not known in advance …
  - How many objects will be allocated at each site; or
  - How many of their hash code values will be referred to.
- Our solution: Make the IDs of a site shorter and shorter …
  - As more and more hash code values are referred to.

Hash code of objects allocated at putProperty()#191



1) Assign a long dynamic ID at first.

2) Occasionally, a random value becomes all zero.

3) Assign a new shorter ID. Maintain a mapping table.

Dynamic ID	Allocation site
000110	→ putProperty()#191
00101	→ putProperty()#191
.....	

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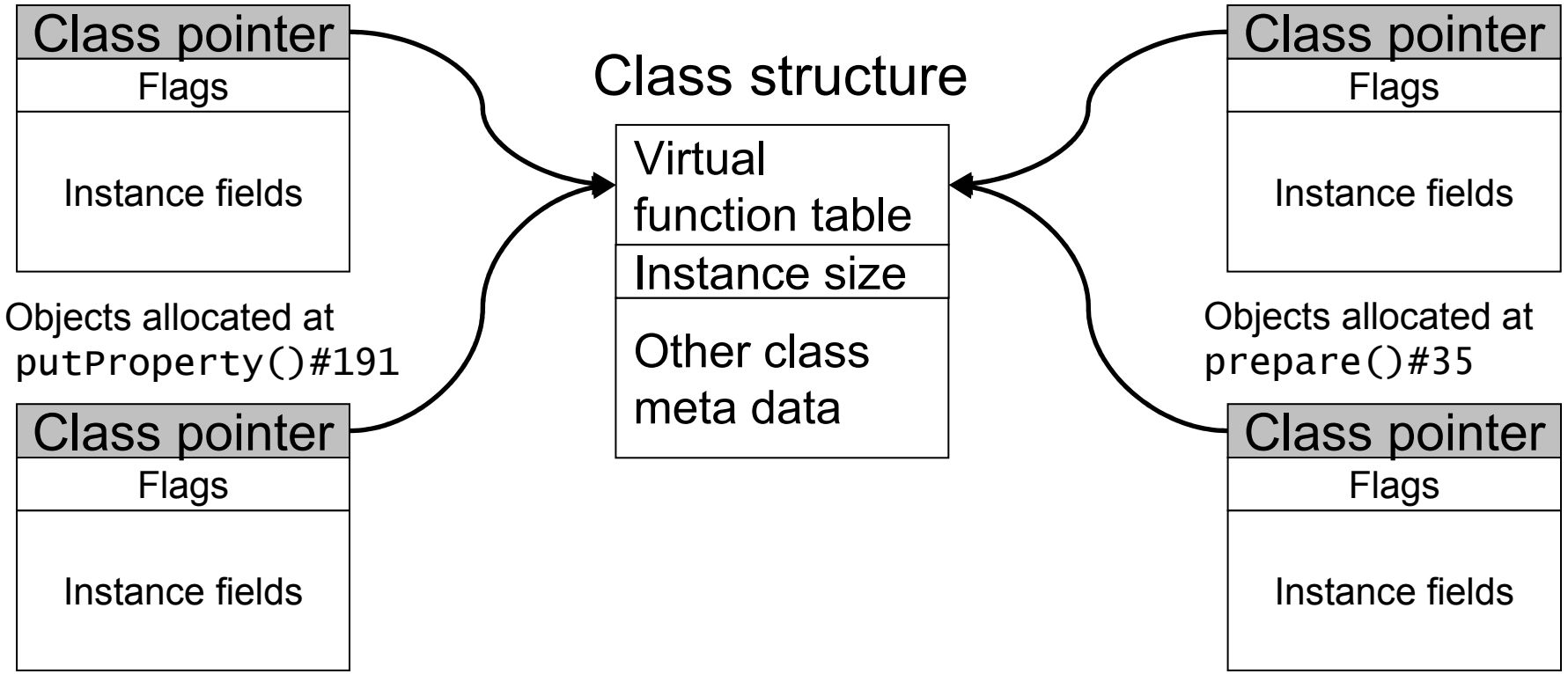
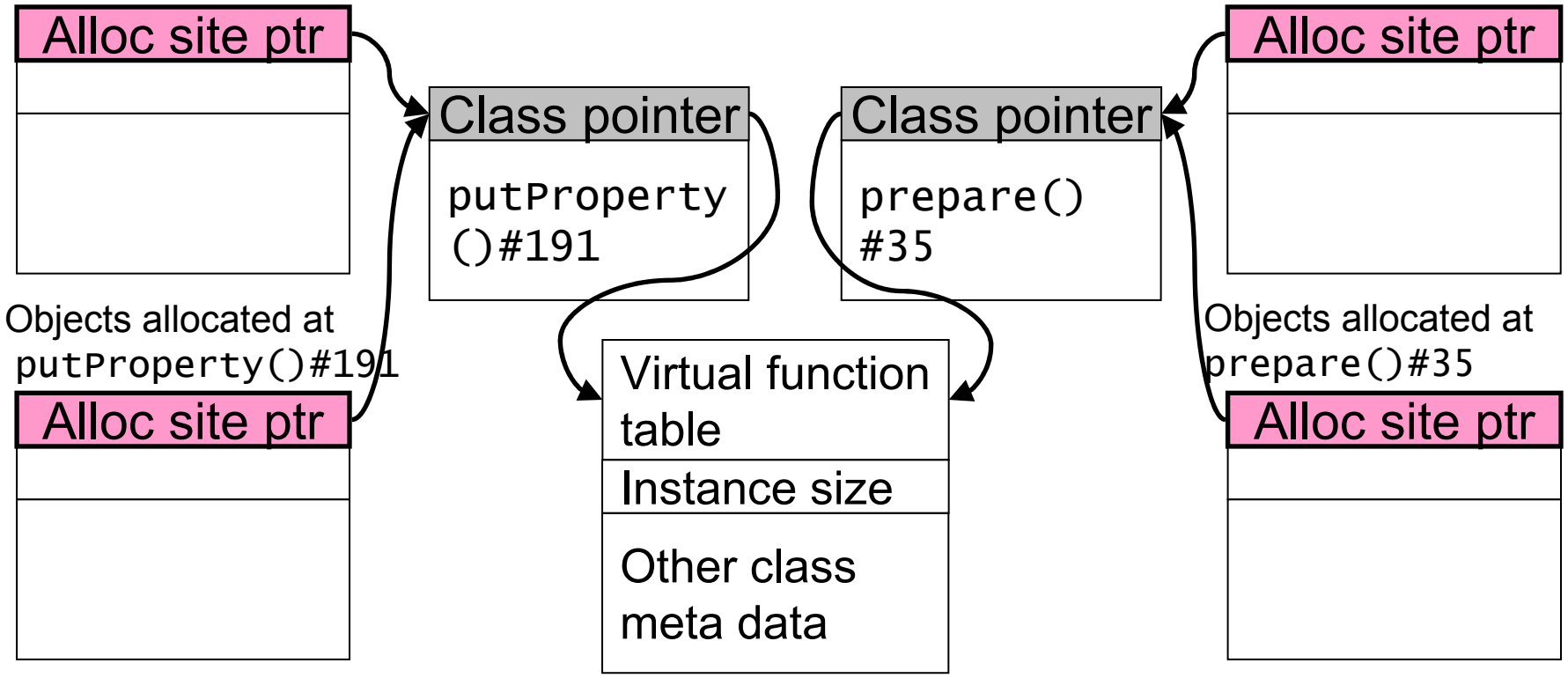
What If There Is No Hash Code Field?

- Some JVMs do not always have a hash code field.
- Almost all JVMs have a class pointer field.
  - To access class meta data.



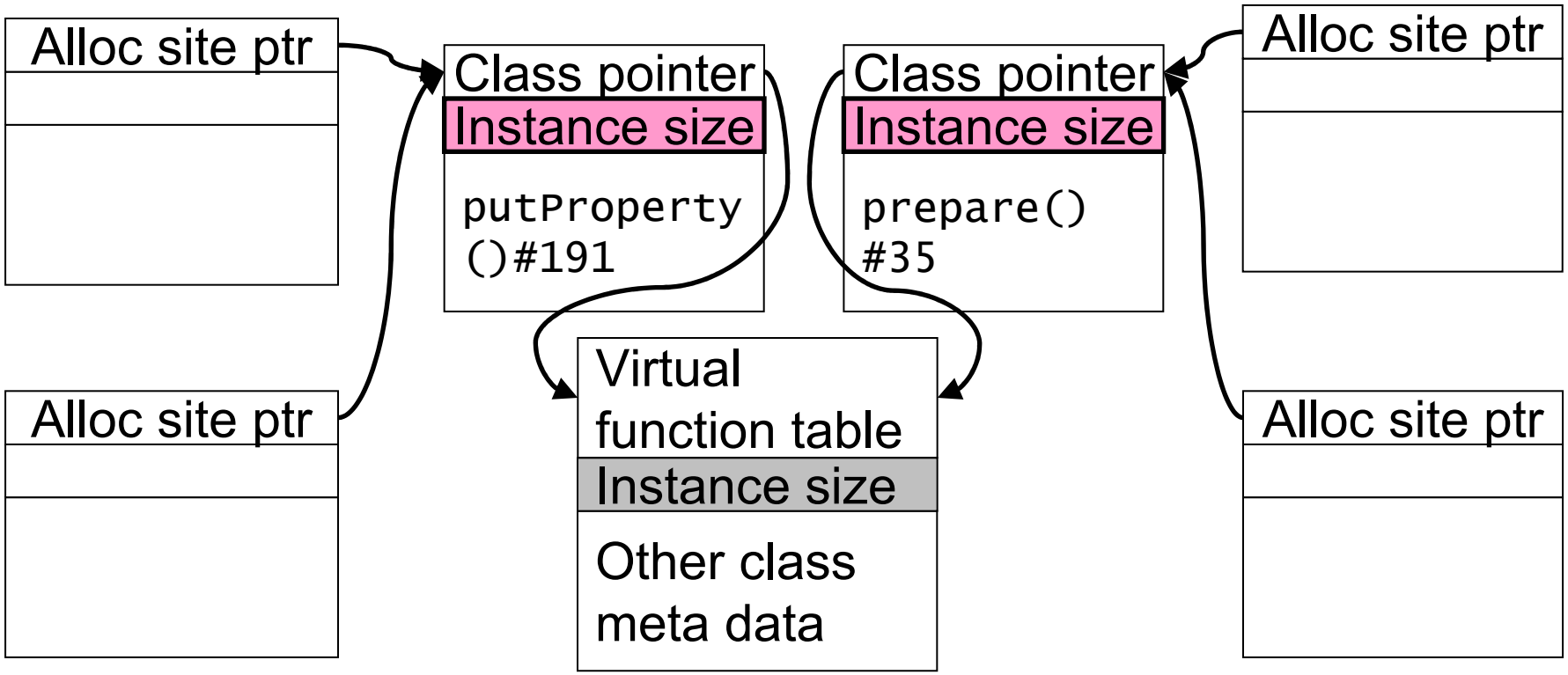
Allocation-Site-via-a-Class-pointer (ASC) Tracker

- Replace the class pointer with a pointer to its allocation site structure.
  - This is possible because each allocation site always allocates objects of the same class.



Mitigating Indirection Overhead (1)

- Duplicate frequently-accessed constant class fields.
- Need to choose carefully which fields to duplicate.
  - Not to increase cache misses.
  - Not to increase space overhead.

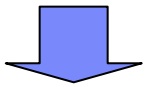


Mitigating Indirection Overhead (2)

Profiling-based devirtualization by a JIT compiler.

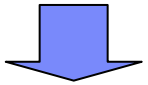
```
if (object->class_ptr != HOT_CLASS)
  goto SlowPath;
/* Inlined method, etc. */
```

Another load needed by ASC Tracker.



```
if (object->alloc_site->class_ptr != HOT_CLASS)
  goto SlowPath;
/* Inlined method, etc. */
```

Emit an allocation-site equality check where possible.



```
if (object->alloc_site != HOT_ALLOCATION_SITE)
  goto SlowPath;
/* Inlined method, etc. */
```

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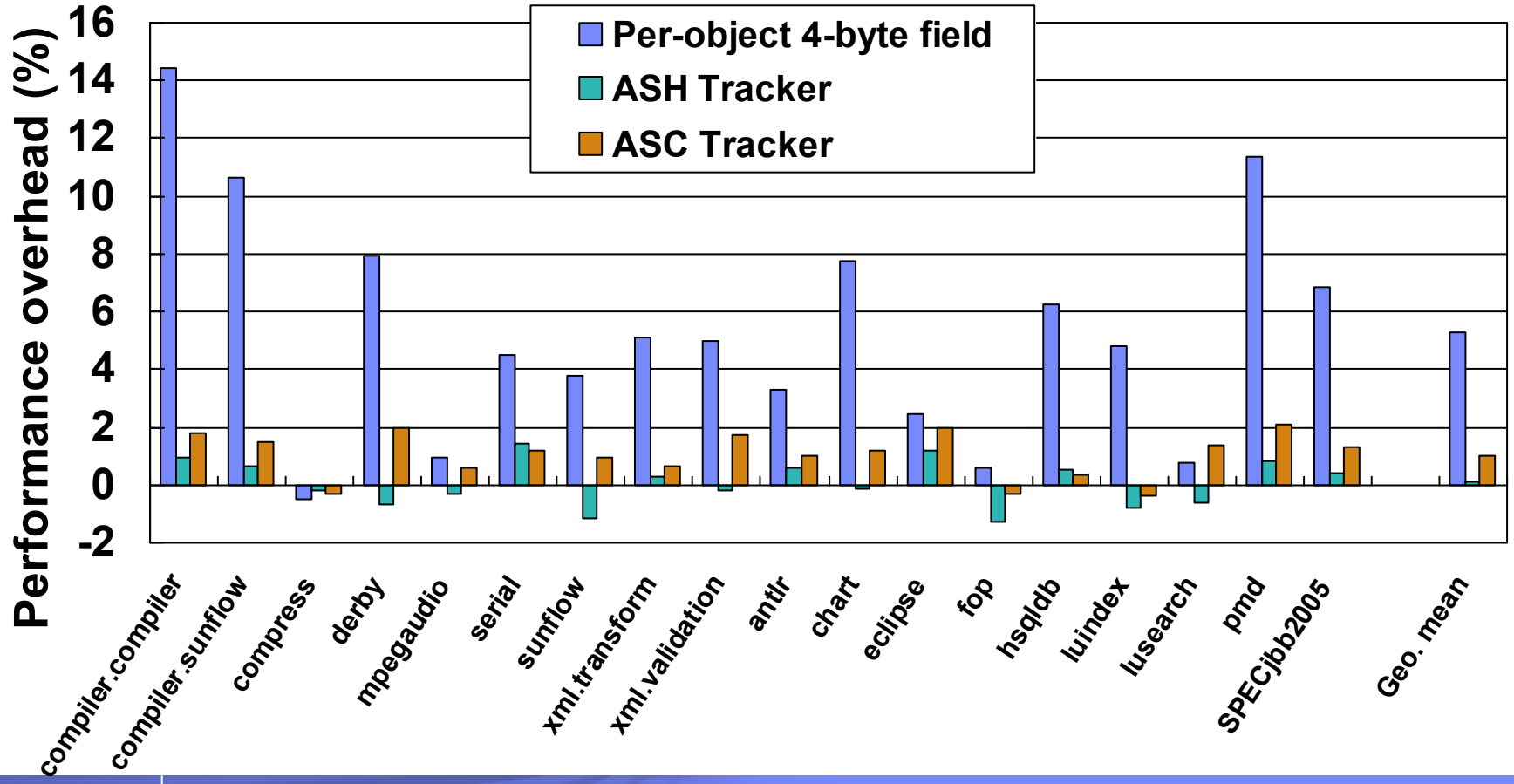
Evaluation

- Environment
  - 64-bit IBM J9/TR JVM 1.6.0 SR3
    - 3-word header (1 word = 32 bits)
    - Generational GC (copying young + mark-and-sweep old GC)
  - 4x minimum Java heap
  - 8-core 1.8GHz Intel Xeon
  - Linux 2.6.18
- Benchmarks
  - SPECjvm2008, DaCapo, and SPECjbb2005
- ASH Tracker
  - Uses a 15-bit hash code field.
  - Shrinks a dynamic ID field from 11 bits to 2 bits.
- ASC Tracker
  - Duplicates an instance-size field and an array-element-class field.

Performance Overhead

- ASH Tracker: on average ~0% and at most 1.4% overhead.
  - Up to 1.73x hash code collisions compared with the baseline.
- ASC Tracker: on average 1.0% and at most 2.0% overhead.



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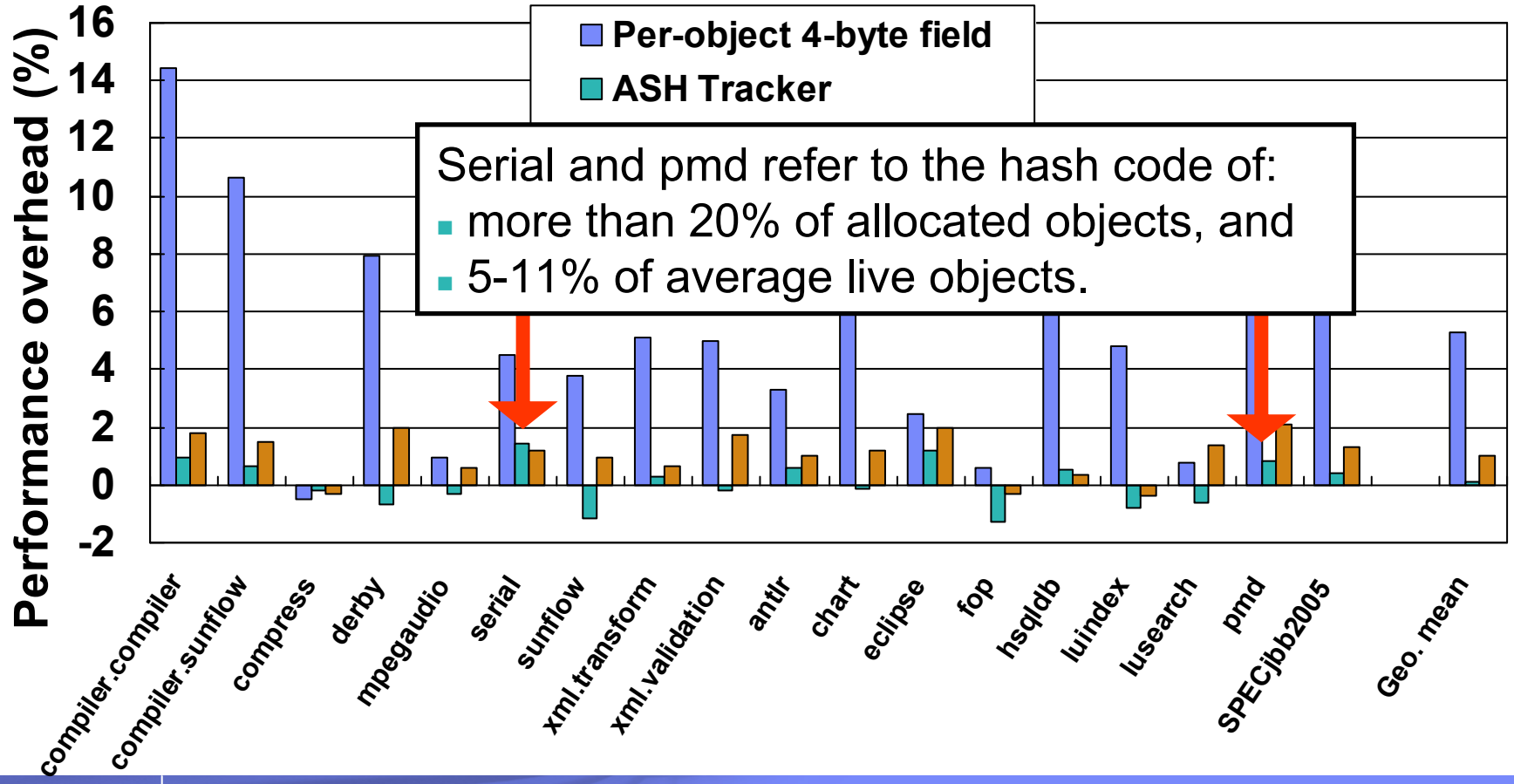

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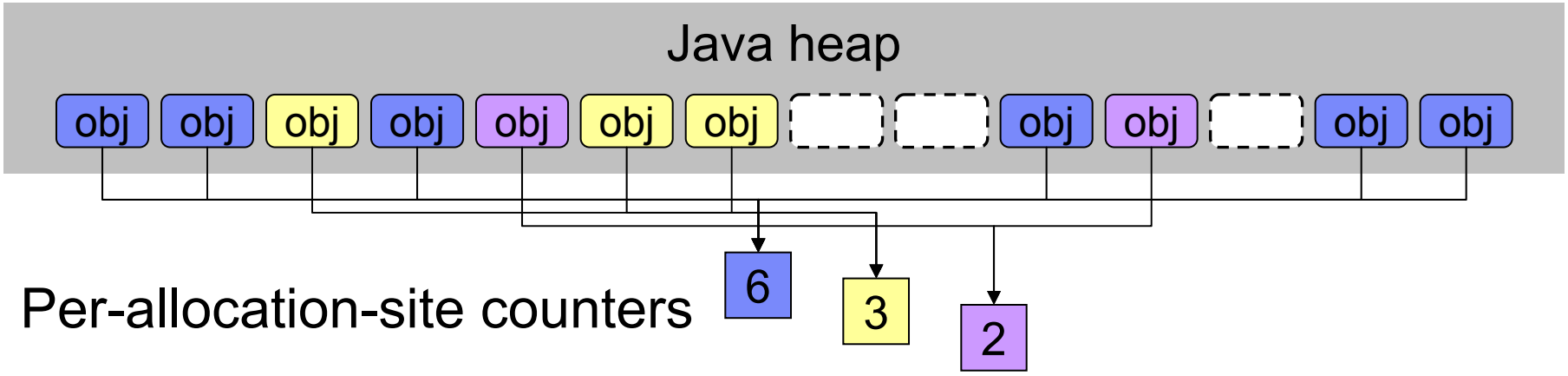
Minimal-Overhead Memory Leak Detector

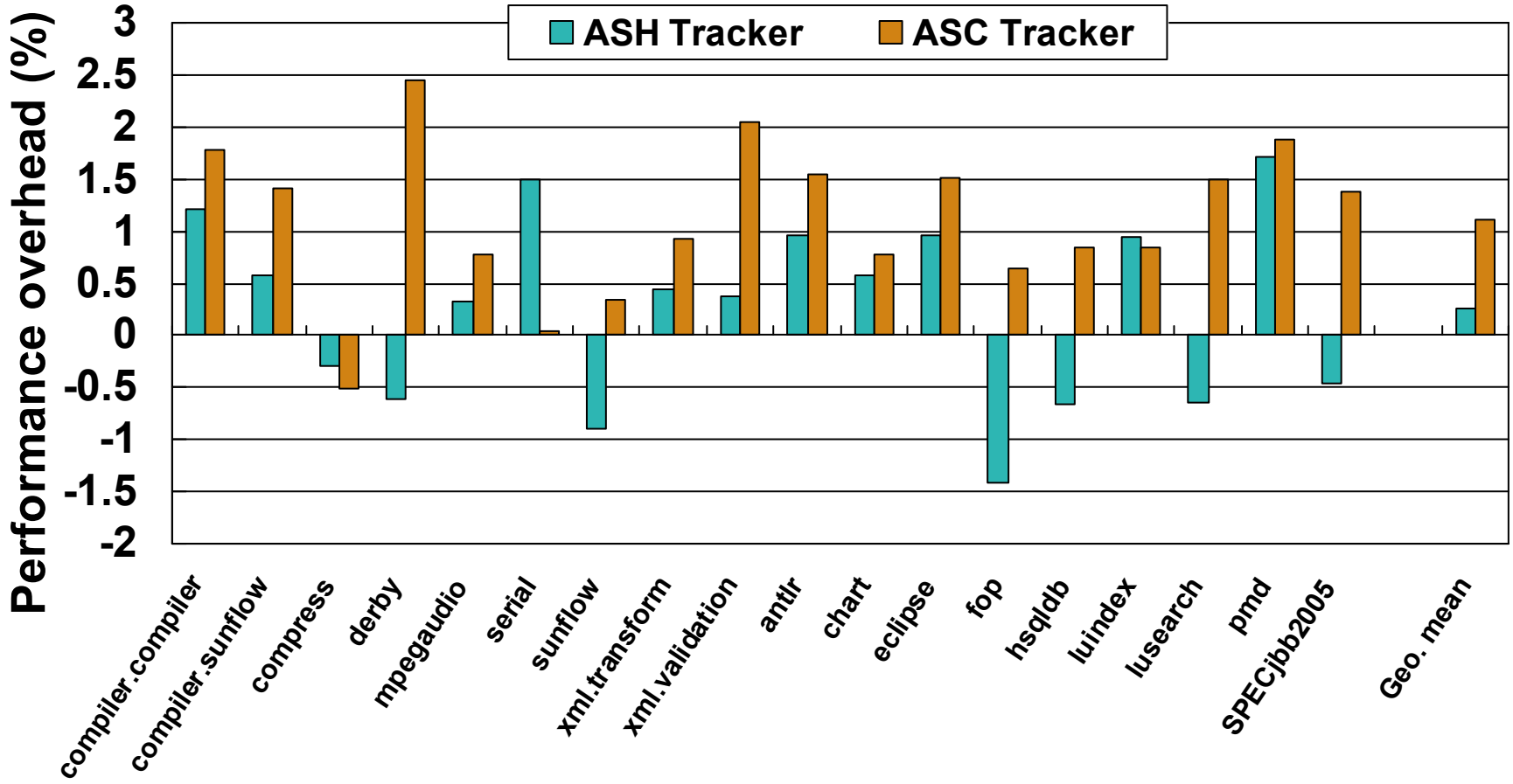
- Scan the entire Java heap at each global GC time.
  - Count the numbers of live objects for each allocation site.
  - Save the numbers in per-allocation-site histories.
- (Inform users of possible memory leaks.)




```
#live objects history          Allocation site
 6, 5, 4, ……                  Property.putProperty()#191
 3, 3, 3, ……                  DataTable.putInteger()#187
 2, 1, 1, ……                  Property.prepare()#35
 ……                           ……
```

Performance Overhead of the Leak Detector

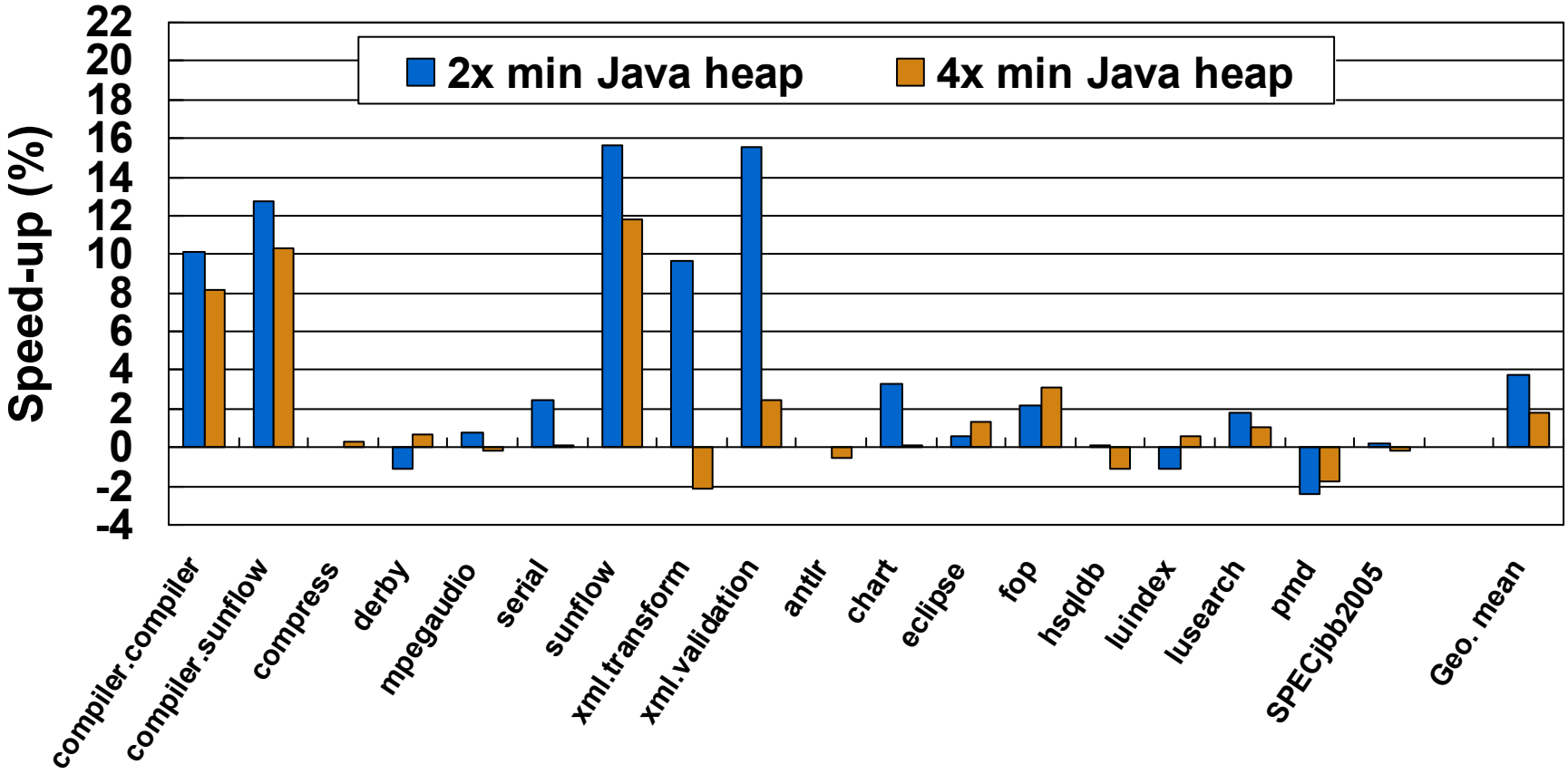
- ASH Tracker: on average 0.3% and at most 1.7% overhead
- ASC Tracker: on average 1.1% and at most 2.4% overhead



Allocation-Site-Based Object Pretenuring for Generational GC

Refer to our paper for more details.

- 4x min Java heap: at maximum 11% speed-up
- 2x min Java heap: at maximum 15% speed-up



Related Work

- Bit-Encoding Leak Location (Bell) [Bond, et al., ASPLOS 2006]
  - Probabilistic allocation site tracker
  - Requires a sufficient number of samples.
  - Cannot identify the allocation site of each object.
    → Not suitable for JVM optimizations.
- Techniques for object header compression [Bacon, et al., ECOOP 2002]
  - Remove the hash code field.
    → Use ASC Tracker.
  - Steal several bits of the class pointer.
    → Steal those bits of the allocation site pointer.

Conclusion

Minimal-overhead allocation site trackers

- ASH Tracker
  - Embeds an allocation site ID into the hash code field.
  - Performance overhead:
    ~0% on average, 1.4% at maximum.
- ASC Tracker
  - Makes the class pointer field point to an allocation site structure.
  - Performance overhead:
    1% on average, 2% at maximum.

- Useful for both reliability and optimization.
  - Reliability: minimal-overhead memory leak detector.
  - Optimization: allocation-site-based object pretenuring.

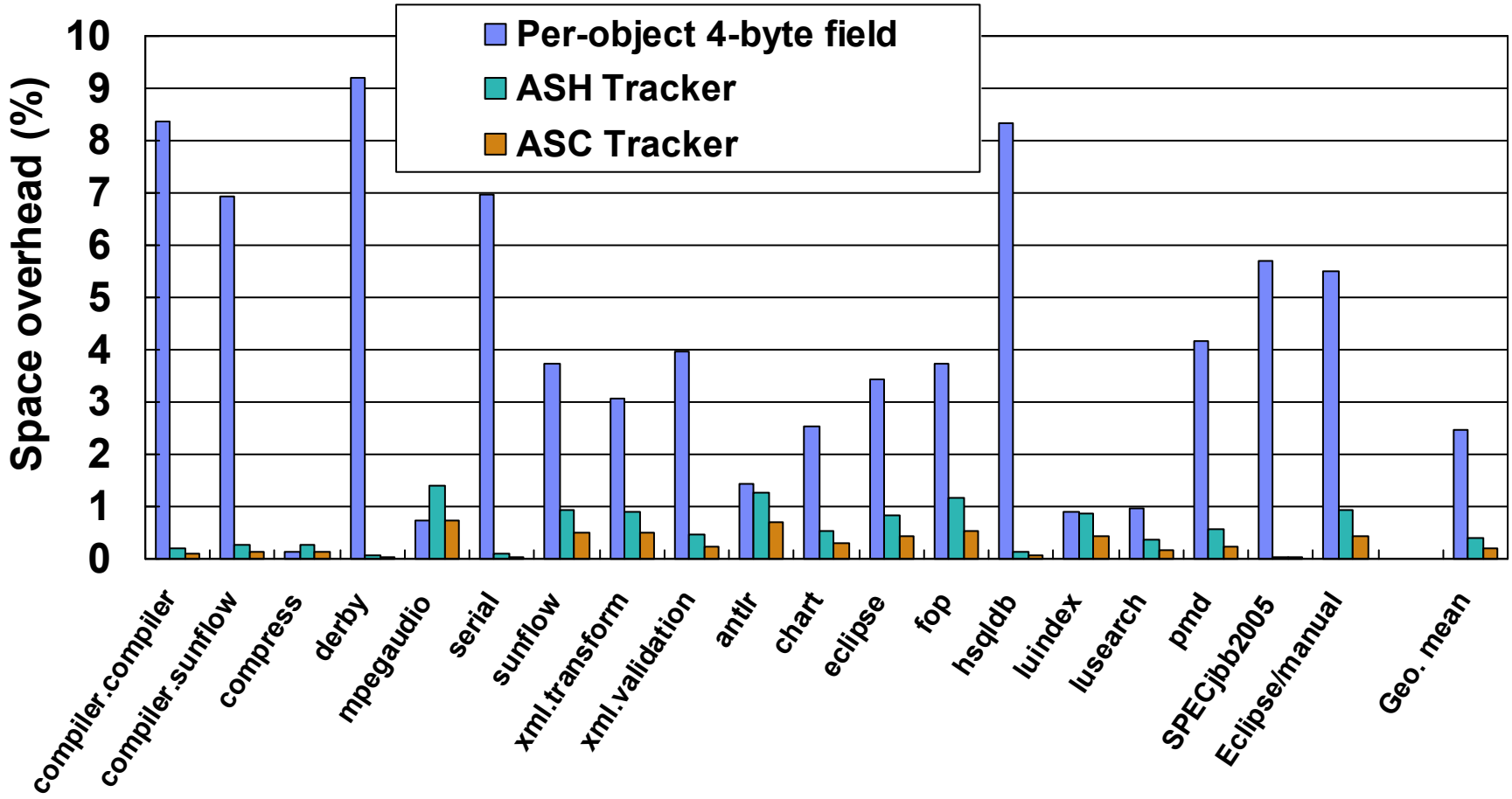
Thank you!

- Questions?

Back-up

Space Overhead Compared with Physical Memory Usage

- ASH Tracker: on average 0.4% overhead
- ASC Tracker: on average 0.2% overhead

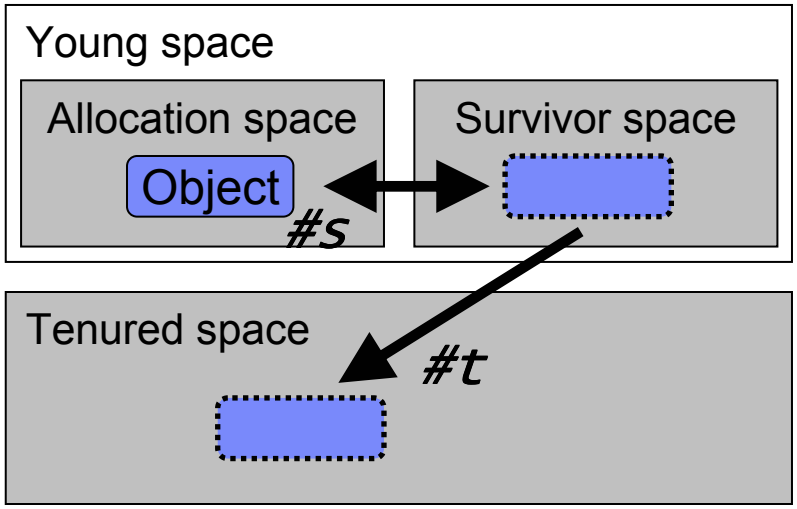


Using ASH Tracker for Object Pretenuring

- Copy likely-to-be-long-lived objects directly to a “tenured” space.
  - Not copying such objects multiple times within a young space.

1. Online profiling

   Compute the ratio of tenured objects (*#t/#s*) for each allocation site at young GC time.



2. Pretenuring

   Enable pretenuring for an allocation site if its ratio exceeds a certain threshold.