Using Page Residency to Balance Tradeoffs in Tracing Garbage Collection

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Motivation: Balancing Tradeoffs

Between copying and non-copying collection:

- use of space and time (*i.e.* overhead)
- semantic constraints (*e.g.* pinning)
- locality, traversal order, *etc.*

Flexibility is critical:

- not all objects should be treated the same
- application behavior changes over time

Adaptive Hybrid Collection

Our goal:

To build a tracing collector that
dynamically balances these tradeoffs

Must determine collection technique...

- separately for each part of the heap
- at the beginning of each collection

Use residency to adapt to runtime conditions

Outline of Talk

Adaptive Hybrid Collection

- use runtime information to combine copying and non-copying collection

Predicting Residency

- runtime property directly related to costs of these techniques

Experimental Results

- show that adaptive collection performs well in many environments

Adaptive Hybrid Collection

Extend *mostly* copying collection (Bartlett)

- reduce fragmentation in constrained GC

Use a similar mechanism to uniformly account for:

- pinned objects
- large objects
- densely populated pages

By generalizing this mechanism, we will develop a family of hybrid collectors.

Mostly Copying Collection

"Copy objects. . . most of the time."

Key ideas:

- divide heap into pages
- determine strategy for each page dynamically: objects may be evacuated or promoted in place

Gain benefits of copying and non-copying collection

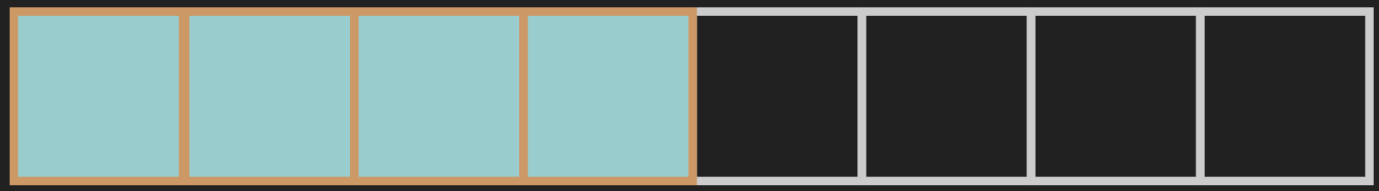
Mostly Copying Collection

divide heap into pages. . .

Mostly Copying Collection

. . . allocate new objects. . .

Mostly Copying Collection

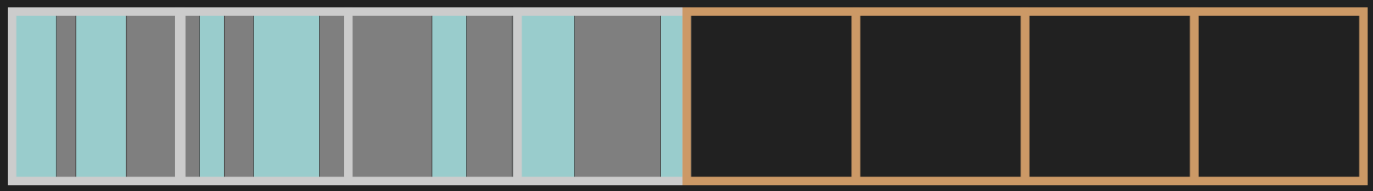


. . . begin collection. . .

Mostly Copying Collection

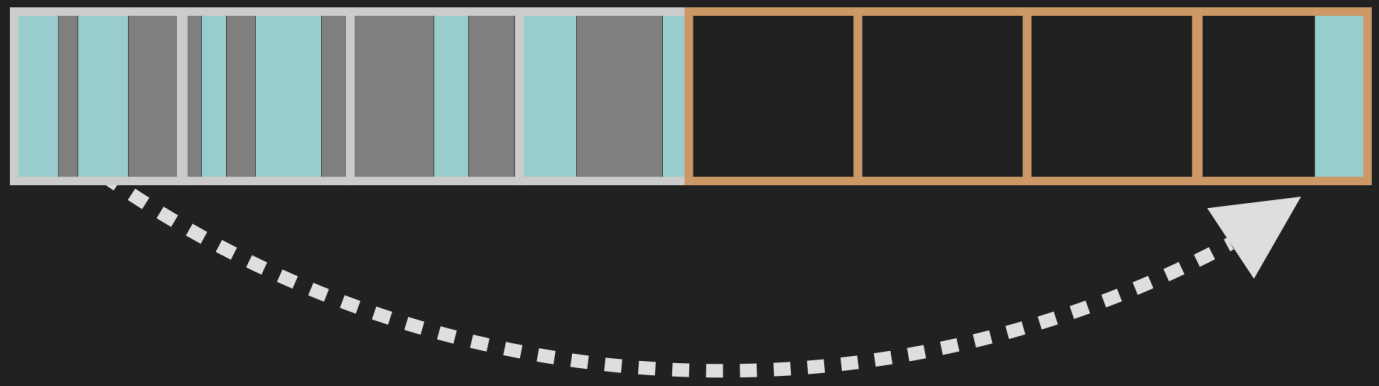
. . . flip. . .

Mostly Copying Collection



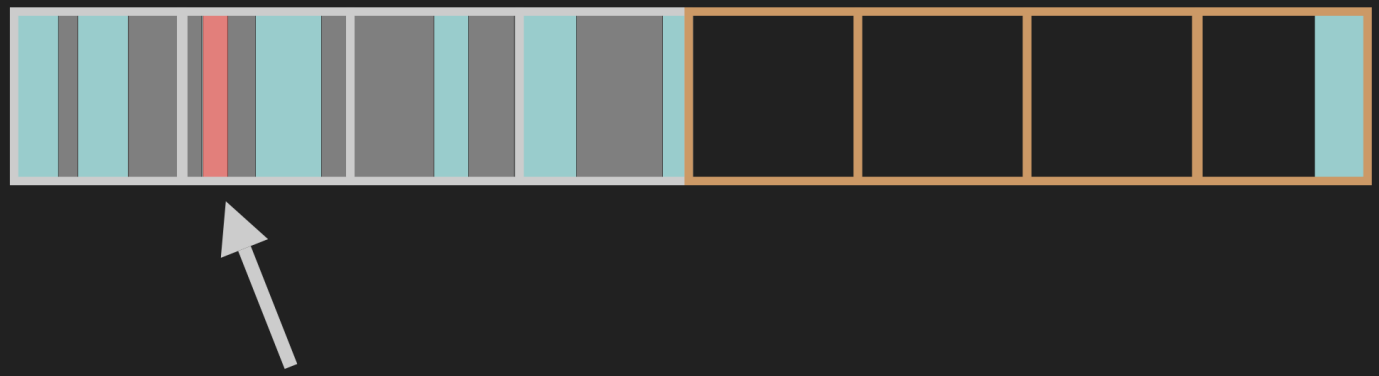
. . . some objects are unreachable. . .

Mostly Copying Collection



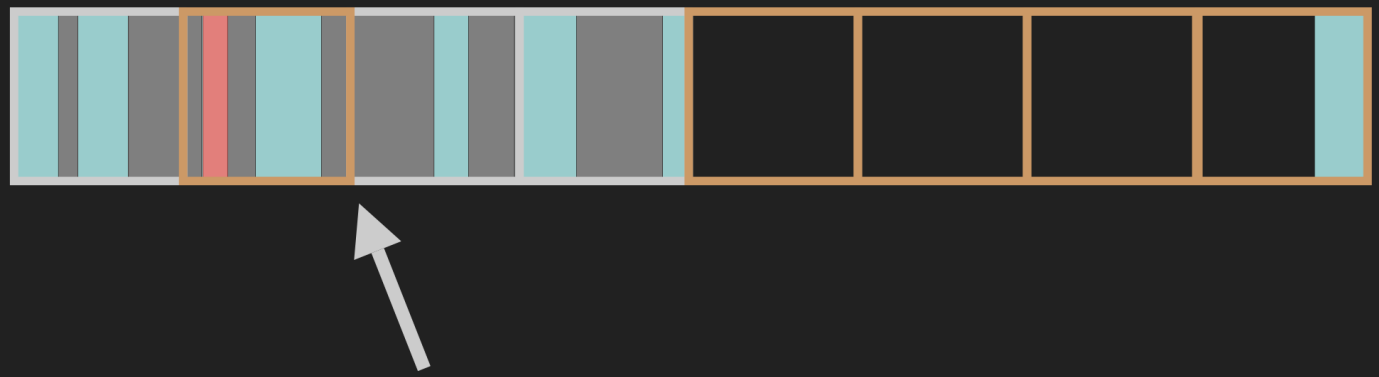
. . . evacuate reachable objects. . .

Mostly Copying Collection



. . . pinned. . .

Mostly Copying Collection



. . . in-place promotion!

Mostly Copying Collection

. . . and reclaim unused space.

Large Objects Shouldn't Be Relocated

Large objects often relegated to separate heap

- . . . because they are expensive to copy

We use in-place promotion instead.

- avoids usual penalties of copying large objects
- no additional heap space required
- use small objects to fill in gaps

Large Objects Shouldn't Be Relocated

They don't cause (much) fragmentation

- little benefit to moving them around

Similarly for densely populated pages:

- expensive to evacuate
- little fragmentation

Page Residency as a Guiding Principle

Residency = density of reachable objects

- avoid evacuating objects from dense pages
- focus on fragmented parts of the heap

Large objects occupy pages with high residency.

- therefore, they are promoted in place

Revisiting Allocation

Copying collectors use a simple space check.

- constant time when there is sufficient space
- requires contiguous unused space

In-place promotion requires more sophisticated management of free space.

- as in mark-sweep collection
- need an unused portion of appropriate size

Revisiting Allocation

Use a list of free gaps on pages promoted in place.

- we use a modified first-fit algorithm

Use residency to avoid allocating on dense pages.

- throw away gaps if residency is too high
- trading space for time

Overview of Our Hybrid Algorithm

Collection strategy is determined for each page.

Two data structures for heap traversal:

- Cheney queues for evacuated objects
- mark stack for objects promoted in place

Allocation using a modified first-fit

- favor free pages (treated as large gaps)
- other free list algorithms also applicable

Two Mechanisms to Reclaim Space

Reclaim space both...

- via evacuation
  - use residency to determine which objects should be evacuated
- during allocation
  - use residency to determine which pages have enough space to make allocation worthwhile

Collector Configurations

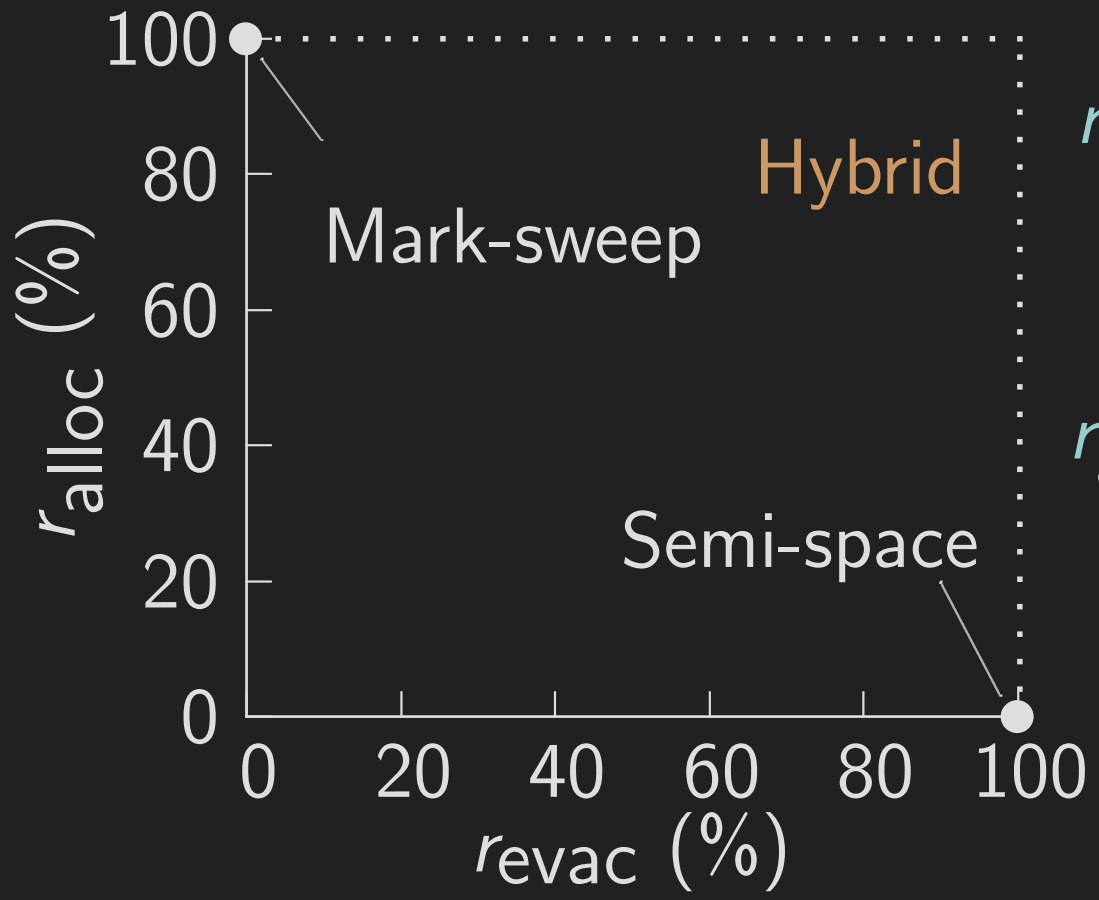
- Two thresholds determine when residency is low enough for evacuation or allocation.

  r_{evac} evacuation threshold,
  maximum residency at which objects are evacuated

  r_{alloc} allocation threshold,
  maximum residency at which free space is reused
  (both measured as % of page)

- Classic algorithms fall out as special cases
  - semi-space: $r_{\text{evac}} = 100\%$, $r_{\text{alloc}} = 0\%$
  - mark-sweep: $r_{\text{evac}} = 0\%$, $r_{\text{alloc}} = 100\%$

A Continuum of Configurations



r_{evac} when objects are evacuated

r_{alloc} when free space is reused

Progress in Talk

So far...

- outlined a hybrid algorithm for garbage collection
- shown how residency thresholds give rise to a continuum of configurations

Next: how to determine residency...

Measuring Residency

Residency can be computed during a heap traversal at little additional cost.

However, we need to know residency at beginning of collection. . .

And to conservatively estimate amount of data to be copied by the end of previous cycle.

Use Past Measurements

One possibility: explicitly measure residency during each collection (using an extra traversal).

Instead, use measurements to predict future values

- historical measurements avoid a second pass over heap
- measured residency still accounts for changes in program behavior over time

Existing Collectors Also Predict Residency

Other hybrids fix residency estimates in advance.

- syntactic properties to distinguish objects
- *e.g.* size, type, allocation point

Age: "Most objects die young."

$\Longrightarrow$ "Nursery is sparsely populated."

- *i.e.* using age to predict residency
- however, generational collectors are often inconsistent in using age (*e.g.* large objects)

Recovering From Poor Predictions

Adaptive GC recovers naturally from poor predictions.

- at most two collections to recover space
- *without* changes to algorithm

Residency is used in two ways:

- to reserve sufficient space for replicas
- to determine how objects are promoted

Overestimation in latter is not a problem.

Recovering From Poor Predictions

Consider the impact of overestimation:

- many sparse pages remain – high fragmentation
- measurements give true residency for each page
- next collection will relocate objects to reclaim space

GC with poor predictions *behaves* like an explicit measurement phase.

- in effect, only corrects predictions when they would be wrong

Allocation Also Compensates For Mistakes

Allocation uses true residency, not predictions.

- actual residency is known at the end of collection

Recovers space *immediately*, no need to wait for another collection

- more overestimation leads to cheaper allocation

Experimental Results

If we know usage patterns of an application in advance, we choose an appropriate algorithm.

- adaptive hybrid GC relieves us of this choice

Consider the impact of heap size on GC overhead

- caveat: other effects of GC not shown here

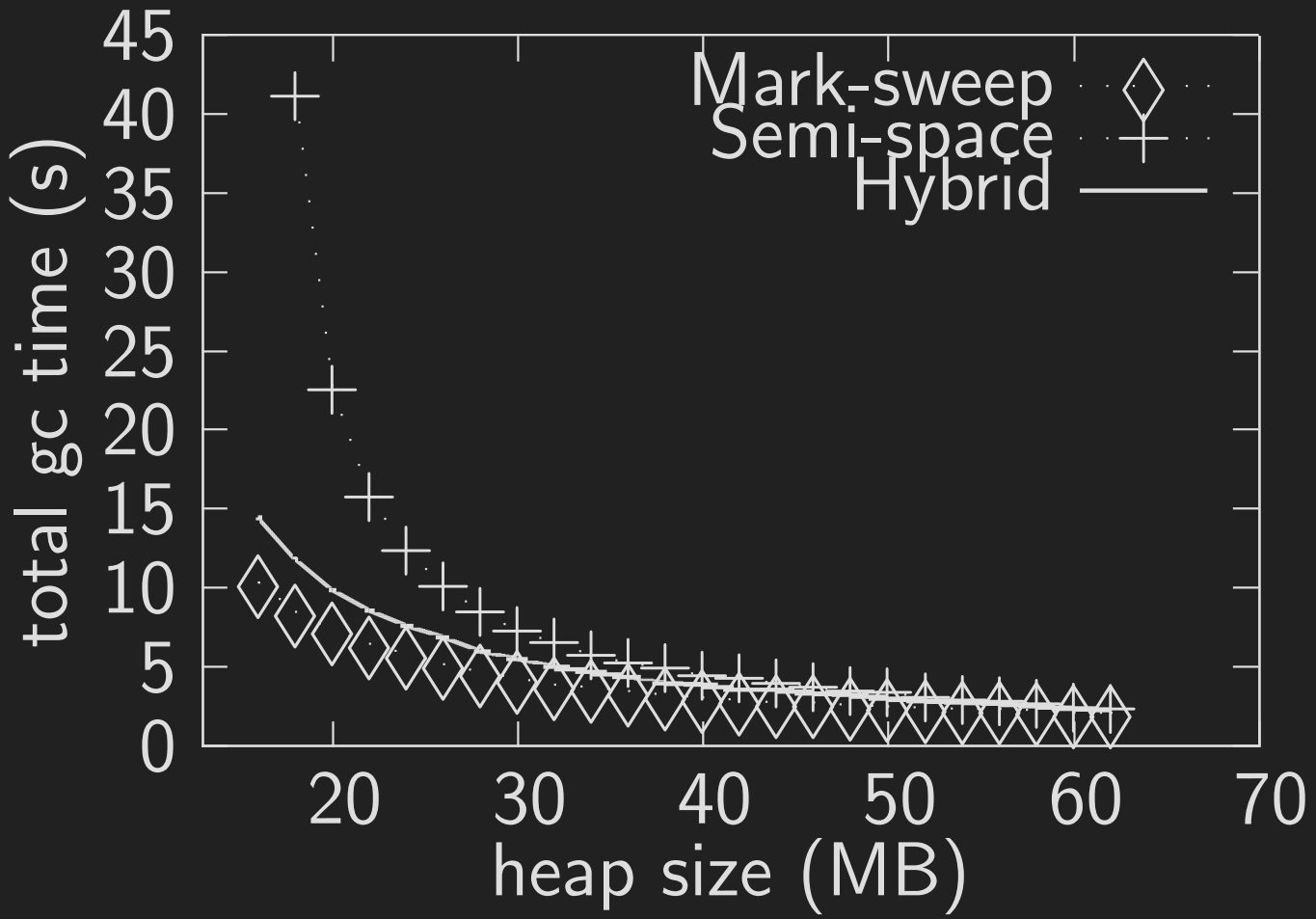
Impact of Heap Size

Heap size = total memory available to collector

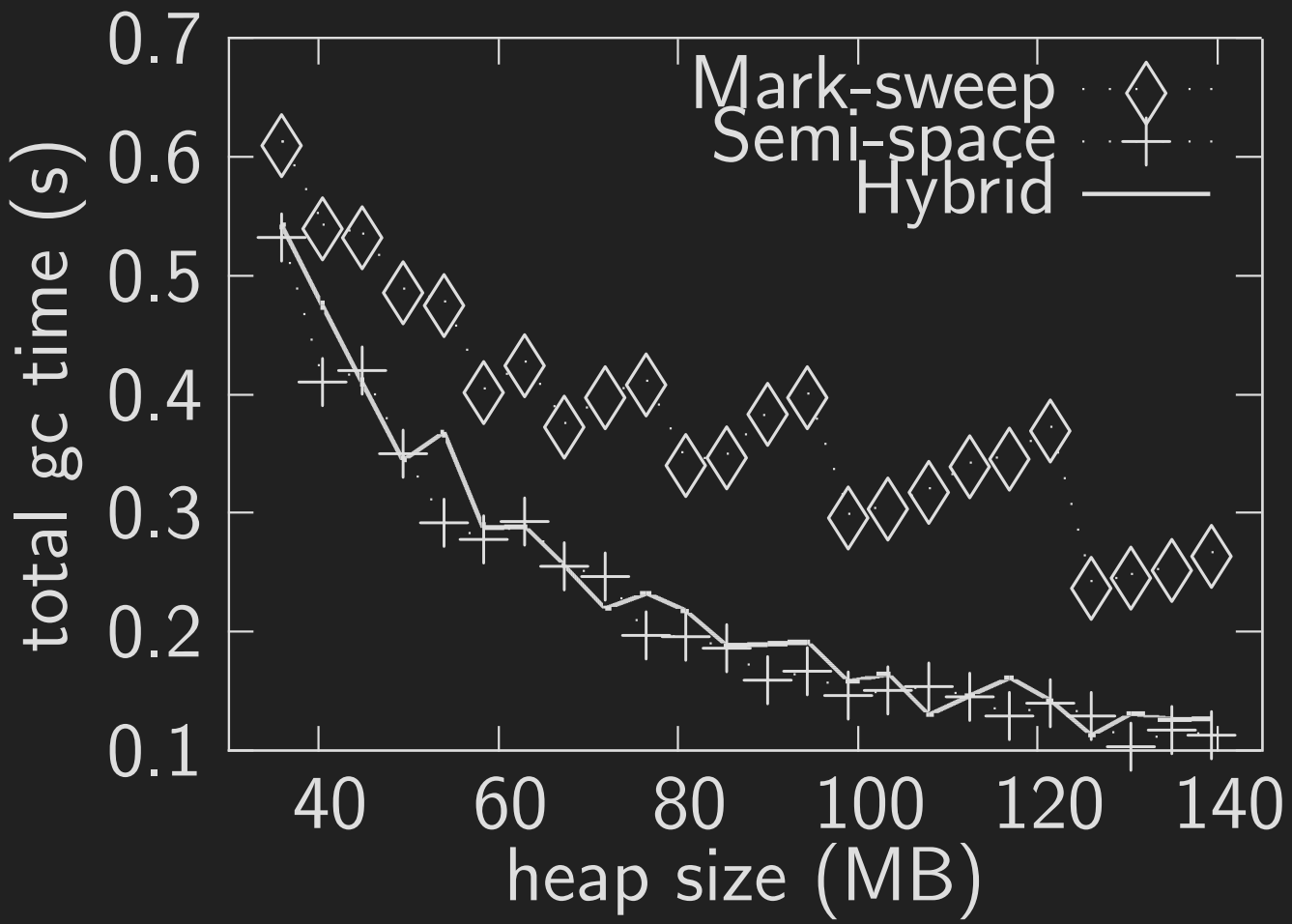
We expect copying collectors to perform well when there is plenty of space.

However, for small heaps, semi-space collectors may not satisfy all allocation requests.

Impact of Heap Size



Impact of Heap Size



Summary of Other Measurements

Same configuration performs well in many different environments

- different applications
- small and large footprints (100 kB to 100 MB)

Insensitive to changes in configuration thresholds

- 90%/90% hybrid is a good choice for our implementation
- small variations don't dramatically change performance

Related Work

- Mostly Copying – Bartlett; Smith & Morrisett
- Dynamic Selection – Soman, Krintz, & Bacon
  (changes collection technique for entire heap)
- Garbage First – Detlefs, Flood, Heller, & Printezis
  (also uses residency as a measure of cost)
- Metronome – Bacon, Cheng, & Rajan
  (different point in the "mostly" design space)

Summary

Adaptive hybrid collection

- combines (non-)copying GC dynamically
- use page residency to guide runtime decisions

Continuous spectrum of tracing collectors

- trade off space for cost of copying objects

Use measurements to adapt to application behavior

- predict residency based on past measurements
- naturally recovers from poor estimates