Shenandoah GC

...and how it looks like in September 2017

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Disclaimers

This talk:

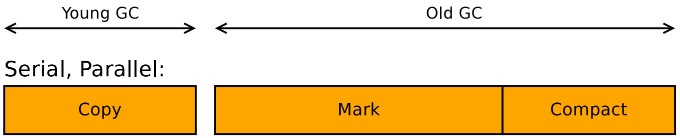
1. ...assumes some knowledge of GC internals: this is implementors-to-implementors talk, not implementors-to-users – we are here to troll for ideas

2. ...briefly covers successes, and thoroughly covers challenges: mind the **availability heuristics** that can confuse you into thinking challenges outweigh the successes

3. ...covers many topics, so if you have blinked and lost the thread of thought, wait a little up until the next (ahem) safepoint

Overview

Overview: Landscape



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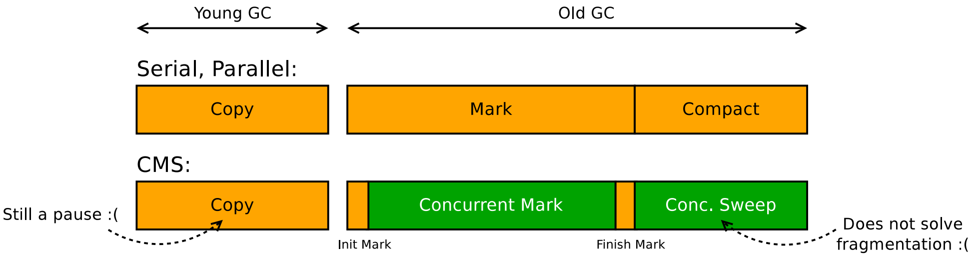

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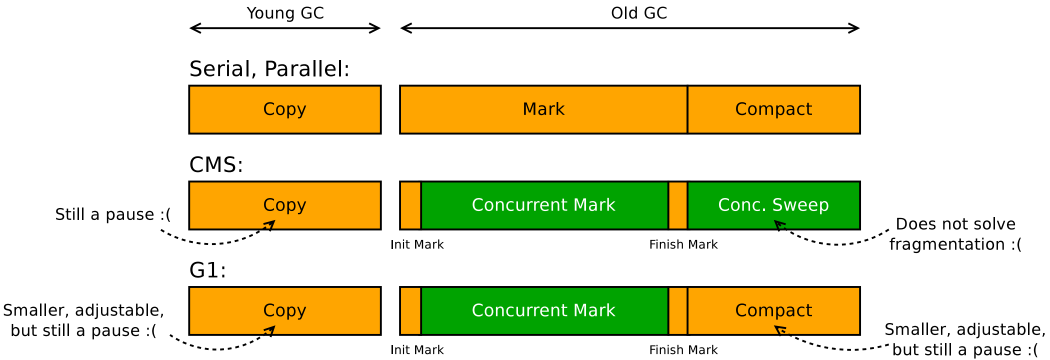

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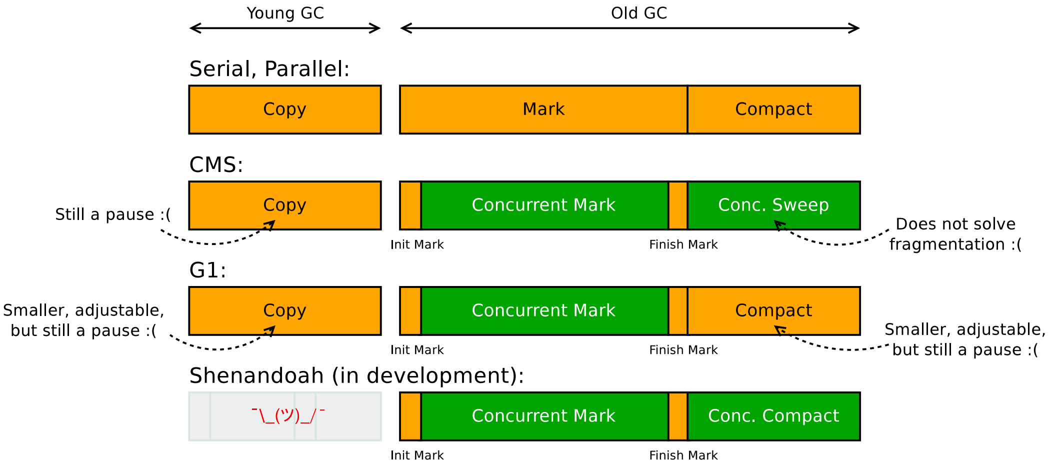

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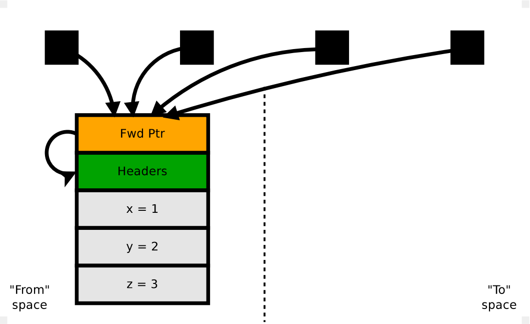
Overview: Key Idea

Brooks forwarding pointer to help concurrent copying:



fwdptr is attached to every object, at all times

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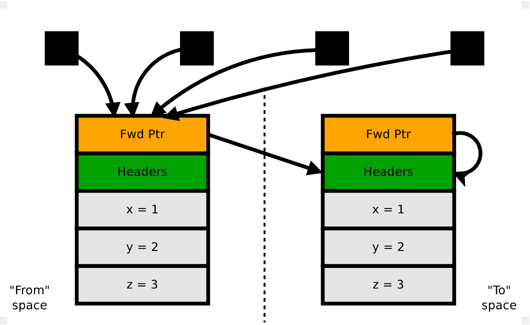

fwdptr always points to most actual (to-space) copy, and gets atomically updated during evacuation

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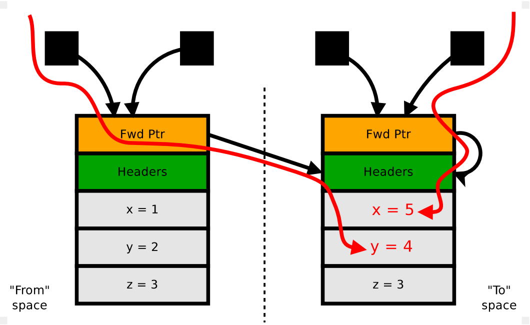

Barriers maintain the to-space invariant:
«All writes happen into to-space copy»

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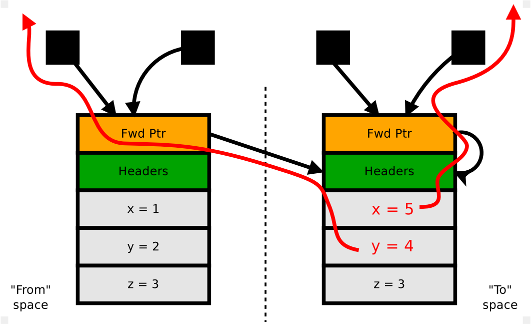
Brooks forwarding pointer to help concurrent copying:



Barriers also help to select the to-space copy for reading

Overview: Key Idea

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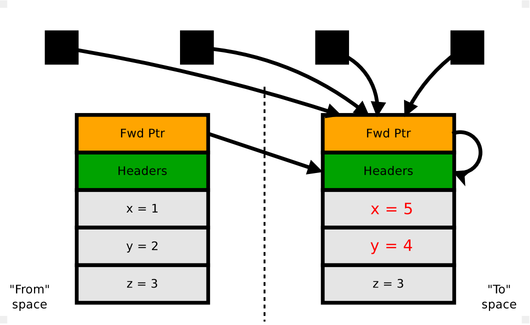
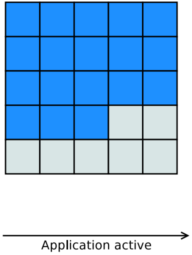


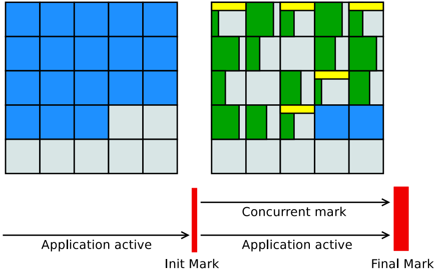
Allows to update the heap references concurrently too

Overview: GC Cycle



Regular cycle:

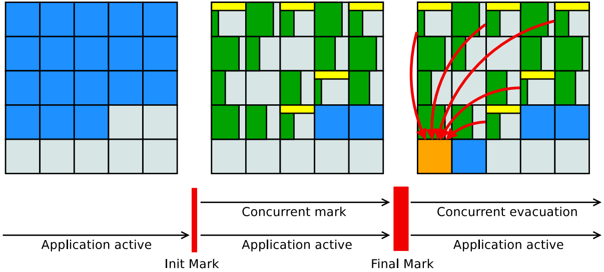
Overview: GC Cycle



Regular cycle:

1. Snapshot-at-the-beginning concurrent mark

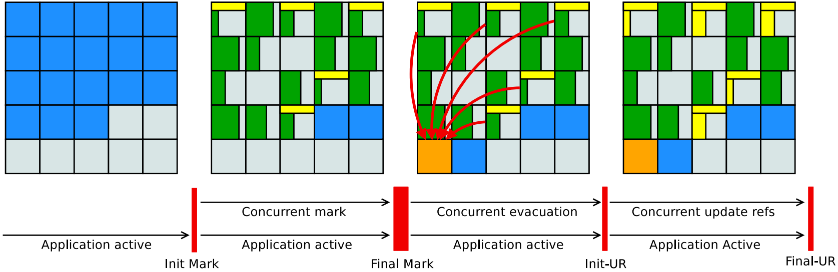
Overview: GC Cycle



Regular cycle:

1. Snapshot-at-the-beginning concurrent mark
2. Concurrent evacuation

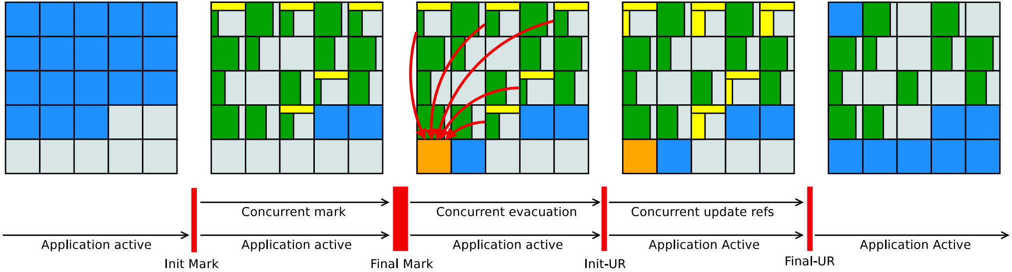
Overview: GC Cycle



Regular cycle:

1. Snapshot-at-the-beginning concurrent mark
2. Concurrent evacuation
3. Concurrent update references (optional)

Overview: GC Cycle



Regular cycle:

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2. Concurrent evacuation
3. Concurrent update references (optional)

Successes

Successes: Almost Concurrent Works!

LRUFragger, 100 GB heap, ≈ 80 GB LDS:

```
Pause Init Mark 0.437ms
Concurrent marking 76780M->77260M(102400M) 700.185ms
Pause Final Mark 77260M->77288M(102400M) 0.698ms
Concurrent cleanup 77288M->77296M(102400M) 0.176ms
Concurrent evacuation 77296M->85696M(102400M) 405.312ms
Pause Init Update Refs 0.038ms
Concurrent update references 85700M->85928M(102400M) 319.116ms
Pause Final Update Refs 85928M->85928M(102400M) 0.351ms
Concurrent cleanup 85928M->56620M(102400M) 14.316ms
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Successes: Concurrent Means Freedom

Mostly concurrent GC is very liberating!

- No rush doing concurrent phases: slow concurrent phase means more frequent cycles ⇒ steal more cycles from application, not pause it extensively
- Heuristics mistakes are (usually) much less painful: diminished throughput, but not increased pauses
- Control the GC cycle time budget: `-XX:ConcGCThreads=...`

Successes: Progress

Concurrent collector runs GC cycles without blocking mutator progress (translation: BMU/MMU is really good)

That means, we can do:

- ...thousands of GC cycles per minute ⇒ Very efficient testing that surface the rarest bugs
- ...**continuous** GC cycles when capacity is overwhelming ⇒ Ultimate sacrifice of throughput for latency
- ...**periodic** GCs without significant penalty ⇒ Idle applications get their floating garbage purged

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Successes: Non-Generational Workloads

Shenandoah does not **need** Generational Hypothesis to hold true in order to operate efficiently

- Prime example: LRU/ARC-like in-memory caches
- It would **like** GH to be true: immediate garbage regions can be immediately reclaimed after mark, and cycle shortcuts
- **Partial** collections may use region age to focus on «younger» regions

Successes: Barriers Injection

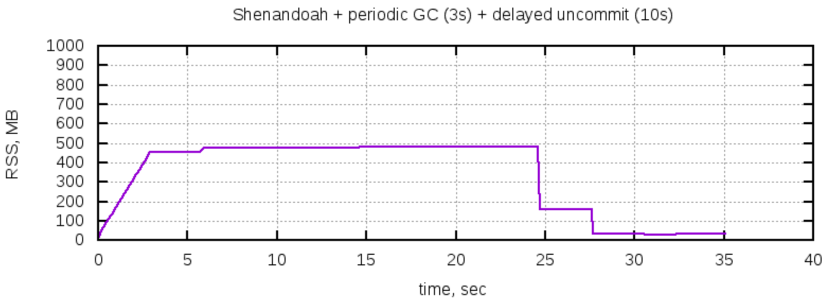
Educated Bystander concern:
Where to inject the barriers?

Reality:

- Most heap accesses from VM are done via native accessors
- Most VM parts (e.g. compilers) hold on to JNI handles
- A very few naked reads and stores are done
- Story gets much better with JEP 304 «GC interface»
- Internal heap verification helps to catch missing barriers

Successes: Heap Management

Regionalized heap allows (un)committing individual regions



Some are willing to trade increased peak footprint for better idle footprint: per-region heap uncommit + periodic GCs

Successes: Releases

Easy to access (development) releases: try it now!

- Development in separate JDK 10 forest, regular backports to separate JDK 9 and 8u forests
- JDK 8u backports ship in RHEL 7.4+, Fedora 24+
- Nightly development builds (tarballs, Docker images)

```
docker run -it --rm shipilev/openjdk:10-shenandoah \
    java -XX:+UseShenandoahGC -Xlog:gc -version
```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Challenges

Challenges: Footprint Overhead

Shenandoah requires additional word per object
for forwarding pointer at all times

- 1.5x worst case and 1.05-1.10x average overhead – but, counted **in Java heap**, not native structures – easier capacity planning
- Current pointer is uncompressed, no gain to compress due to object alignment constraints
- Moving fwdptr into synthetic object field promises substantial improvements – but, read barriers are already very overheady

Challenges: Barriers Overhead

Shenandoah requires much more barriers

1. SATB barriers for regular cycles
2. Write barriers on **all stores**, not only reference stores
3. Read barriers on **almost all heap reads**
4. Other exotic flavors of barriers: acmp, CAS, clone, ...

Challenges: Read Barriers

```
# Read Barrier: dereference via fwdptr
mov    -0x8(%r10),%r10     # obj = *(obj - 8)

# read the field at offset 0x30
mov    0x30(%r10),%r10d    # val = *(obj + 0x30)
```

- Very simple: single instruction
- Very frequent: before almost every heap read
- Optimizeable: move heap accesses ⇒ move the barriers
- Accounts for 0..15% throughput hit, depending on the workload

Challenges: Write Barriers

```
# Read TLS flag and see if evac is enabled
movzbl 0x3d8(%r15),%r11d    # flag = *(TLS + 0x3d8)
test   %r11d,%r11d          # if (flag) ...
jne    OMG-EVAC-ENABLED     # No, no, no!

# Not enabled: read barrier
mov    -0x8(%rbp),%r10      # obj = *(obj - 8)

# Store into the field!
mov    %r10,0x30(%r10)      # *(obj + 0x30) = r10
```

Challenges: Write Barriers

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Writing to field? Locking on object? Computing identity hash code? Writing down new klass? All those are object stores, all require WB

Challenges: Write Barriers

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```

Writes are rare, fast-path is fast, throughput overhead is 0..5%

Challenges: Exotic Barriers

Shenandoah-specific barriers: making sure comparisons work when **both** copies of the object are reachable.

Unequal machine ptrs $\neq$ unequal Java references now!

- `acmp` barrier: on comparison failure, do RBs, compare again
- Java ref comparisons in native VM code have to do it too
- `CAS` barrier: on CAS failure, do magic to dodge false positives
- Normally cost $< 1\%$ throughput

Challenges: Compiler Support

The key thing to cope with barriers overhead is Shenandoah-specific compiler optimizations *(this is also the major source of interesting bugs)*

- Hoisting read and write barriers out of the loops
- Eliminating barriers on known new objects, known constants
- Bypassing read barriers on unordered reads, e.g. `final`-s
- Optimizeable barriers straight in IR
- Coalescing barriers: SATB+WB, back-to-back barriers, etc

Challenges: Compiler Support[1]

	C1			C2		
Test	**G1**	**Shen**	**%diff**	**G1**	**Shen**	**%diff**
Cmp	79	74	-7%	127	121	-5%
Cpr	125	86	-31%	146	125	-15%
Cry	79	63	-21%	232	227	-2%
Drb	78	70	-11%	165	156	-6%
Mpa	31	21	-33%	50	40	-19%
Sci	42	31	-25%	74	66	-10%
Ser	1639	1279	-22%	2471	2101	-15%
Sun	99	75	-24%	112	98	-13%
Xml	89	70	-21%	190	170	-11%

C1 codegens good barriers, but C2 **also** does high-level optimizations

[1] Caveat: Author made this experiment while inebriated after conference dinner, so...

Challenges: STW Woes

Pauses $\approx 1\ ms$ leave little time budget to deal with,
but need to scan roots, cleanup runtime stuff, walk over regions...

Consider:

- Thread wakeup latency is easily more than $200\ us$: parallelism does not give you all the bang – some parallelism is still efficient
- Processing 10K regions means taking $100\ ns$ per region. Example: you can afford marking regions as «dirty», but cannot afford actually recycling them during the pause

In Progress

In Progress: VM Support

Pauses $\leqslant 1\ ms$ require more runtime support

Some examples:

- Time-To-SafePoint takes about that even without loopy code
- Safepoint auxiliaries: stack scans for method aging takes $> 1\ ms$, cleanup can easily take $\ggg 1\ ms$
- Lots of roots, many are hard/messy to scan concurrently or in parallel: StringTable, synchronizer roots, etc.

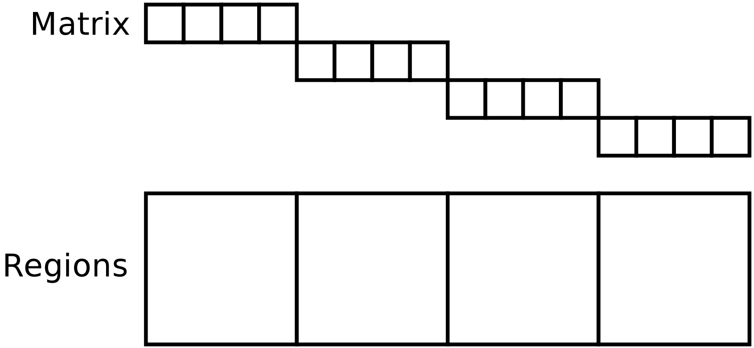
In Progress: Partials

Full heap concurrent cycle takes the *throughput* toll on application.
Idea: partial collections!

- Requires knowing what parts of heap to scan for incoming refs
  - Card Table for Serial, Parallel, CMS
  - Card Table + Remembered Sets for G1
- Differs from regular cycle: selects the collection set without prior marking, thus more conservative
- *Generational* is the special case of partial

In Progress: Partials, Connection Matrix

Concurrent collector allows for very coarse «connection matrix»:



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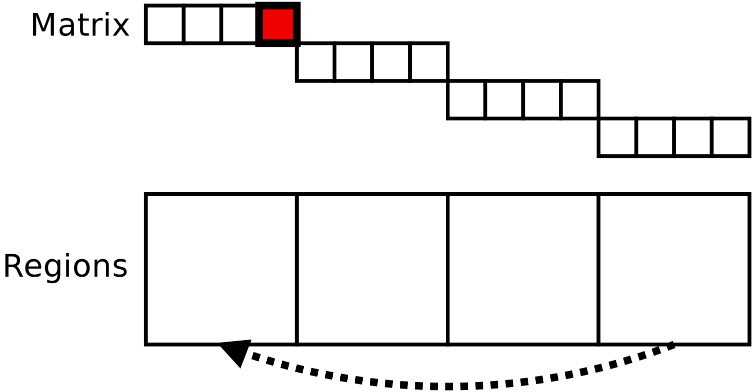

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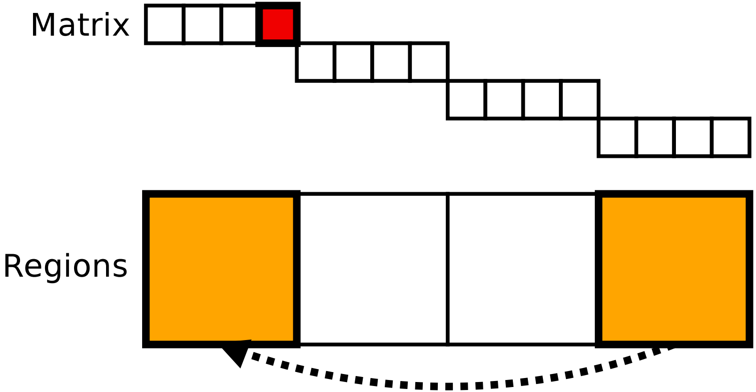


In Progress: Partial, Status

Current partial machinery does work!

- Implemented GC infra, and matrix barriers in all compilers
- Can use timestamps to bias towards younger and older regions
- Caveat, they are STW in current experiment:

```
GC(7) Pause Partial 2103M->2106M(10240M) 4.209ms
GC(7) Concurrent cleanup 2106M->59M(10240M) 5.288ms
```

- Anecdote: sometimes, partial STW is shorter than regular STWs

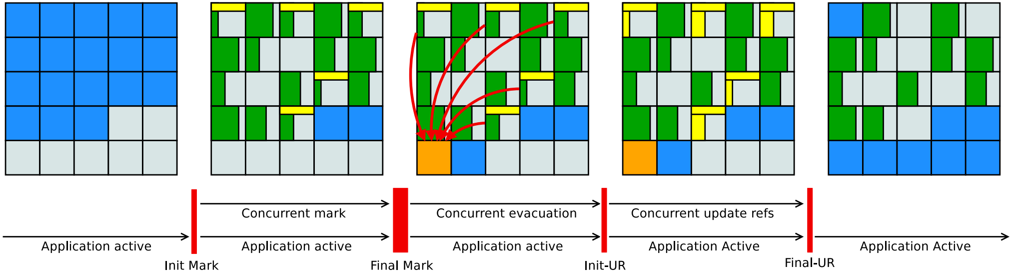
In Progress: Concurrent Partial

Next step:
making partial collections *concurrent*
(work in progress)

Q: Matrix consistency during concurrent partial?
Q: New barriers required?
Q: Regular concurrent cycle is the special case of partial?

In Progress: Traversal Order

Spot the trouble:



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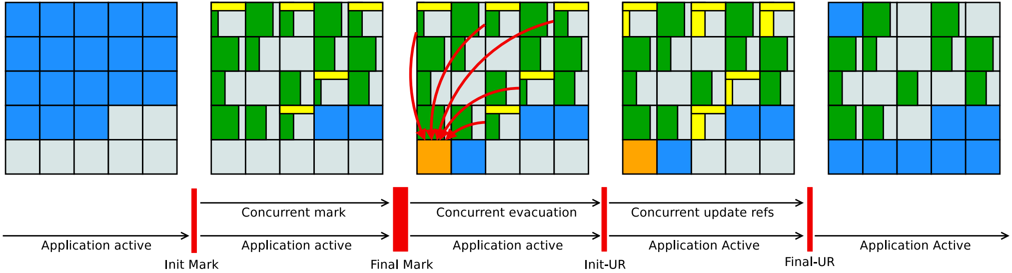

Separate marking and evacuation phases mean collector maintains the *allocation* order, not the *traversal* order

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In Progress: Traversal Order

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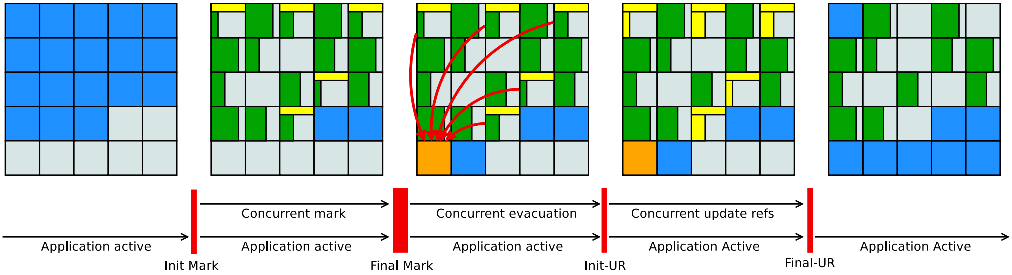
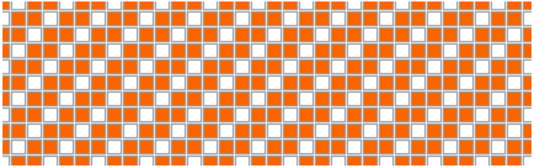


Q: Can coalesce evacuation and update-refs?

Q: Concurrent Partial can coalesce the phases?

In Progress: Humongous and 2^K allocs

`new byte[1024*1024]` is the best fit for regionalized GC?



- Actually, in G1-style humongous allocs, the **worst** fit: objects have headers, and 2^K-sized alloc would barely **not** fit, wasting one of the regions

Q: Can be redone with segregated-fits freelist maintained separately?

In Progress: Application Pacing

Concurrent collector GC relies on collecting faster than applications allocate: applications **always** see there is available memory

- In practice, this is frequently true: applications rarely do allocations only, GC threads are high-priority, there enough space to absorb allocations while GC is running...
- In some cases of *overloaded* heap, application outpaces GC, yielding Allocation Failure, and prompting STW

Q: Pace the application when heap is close to exhaustion?

In Progress: SATB or IU

SATB overestimates liveness:
all *new* allocations during mark are implicitly live

- Keeps lots of floating garbage that would need to wait for another cycle to be collected
- Has interesting implications on weak references processing: e.g. deadly embracing `Reference.get()`...

Q: Is incremental update more suitable here?

Conclusion

Conclusion: Ready for Experimental Use

Try it.

Break it.

Report the successes and failures.

`https://wiki.openjdk.java.net/display/shenandoah/Main`