Scalable Garbage Collection
with Guaranteed MMU

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Problem: Garbage Collection

- Naïve GC introduces pauses
- Generational GC introduces (infrequent) pauses
  - Still disruptive and annoying for users
- Real-time / incremental / concurrent can eliminate delays
  - but at significant cost
Goal:
Scalability in space and time

SPACE: GC META DATA + BOUNDING FLOAT. TIME: PAUSE TIMES, MMU. (Not worried so much about very fine-grained control flow between collector and mutator, but rather the experience for the end-user in interactive applications.)
Control Space:
Metadata & Floating Garbage
Control Time: Max Pause as metric?
(an artificial illustration)
Minimum Mutator Utilization (MMU)

[Cheng and Blelloch ’01]
interval
interval
Our Scalability Theorem

For \textit{all} mutators, no matter what the mutator does:

1. Max GC pause length is independent of heap size
2. MMU bounded from below, independent of heap size
3. Memory usage is \( O(P) \), where \( P \) = peak volume of reachable objects

- Most incremental collectors do not provide theorems like this
- Blelloch and Cheng ’99 is an important exception, but they only provide (1) and (3), not (2).
- We believe they could have proven (2.) after they introduced MMU in 2001, but constant overheads are unclear
“Simple” Idea

- Partition heap into fixed sized “regions”
- Collect each region independently
- Since regions are bounded in size, can do this in bounded time, right (?)
“Simple” Idea

• Partition heap into fixed sized “regions”
• Collect each region independently
• Since regions are bounded in size, can do this in bounded time, right (?)

(Yes, but just barely)
Regional GC Illustrated (review of Cheney)
Here's a region. The ovals are objects, the arrows are references. If you care, you might notice that the orange arrows cross regions (as opposed to the yellow ones) We're just going to collect the middle stuff; the \{A, X, Y\} belong to regions elsewhere. Start by scanning the object A
Scanning A implies M is reachable from A; copy M to M' (which includes that reference to N), install a forwarding pointer from M to M', and continue scanning A.
Scanning A also finds a reference to O, so forward that to O’. We’re done scanning A, so let’s just continue from left-to-right and scan M’ next.
Scanning $M'$ uncovers that reference to $N$; forward that to $N'$. Continuing left-to-right means scanning $O'$ and $N'$, which uncovers no more references within the region. So move on to the right side, where we have $X$ and $Y$...
Scanning Y reveals that reference to O that needs to be updated to O'. Now we’ve finished scanning everything we need to. Note there are no more references into the region we were collecting; we can reclaim it!
And we are done.
I hand-waved about scanning the stuff on the left and right of the region, but in fact that's the name of the game here!
Goal: Avoid inspecting extraneous state

We don’t want to scan the whole heap outside of the region, because that would break our pause time bounds.
Remembered Set?

([Lieberman and Hewitt '83]),
[Ungar '84]

We might first take inspiration from generational collectors. The original Lieberman and Hewitt paper on GenGC was actually trying to solve the very problem we’re talking about. So how about REMEMBERING the objects that have region-crossing references?
Remembered Set $\supseteq \{a, m, y\}$

So we could try to maintain a remembered set that captures all of the objects with region-xing ref’s (and maybe others too; it’s allowed to be imprecise).
Problem with Remembered Set
Remembered set can grow proportional to size of heap

scan time generally not proportional to region size
Remembered Set holds junk irrelevant to current GC

(still useful; still used)
Try maintaining state per-region?

(Garbage-First [Detlefs ’04])
PATTER: “Don’t have a slogan. Realized workshop deadline was approaching, so I’ll resort to just summarizing the approach here, and later we will refine our view of the approach after the whole picture has been developed.”
Summarize as deadline approaches; Refine after whole picture has been developed
Summary Sets
This summary set $\supseteq \{ \&a[1], \&a[3], \&y[0] \}$

Apologies for the C notation. It's there to STRESS that we're talking tracking locations, not objects, in the summary sets. The paper discusses this more. Note also that M is not in this summary set; its slot will be present in the summary set for some OTHER region.
Summary Set Structure

- Summary set structure focuses attention away from irrelevant objects
- Does it work?
  - Popular objects / regions
  - Space cost
#1: The Popularity Problem

- Many locations may point to one object
  - (or group of objects co-located in same region)

- Implies LARGE summary for that region

This is a real-world issue; consider the symbol table for a compiler, or instances of the singleton pattern, interned objects, ... etc
#2: The Space Problem

- Maintaining *precise* summary sets for every region at all times is unrealistic
  - (too much overhead in time)

- Maintain *imprecise* summary sets?
  - Entails unacceptable worst case space overhead
  - i.e. \(O(N^2)\) where \(N\) is heap size
  - Garbage-First [Detlefs ’04] had this problem
Insight from Lake Woebegon

[Keillor ’85]
Solving both problems: Insight #1

- Not all regions can be more popular than average
  - Generalizes nicely via a pigeon-hole argument

- Therefore, we may be able to skip collection of popular regions entirely!
Applying Popularity Insight

- Do not maintain summary sets at all times
- Instead construct afresh on “just-in-time” basis
- Wave off collection of popular regions
  - i.e. those with summary set \( \geq S \cdot R \)
  - (don’t bother finishing their summaries)
New problem

- Constructing one summary generally requires scanning whole heap
- Not necessarily time between collection of region $r$ to construct summary for region $r'$
Insight #2

• Amortize the effort!

• Construct the summary sets for many regions at once during one incremental scan
The Basic Idea
The Basic Idea

UNFILLED

U1
U2

FILLED

F14
F13
F12
F11
F10

READY

R2
R3
R4

SUMMARIZING

S5
S6
S7
S8
S9
The Basic Idea

UNFILLED

U1  U2  U3

U15

READY

R3  R4

FILLED

F14  F13  F12  F11  F10

SUMMARIZING

S5  S6  S7  S8  S9
The Basic Idea

UNFILLED
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The Basic Idea

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U1  U2  U4  U3

FILLED

F15  F14  F13  F12  F11  F10

READY

SUMMARIZING

S5  S6  S7  S8  S9

ready!
The Basic Idea

UNFILLED

U1  U2  U4
U3

FILLED

F15  F14  F13  F12  F11  F10

READY

R5  R6  R7  R9

SUMMARIZING

summarize!
The Basic Idea

UNFILLED
- U1
- U2
- U4
- U3

FILLED
- F13

READY
- R5
- R6
- R7
- R9

SUMMARIZING
- S15
- S14
- S12
- S11
- S10
What about skipping the popular regions?
NOTE: You have to choose the right policy parameters here for the theorem to hold true!
Last Problem & Insight #3

- How to collect region crossing cycles?
  - How to ensure amount of floating garbage remains in \( O(\text{Reachable State}) \)?

- Use Snapshot-at-the-Beginning (SATB) [Yuasa’90] to refine remembered set and summary sets
  - (also ensures popular regions won’t hold onto other regions’ state forever!)

the paper discusses this more
SATB Refinement Illustrated
what if (a) were unreachable and in a region with popular objects?
Before Refinement

(a) (not collected)

(m) (still collected)
After Refinement

(a) (not collected)

(m) n o p q

(x)

(y) (still collected)
Prototype implementation in Larceny
Evaluation:
One Difficult Benchmark
The Queue Benchmark

- Repeatedly:
  - allocate list of one million elements
  - store each list into circular buffer of size $k$
- List elements drawn from $p$ popular objects
  - (for $p$ of zero, list elements are small integers)
- Regular steady-state behavior
  - approximating pause time: “MaxVary”

MaxVary: calculated by subtracting the average time to create a million element list from the longest time to create one of those lists. Reasonably approximates pause time under certain assumptions
Comparison against: Larceny, other Schemes, and JVM
## queue 160 MB

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<tr>
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<th>Elapsed</th>
<th>GC Time</th>
<th>GC Pause</th>
<th>MaxVary</th>
<th>MaxRSIZE</th>
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Gambit: Stop&Copy; Ypsilon: MostlyConcurrent; Chicken: Cheney-on-the-MTA; PLT: Generatational; Ikarus: Generational. Suffixes legend:: Regional, Generational, Parallel, Stopandcopy, IncrementalMarkSweep
### queue 800 MB

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queue 800 MB + 50 pop. obj.’s

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Point out that the blur of triangles is a bunch of entries for the Regional Collector!
Observed MMU, 800 MB live

- **Regional**
- **Generational**
- **Stop and Copy**

0 ms  | 2,500 ms  | 5,000 ms  | 7,500 ms  | 10,000 ms
0%    | 7.5%      | 15.0%     | 22.5%     | 30.0%
Related Work (lots)

- “Windows” of MarkCopy [Sachindran & Moss ’03]
- Parallel Incremental Compaction [Ben-Yitzhak et al ’02]
- Older-First GC [Stefanovic et al. ’02] [Hansen and Clinger ’02]
- Metronome [Bacon et al 2003]

Windows are much like our Summary Sets; Parallel Incr Compaction also had something much like our Summary Set Structure. (The specific goals of those systems differed from our own.)

For OLDER FIRST, the connection is that our round robin selection of regions to collect is very much like an older-first strategy.

For METRONOME, they do provide guarantees on MMU and SPACE USAGE, but only when given a priori models of the particular mutator behavior (!). We have an explicit goal of not requiring such knowledge in the collector.
Future Work

- SATB Marking and Summarization could be performed concurrently with the mutator
- Regional copying GC could itself be parallelized
- More thorough description of the implementation technologies ("what fun hacks did Felix need?")
Conclusion

- Described and prototyped a *regional* collector
  - novel, elegant solutions for popularity and float
- Proved that regional collector is *scalable*
- Compared performance for near worst case benchmark
Thanks
Summarize as deadline approaches; Refine after whole picture has been developed.

(a slide I did not think to include at actual workshop, but WISH I HAD, as it completes the "slogan story" appropriately at the end of the design presentation.)

(a slide I did not include at the end of presentation at actual workshop, but wish I had.)