Shenandoah GC

Part I: The Garbage Collector That Could

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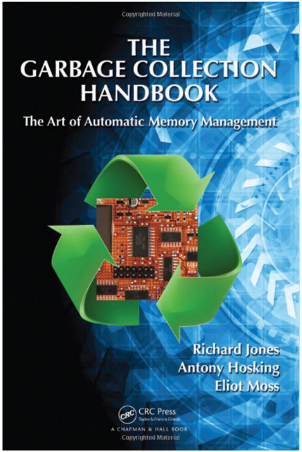
Safe Harbor / Тихая Гавань

Anything on this or any subsequent slides may be a lie. Do not base your decisions on this talk. If you do, ask for professional help.

Всё что угодно на этом слайде, как и на всех следующих, может быть враньём. Не принимайте решений на основании этого доклада. Если всё-таки решите принять, то наймите профессионалов.

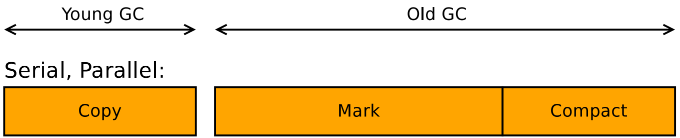
This Message Is Brought To You By



- IMHO, discussing GC without having first read the «GC Handbook» is a waste of time, and regurgitating known stuff
- It may appear that $\$name$ GC is a super-duper-innovative, but in fact many GCs reuse (or reinvent) ideas from that textbook

Overview

Overview: Landscape



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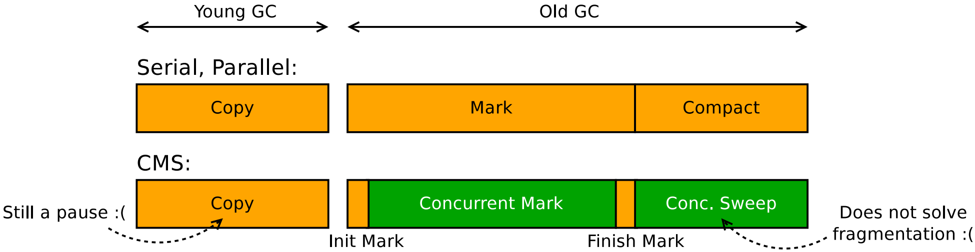

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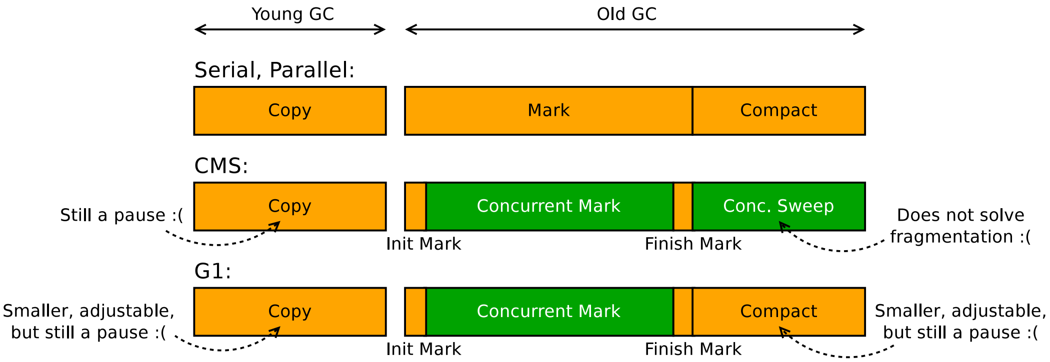
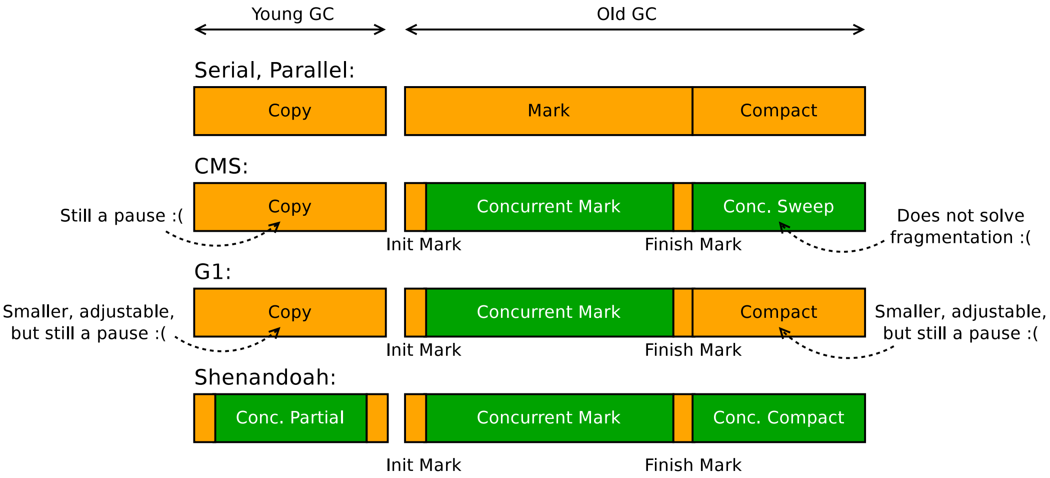
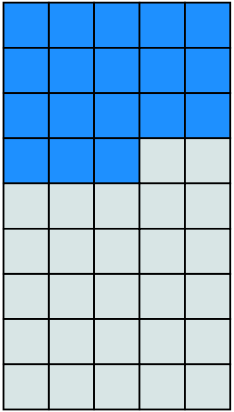


Overview: Landscape



redhat

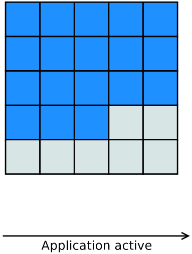
Overview: Heap Structure



Shenandoah is a *regionalized* GC

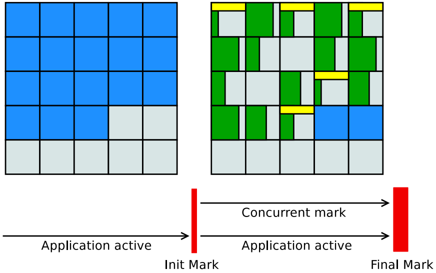
- Heap division, humongous regions, etc are similar to G1
- Collects garbage regions first by default
- Not generational by default, no young/old separation, even temporally
- Tracking inter-region references is not needed by default

Overview: Cycle



Three major phases:

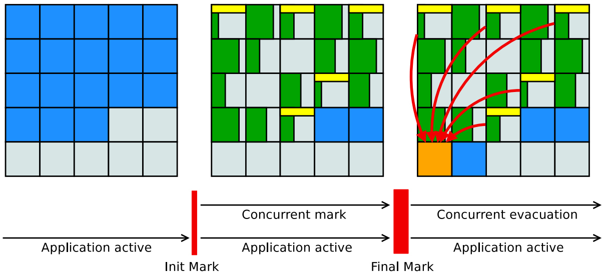
Overview: Cycle



Three major phases:

1. Snapshot-at-the-beginning concurrent mark

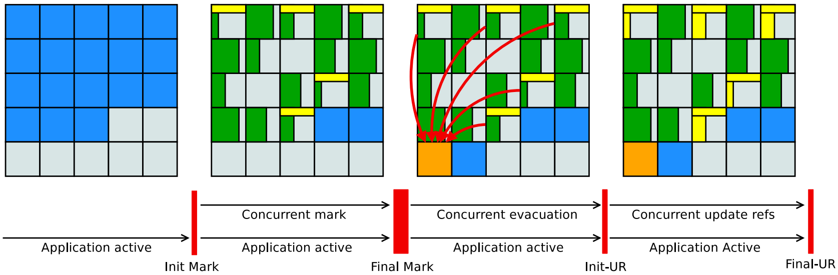
Overview: Cycle



Three major phases:

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

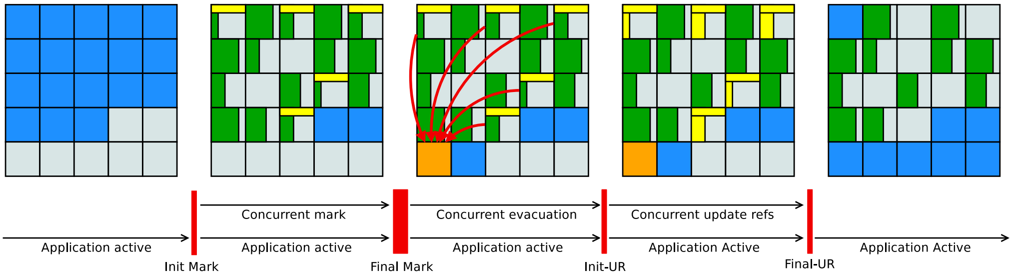
Overview: Cycle



Three major phases:

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

Overview: Cycle



Three major phases:

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2. Concurrent evacuation
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Overview: Usual Log

LRUFragger, 100 GB heap, ≈ 80 GB LDS:

```
Pause Init Mark 0.437ms
Concurrent marking 76780M->77260M(102400M) 700.185ms
Pause Final Mark 0.698ms
Concurrent cleanup 77288M->77296M(102400M) 3.176ms
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 0.351ms
Concurrent cleanup 85928M->56620M(102400M) 14.316ms
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Basics

Concurrent Mark: Reachability

To catch a garbage, you have to ~~*think like a garbage*~~
know if there are references to the object

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Three basic approaches:

1. **No-op**: ignore the problem, and treat everything as reachable *(see Epsilon GC)*

Concurrent Mark: Reachability

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2. **Mark-***: walk the object graph, find reachable objects, treat *everything else* as garbage

Concurrent Mark: Reachability

To catch a garbage, you have to ~~*think like a garbage*~~
know if there are references to the object

Three basic approaches:

1. **No-op**: ignore the problem, and treat everything as reachable *(see Epsilon GC)*
2. **Mark-***: walk the object graph, find reachable objects, treat *everything else* as garbage
3. **Reference counting**: count the number of references, and when refcount drops to 0, treat the object as garbage

Concurrent Mark: Three-Color Abstraction

Assign *colors* to the objects:

1. White: not yet visited
2. Gray: visited, but references are not scanned yet
3. Black: visited, and fully scanned

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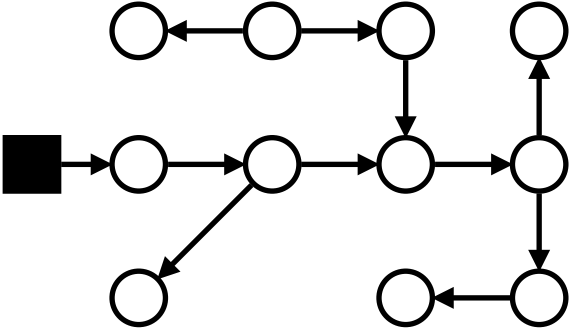
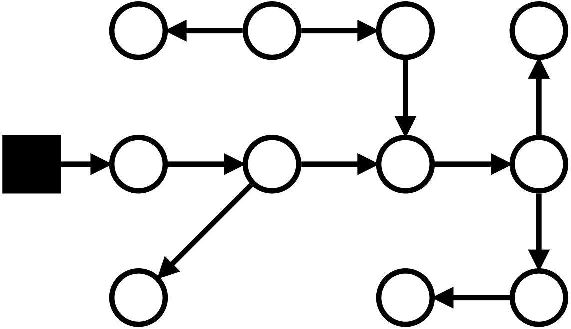
Daily Blues:
«All the marking algorithms do is
coloring white gray, and then coloring gray black»

Concurrent Mark: Stop-The-World Mark



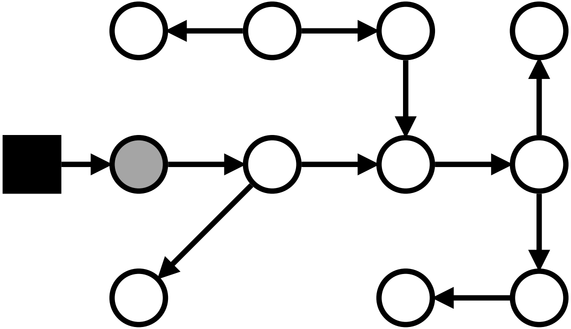
When application is stopped, everything is trivial!
Nothing messes up the scan...

Concurrent Mark: Stop-The-World Mark



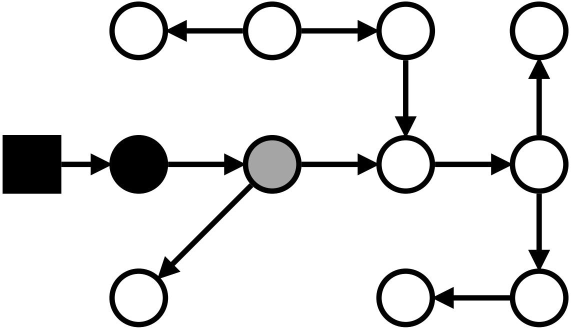
Found all roots, color them Black,
because they are implicitly reachable

Concurrent Mark: Stop-The-World Mark



References from Black are now Gray, scanning Gray references

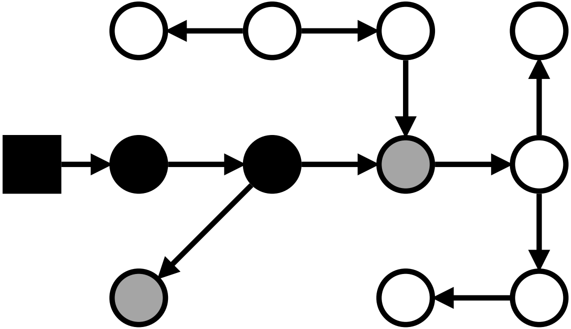
Concurrent Mark: Stop-The-World Mark



Finished scanning Gray, color them Black;
new references are Gray

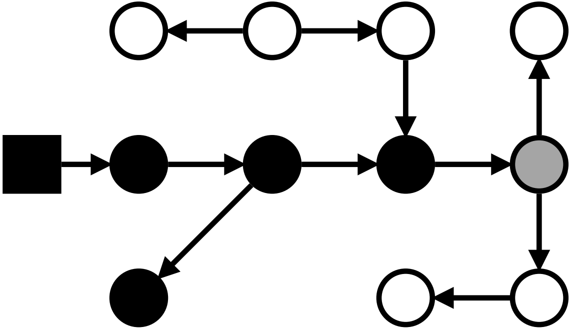
redhat.

Concurrent Mark: Stop-The-World Mark



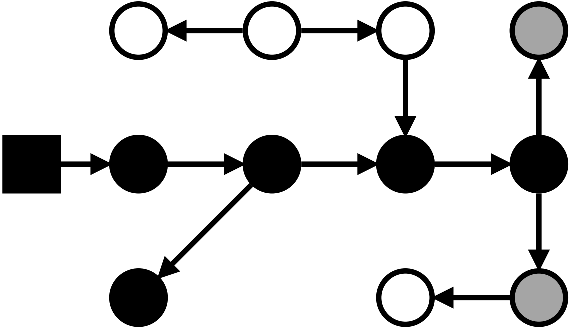
Gray $\rightarrow$ Black;
reachable from Gray $\rightarrow$ Gray

Concurrent Mark: Stop-The-World Mark



Gray → Black;
reachable from Gray → Gray

Concurrent Mark: Stop-The-World Mark



Gray → Black;
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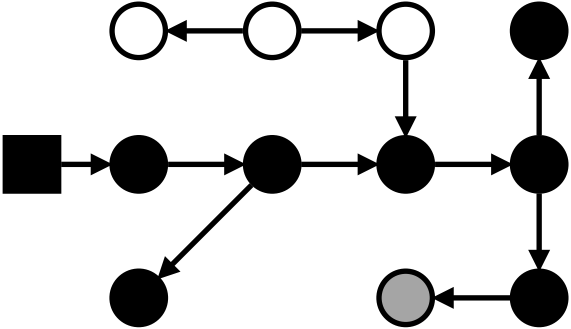
Concurrent Mark: Stop-The-World Mark



Gray → Black;
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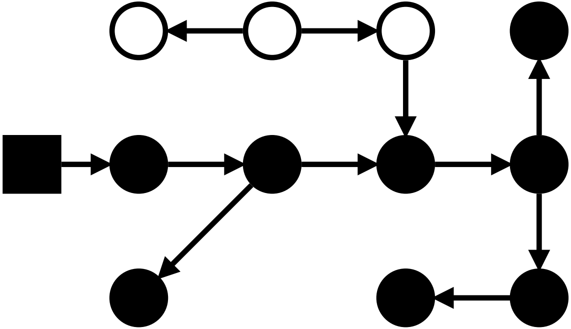


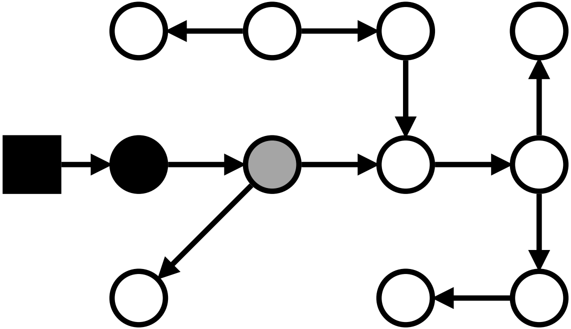
Finished: everything reachable is Black;
all garbage is White

Concurrent Mark: Mutator Problems

With **concurrent** mark everything gets complicated: the application runs and actively mutates the object graph during the mark

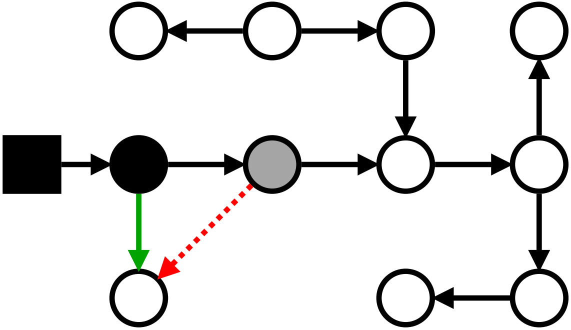
We contemptuously call it *mutator* because of that

Concurrent Mark: Mutator Problems



Wavefront is here,
and starts scanning the references in Gray object...

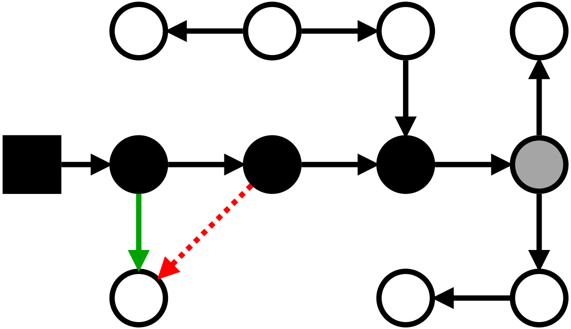
Concurrent Mark: Mutator Problems



Mutator removes the reference from Gray...
and inserts it to Black!

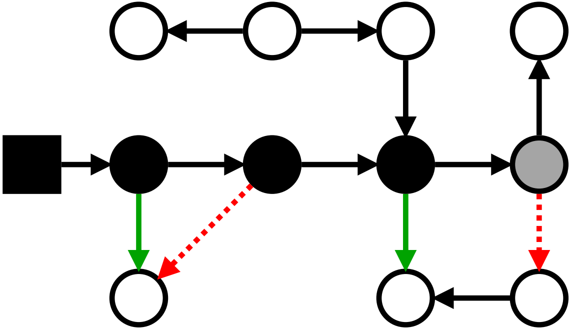
redhat

Concurrent Mark: Mutator Problems



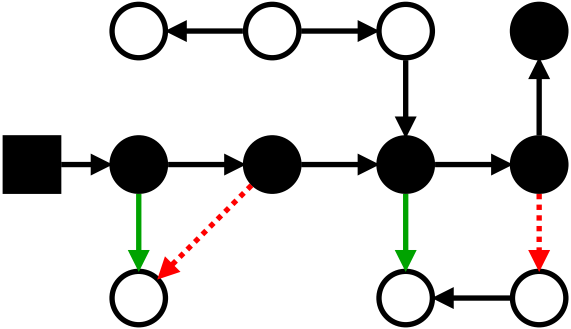
...or mutator inserted the reference to
transitively reachable White object into Black

Concurrent Mark: Mutator Problems



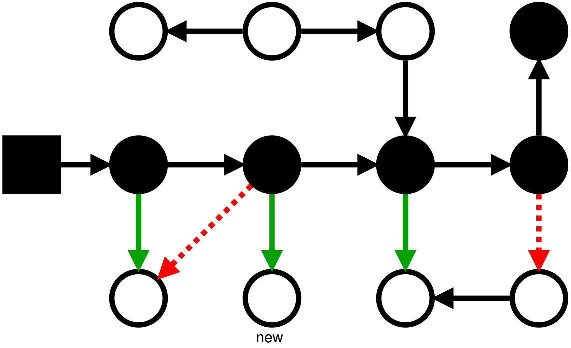
...or mutator inserted the reference to *transitively reachable* White object into Black

Concurrent Mark: Mutator Problems



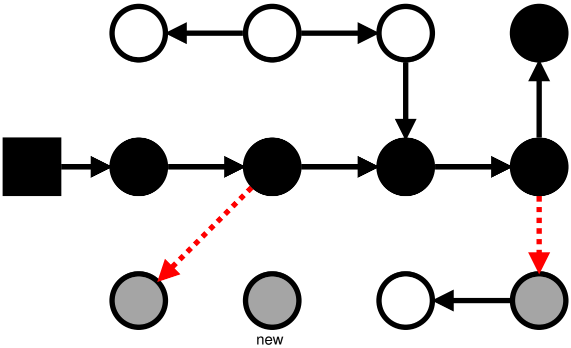
Mark had finished, and boom: we have reachable **White** objects, which we will now reclaim, corrupting the heap

Concurrent Mark: Mutator Problems



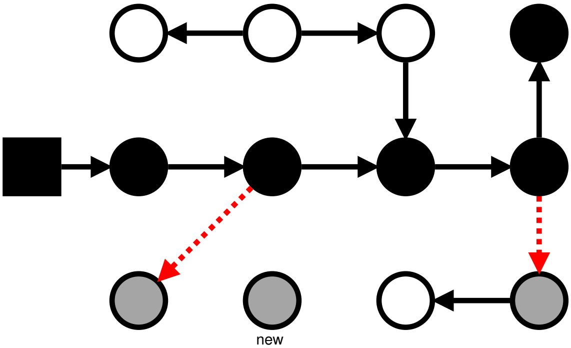
Another quirk: created new **new object**,
and inserted it into Black

Concurrent Mark: SATB



Color all **removed** referents Gray

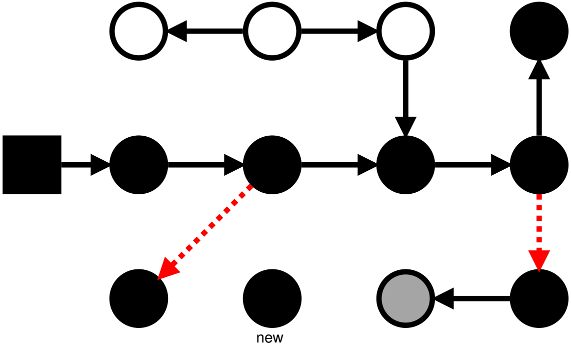
Concurrent Mark: SATB



Color all new objects **Black**

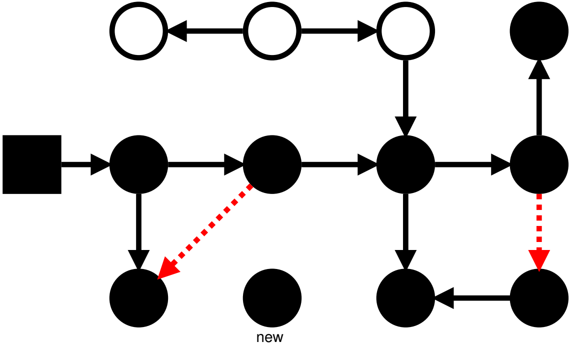
redhat

Concurrent Mark: SATB



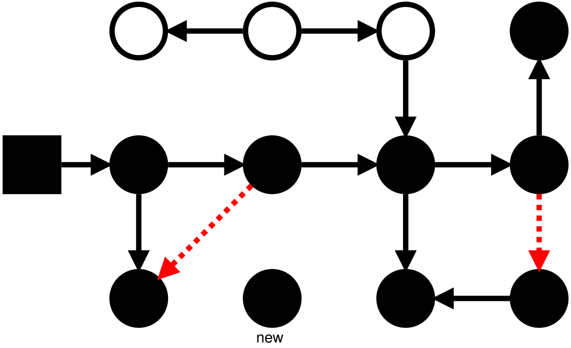
Finishing...

Concurrent Mark: SATB



Done!

Concurrent Mark: SATB



«Snapshot At The Beginning»:
marked *all reachable at mark start*

Concurrent Mark: SATB Barrier, Fastpath

```
# read TLS flag
movsbl 0x378(%r15),%r10       # flag = *(TLS + 0x378)

# if that flag is up...
test   %r10,%r10              # if (flag) ...
jne    OMG-SATB-ENABLED

# perform the actual store to %r12 and offset 0x42
mov    %r11,0x42(%r12)        # *(obj + 0x42) = r11
```

Concurrent Mark: SATB Barrier, Midpath

```
OMG-SATB-ENABLED:
  # read the old value from the field
  mov    0x2c(%rbp),%r10d      # oldval = *(obj + 0x2c)

  # take the the head of thread-local buffer
  mov    0x388(%r15),%r11      # qhead = *(TLS + 0x388)

  # then tens of instructions that add old value
  # to local buffer, check for overflow, call into
  # VM slowpath to process the thread-local buffer, etc.
```

Concurrent Mark: Two Pauses

Init Mark:

1. Stop the mutator to avoid races
2. Color the rootset Black
3. Arm SATB barriers

Final Mark:

1. Stop the mutator to avoid races
2. Drain the SATB buffers
3. Finish work from SATB updates

redhat

Concurrent Mark: Two Pauses

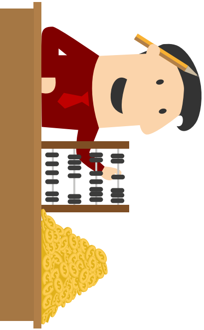
Init Mark:

1. Stop the mutator to avoid races
2. Color the rootset Black ← most heavy-weight
3. Arm SATB barriers

Final Mark:

1. Stop the mutator to avoid races
2. Drain the SATB buffers
3. Finish work from SATB updates ← most heavy-weight

Concurrent Mark: Barriers Cost[1]



	Throughput hit, %
	SATB
Cmp	-2.8
Cps	
Cry	
Der	-1.6
Mpg	
Smk	
Ser	
Sfl	
Xml	-2.6

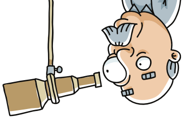
[1] Performance compared to STW Shenandoah with all barriers disabled

Concurrent Mark: Observations

1. Throughput-wise, well engineered STW GC would beat well engineered concurrent GC

   Translation: If you don't care about GC pauses, just use good STW GC

Concurrent Mark: Observations



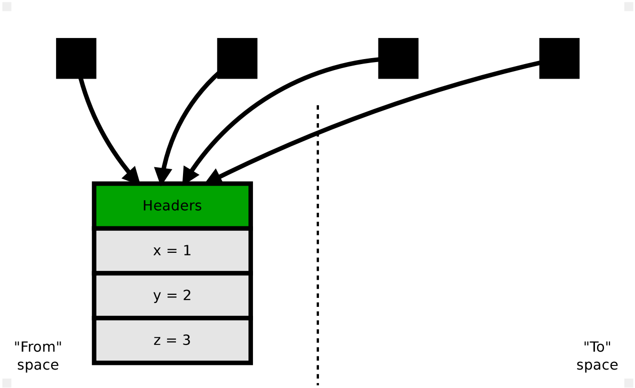
1. Throughput-wise, well engineered STW GC would beat well engineered concurrent GC

   Translation: If you don't care about GC pauses, just use good STW GC

2. Barrier costs are there even without GC cycles happening

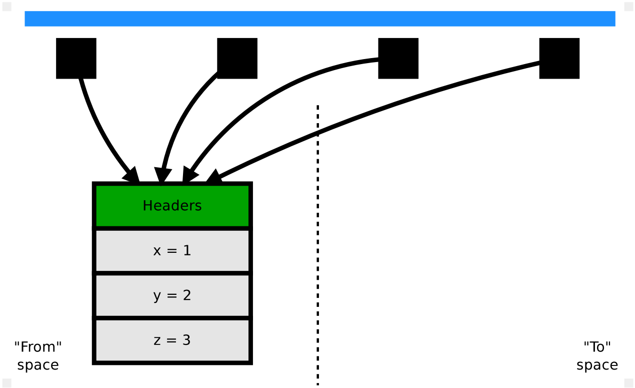
   Translation: Running the application that causes no GC cycles? Less sophisticated GC gives less overheads

Concurrent Copy: Stop-The-World



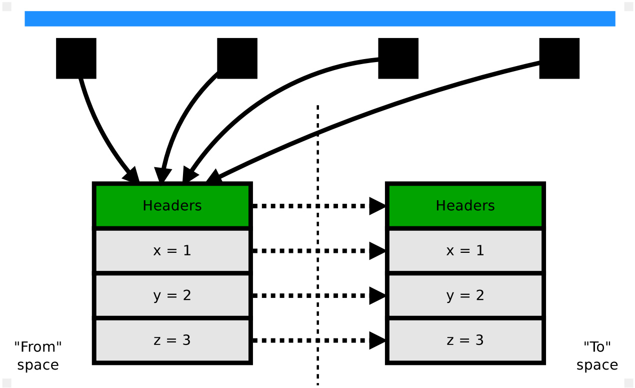
Problem:
there is the object, the object is referenced from somewhere, need to move it to new location

Concurrent Copy: Stop-The-World



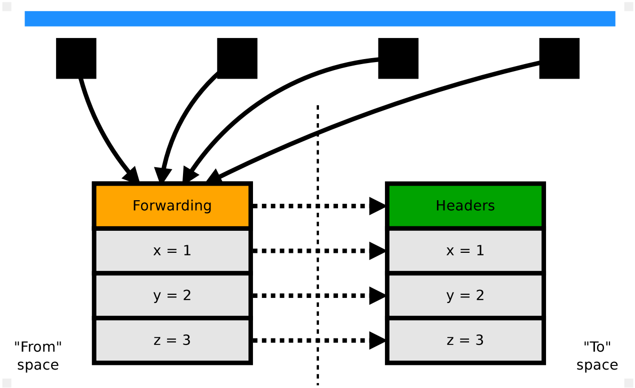
Step 1: Stop The World, evasive maneuver to distract mutator from looking into our mess

Concurrent Copy: Stop-The-World



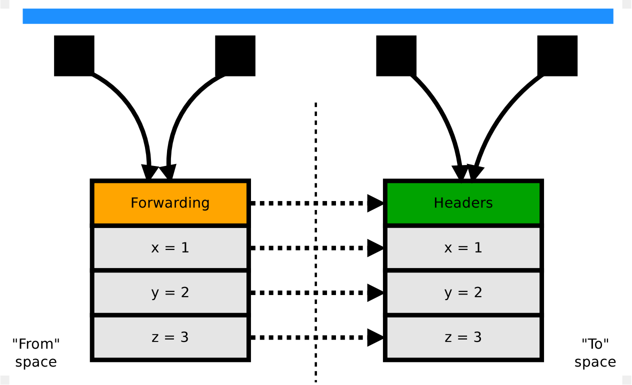
Step 2:
Copy the object with all its contents

Concurrent Copy: Stop-The-World



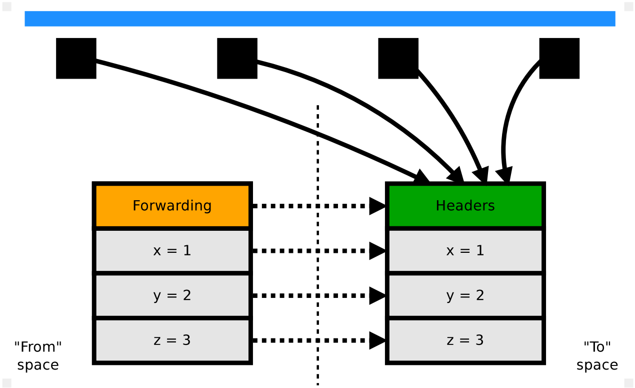
Step 3.1:
Update all references: save the pointer that forwards to the copy

Concurrent Copy: Stop-The-World



Step 3.2:
Update all references: walk the heap, replace all refs with fwdptr destination

Concurrent Copy: Stop-The-World



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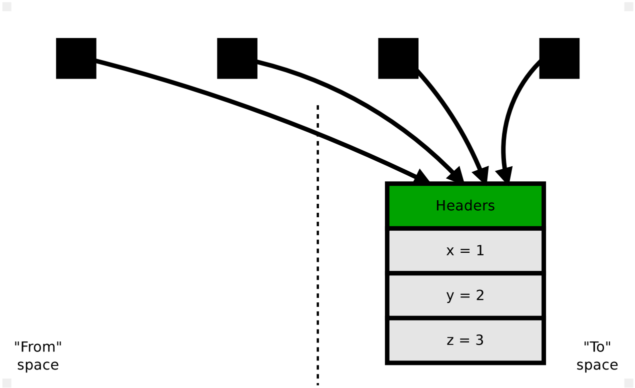
Concurrent Copy: Stop-The-World



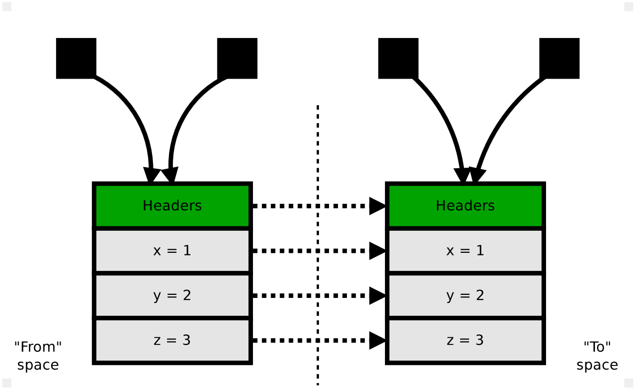
Everything is fine in the world, set the mutators free! Done!

Concurrent Copy: Mutator Problems

http://vernova-dasha.livejournal.com/77066.html

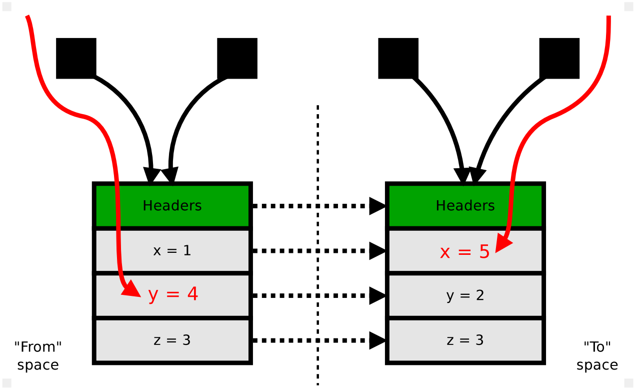
With **concurrent** copying everything gets is significantly harder: the application writes into the objects while we are moving the same objects!

Concurrent Copy: Mutator Problems



While object is being moved, there are *two* copies of the object, and both are reachable!

Concurrent Copy: Mutator Problems



Thread A writes $y = 4$ to one copy, and Thread B writes $x = 5$ to another. Which copy is correct now, huh?

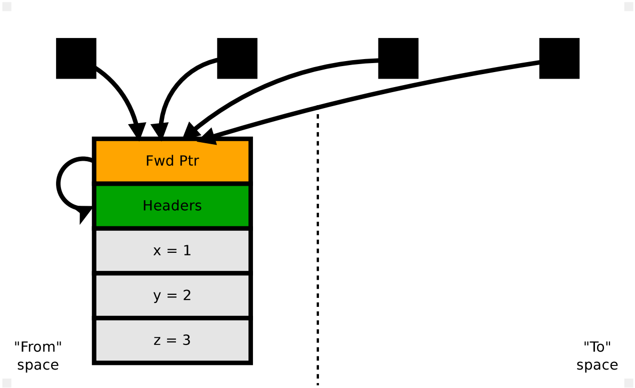
Concurrent Copy: Java Analogy

```java
class VersionUpdater<T, V> {
  final AtomicReference<T> ref = ...;

  void writeValue(V value) {
    do {
      T oldObj = ref.get();
      T newObj = copy(oldObj);
      newObj.set(value);
    } while (!ref.compareAndSet(oldObj, newObj));
  }
}
```

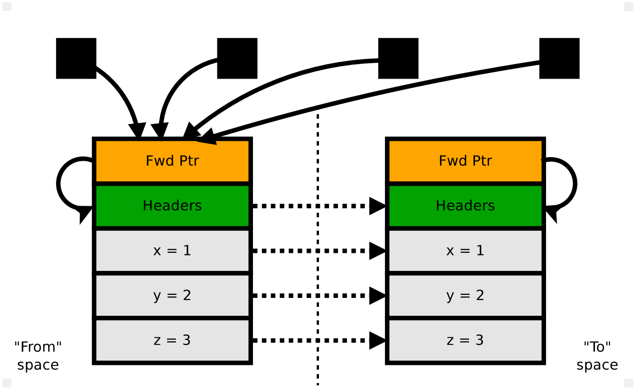
Everyone wrote this thing about a hundred times...

Concurrent Copy: Brooks Pointers



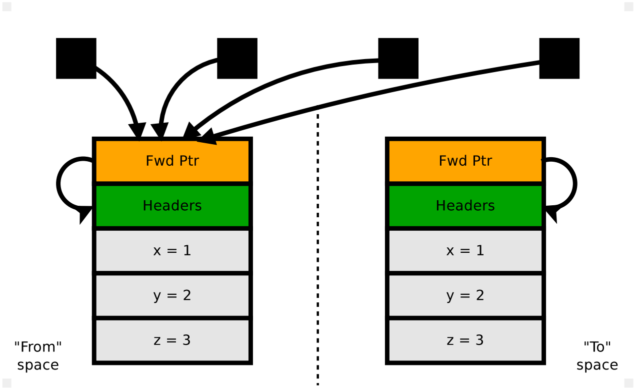
Idea:
Brooks pointer: object version change with additional atomically changed indirection

Concurrent Copy: Brooks Pointers



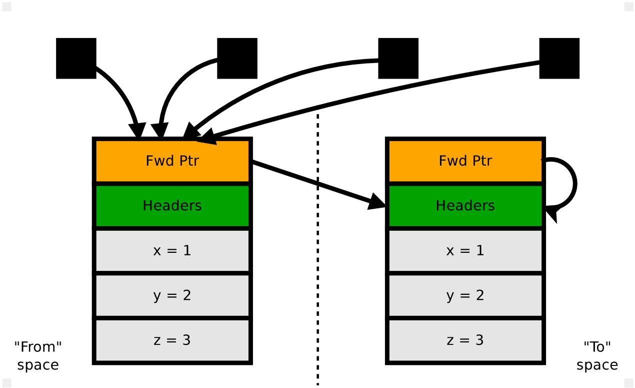
Step 1:
Copy the object, initialize its forwarding pointer to self

Concurrent Copy: Brooks Pointers



We now have the copy of the object, but no one knows about it

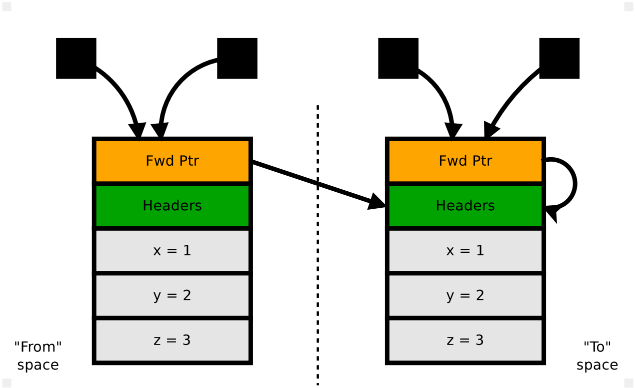
Concurrent Copy: Brooks Pointers



Step 2:
CAS! Atomically install forwarding pointer to point to new copy. If CAS had failed, discover the copy via forwarding pointer

redhat

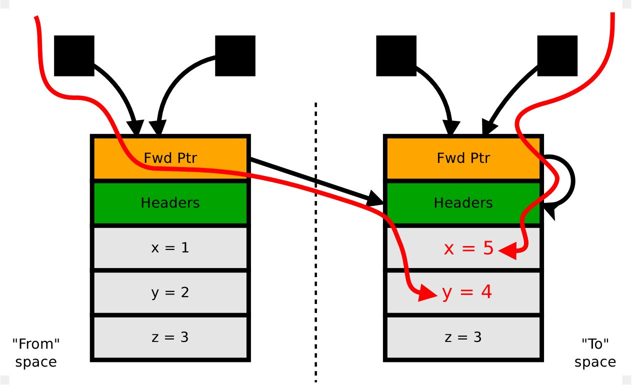
Concurrent Copy: Brooks Pointers



Step 3:
Rewrite the references at our own pace in the rest of the heap

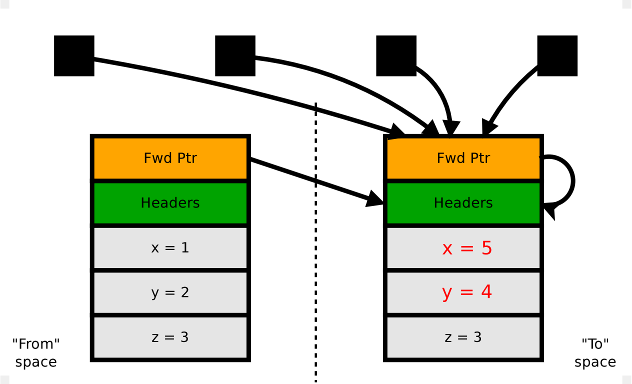
redhat

Concurrent Copy: Brooks Pointers



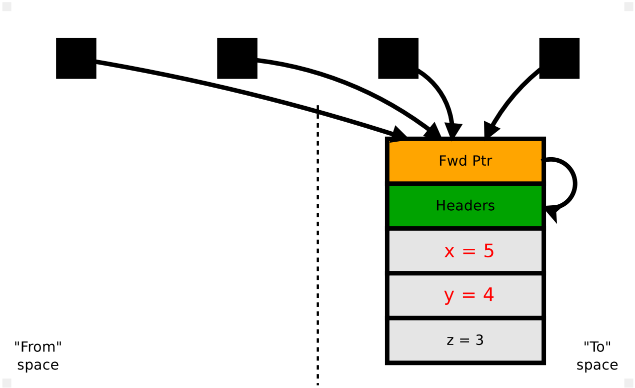
If somebody reaches the old copy via the old reference, it has to dereference via fwdptr and discover the actual object copy!

Concurrent Copy: Brooks Pointers



Step 4:
All references are updated, recycle the from-space copy

Concurrent Copy: Brooks Pointers



Done!

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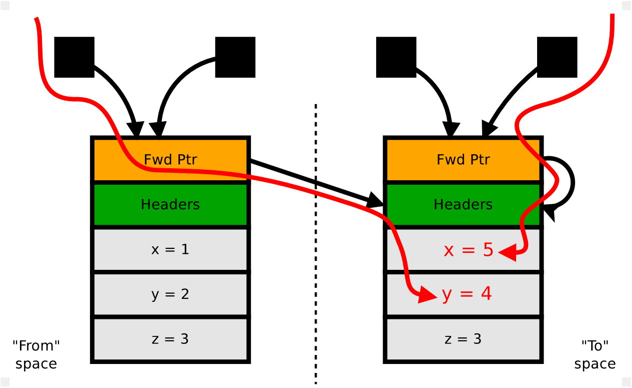
Write Barriers: Motivation



To-space invariant:
Writes should happen in to-space **only**, otherwise they are lost when cycle is finished

Write Barriers: Fastpath

```
# read the thread-local flag
movzbl 0x3d8(%r15),%r11d    # flag = *(TLS + 0x3d8)

# if that flag is set, then...
test   %r11d,%r11d          # if (flag) ...
jne    OMG-EVAC-ENABLED

# make sure we have the to-copy
mov    -0x8(%rbp),%r10      # obj = *(obj - 8)

# store into to-copy r10 at offset 0x30
mov    %r10,0x30(%r10)      # *(obj + 0x30) = r10
```

Write Barriers: Slowpath

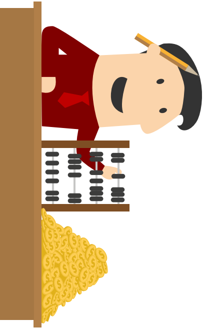
```
stub Write(val, obj, offset) {
  if (evac-in-progress &&            // in evacuation phase
      in-collection-set(obj) &&      // target is in from-space
      fwd-ptrs-to-self(obj)) {       // no copy yet
    val copy = copy(obj);
    *(copy + offset) = val;          // actual write
    if (CAS(fwd-ptr-addr(obj), obj, copy)) {
      return;                        // success!
    }
  }
  obj = fwd-ptr(obj);       // write to actual copy
  *(obj + offset) = val; // actual write
}
```

Write Barriers: GC Evacuation Code

```
stub evacuate(obj) {
  if (in-collection-set(obj) && // target is in from-space
      fwd-ptrs-to-self(obj)) {  // no copy yet
    copy = copy(obj);
    CAS(fwd-ptr-addr(obj), obj, copy);
  }
}
```

Termination guarantees:
Always copy **out of** collection set.
Double forwarding is the GC error.

Write Barriers: Barriers Cost[1]



	Throughput hit, %	
	SATB	WB
Cmp	-2.8	-2.9
Cps		-1.5
Cry		
Der	-1.6	-2.5
Mpg		-9.9
Smk		-1.7
Ser		-2.6
Sfl		
Xml	-2.6	-2.8

[1] Performance compared to STW Shenandoah with all barriers disabled

Write Barriers: Observations

1. Shenandoah needs WB on **all** stores

   Translation: Field stores, locking the object, computing the identity hash code the first time, etc – all require write barriers

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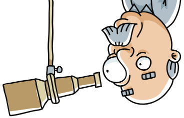
Write Barriers: Observations



1. Shenandoah needs WB on **all** stores

   Translation: Field stores, locking the object, computing the identity hash code the first time, etc – all require write barriers

2. Application steps on WB slowpath very rarely: only during evacuation phase, on a few evacuated objects, on those objects that were not yet visited by GC

   Translation: In practice, WBs have low overhead

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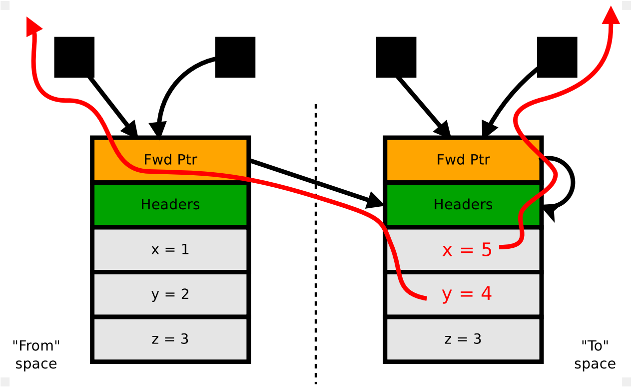
Read Barriers: Motivation



Heap reads have to (?) dereference via the forwarding pointer, to discover the actual object copy

Read Barriers: Implementation

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

# heap read!
mov     0x30(%r10),%r10d     # val = *(obj + 0x30)
```

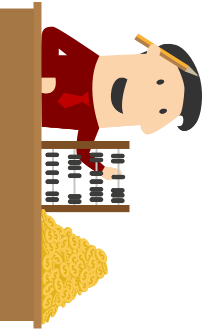
Read Barriers: Implementation

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

# heap read!
mov     0x30(%r10),%r10d    # val = *(obj + 0x30)
```

Benchmark	Score		Units
	base	+3 RBs	
time	4.6 ± 0.1	5.3 ± 0.1	ns/op
L1-dcache-loads	12.3 ± 0.2	15.1 ± 0.3	#/op
cycles	18.7 ± 0.3	21.6 ± 0.3	#/op
instructions	26.6 ± 0.2	30.3 ± 0.3	#/op

Read Barriers: Barriers Cost[1]



	Throughput hit, %		
	SATB	WB	RB
Cmp	-2.8	-2.9	-9.8
Cps		-1.5	-11.6
Cry			
Der	-1.6	-2.5	-8.9
Mpg		-9.9	-10.9
Smk		-1.7	-0.7
Ser		-2.6	-9.4
Sfl			-12.2
Xml	-2.6	-2.8	-13.7

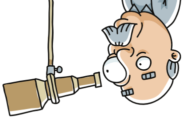
[1] Performance compared to STW Shenandoah with all barriers disabled

Read Barriers: Observations

1. RBs are cheap, but there are **lots** of them
   Translation: cannot make RBs much heavier[2]

[2]Use tagged/colored pointers seems odd because of this

Read Barriers: Observations



1. RBs are cheap, but there are **lots** of them

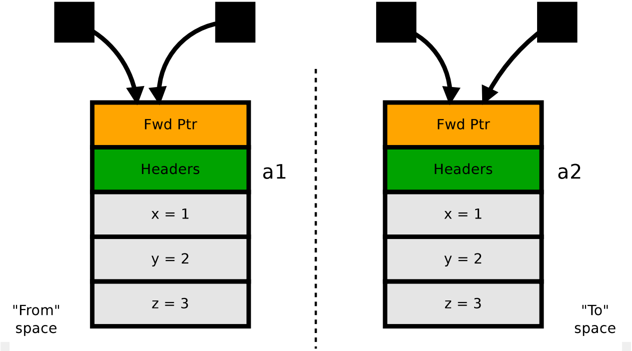
   Translation: cannot make RBs much heavier[2]

2. The observed overhead depends heavily on optimizers ability to eliminate, hoist and coalesce barriers

   Translation: high-performance GC development assumes optimizing compiler work

[2] Use tagged/colored pointers seems odd because of this

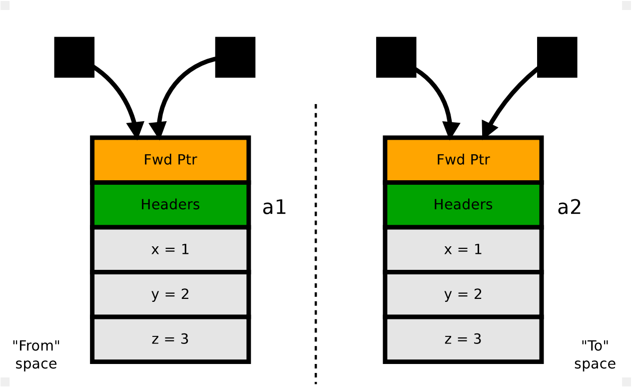
CMP: Trouble



What if we compare from-copy and to-copy *themselves*?

`(a1 == a2)` → ???

CMP: Trouble



What if we compare from-copy and to-copy *themselves*?

(a1 == a2) → ???

But *machine ptrs* are not equal... Oops.

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CMP: Exotic Barriers

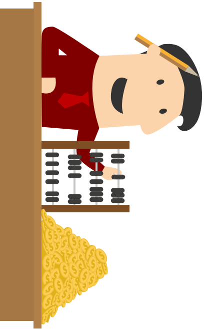
Having two *physical* copies of the same *logical* object,
«==» has to compare *logical* objects

```
# compare the ptrs; if equal, good!
cmp     %rcx,%rdx            # if (a1 == a2) ...
je      EQUALS

# false negative? have to compare to-copy:
mov     -0x8(%rcx),%rcx    # a1 = *(a1 - 8)
mov     -0x8(%rdx),%rdx    # a2 = *(a2 - 8)

# compare again:
cmp     %rcx,%rdx            # if (a1 == a2) ...
```

CMP: Barriers Cost[1]



	Throughput hit, %			
	SATB	WB	RB	CMP
Cmp	-2.8	-2.9	-9.8	-4.0
Cps		-1.5	-11.6	
Cry				-4.3
Der	-1.6	-2.5	-8.9	
Mpg		-9.9	-10.9	
Smk		-1.7	-0.7	
Ser		-2.6	-9.4	
Sfl			-12.2	
Xml	-2.6	-2.8	-13.7	

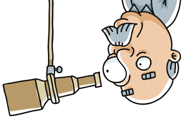
[1] Performance compared to STW Shenandoah with all barriers disabled

CMP: Observations

1. Full-fledged «==» reference comparisons are rare, and special kinds of comparisons are well-optimized

   Translation: cmp barriers are not affecting much, `a == null` does not require barriers, etc.

CMP: Observations



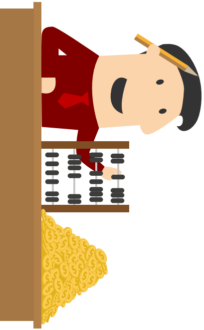
1. Full-fledged «==» reference comparisons are rare, and special kinds of comparisons are well-optimized

   Translation: cmp barriers are not affecting much, `a == null` does not require barriers, etc.

2. There is also the problem with reference CASes, but the failure there is also rare

   Translation: if CAS had failed, you have much larger performance problems...

Overall: Barriers Cost[1]



	Throughput hit, %				
	SATB	WB	RB	CMP	TOTAL
Cmp	-2.8	-2.9	-9.8	-4.0	-18.8
Cps		-1.5	-11.6		-14.6
Cry				-4.3	-4.3
Der	-1.6	-2.5	-8.9		-13.2
Mpg		-9.9	-10.9		-21.3
Smk		-1.7	-0.7		-2.6
Ser		-2.6	-9.4		-13.4
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Xml	-2.6	-2.8	-13.7		-18.9

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Overall: Observations

1. Shenandoah barriers **do not** require special hardware or special OS support!

   Translation: No need for kernel patches, pricey hardware, vendor lock-in distros, etc

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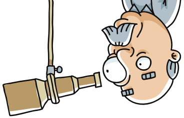

1. Shenandoah barriers **do not** require special hardware or special OS support!

   Translation: No need for kernel patches, pricey hardware, vendor lock-in distros, etc

2. The throughput hit is mostly acceptable, taking note the latency improvements achieved

   Translation: Latency-throughput tradeoff is here. Do not need low latency? Use STW GC.

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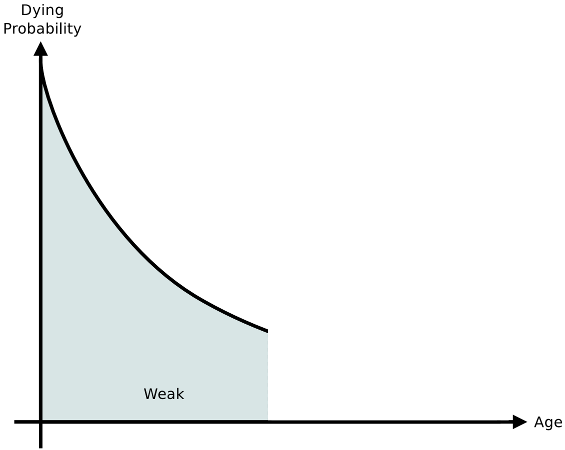
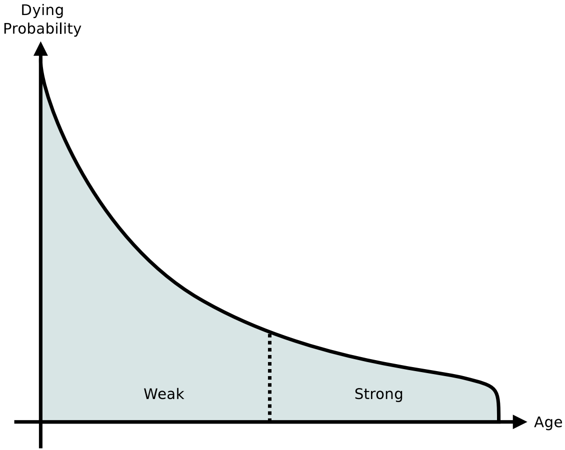
Intermezzo

Intermezzo: Generational Hypotheses, Weak



Weak hypothesis:
most objects die young

Intermezzo: Generational Hypothesis, Strong



Strong hypothesis:
the older the object,
the less chance it has
to die

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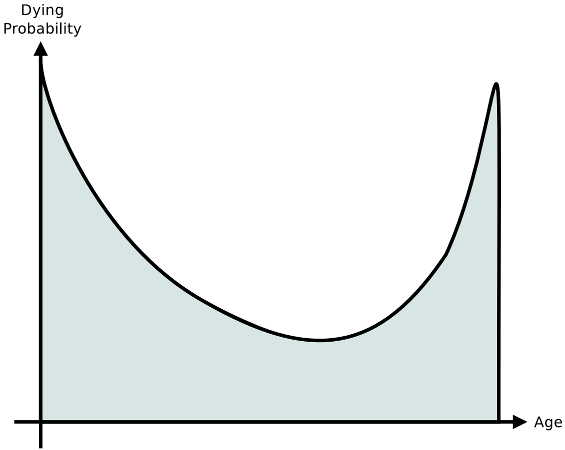
Intermezzo: Generational Hypothesis, Strong



Strong hypothesis: the older the object, the less chance it has to die

In-memory LRU-like caches are the prime counterexamples

Intermezzo: LRU, Pesky Workload

Very inconvenient workload for *simple* generational GCs
(those that follow weak GH, and trust in strong GH)

1. Appears to be weak GH workload in the beginning
2. As cache population grows, Live Data Set (LDS) grows too. LDS is measured in gigabytes – it is a cache, after all
3. As cache gets full, old objects start to die, violating strong GH, much to naive GC surprise
4. GC heuristics trips over and burns

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Intermezzo: The Simplest LRU

The simplest LRU implementation in Java?

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Intermezzo: The Simplest LRU

The simplest LRU implementation in Java?

```
cache = new LinkedHashMap<>(size*4/3, 0.75f, true) {
  @Override
  protected boolean removeEldestEntry(Map.Entry<> eldest) {
    return size() > size;
  }
};
```

Intermezzo: Testing

Boring config:

1. Latest improvements in all GCs: shenandoah/jdk10 forest
2. Decent multithreading: 8 threads on 16-thread i7-7820X
3. Larger heap: `-Xmx100g -Xms100g`
4. 90% hit rate, 90% reads, 10% writes
5. Size (LDS) = 0..100% of `-Xmx`

Varying cache size ⇒ varying LDS ⇒ make GC uncomfortable

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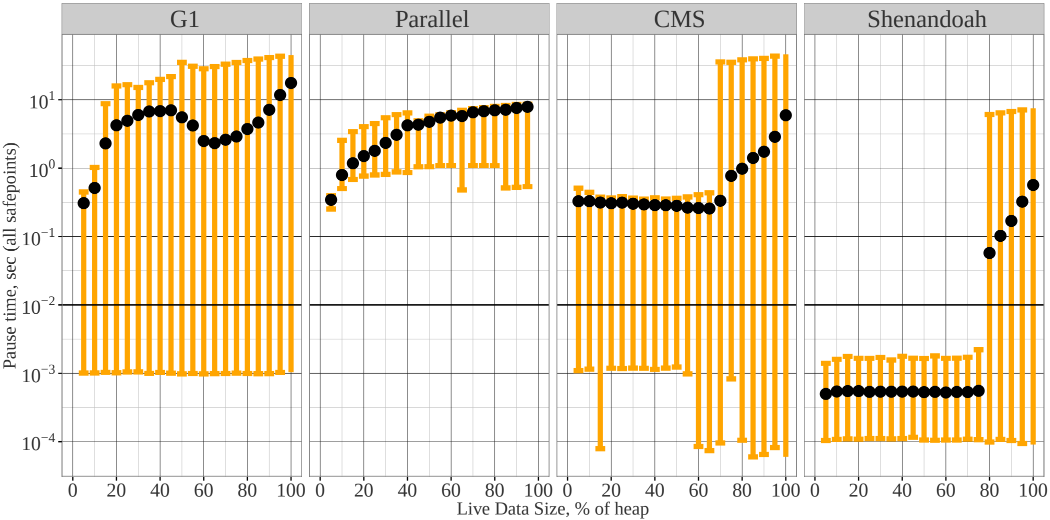
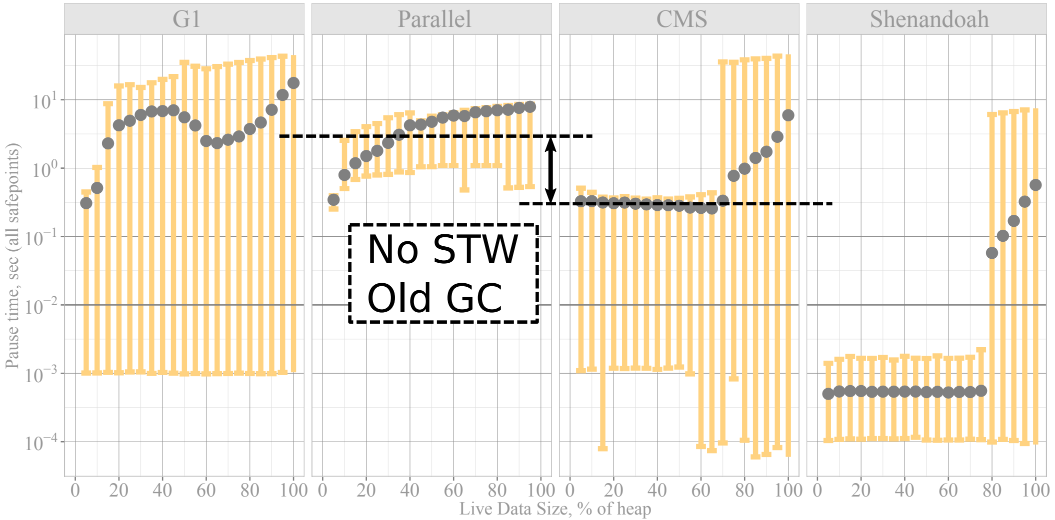
Intermezzo: Pauses vs. LDS



Intermezzo: Pauses vs. LDS



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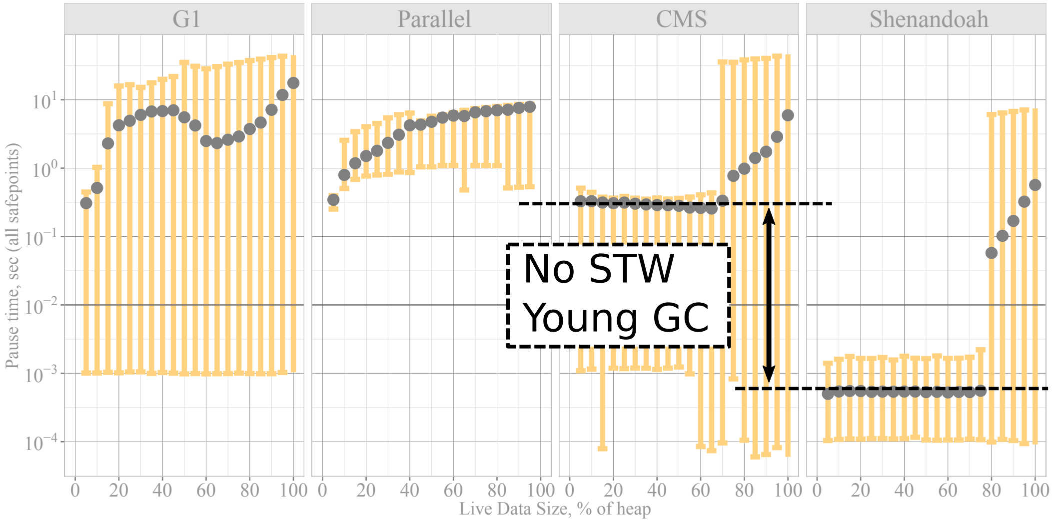
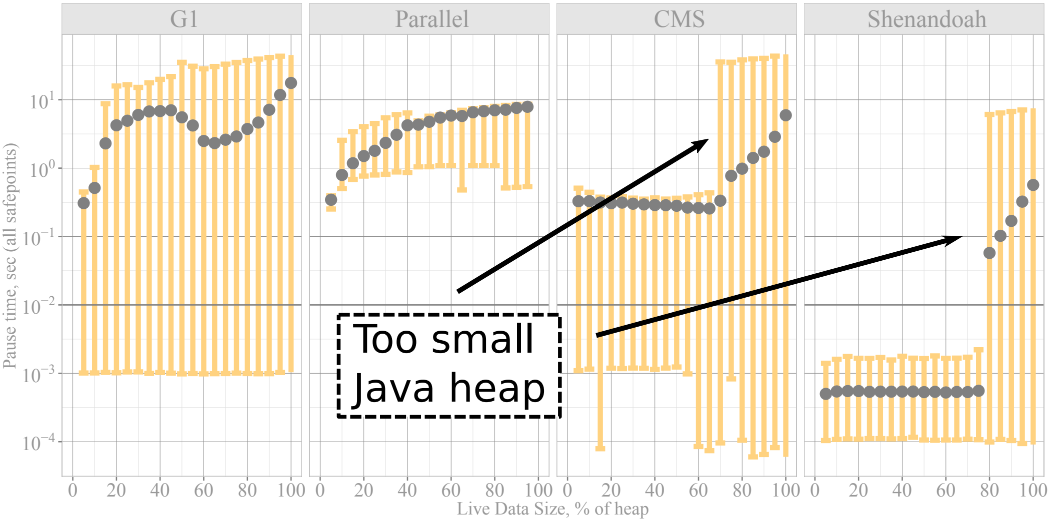
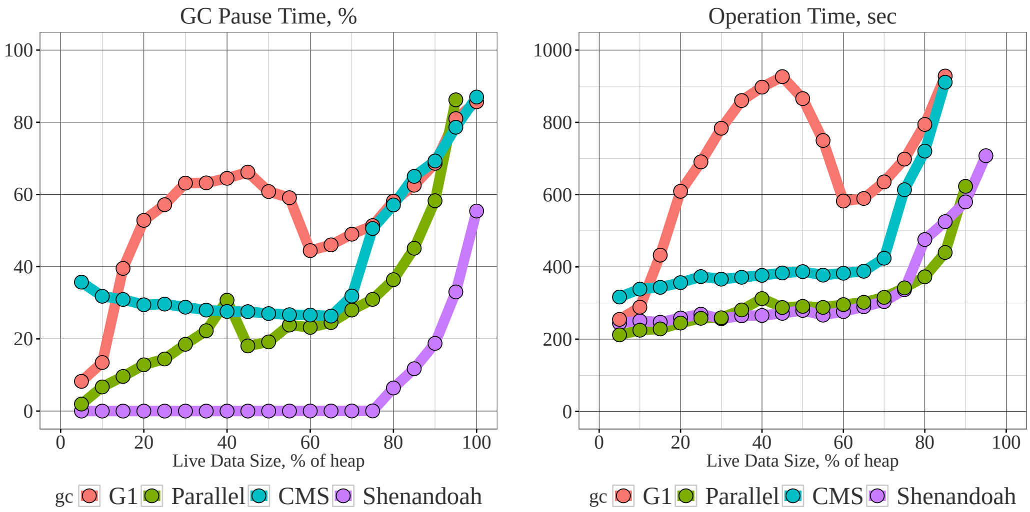
Intermezzo: Pauses vs. LDS



Intermezzo: Pauses vs. LDS



Intermezzo: Perf vs. LDS



Advanced

Advanced: Major Assumption

Concurrent 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...
- But you have to also take care about unhappy paths!

Advanced: Living Space

Problem:
Concurrent GC needs breathing room to succeed

Things that help:

- Aggressive heap expansion: prefer taking more memory
- Immediate garbage shortcuts: free memory early
- Partial collections: collect easy parts of heap first
- Mutator pacing: stall allocators before they hit the wall

Footprint: Living Space

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Footprint: Internals

Usual **active** footprint overhead: 3..15% of heap size

1. Java heap: forwarding pointer (8 bytes/object)
2. Native: 2 marking bitmaps (1/64 bits per heap bit)
3. Native: $N_CPU workers ($\approx$ 2 MB / GC thread)
4. Native: region data ($\approx$ 1 KB per region)

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Example: `-XX:+UseShenandoahGC -Xmx100G` means:
≈ 90..95 GB accessible for Java objects,
≈ 103 GB RSS for GC parts

Footprint: Internals

Usual **active** footprint overhead: 3..15% of heap size

But all of that is totally dwarfed by GC heap sizing policies

Example: `-XX:+UseShenandoahGC -Xmx100G` means:
$\approx$ 90..95 GB accessible for Java objects,
$\approx$ 103 GB RSS for GC parts

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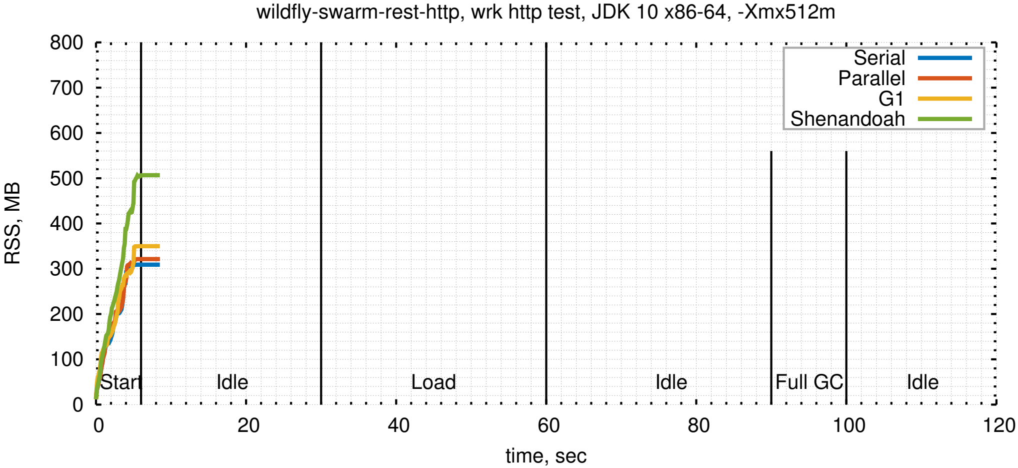
Footprint: Microservice Example



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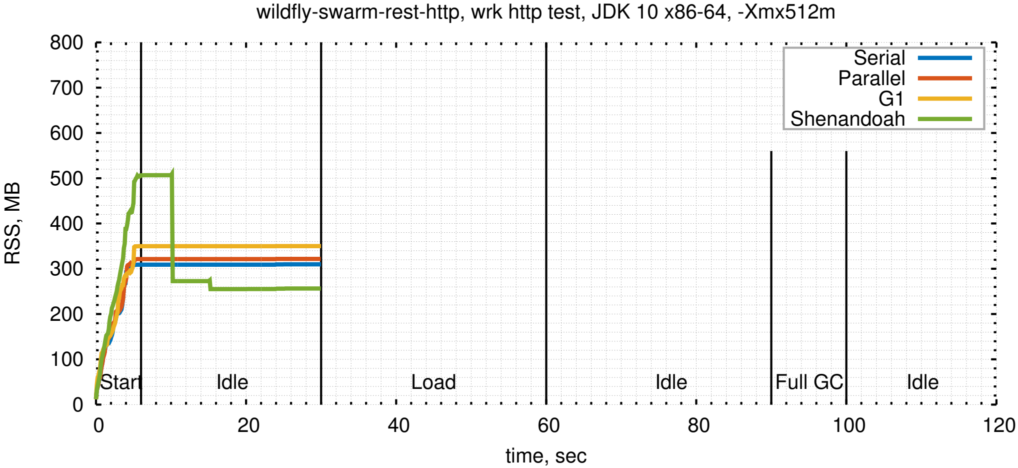

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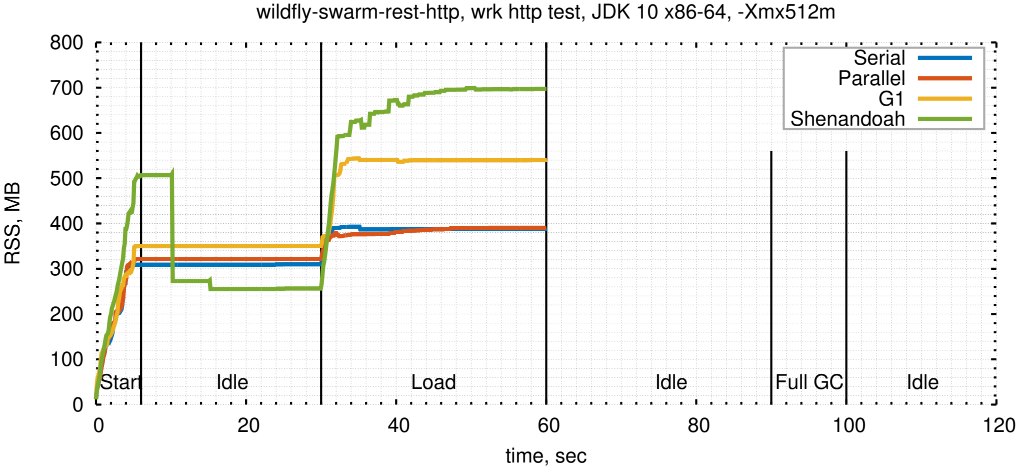

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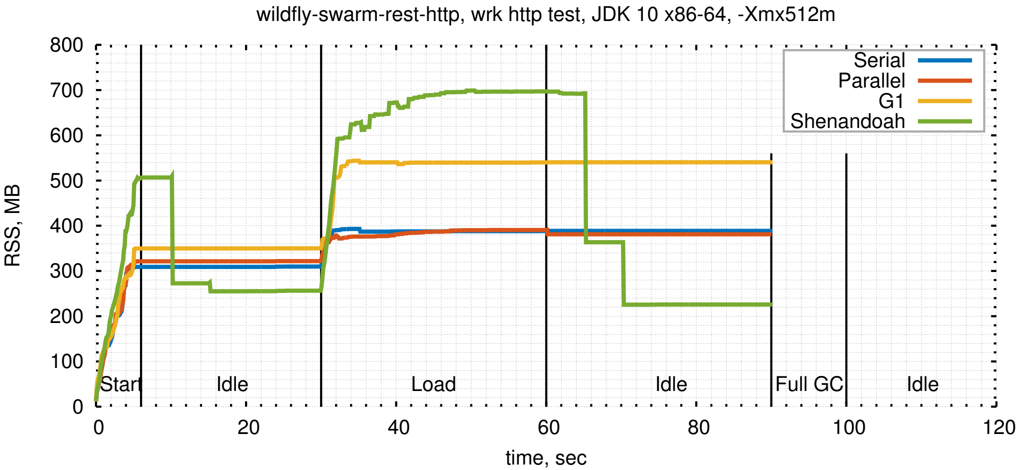

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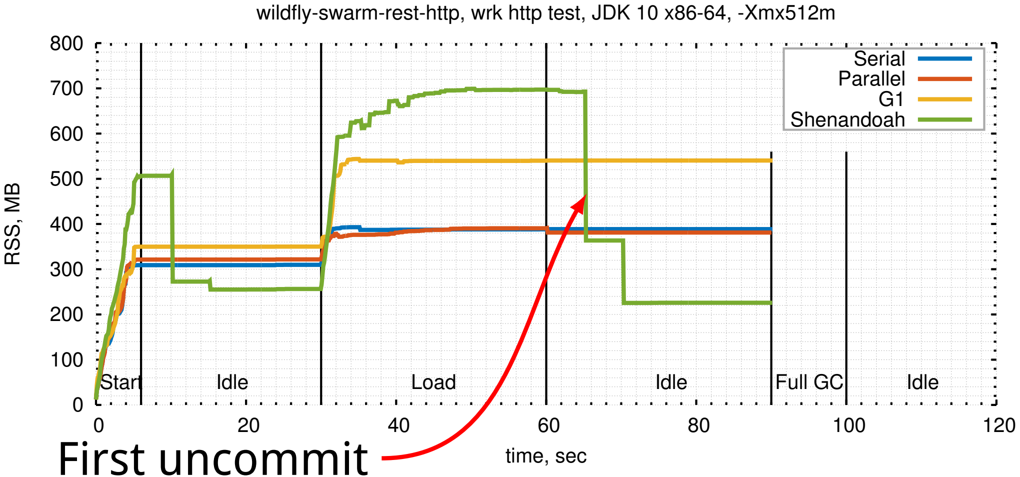

First uncommit

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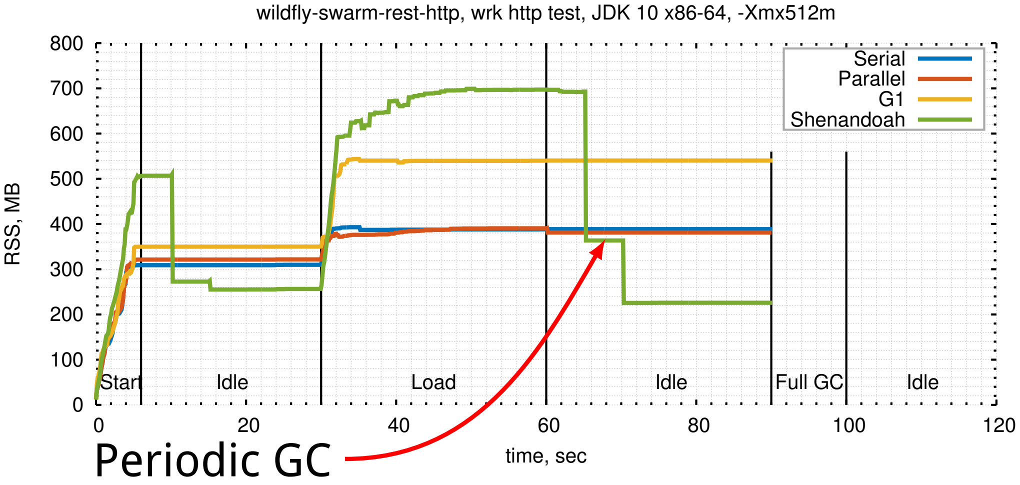

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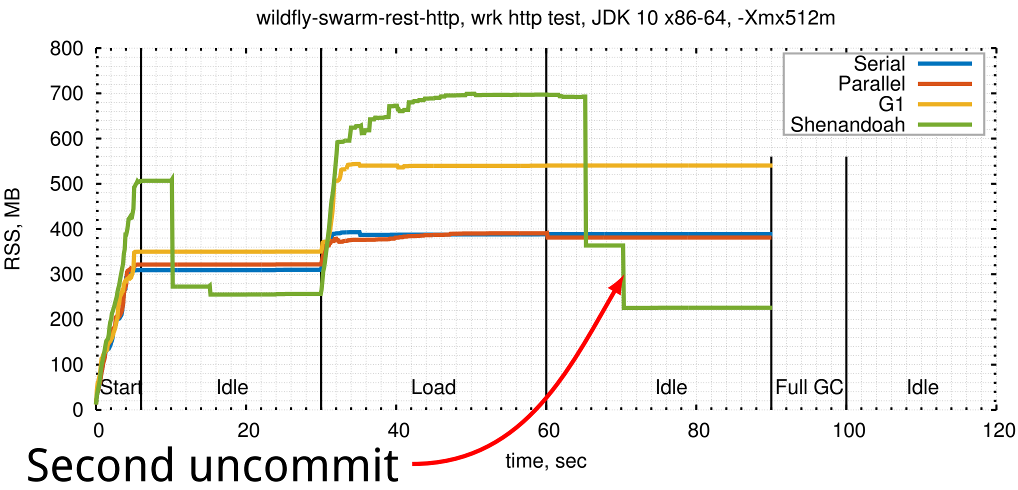

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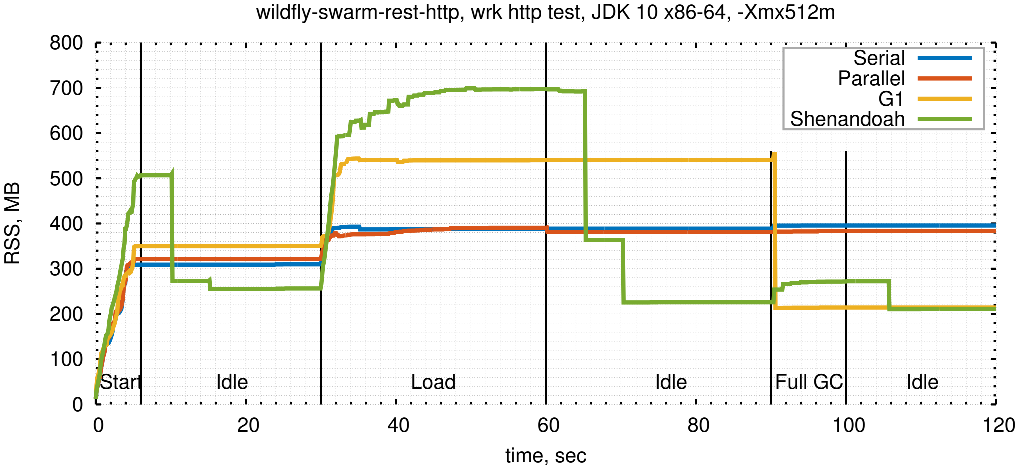

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Footprint: Shenandoah's M.O.

**«We shall take all the memory when we need it,
but we shall also give it back when we don't»**

1. Start with `-Xms` committed memory
2. Expand aggressively under load up to `-Xmx`
3. Stay close to `-Xmx` under load
4. Uncommit the heap and bitmaps down to zero when idle
5. Do periodic GCs to knock out floating garbage when idle

Tunables: `-Xms`, `-Xmx`, periodic GC interval, uncommit delay

Immediates: Living Space

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Concurrent GC needs breathing room to succeed

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- Aggressive heap expansion: prefer taking more memory
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- Mutator pacing: stall allocators before they hit the wall

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Immediates: Obvious Shortcut

```
GC(7) Pause Init Mark 0.614ms
GC(7) Concurrent marking 76812M->76864M(102400M) 1.650ms
GC(7)   Total Garbage: 76798M
GC(7)   Immediate Garbage: 75072M, 2346 regions (97% of total)
GC(7) Pause Final Mark 0.758ms
GC(7) Concurrent cleanup 76864M->1844M(102400M) 3.346ms
```

Exploiting weak gen hypothesis:

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2. Lots of fully dead regions, because most objects are dead

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Exploiting weak gen hypothesis:

1. Mark is fast, because most things are dead
2. Lots of fully dead regions, because most objects are dead
3. Cycle shortcuts, because why bother...

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Partials: Living Space

Problem:

Concurrent GC needs breathing room to succeed

Things that help:

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- Immediate garbage shortcuts: free memory early
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Partials: Heap Segregation

Central Dogma:
Segregate parts of the heap by some property (age, size, class, context, thread), and collect the subheaps separately

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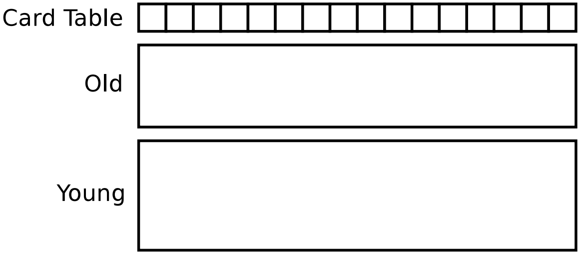
Segregate parts of the heap by some property (age, size, class, context, thread), and collect the subheaps separately

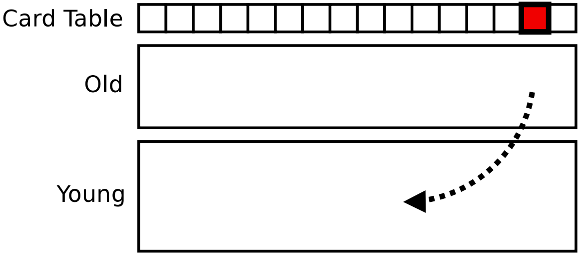
Pesky detail:
requires knowing the incoming references to the collected sub-heap

Partials: Serial/Parallel/CMS



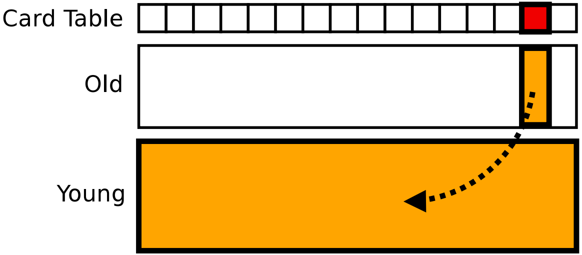
Most GCs exploit this by dividing the heap into *generations*

Partials: Serial/Parallel/CMS



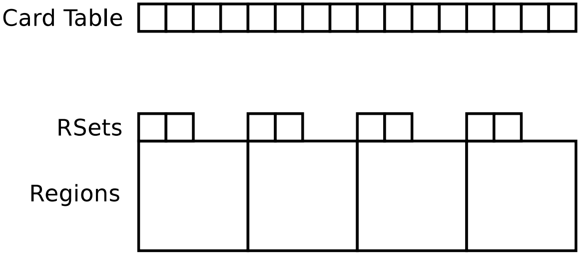
Young gen can be collected separately, if we know the incoming references from Old gen. Card Table records this for us with the write barriers

Partials: Serial/Parallel/CMS



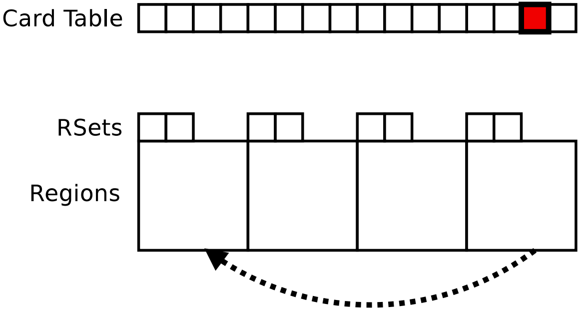
Young collection processes Young gen, and dirty parts of Old gen, thus maintaining heap integrity

Partials: G1



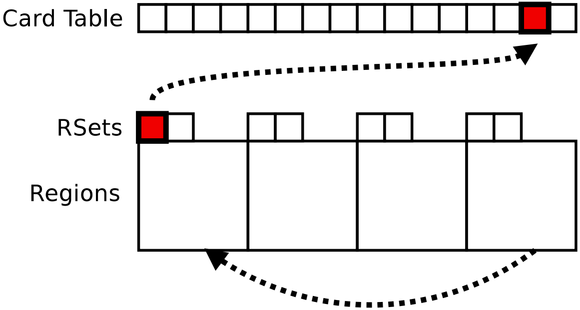
G1 is more advanced: it has Remembered Sets

Partials: G1



Write barrier marks the Card Table. But it is *not enough* to quickly collect a single region: we would need to scan all dirty cards

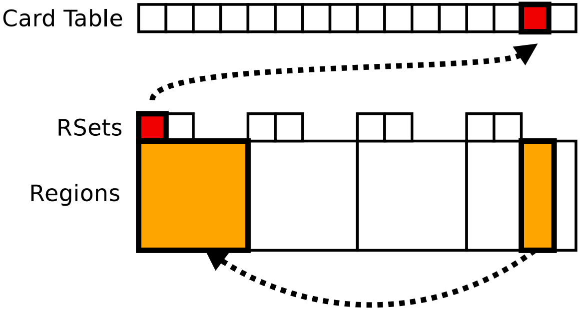
Partials: G1



Using Card Table, G1 asynchronously builds Remembered Sets: the list of blocks that contain references to *each region*

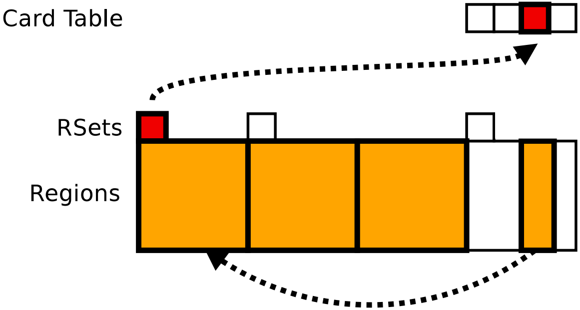
redhat

Partials: G1



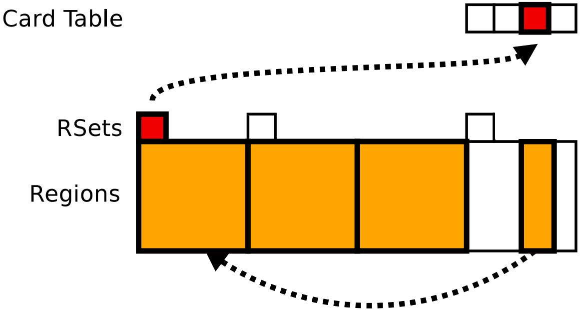
Now we can quickly collect a single region: RSet tells us what dirty parts related to the concrete region

Partials: G1



In practice, naive RSets are uber-large. G1 becomes *generational*: some regions are young, and no need to record references between them

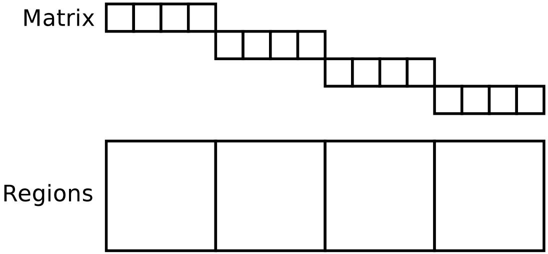
Partials: G1



Interesting trade-off: cannot collect a single young region now!

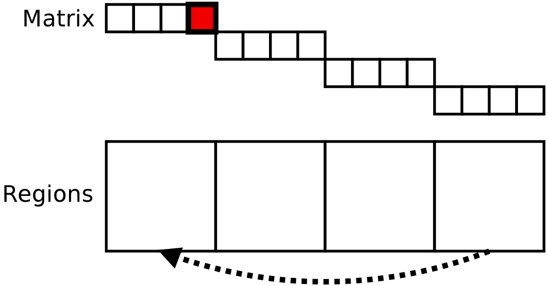
Requires a careful balancing act to make sure pause times are good, and RSet footprint is small!

Partials: Shenandoah



Idea: why not to have *much coarser* card table, but for each region?

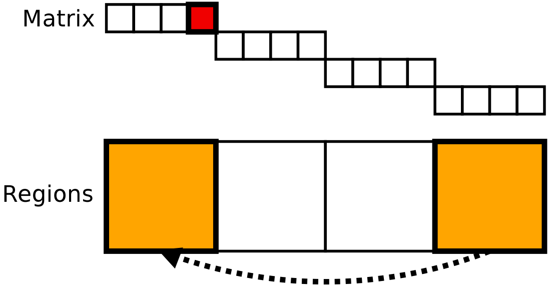
Partials: Shenandoah



Then we can support *the connection matrix*, and know things about heap connectivity

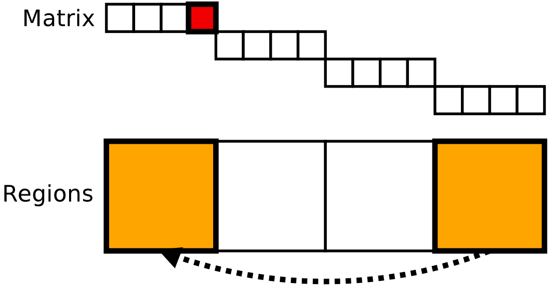
redhat.

Partials: Shenandoah



Example: collect first region, and matrix tells us we also need to scan the fourth.

Partials: Shenandoah



Example: collect first region, and matrix tells us we also need to scan the fourth.

This works because the GC is *concurrent*, and we can spend time scanning the entire region!

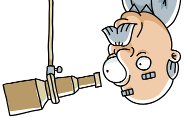
Partials: Example

```
GC(75) Pause Init Mark 0.483ms
GC(75) Concurrent marking 33318M->45596M(51200M) 508.658ms
GC(75) Pause Final Mark 0.245ms
GC(75) Concurrent cleanup 45612M->16196M(51200M) 3.499ms
```

vs

```
GC(193) Pause Init Partial 1.913ms
GC(193) Concurrent partial 27062M->27082M(51200M) 0.108ms
GC(193) Pause Final Partial 0.570ms
GC(193) Concurrent cleanup 27086M->17092M(51200M) 15.241ms
```

Partials: Observations (so far)



1. Maintaining the connectivity data means more barriers!

   Translation: The increased GC efficiency need to offset more throughput overhead

2. *Optionality* helps where barriers overhead is too much

   Translation: No need to pay when partial doesn’t help

3. Advanced policies are possible, beyond generational

   Example: Take out lonely old regions

Mutator Pacing: Living Space

Problem:
Concurrent GC needs breathing room to succeed

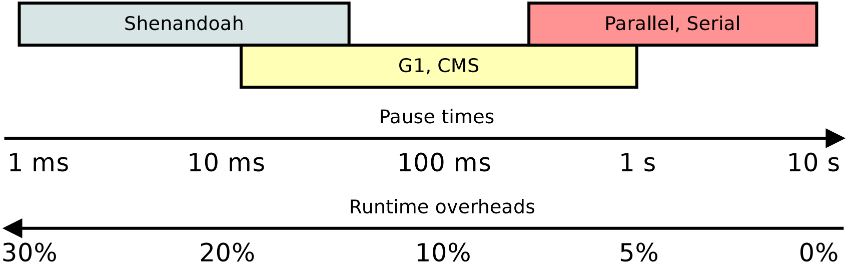
Things that help:

- Aggressive heap expansion: prefer taking more memory
- Immediate garbage shortcuts: free memory early
- Partial collections: collect easy parts of heap first
- Mutator pacing: stall allocators before they hit the wall

Conclusion

Conclusion: In Single Picture

Universal GC does not exist:
either low latency, or high throughput
(, or low memory footprint)



Choose this for your workload!

Conclusion: In Single Paragraph

1. No GC could detect what tradeoffs you are after: you have to tell it yourself

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Conclusion: In Single Paragraph

1. No GC could detect what tradeoffs you are after: you have to tell it yourself
2. Stop-the-world GCs beat concurrent GCs in throughput and efficiency. Parallel is your choice!
3. Concurrent Mark trims down the pauses significantly. G1 is ready for this, use it!
4. Concurrent Copy/Compact needs to be solved for even shallower pauses. This is where Shenandoah comes in!

Conclusion: Releases

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

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

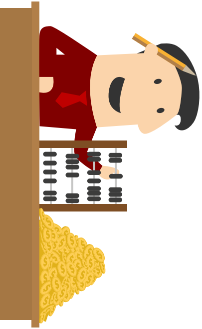
- Development in separate JDK 10 forest, regular backports to separate JDK 9 and 8u forests
- JDK 8u backport ships in RHEL 7.4+, Fedora 24+, and derivatives (CentOS, Oracle Linux, Amazon Linux, etc)
- Nightly development builds (tarballs, Docker images)

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


redhat.

Trivia

Trivia: Compiler Support



	C1			C2		
Test	G1	Shen	%diff	G1	Shen	%diff
Cmp	78	72	-7%	127	116	-8%
Cpr	125	86	-31%	146	125	-15%
Cry	79	62	-21%	238	240	+1%
Drb	75	69	-7%	165	150	-9%
Mpa	31	21	-33%	50	40	-20%
Sci	42	32	-23%	74	70	-5%
Ser	1626	1293	-20%	2450	2172	-11%
Sun	93	74	-20%	111	97	-13%
Xml	88	72	-19%	190	168	-12%

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

Trivia: JMM Tricks

We can read from-copy (i.e. skip RBs), as long as:

1. No locks, `volatile` reads/writes, memory barriers
2. No calls into the opaque methods

Trivia: JMM Tricks

We can read from-copy (i.e. skip RBs), as long as:

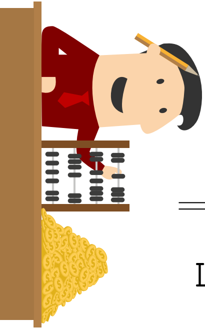
1. No locks, `volatile` reads/writes, memory barriers
2. No calls into the opaque methods

As the rule, we can:

1. Avoid re-doing RBs after safepoints
2. Erase RBs when reading `final`-s

redhat.

Trivia: JMM Tricks



`final` on fields finally improves performance!

Benchmark	Score plain	Score final	Units
time	2.7 ± 0.1	2.6 ± 0.1	ns/op
L1-dcache-loads	13.2 ± 0.1	11.2 ± 0.1	#/op
instructions	29.6 ± 0.6	28.5 ± 0.3	#/op

Trivia: Mark Solutions

Two classic approaches to solve this:

1. **Incremental Update**: intercept the stores, and process *insertions*, thus traversing new paths – good, but has weak termination guarantees
2. **Snapshot-at-the-Beginning**: intercept the stores, and process *deletions*, thus mitigating the destructive mutations – also good, but overestimates liveness

(there are also non-classic approaches, but not for this talk)