Operating Systems
CMPSCI 377
Garbage Collection

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Questions To Come

- Terms:
  - **Tracing**
  - **Copying**
  - **Conservative**
  - **Parallel GC**
  - **Concurrent GC**
- **Runtime** & **space** costs
  - **Live objects**
  - **Reachable objects**
  - **References**

Explicit Memory Management

- `malloc/new`
  - allocates space for an object
- `free/delete`
  - returns memory to system

- Simple, but tricky to get right
  - Forget to **`free`** ⇨ memory leak
  - **`free`** too soon ⇨ "dangling pointer"
  - Double **`free`**, invalid **`free`**...

Dangling Pointers

```
Node x = new Node (“happy”);
Node ptr = x;
delete x;           // But I’m not dead yet!
Node y = new Node (“sad”);
cout << ptr->data << endl;      // sad ☹
```

- Insidious, hard-to-track down bugs

Solution: Garbage Collection

- **Garbage collector** periodically scans objects on heap
  - No need to `free`
  - **Automatic memory management**

- Reclaims ***non-reachable*** objects
  - Won't reclaim objects until they're **dead** (actually somewhat later)

No More Dangling Pointers

```
Node x = new Node ("happy");
Node ptr = x;
// x still live (reachable through ptr)
Node y = new Node ("sad");
cout << ptr->data << endl;  // happy! ☺
```

So why not use GC
all the time?

Because This Guy Says Not To

Slightly More Technically…

- "GC **impairs performance**"
  - Extra processing
    - *collection, copying*
  - Degrades cache performance (*ibid*)
  - Degrades page locality (*ibid*)
  - Increases memory needs
    - *delayed reclamation*

On the other hand…

- No, “GC **enhances performance!**”
  - Faster allocation
    - *pointer-bumping vs. freelists*
  - Improves cache performance
    - *no need for headers*
  - Better locality
    - *can reduce fragmentation, compact data structures according to use*

Outline

- Classical GC algorithms
- Quantifying GC performance
  - A hard problem
- Oracular memory management
- GC vs. `malloc/free` bakeoff

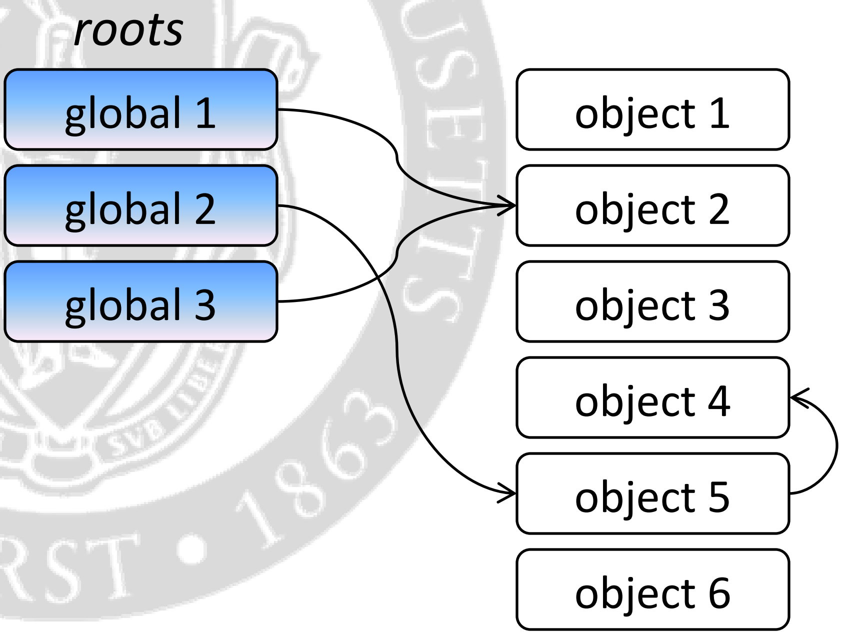
Classical Algorithms

- Three classical algorithms
  - **Mark-sweep**
  - **Reference counting**
  - **Semispace**
- Tweaks
  - **Generational garbage collection**
- Out of scope
  - **Parallel** – perform GC in parallel
  - **Concurrent** – run GC at same time as app
  - **Real-time** – ensure bounded pause times

Mark-Sweep

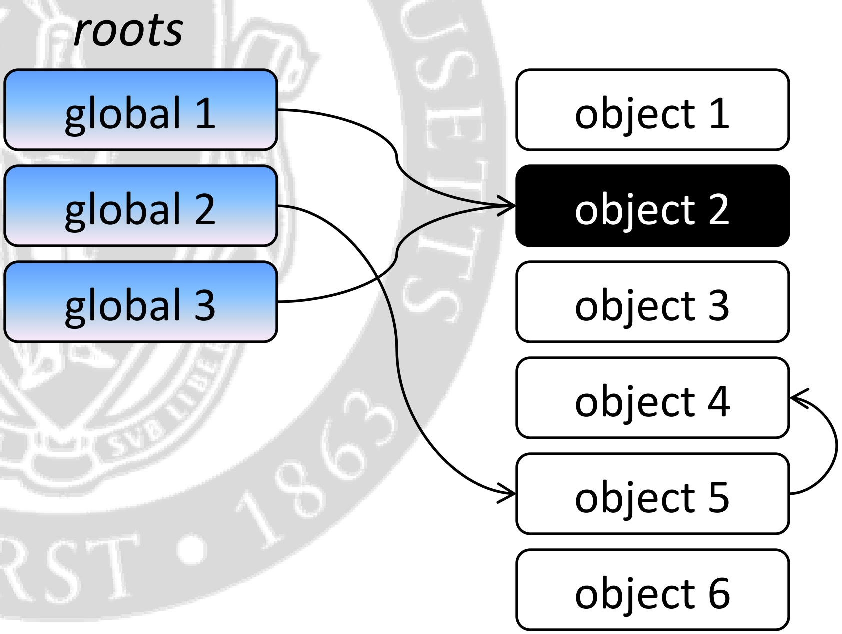
- Start with **roots**
  - Global variables, variables on stack & in registers
- Recursively visit every object through pointers
  - **Mark** every object we find (set **mark bit**)
- **Everything not marked = garbage**
  - Can then **sweep** heap for unmarked objects and free them

Mark-Sweep Example



- Initially,
  all objects **white**
  (garbage)

Mark-Sweep Example



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- Visit objects, following **object graph**

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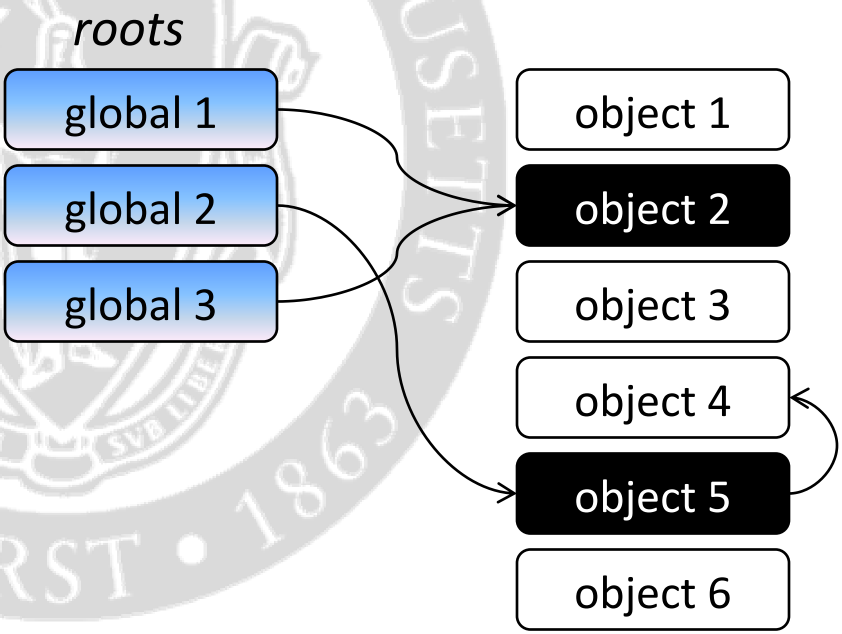

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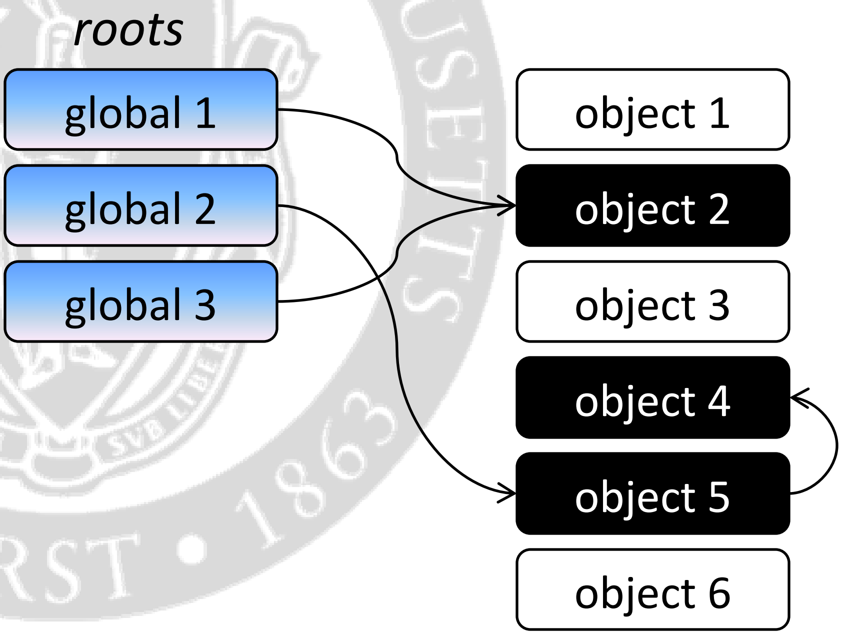

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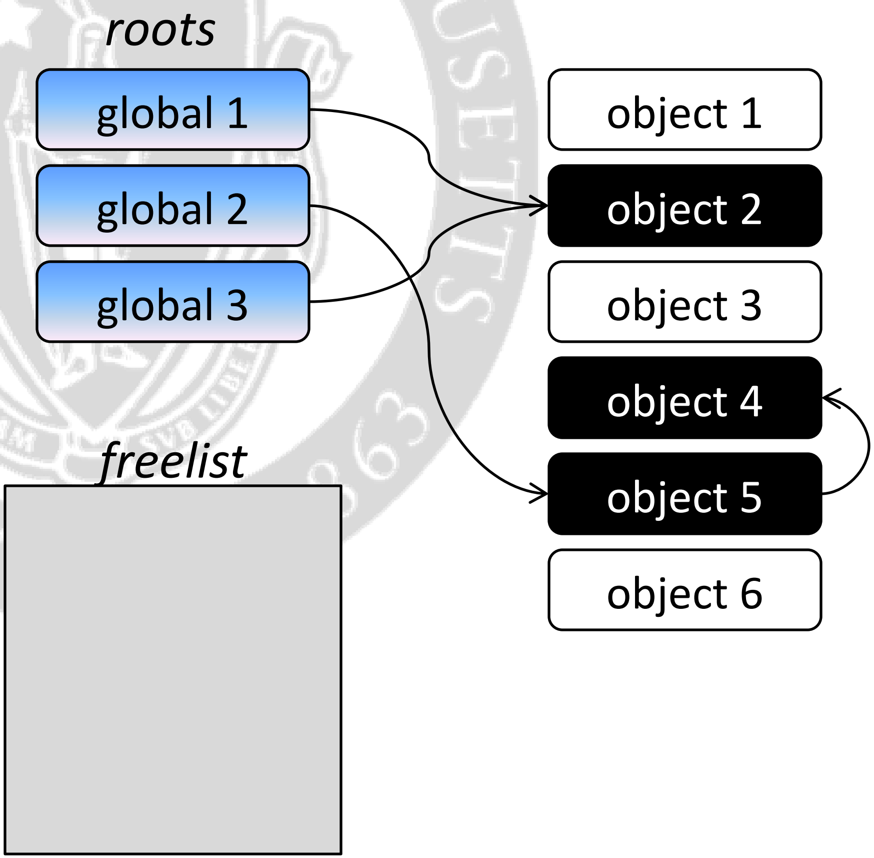
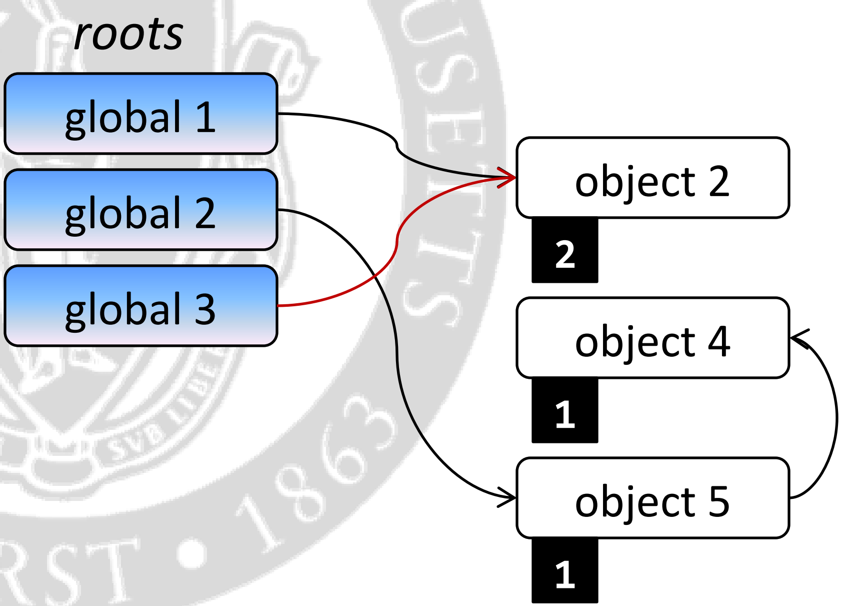


- Initially, all objects **white** (garbage)
- Visit objects, following **object graph**
- Can sweep immediately or **lazily**

Reference Counting

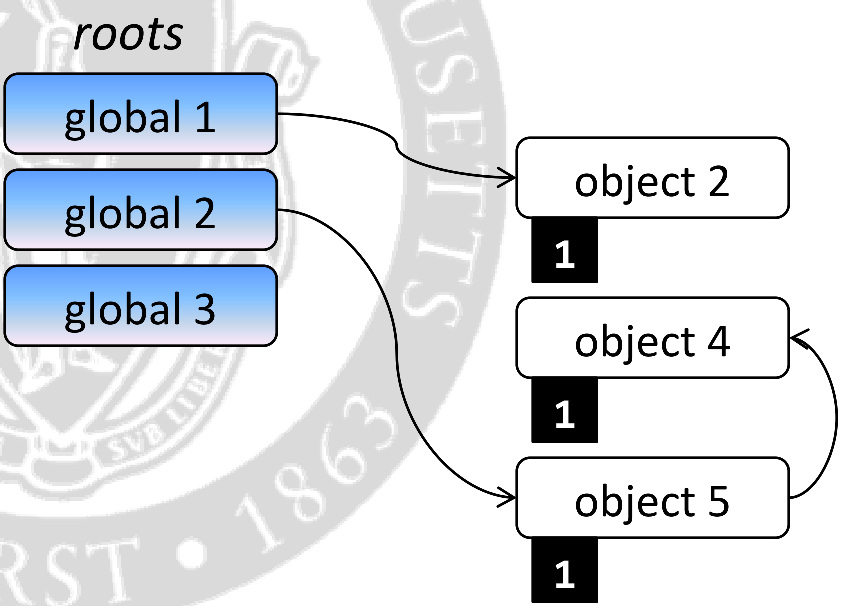
- For every object, maintain **reference count** = number of incoming pointers
  - `a->ptr = x` $\Rightarrow$ `refcount(x)++`
  - `a->ptr = y` $\Rightarrow$ `refcount(x)--; refcount(y)++`
- Reference count = 0 $\Rightarrow$ no more incoming pointers: **garbage**

Reference Counting Example



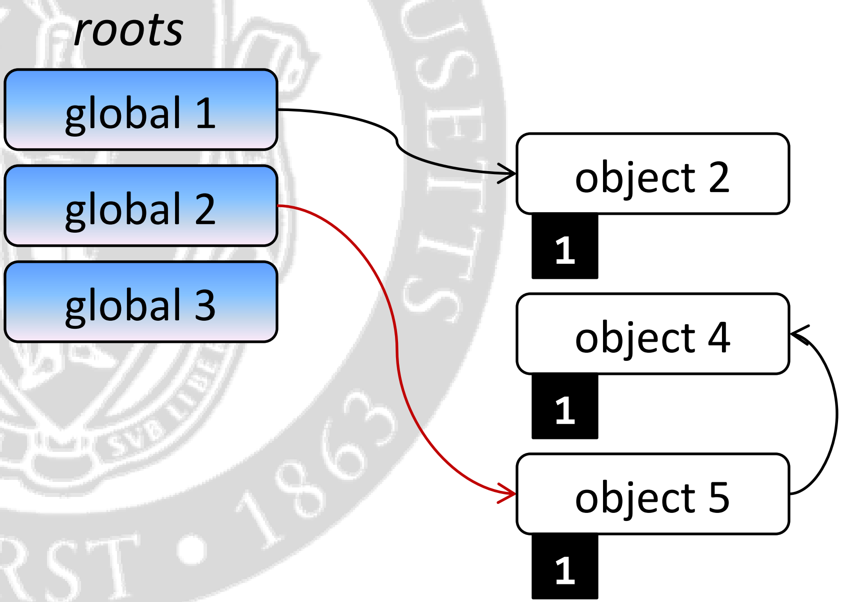
- New objects: ref count = 1

Reference Counting Example



- New objects: ref count = 1
- Delete pointer: refcount--

Reference Counting Example



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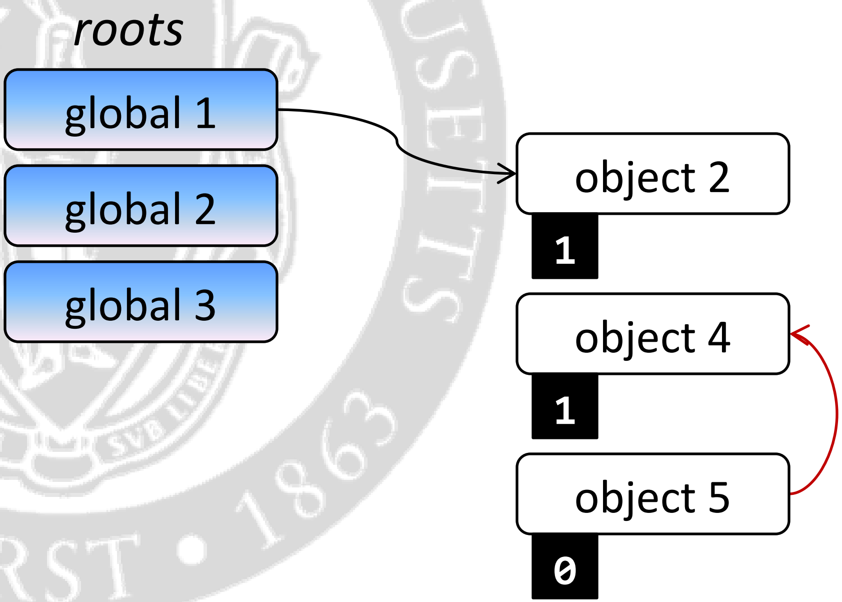

- New objects: ref count = 1
- Delete pointer: refcount--
  - And recursively delete pointers

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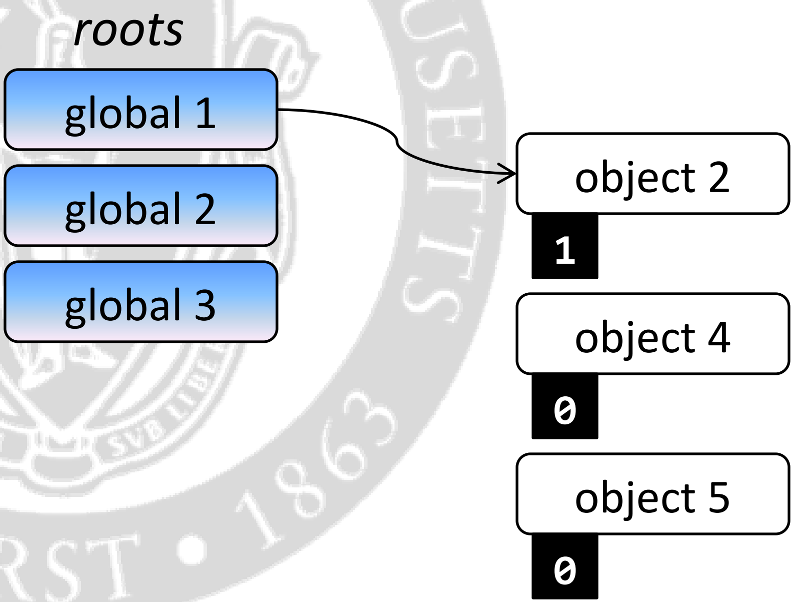
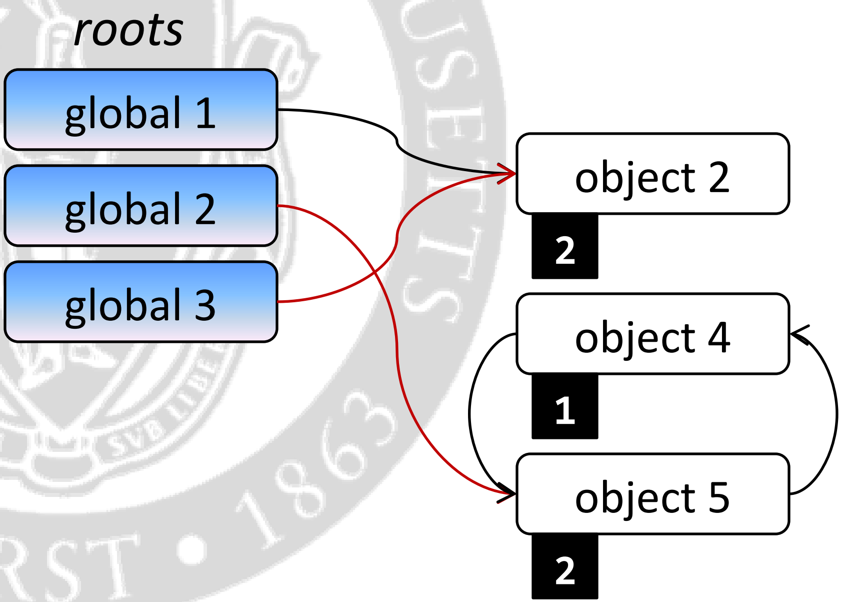


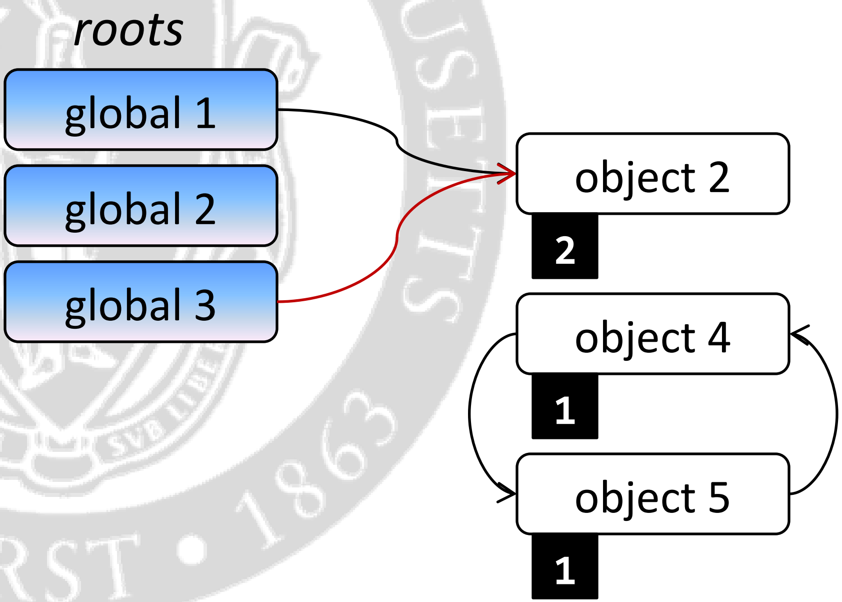
- New objects: ref count = 1
- Delete pointer: refcount--
  - And recursively delete pointers
- refcount == 0: put on freelist

Cycles & Reference Counting



- **Big problem: cycles**

Reference Counting Example



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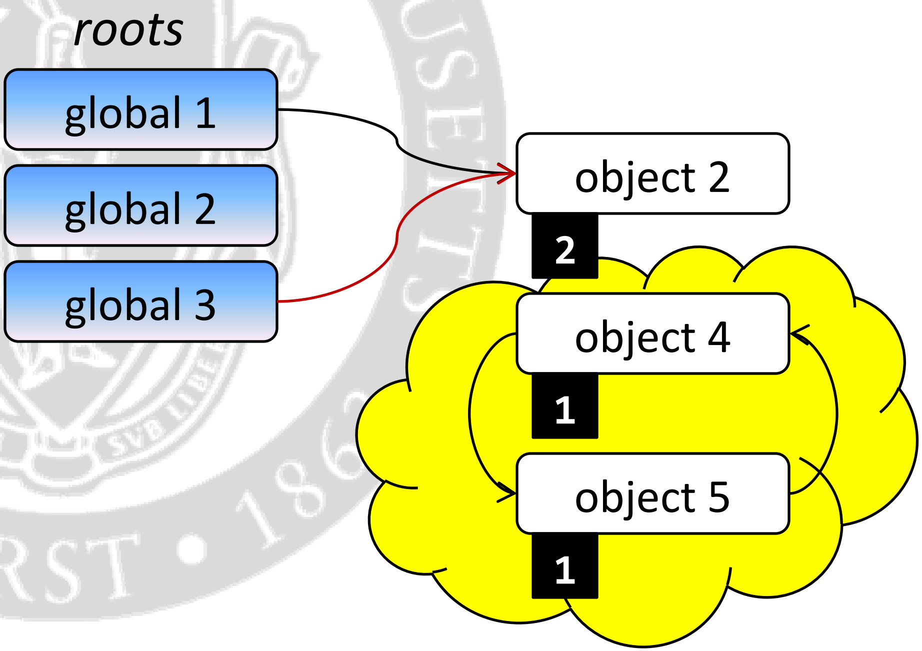
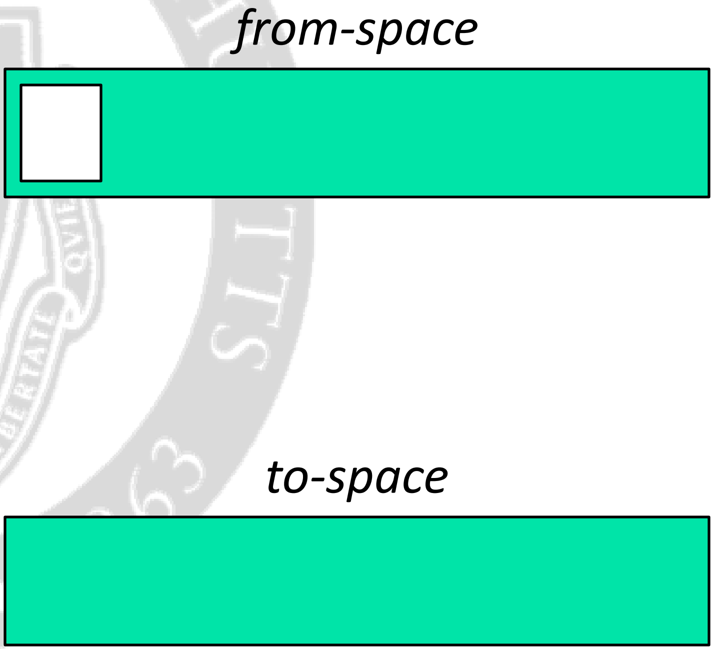


- **Big problem**: **cycles**
  - Cycles lead to unreclaimable garbage
- Need to do periodic tracing collection (e.g., mark-sweep)

Semispace

- Divide heap in two **semispaces**:
  - Allocate objects from **from-space**
- When from-space fills,
  - **Scan** from roots through live objects
  - **Copy** them into **to-space**
- When done, *switch the spaces*
  - Allocate from leftover part of to-space

Semispace Example



- Allocate in from-space
  - **Pointer bumping**

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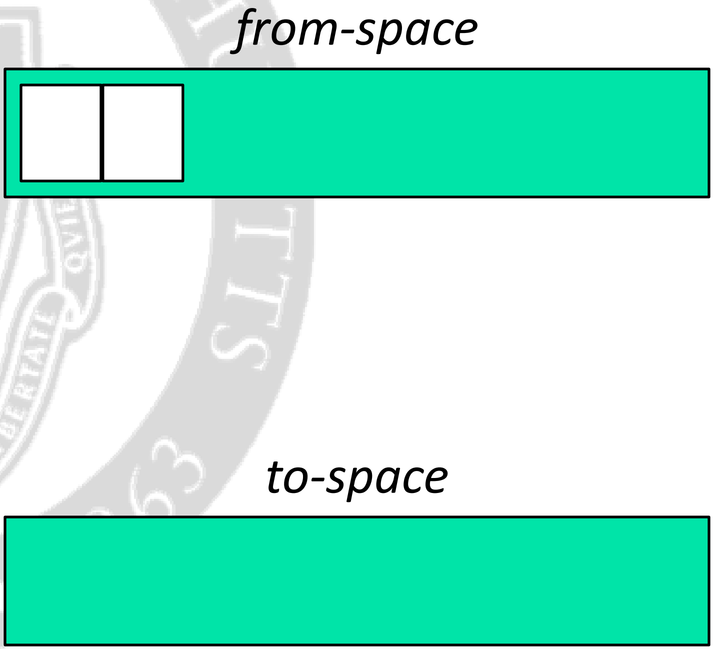

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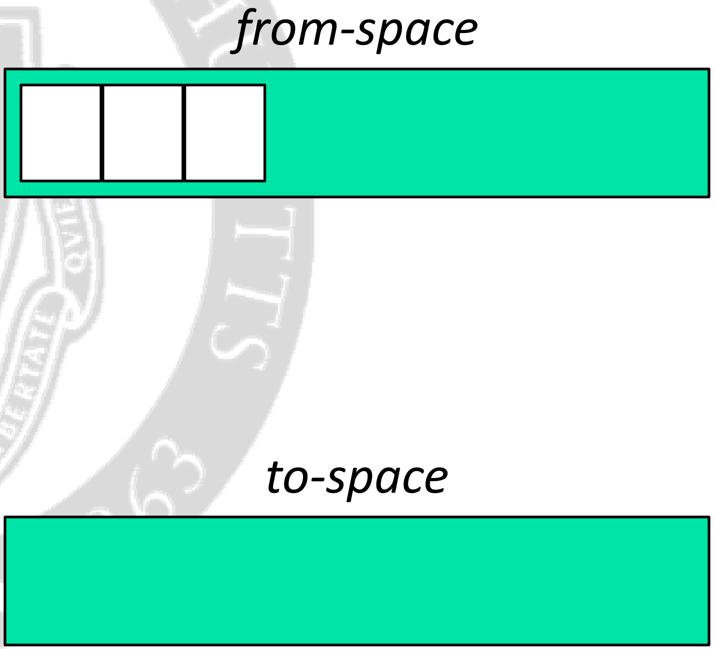

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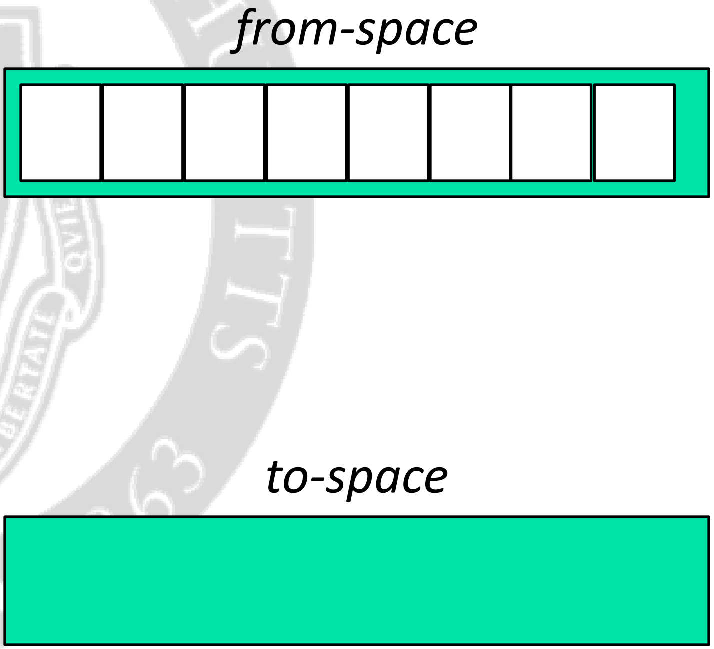

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- Copy live objects into to-space

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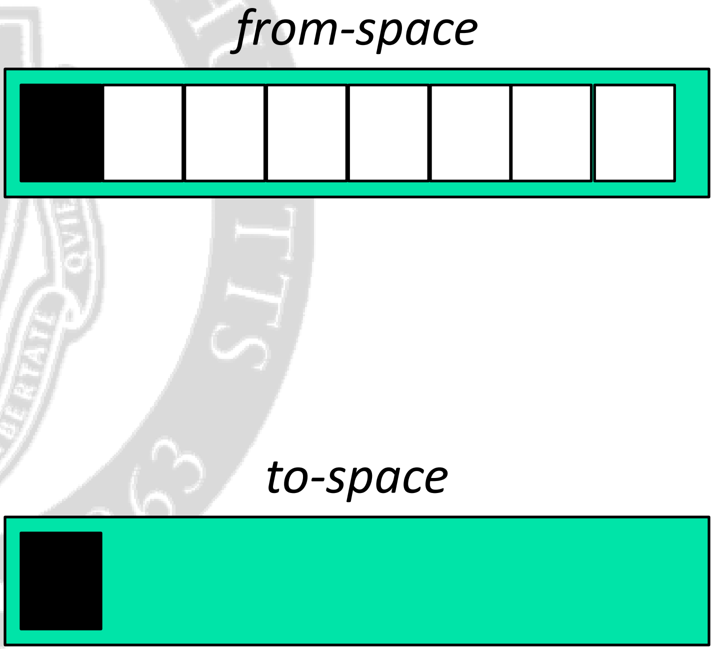

- Allocate in from-space
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- Copy live objects into to-space
  - Leaves **forwarding pointer**

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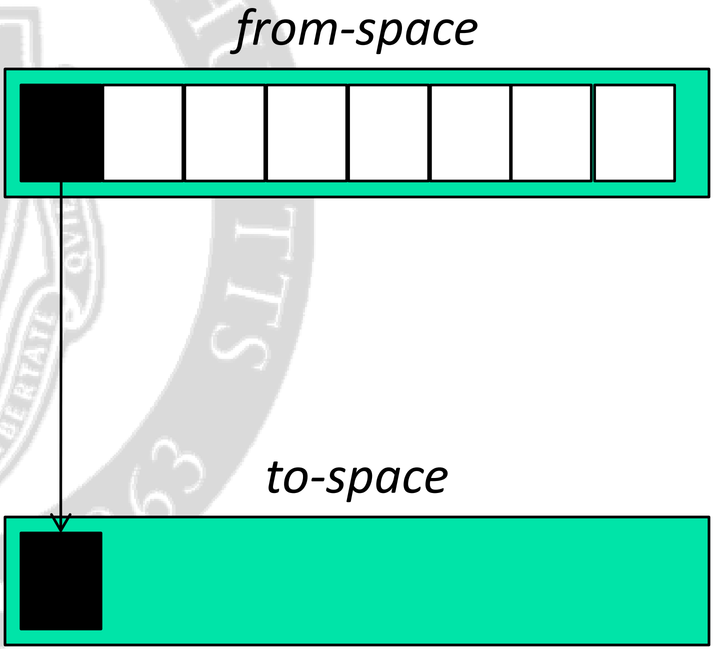

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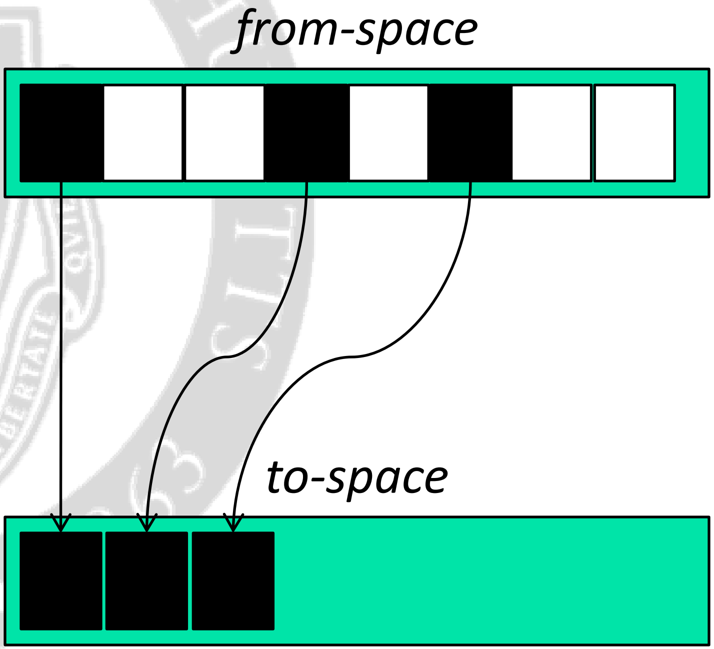

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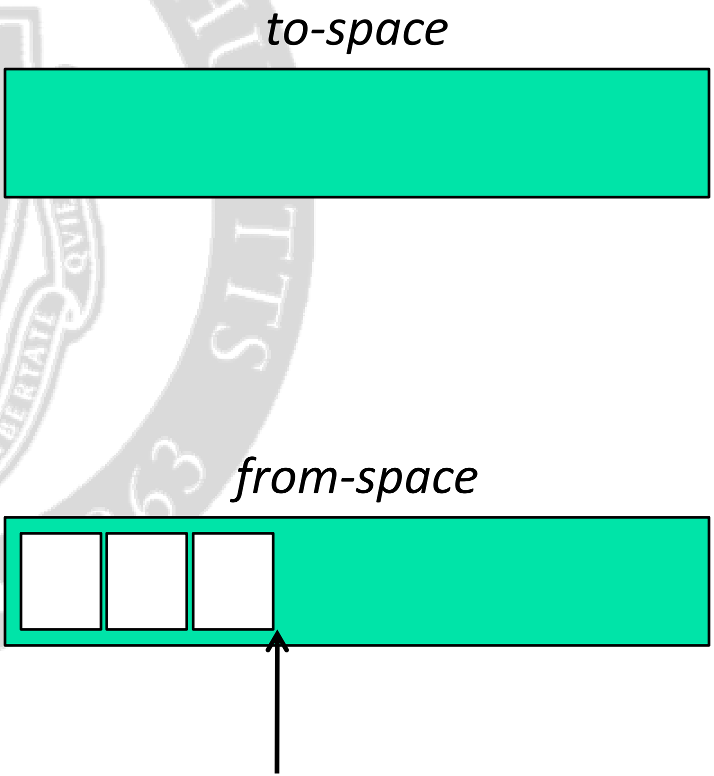
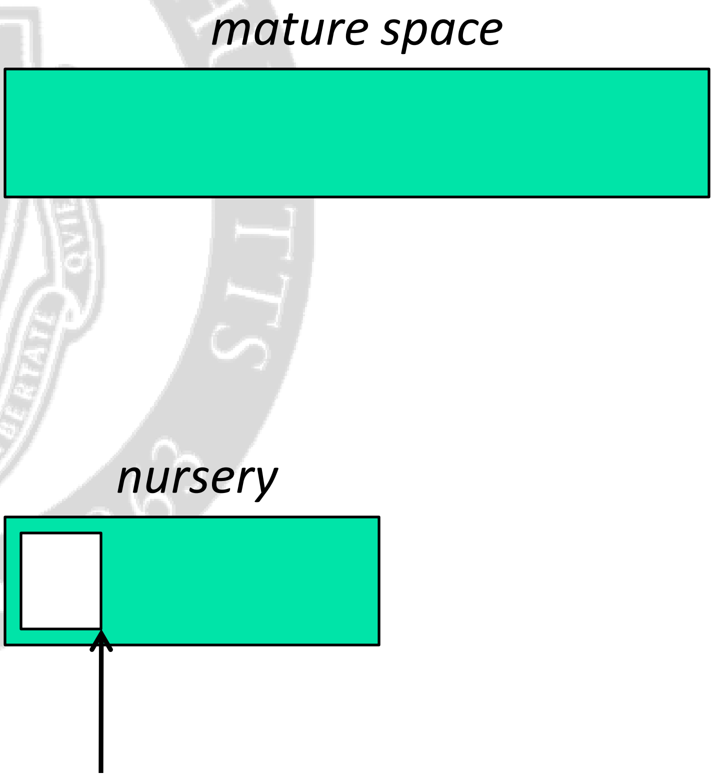


- Allocate in from-space
  - **Pointer bumping**
- Copy live objects into to-space
  - Leaves **forwarding pointer**
- **Flip** spaces; allocate from end

Generational GC

- Optimization for copying collectors
  - **Generational hypothesis:**
    "most objects die young"
  - **Common-case optimization**
- Allocate into **nursery**
  - Small region
  - Collect frequently
    - Copy out **survivors**
- **Key idea:** keep track of pointers from **mature space** into **nursery**

Generational GC Example



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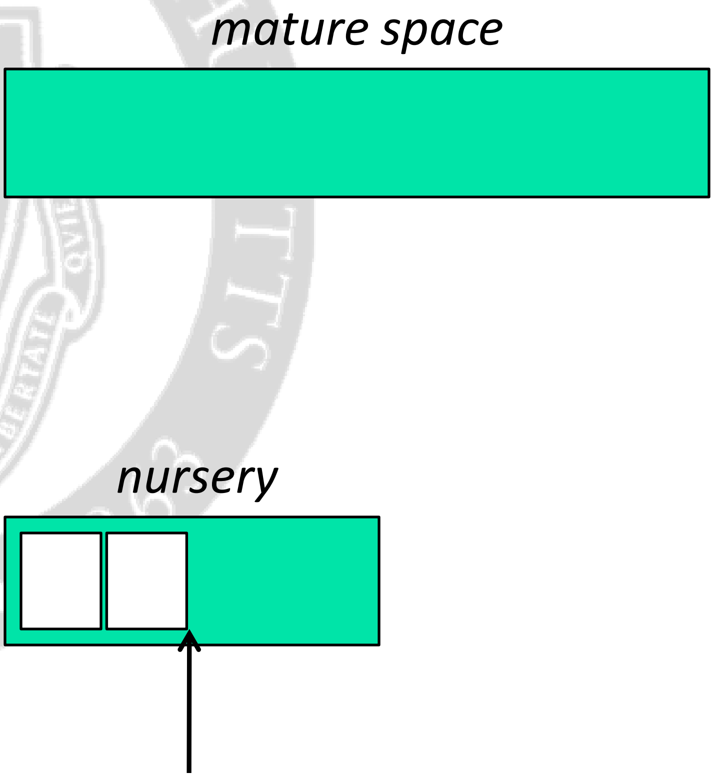

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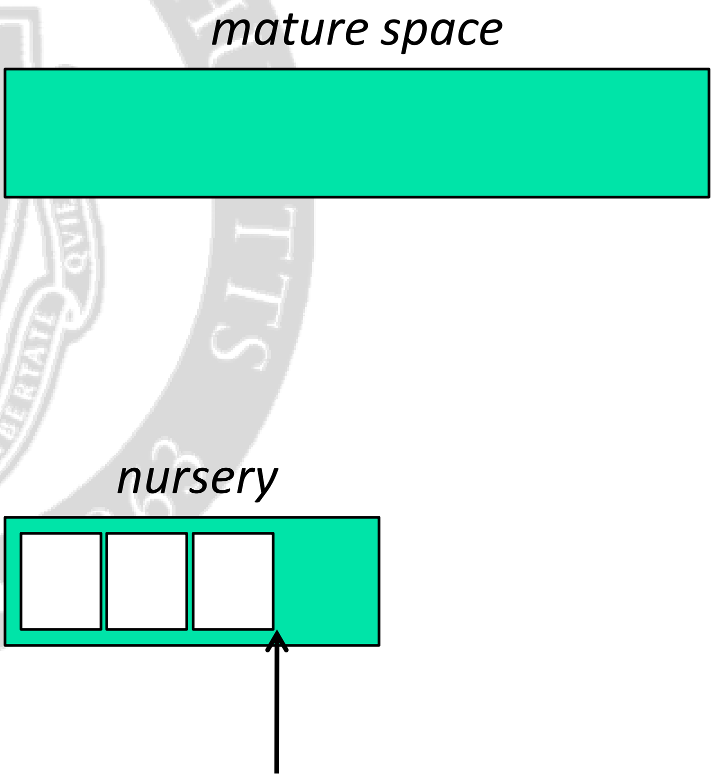

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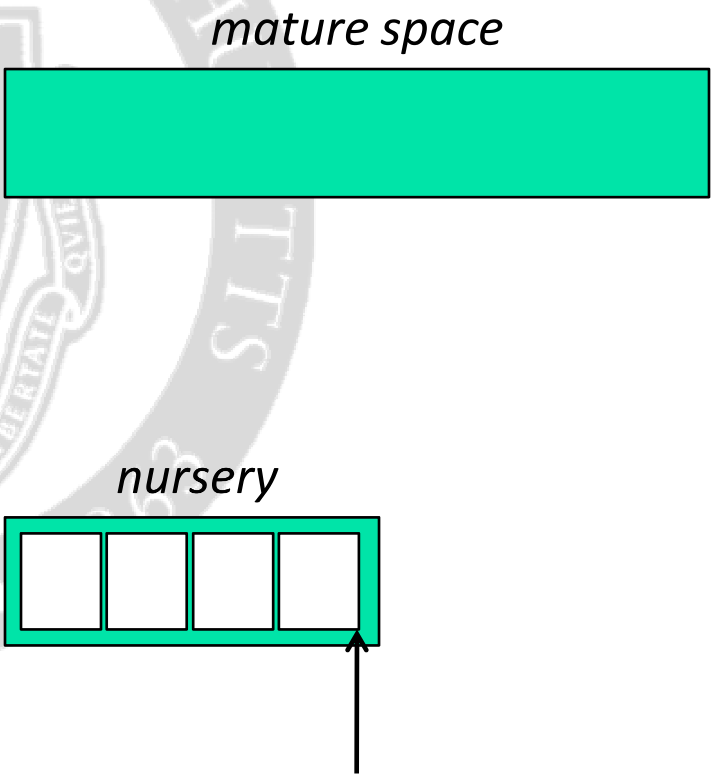

- Copy out survivors (via roots & mature space pointers)

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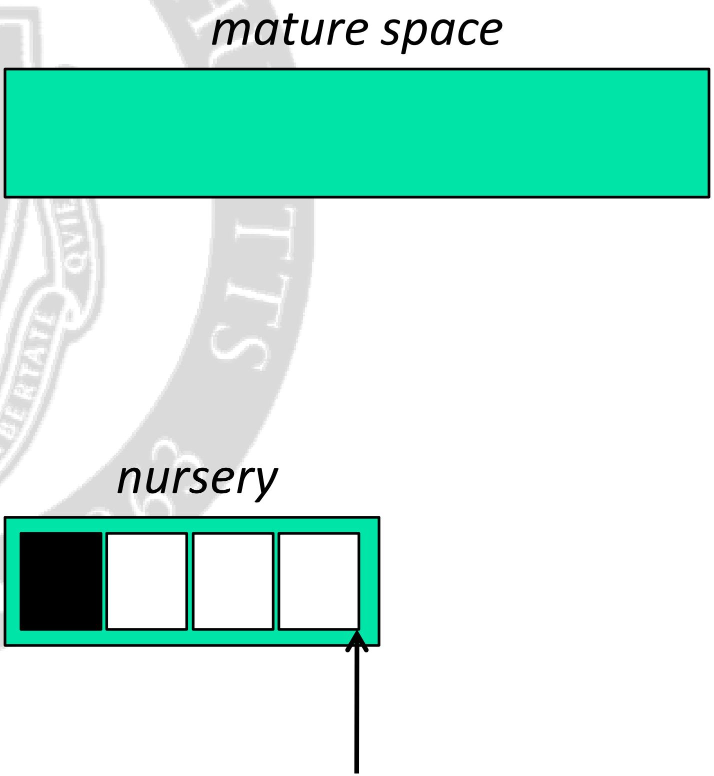

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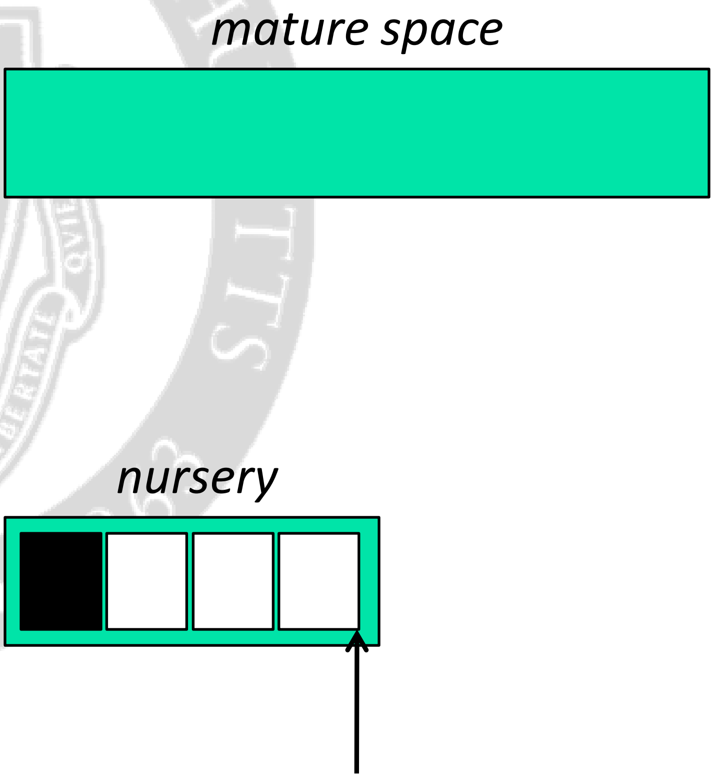

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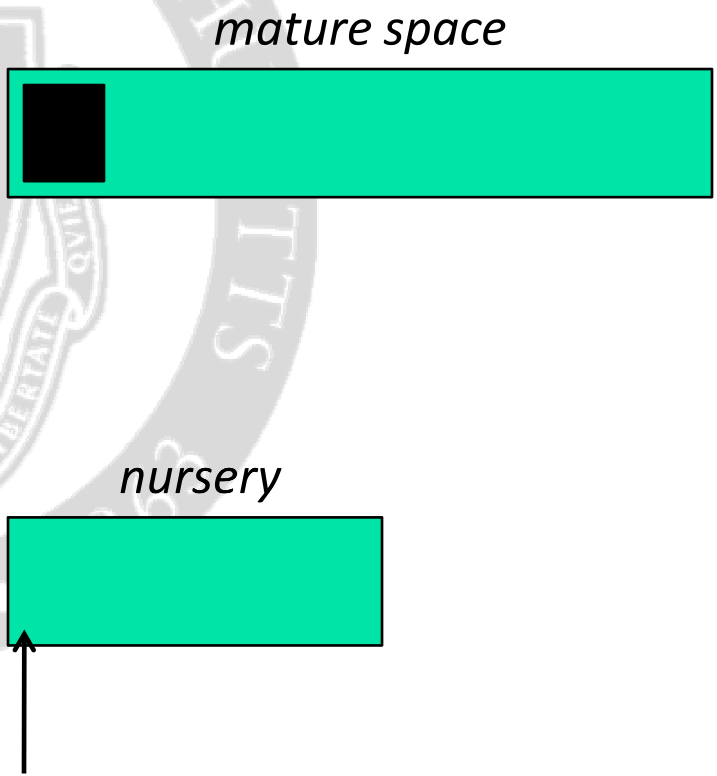

- Copy out survivors (via roots & mature space pointers)
- Reset allocation pointer & continue

Conservative GC

- **Non-copying** collectors for C & C++
  - Must identify pointers
    - "Duck test": if it looks like a pointer, it's a pointer
  - Trace through "pointers", marking everything
- Can link with Boehm-Demers-Weiser library ("libgc")

GC vs. malloc/free

Comparing Memory Managers

```
Node v = malloc(sizeof(Node));
v->data=malloc(sizeof(NodeData))
memcpy(v->data, old->data,
                sizeof(NodeData));
free(old->data);
v->next = old->next;
v->next->prev = v;
v->prev = old->prev;
v->prev->next = v;
free(old);
```

BDW Collector

Using GC in C/C++ is easy:

Comparing Memory Managers

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Node v = malloc(sizeof(Node));
v->data=malloc(sizeof(NodeData));
memcpy(v->data, old->data,
           sizeof(NodeData));
free(old->data);
v->next = old->next;
v->next->prev = v;
v->prev = old->prev;
v->prev->next = v;
free(old);
```

BDW Collector

…slide in BDW and ignore calls to **free**.

What About Other Garbage Collectors?

- Compares **`malloc`** to GC, but only *conservative*, *non-copying* collectors
  - Can't reduce fragmentation, reorder objects, etc.
- But: faster *precise, copying* collectors
  - Incompatible with C/C++
  - Standard for Java…

Comparing Memory Managers

```
Node node = new Node();
node.data = new NodeData();
useNode(node);
node = null;
...
node = new Node();
...
node.data = new NodeData();
...
```

Lea Allocator

Adding **`malloc`**/**`free`** to Java:
not so easy…

Comparing Memory Managers

```
Node node = new Node();
node.data = new NodeData();
useNode(node);
node = null;
...
node = new Node();
...
node.data = new NodeData();
...
```

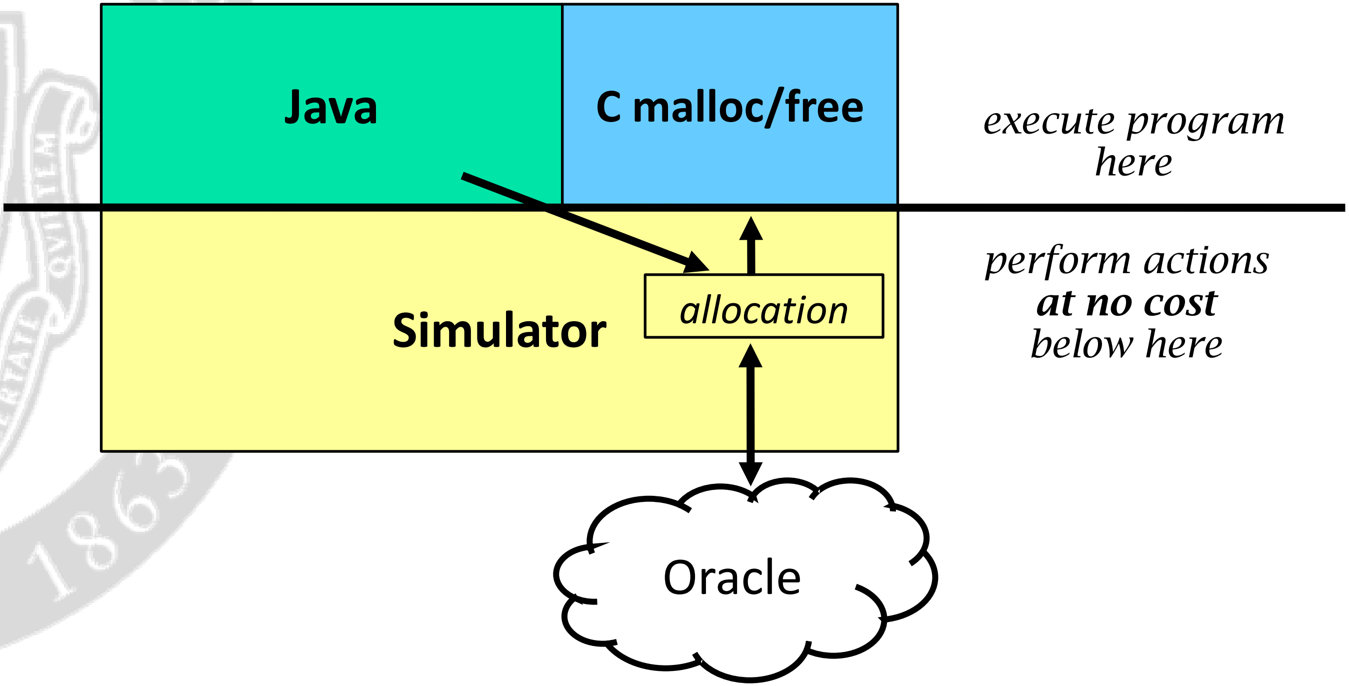
free(node)?

free(node.data)?

Lea Allocator

... need to insert **`frees`**, but where?

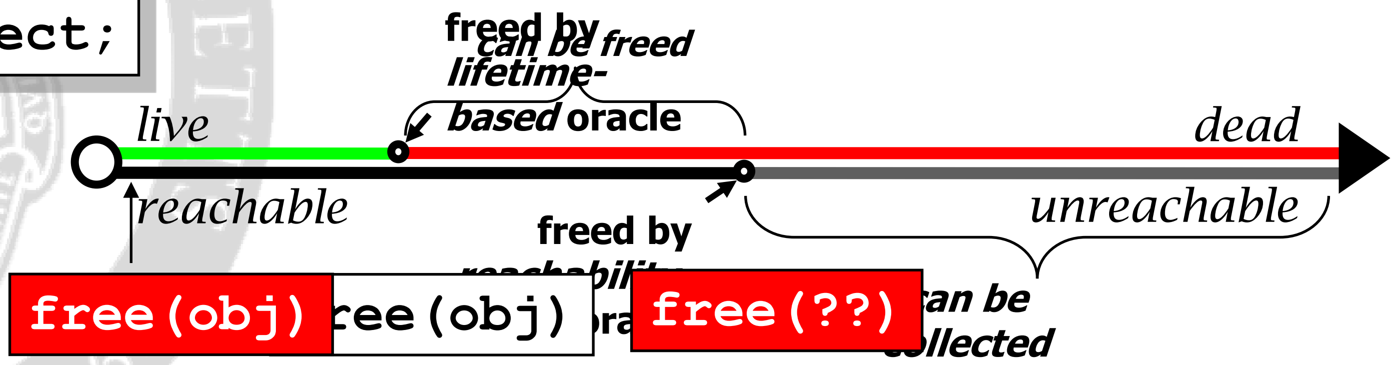
Oracular Memory Manager



- Consult oracle at each allocation
  - Oracle does not disrupt hardware state
  - Simulator invokes `free()`…

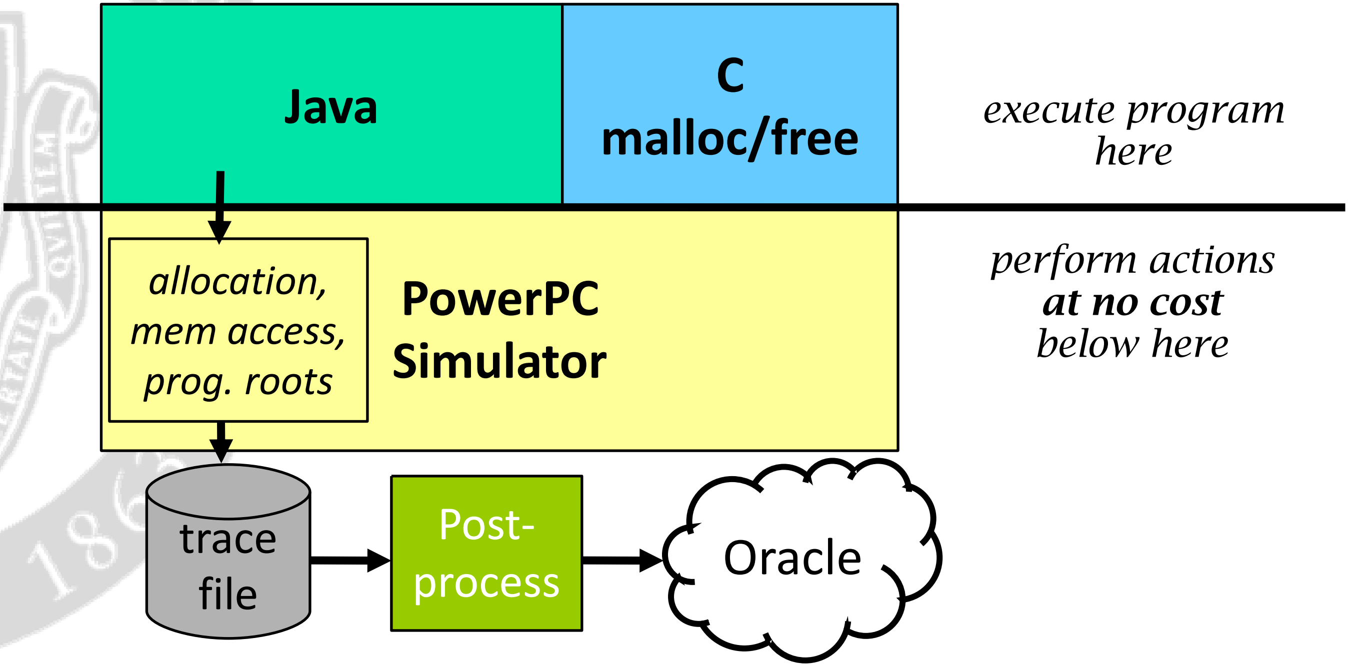
Object Lifetime & Oracle Placement

```
obj =
new Object;
```



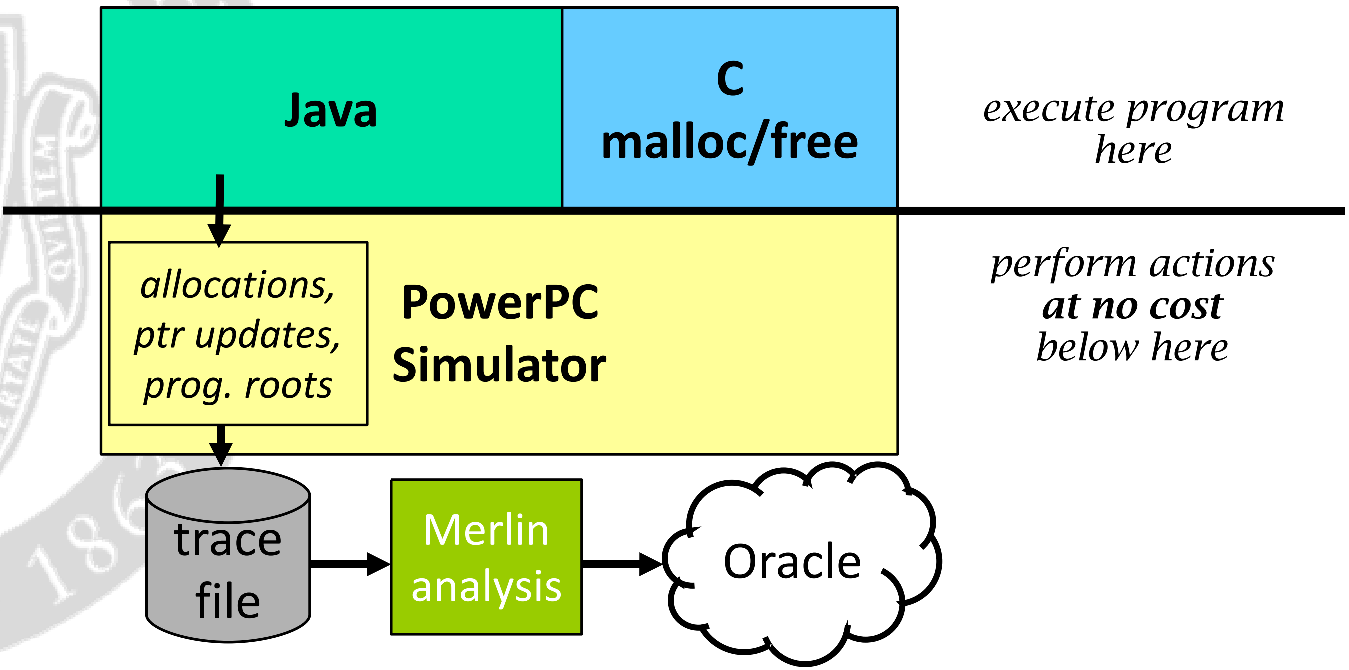
- Oracles bracket placement of **`frees`**
  - **Lifetime-based**: most aggressive
  - **Reachability-based**: most conservative

Liveness Oracle Generation



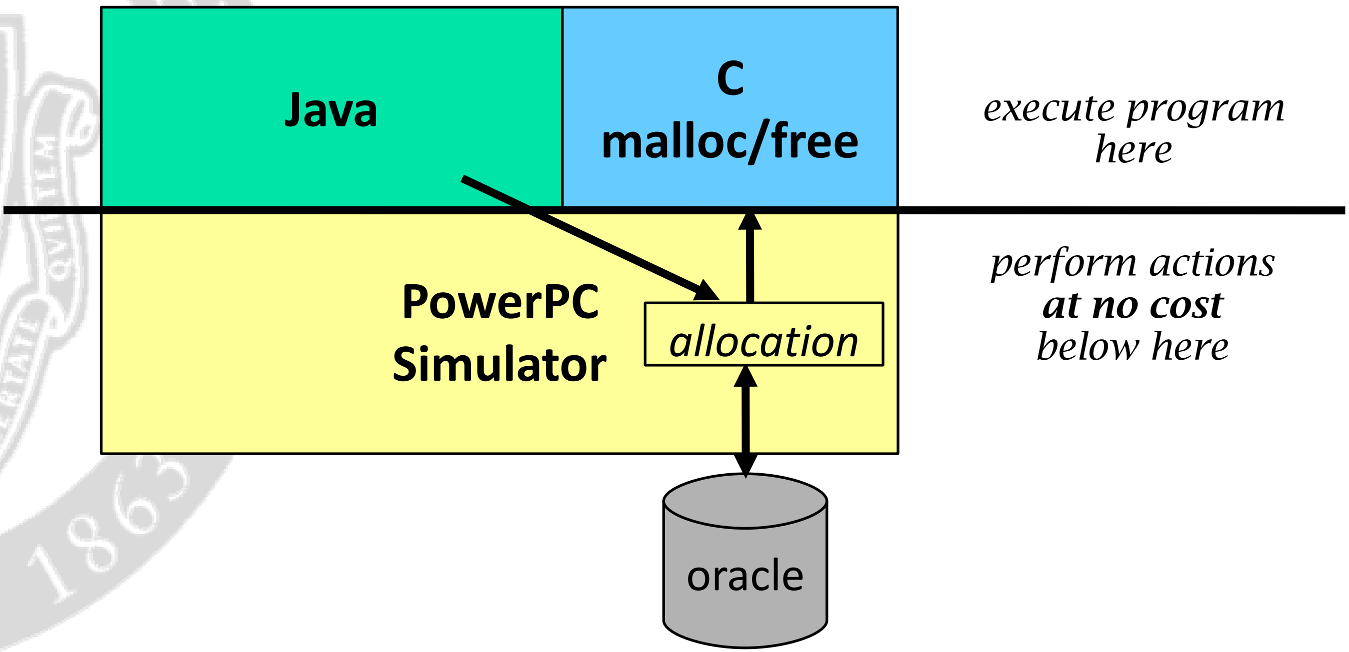
- **Liveness**: record allocs, memory accesses

Reachability Oracle Generation



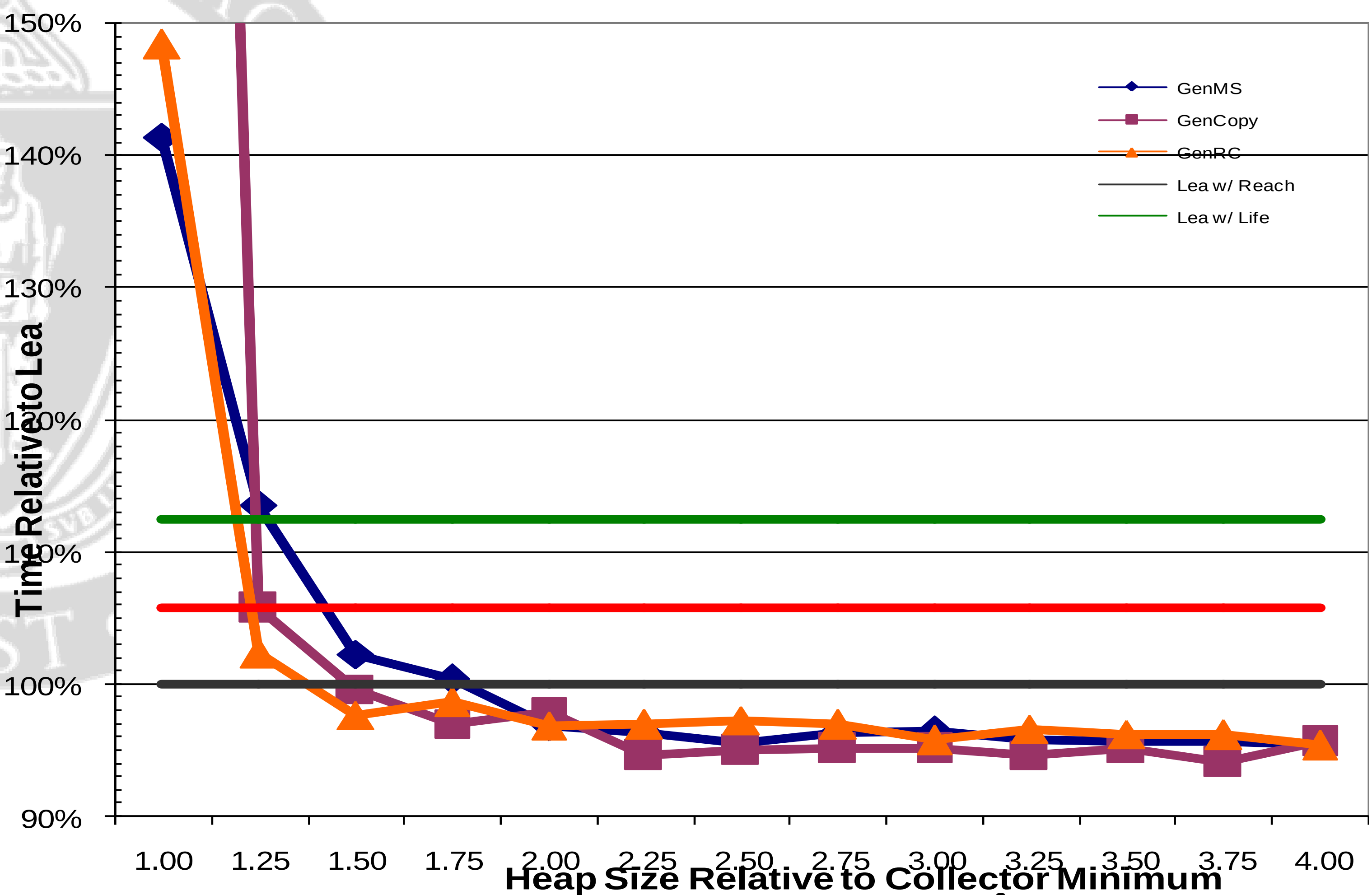
- **Reachability:**
  - Illegal instructions mark heap events (especially pointer assignments)

Oracular Memory Manager



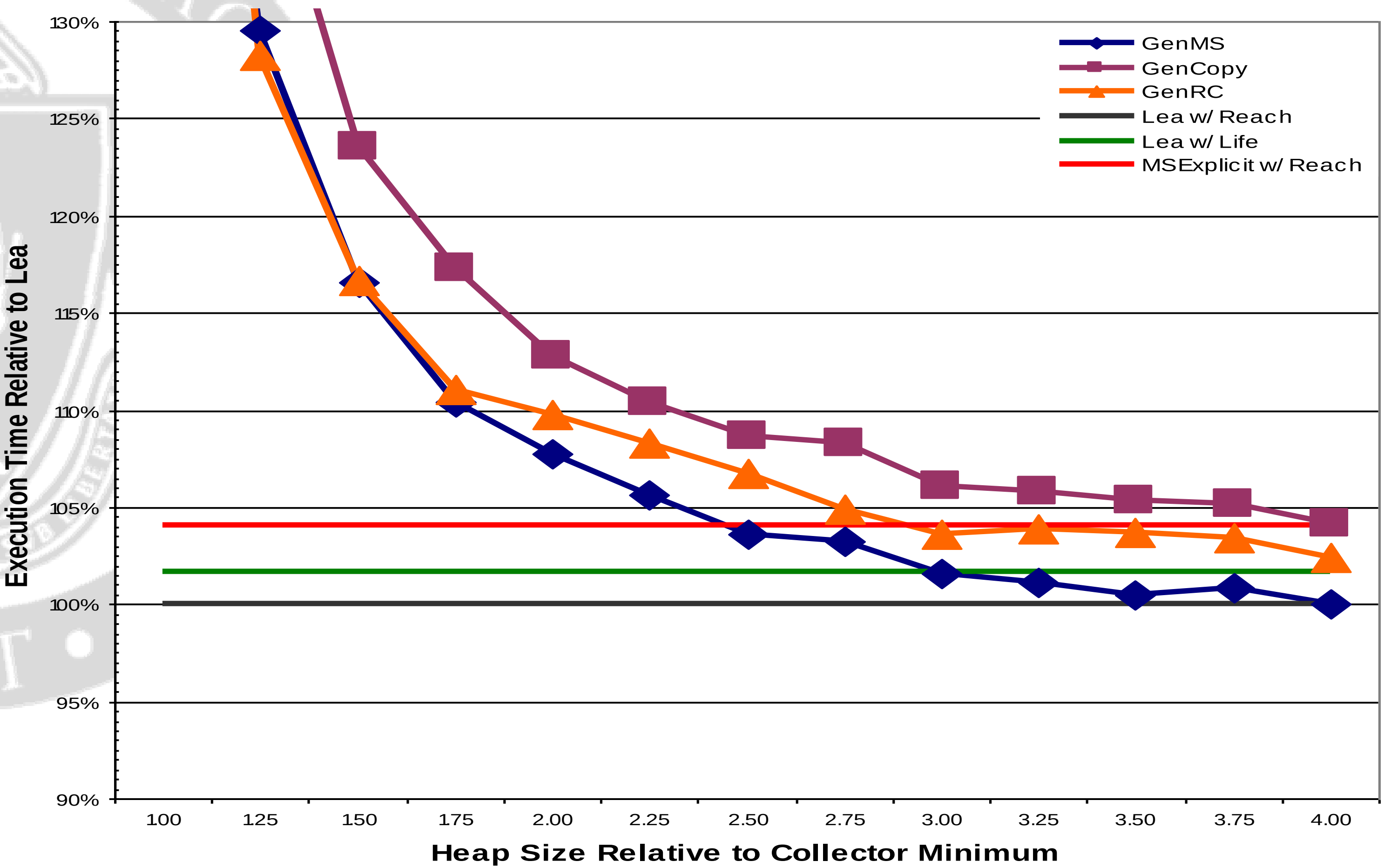
- Run & consult oracle before each allocation
  - When needed, modify instruction to call `free`
  - Extra costs (oracle access) hidden by simulator

Execution Time for pseudoJBB



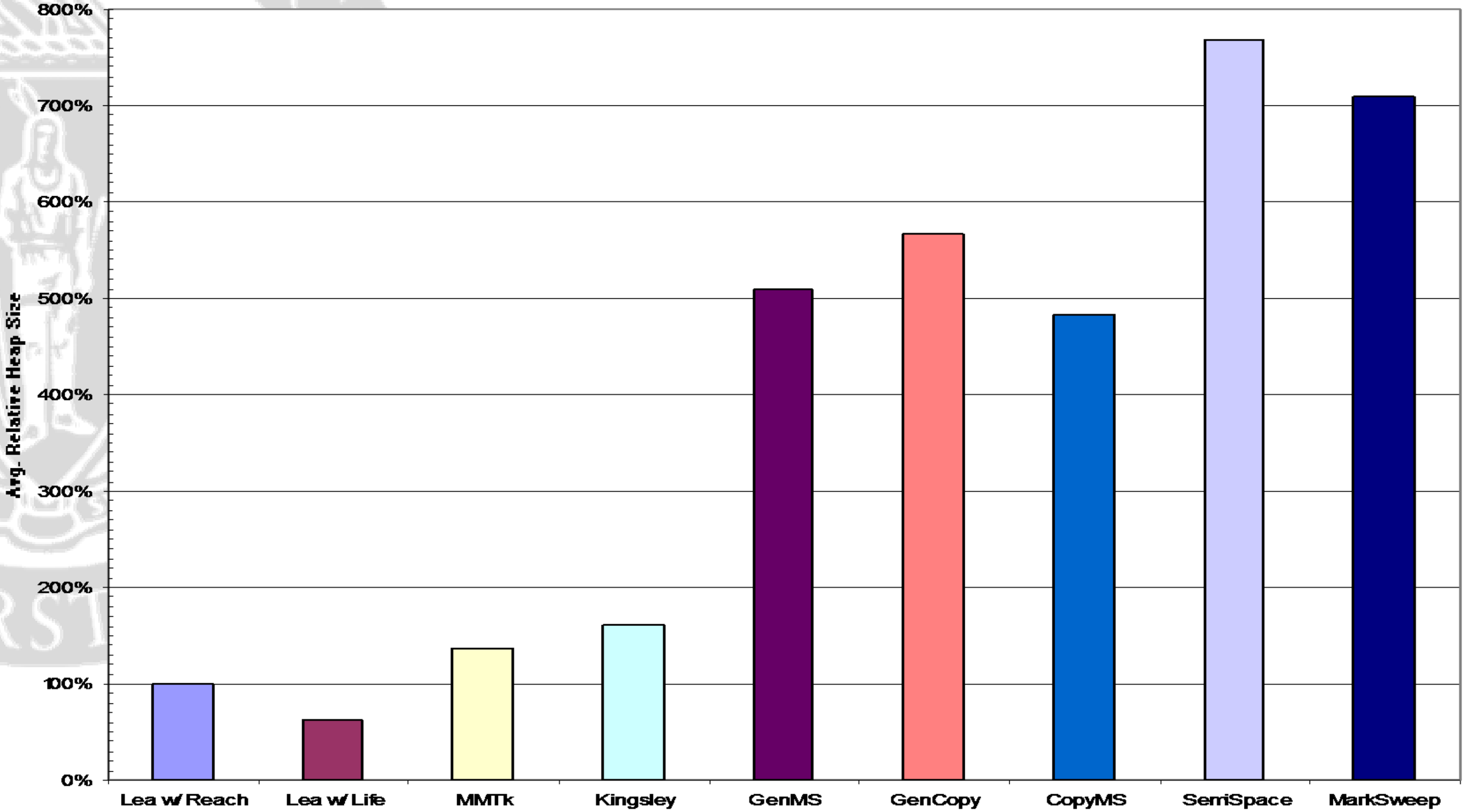
GC can be **faster** than **malloc/free**

Geo. Mean of Execution Time



Trades space for time

Footprint at Quickest Run



GC uses much more memory for speed

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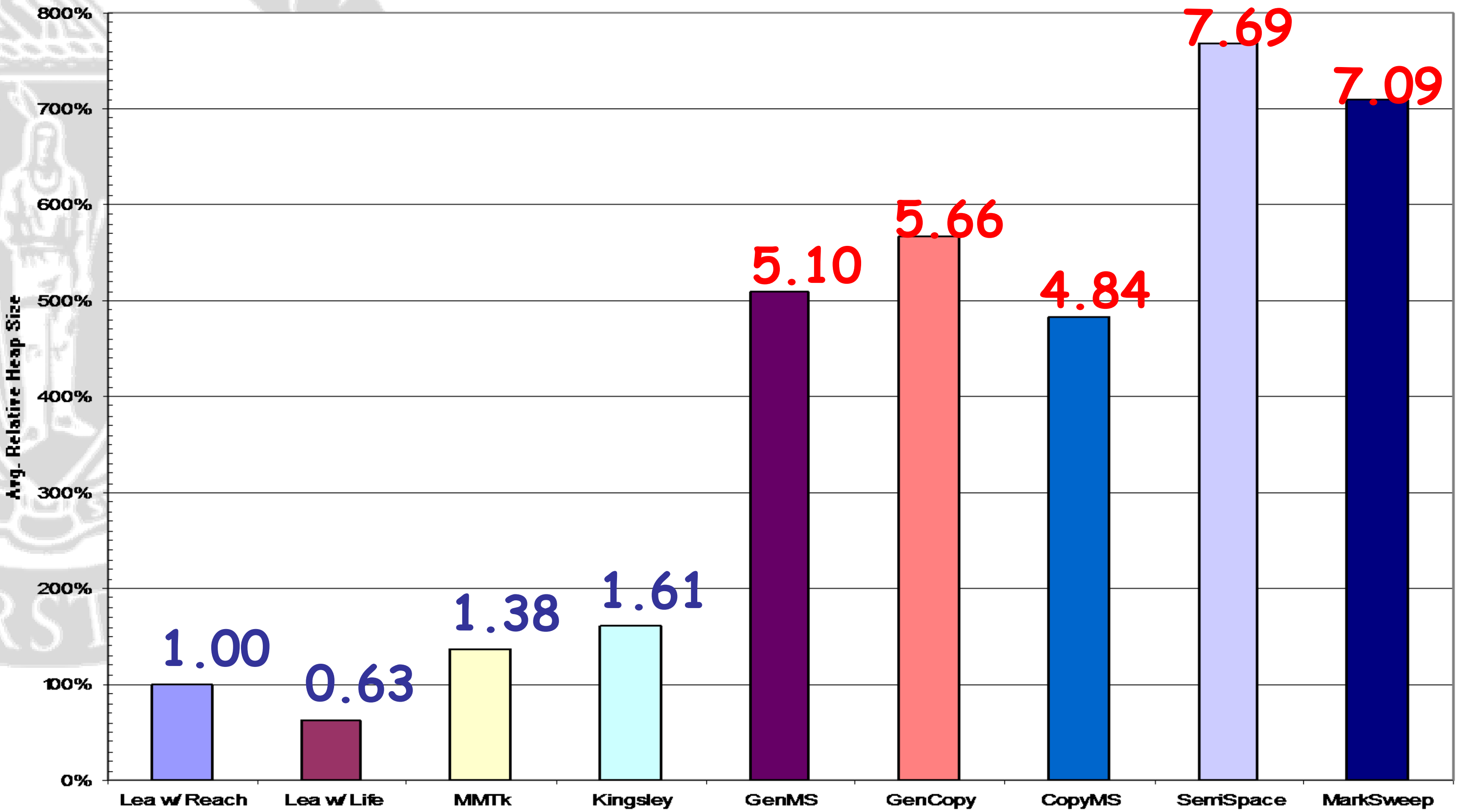
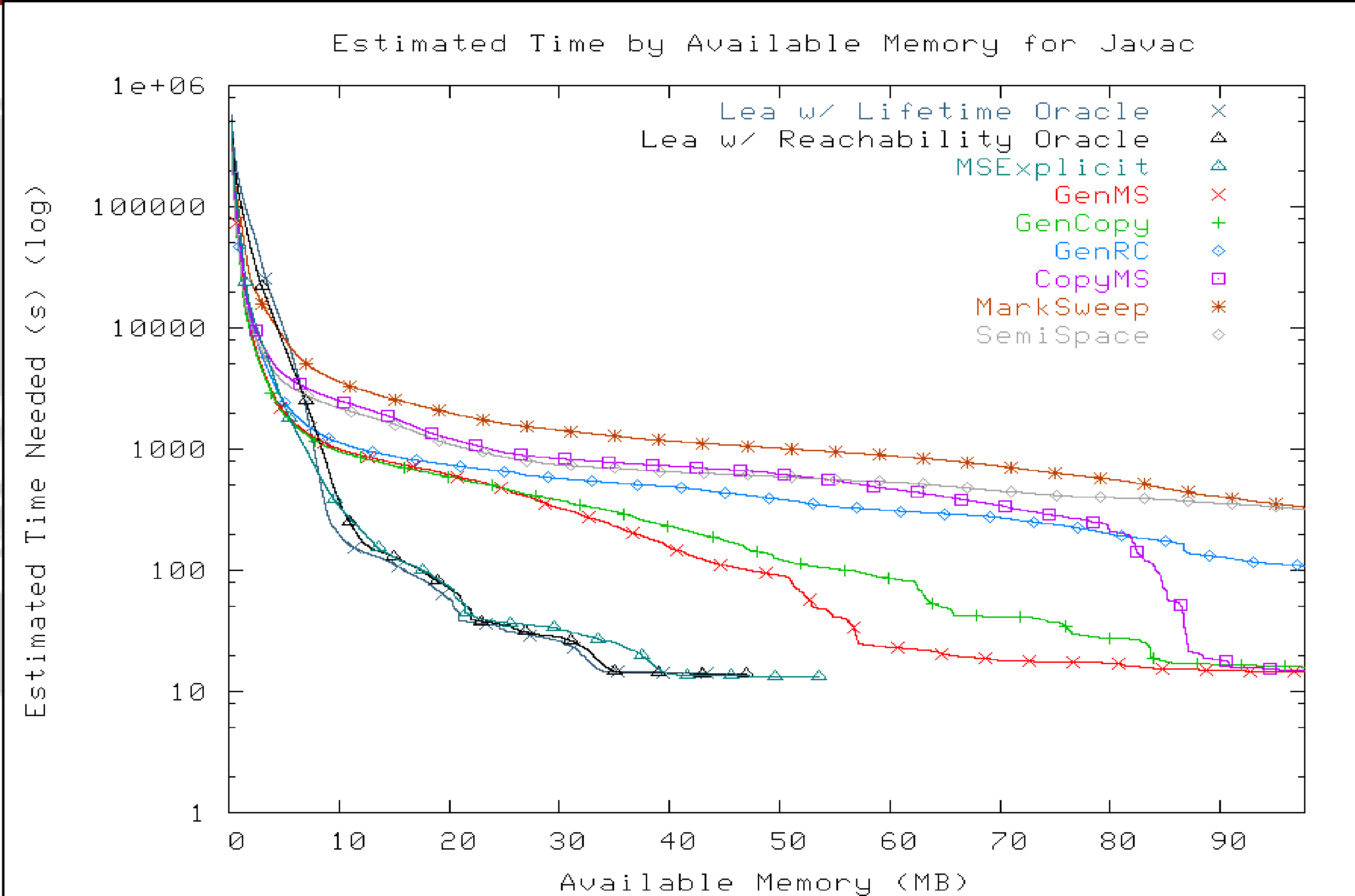


GC uses much more memory for speed

Javac Paging Performance



GC: **poor** paging performance

Summary of Results

- Best collector equals Lea's performance…
  - Up to 10% faster on some benchmarks
- … but uses more memory
  - Quickest runs require 5x or more memory
  - GenMS at least doubles mean footprint

When to Use Garbage Collection

- Garbage collection fine **if**
  - system has more than 3x needed RAM
  - and no competition with other processes
  - **or** avoiding bugs / security more important
- Not so good:
  - Limited RAM
  - Competition for physical memory
  - Depends on RAM for performance
    - In-memory database
    - Search engines, etc.

The End