(1) (2) (3)

Runtime Object Lifetime Profiler for Latency Sensitive Big Data Applications

Rodrigo Bruno(1)*, Duarte Patrício(2), José Simão(2), Luís Veiga(2), Paulo Ferreira(2,3)

EuroSys 2019 @ Dresden, 25-28 March

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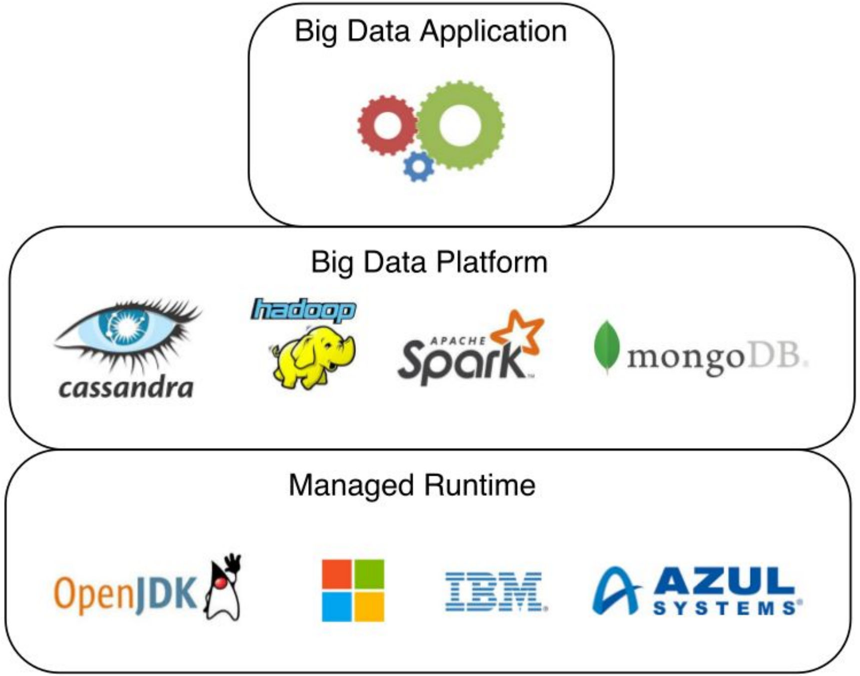
* Work done while at (2)

Big Data Application Stack



Big Data Application

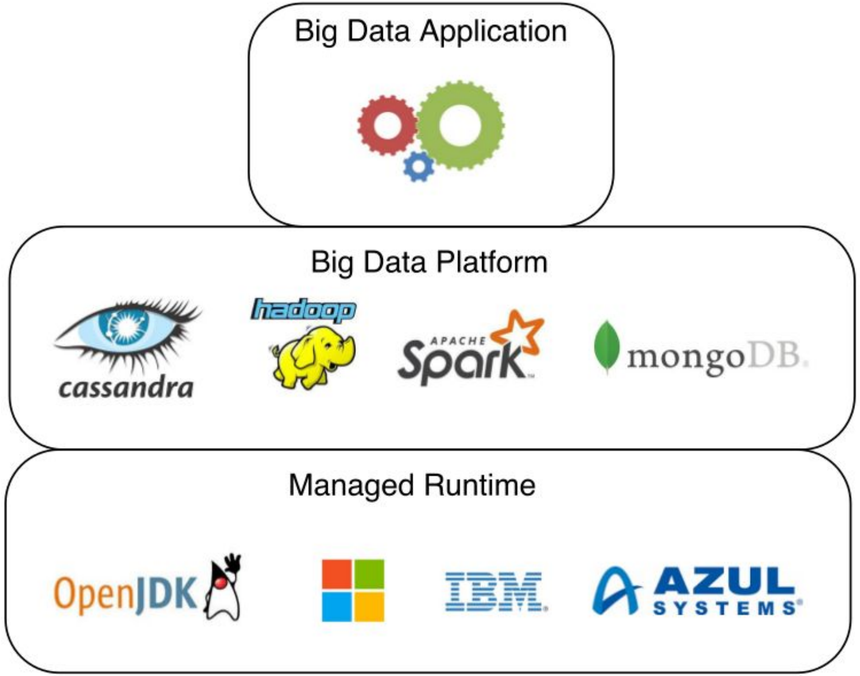
Big Data Platform

Managed Runtime

Big Data Application Stack

Examples of Latency Sensitive apps

- Banking applications and services
- Context-Aware Ad services
- Games
- …



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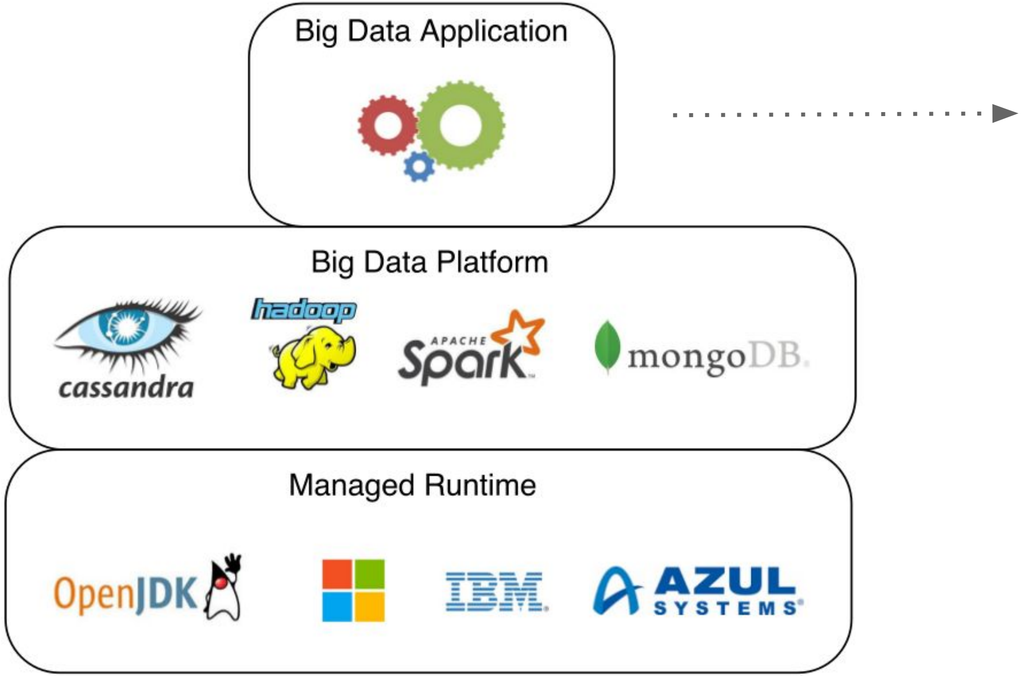

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SLAs can be easily compromised

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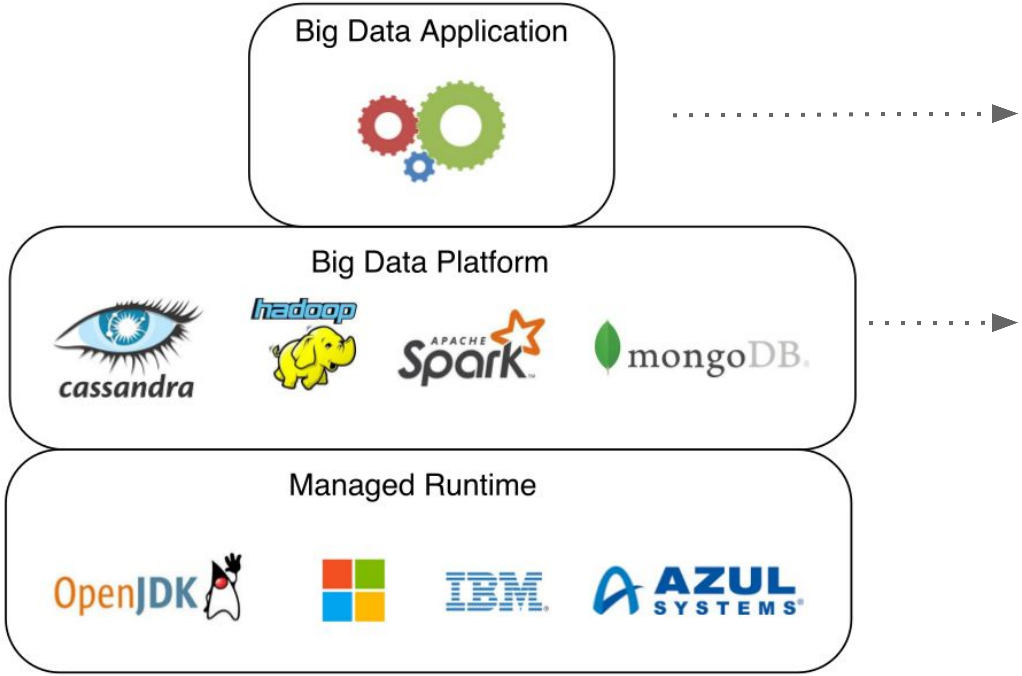

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Slow Platform Response Time

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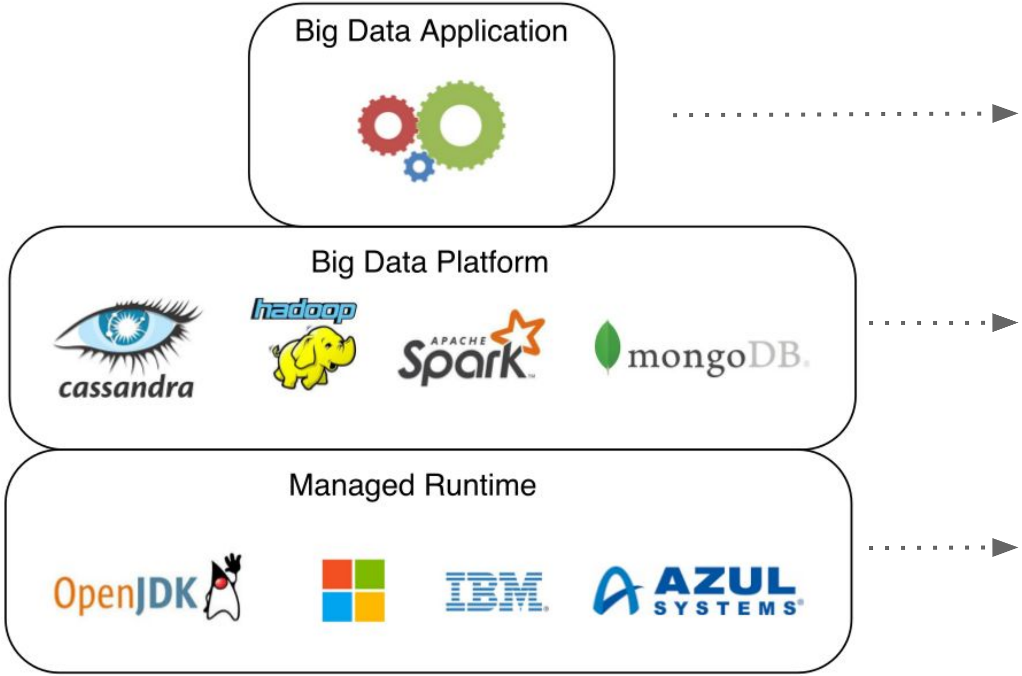
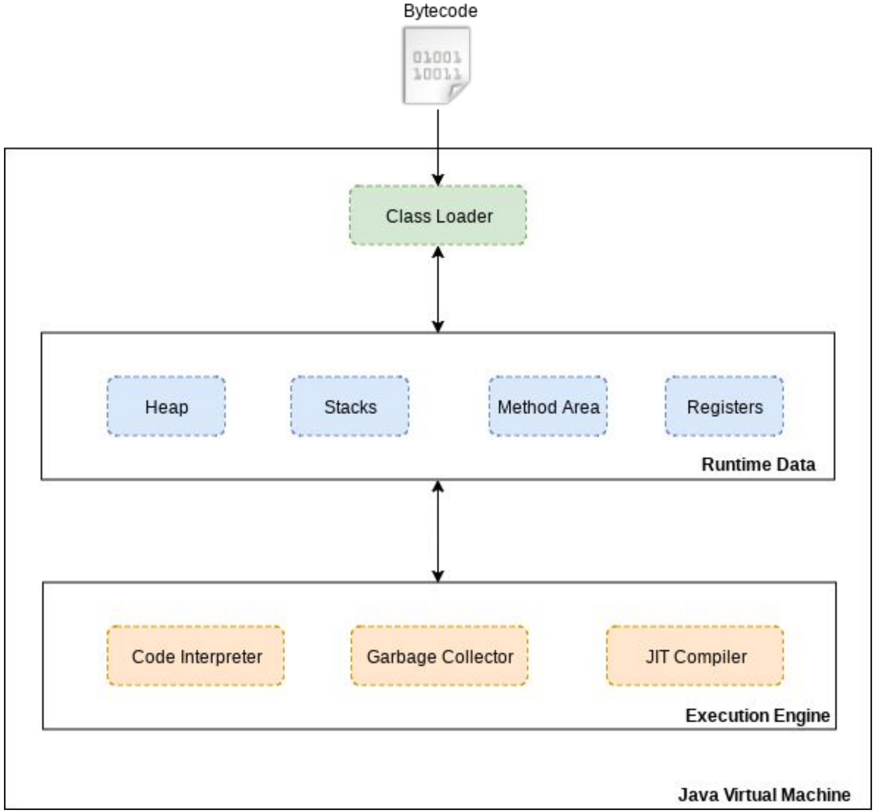


SLAs can be easily compromised

Slow Platform Response Time

Application Threads are being hold

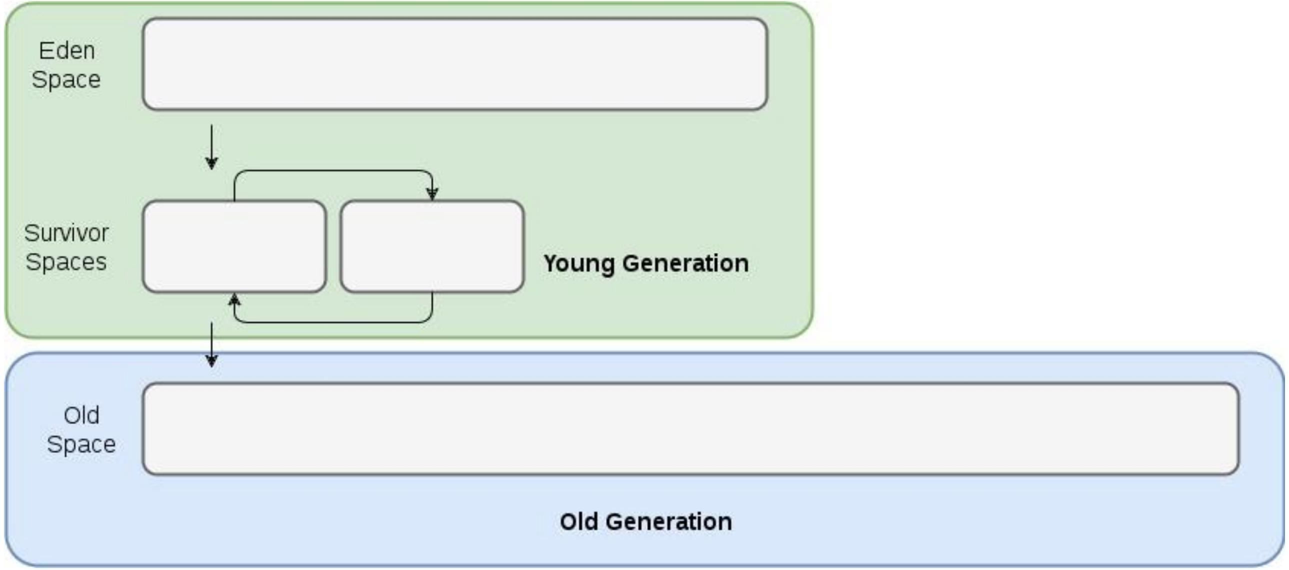
GC-induced Application Latency



GC is known to have difficulties scaling to high number of cores and memory, mainly w.r.t. Latencies:

- [ACM CSUR 2018]
- [DSN 2018]
- [ISMM 2017]
- [ISMM 2015]
- [ASPLOS 2013]
- ...

OpenJDK HotSpot Generational GCs (PS, CMS, G1)



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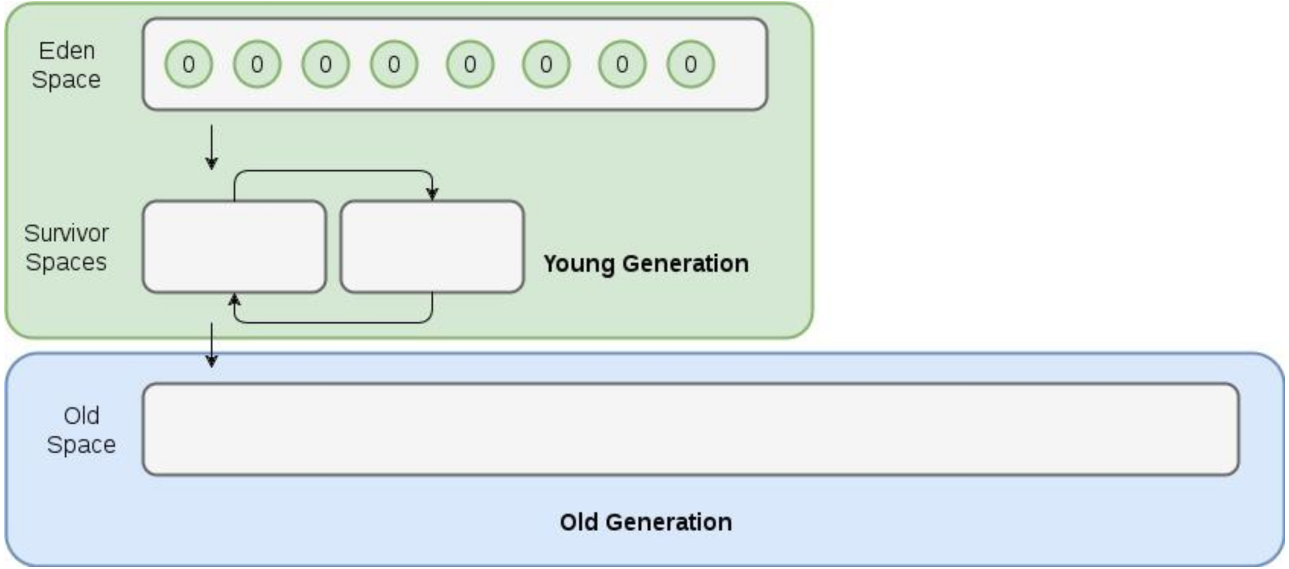

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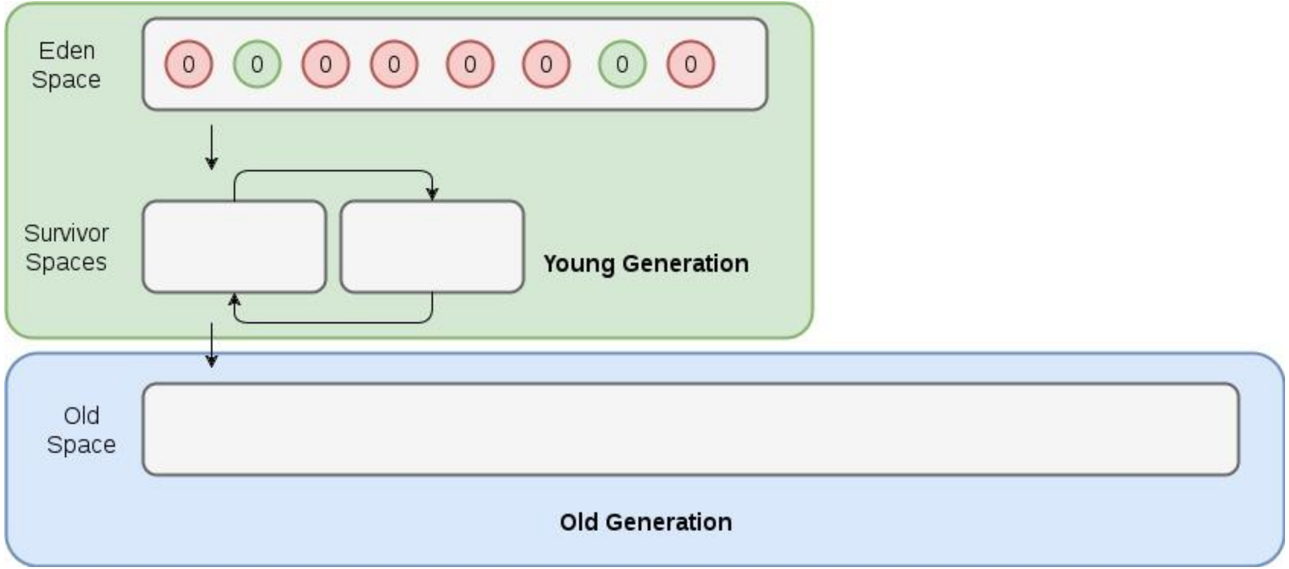

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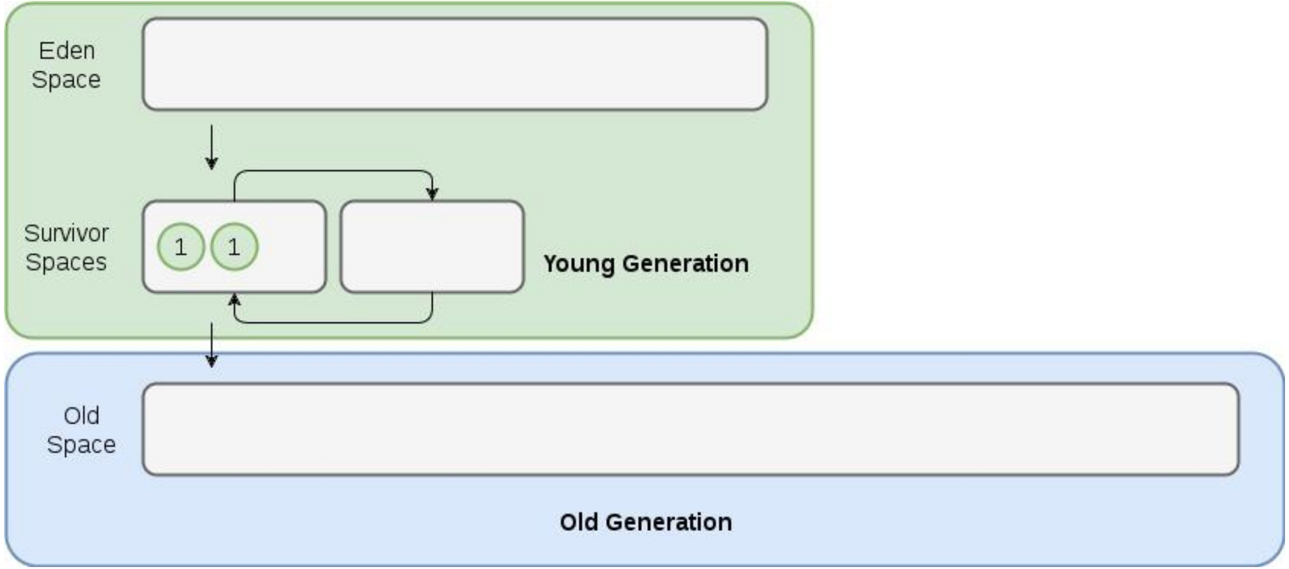

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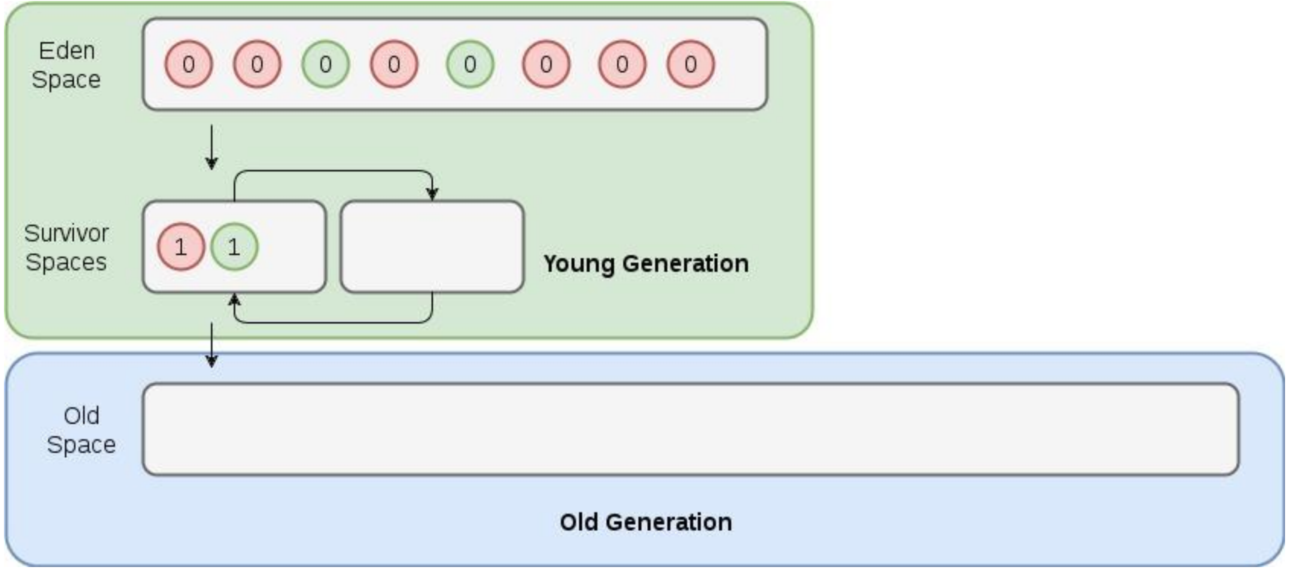

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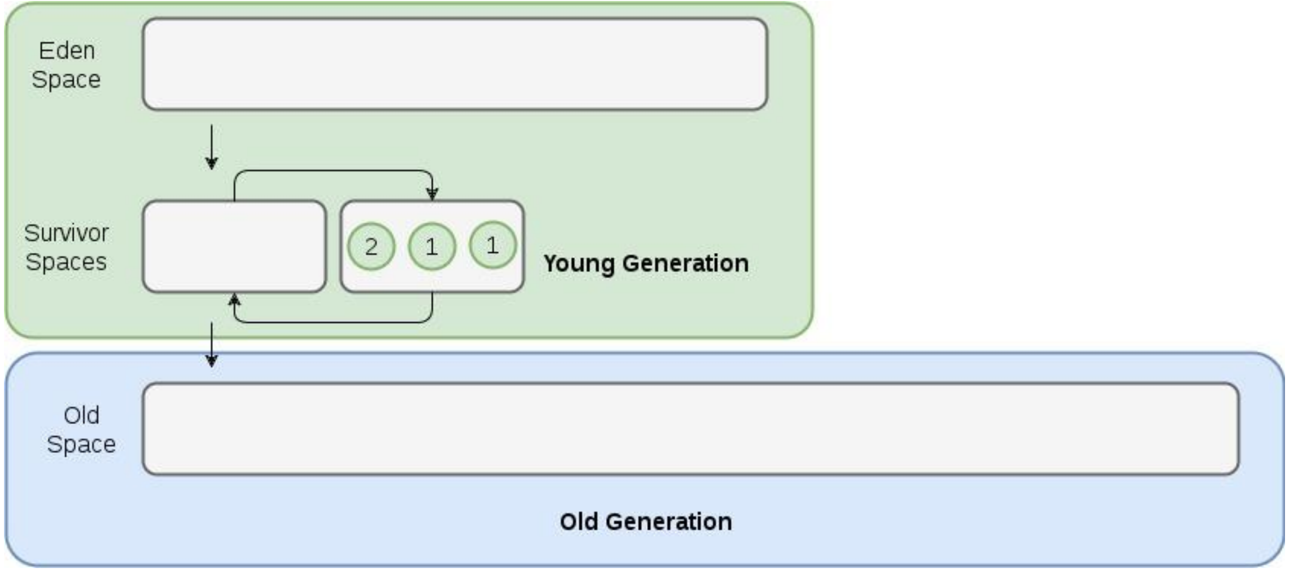

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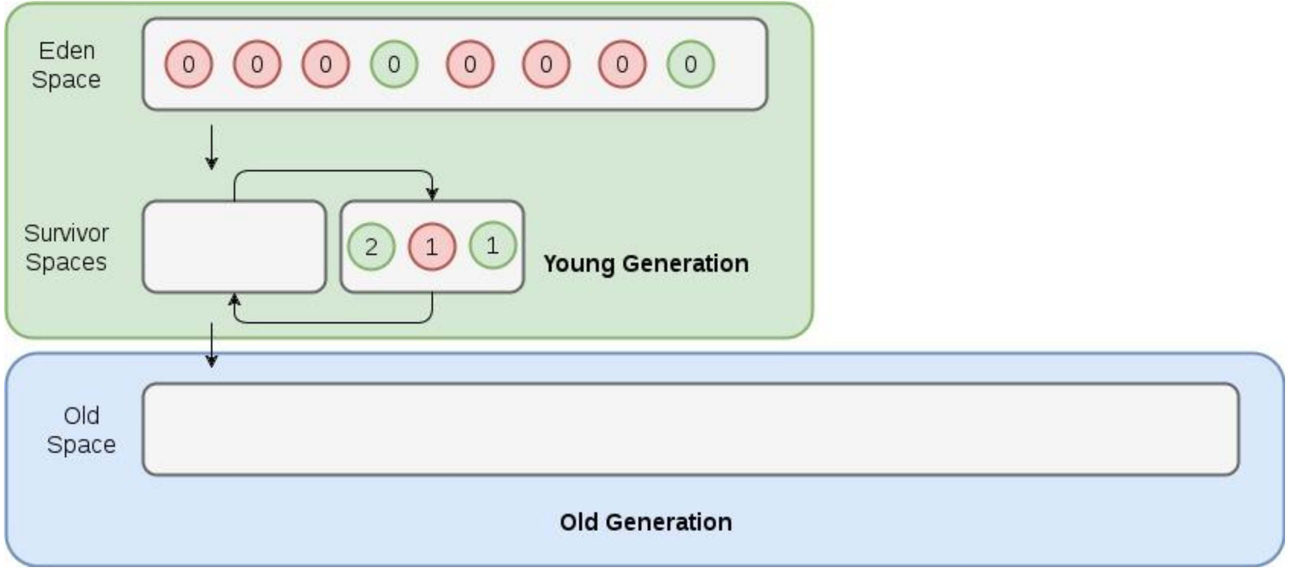

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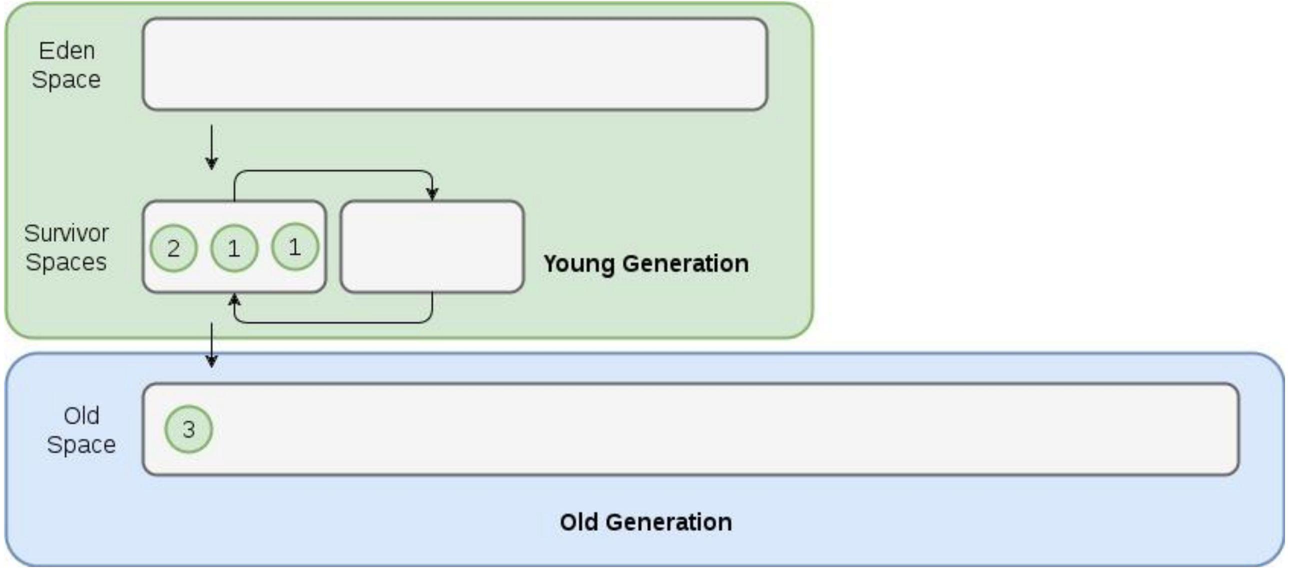

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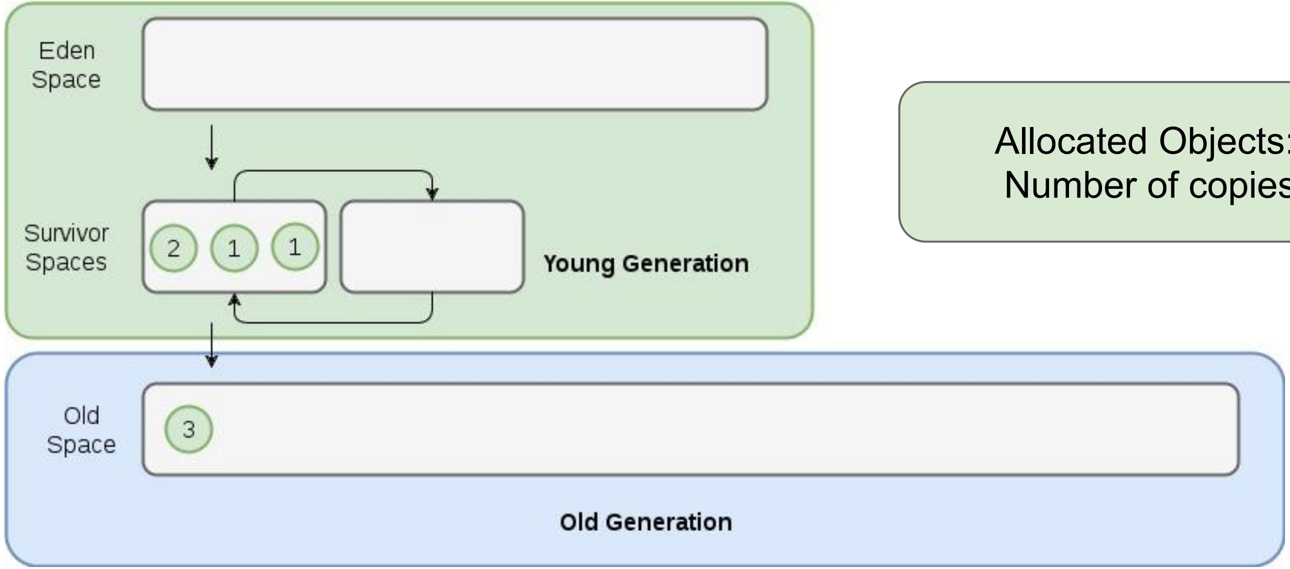

Allocated Objects: **32**
Number of copies: **9**

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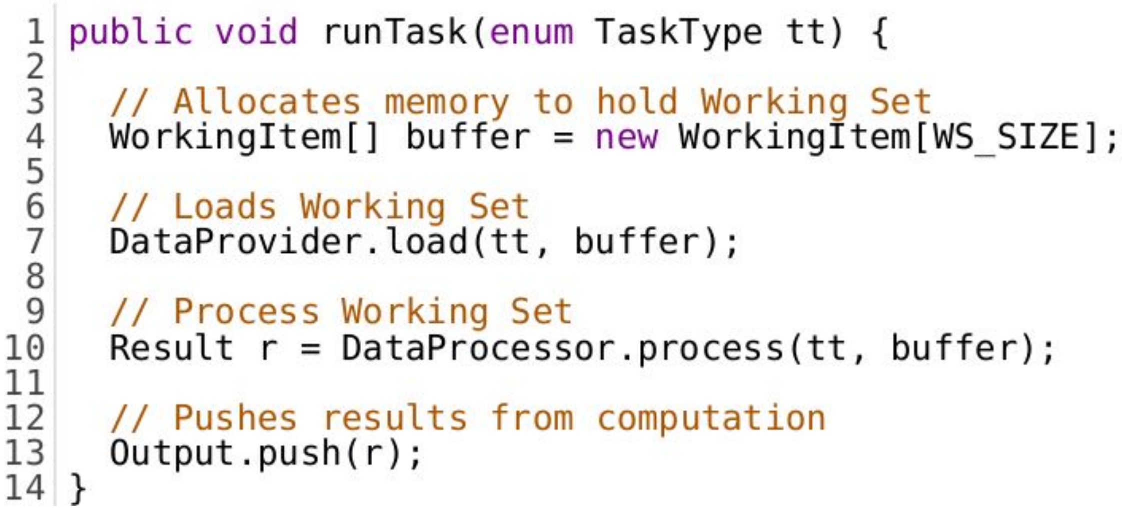
Big Data Application (simplification)



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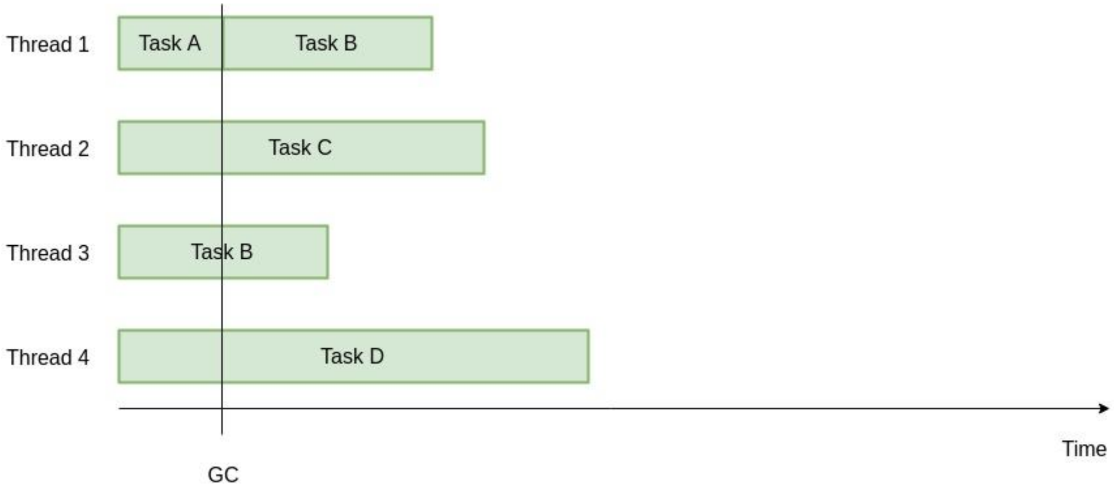
  DataProvider.load(tt, buffer);

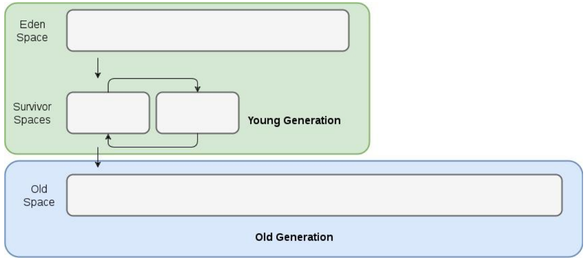
  // Process Working Set
  Result r = DataProcessor.process(tt, buffer);

  // Pushes results from computation
  Output.push(r);
}
```

- 4 threads (one per core), running ‘runTask’ method in loop
- Each task consumes 500 MB of memory (Working Set size)
- Eden is 2GB in size
- Tasks can take different amounts of time to finish

Big Data Application in HotSpot GCs





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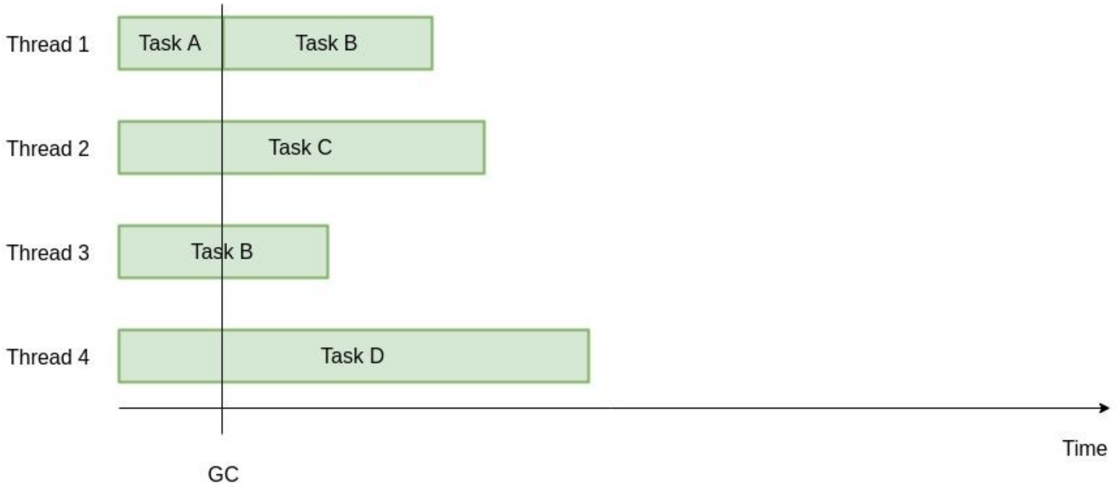
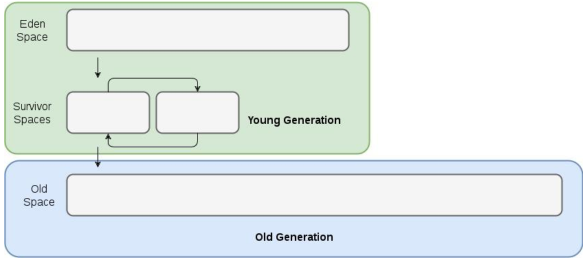


Young generation is full and Thread 1 needs more memory to allocate WS for Task B.

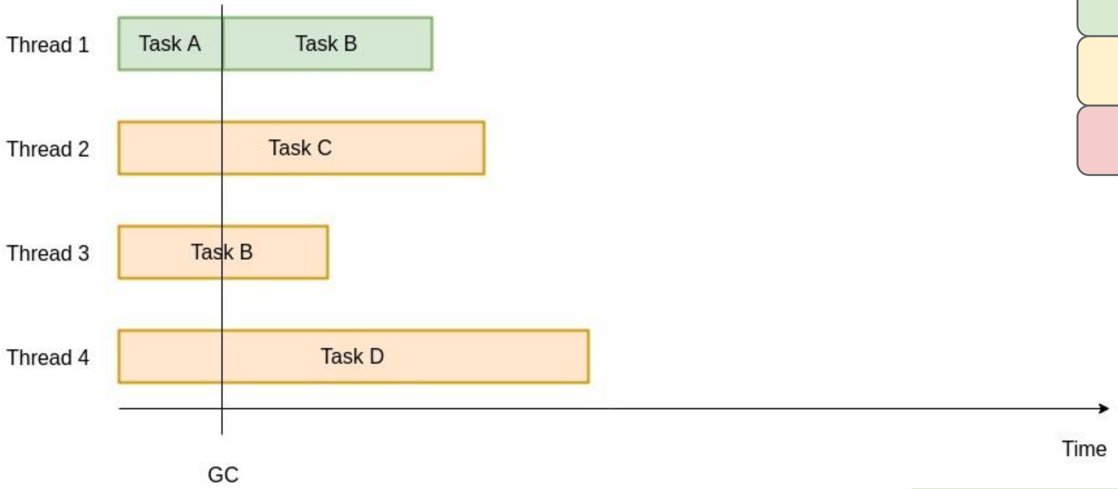


Big Data Application in HotSpot GCs

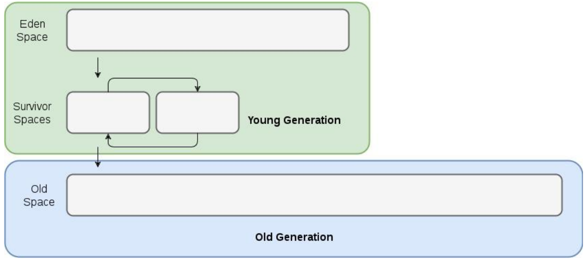
WS not copied

WS copied once

WS copied twice



Copies 3 WS = 1500 MB!



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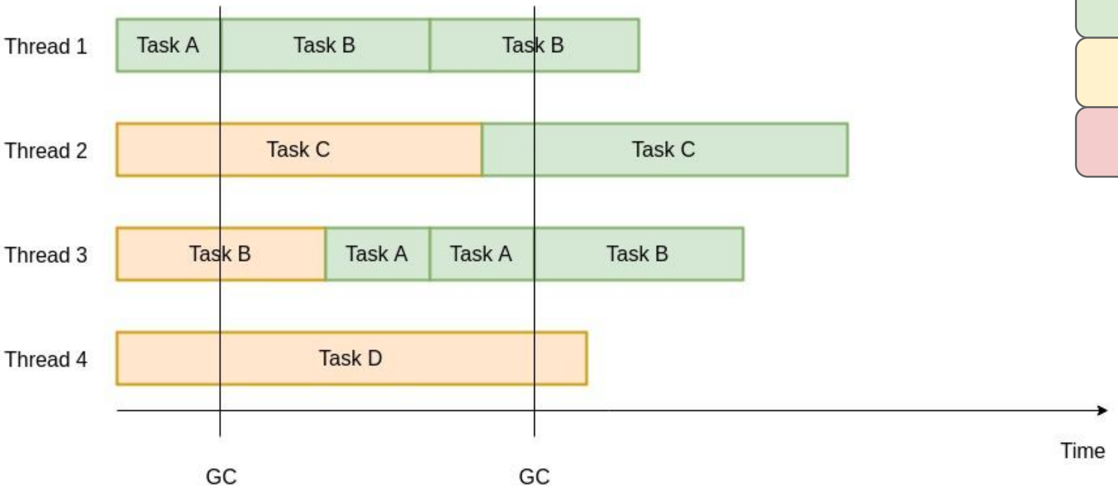

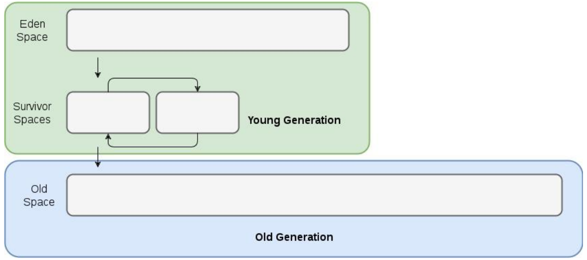

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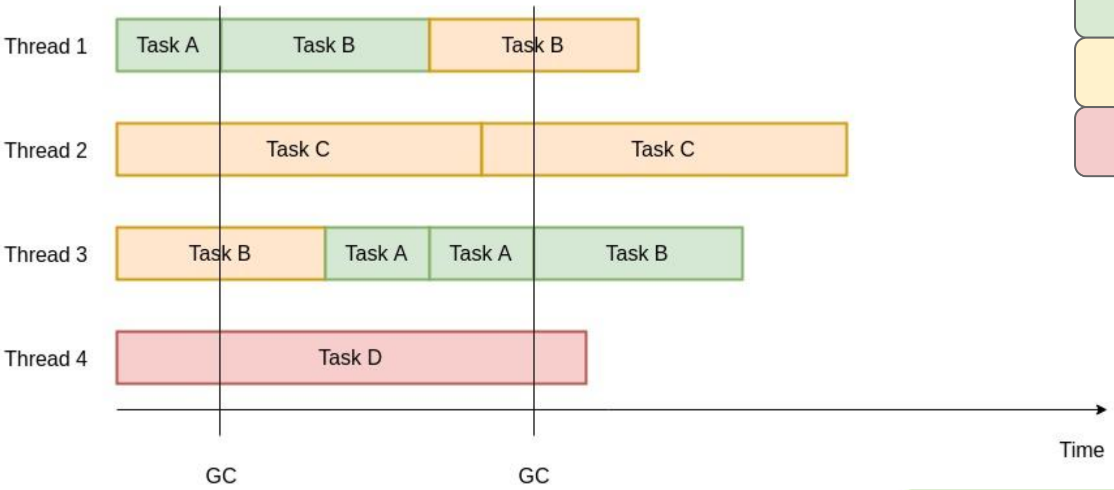

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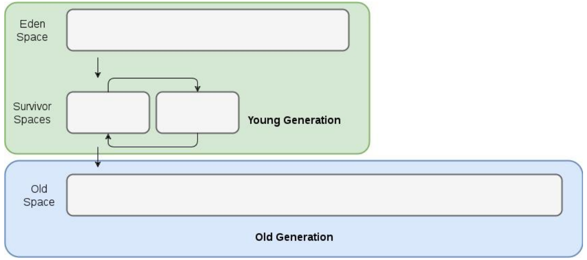

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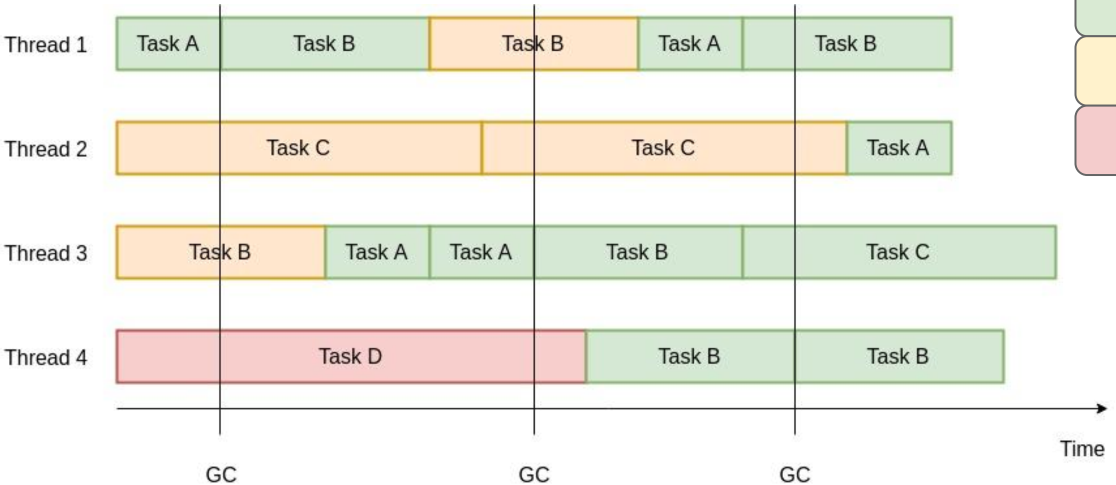

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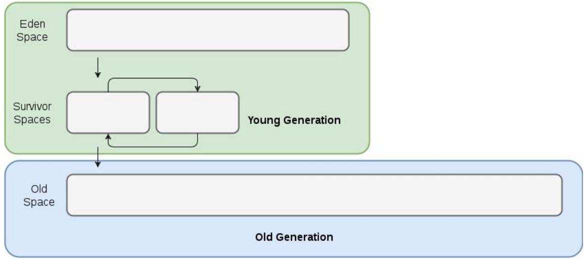

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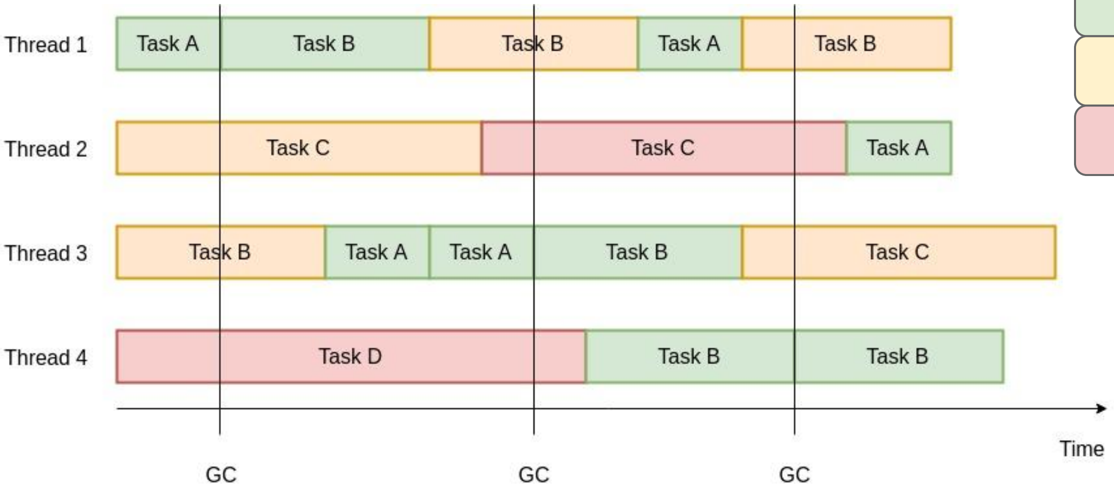

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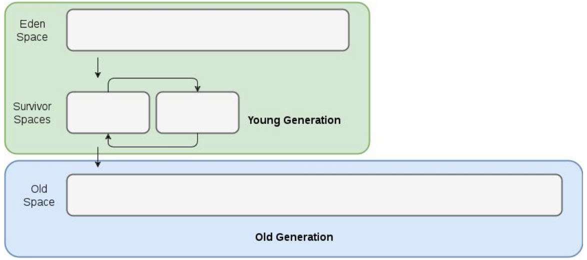

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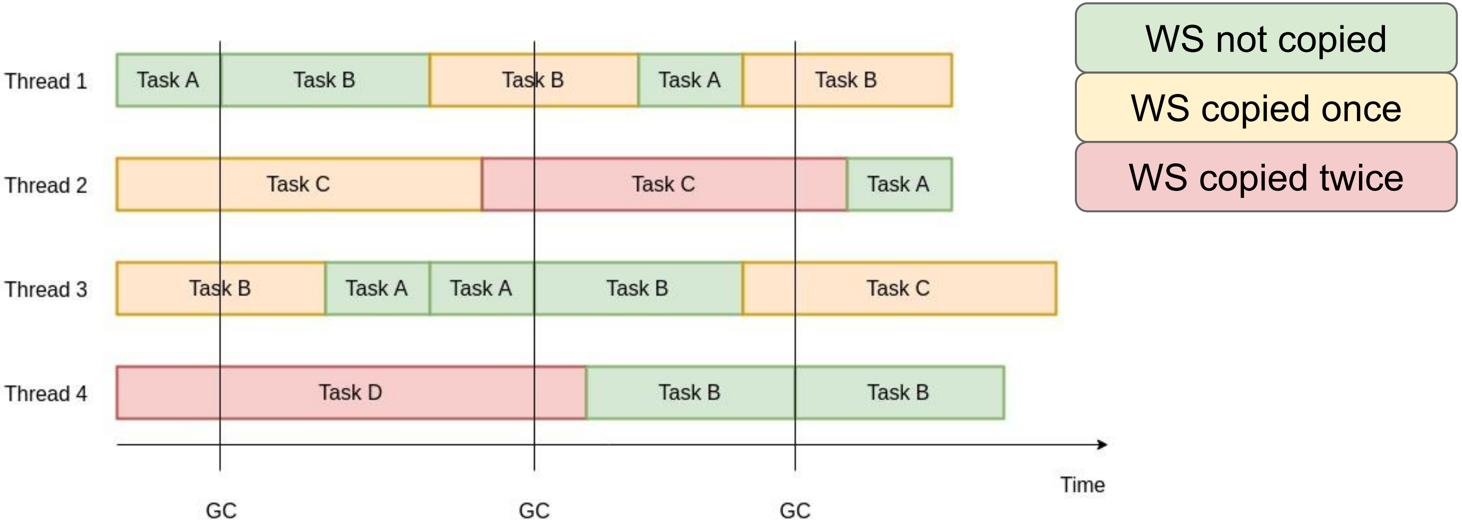

Object copy per GC cycle: 1500 MB
Total amount of object copy: 4500 MB

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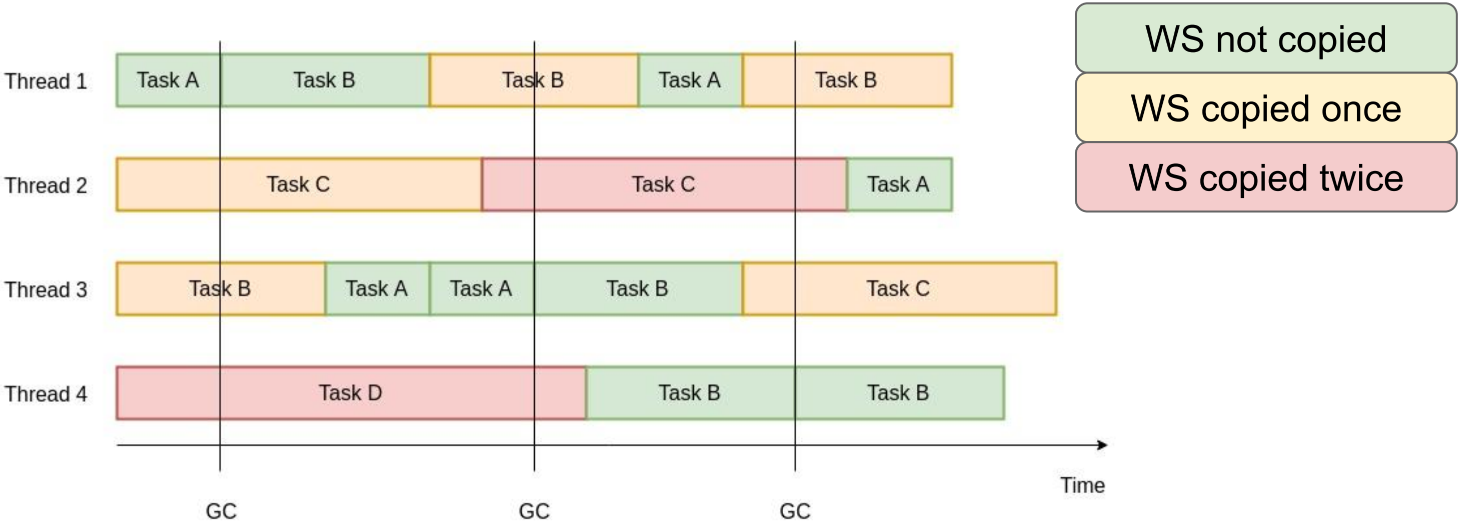

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Assuming average RAM bandwidth of 20GB/s (DDR4)

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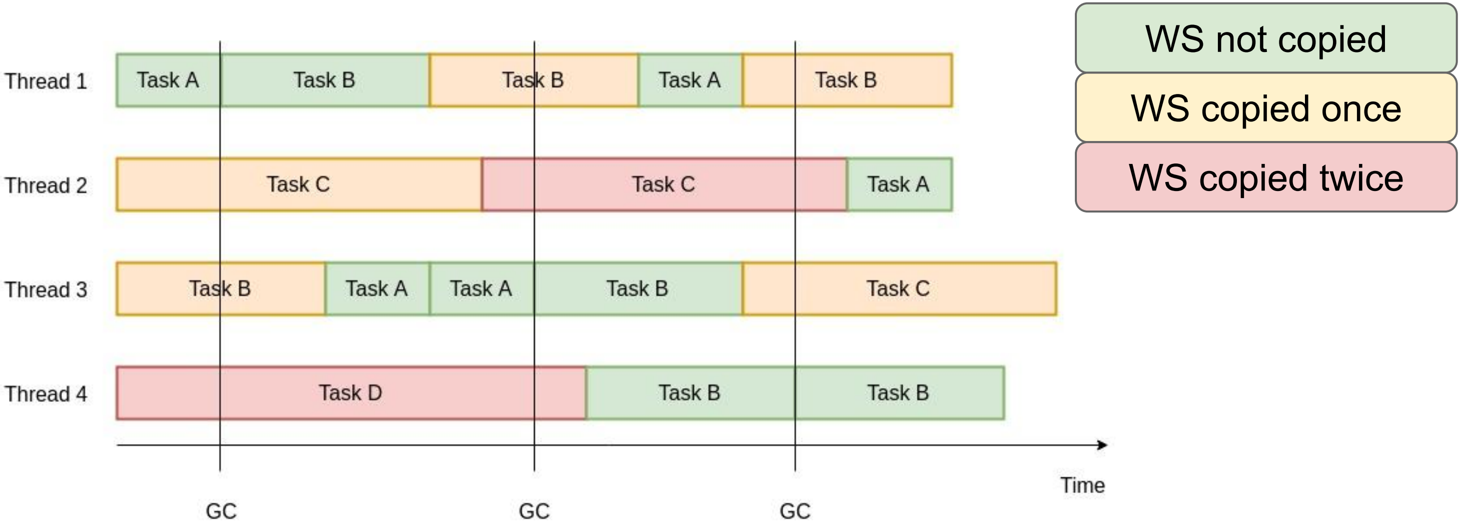

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4 Threads, Eden 2GB = copy 3 tasks (1500 MB) ~= **150 ms**

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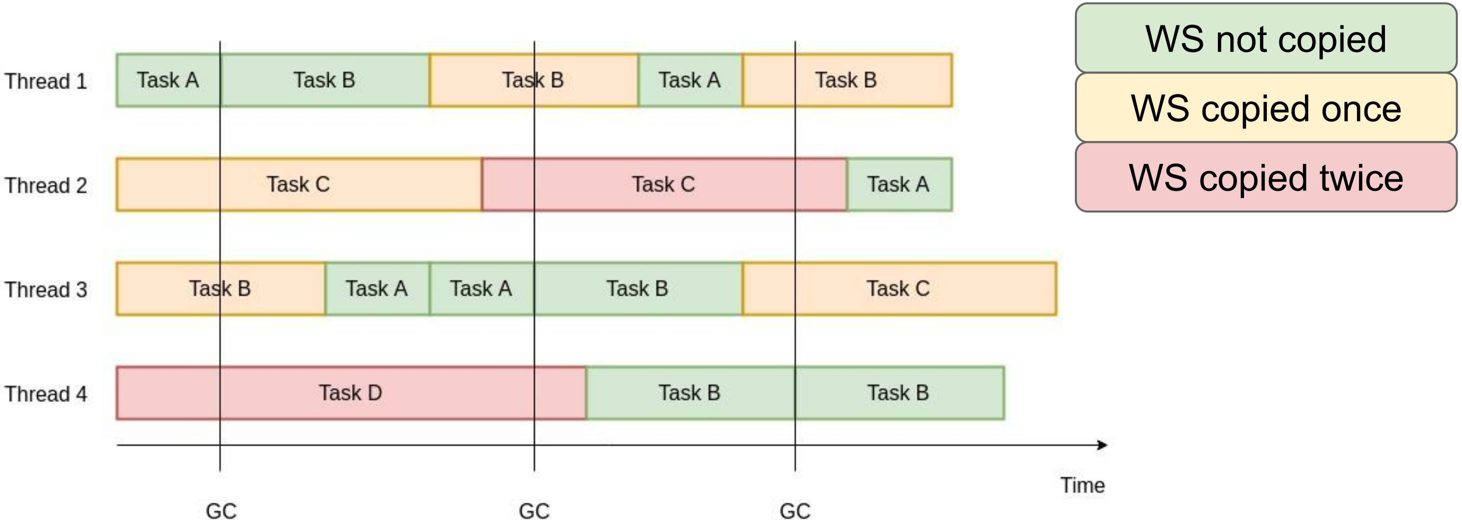

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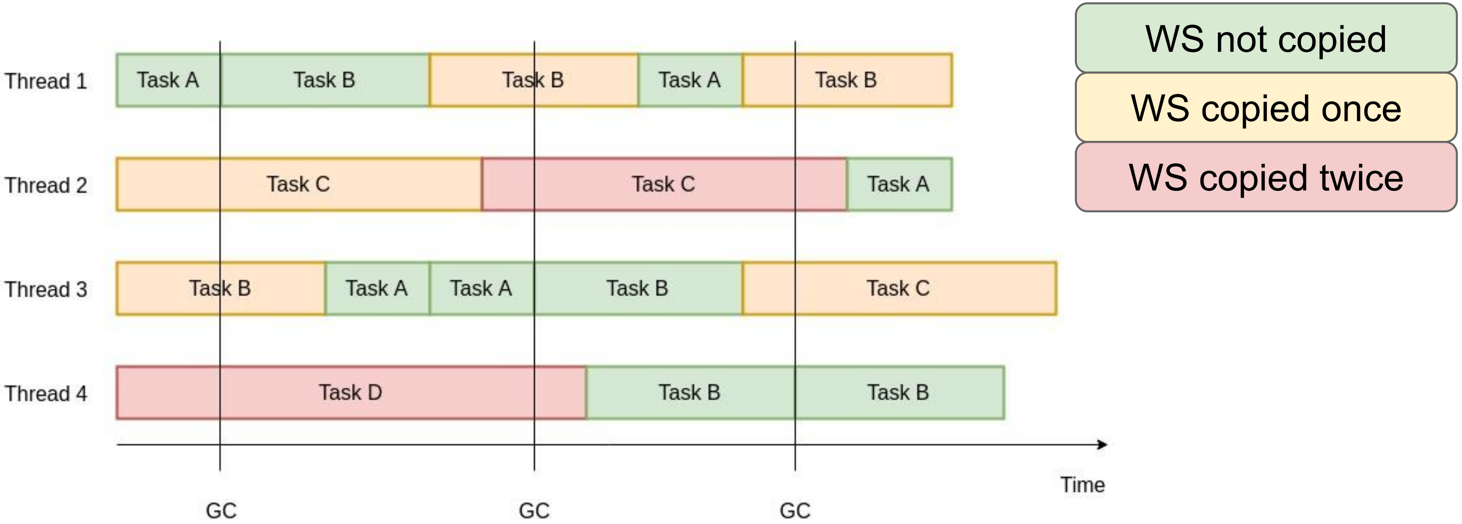

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16 Threads, Eden 8GB = copy 15 task (7500 MB) ~= **750 ms**

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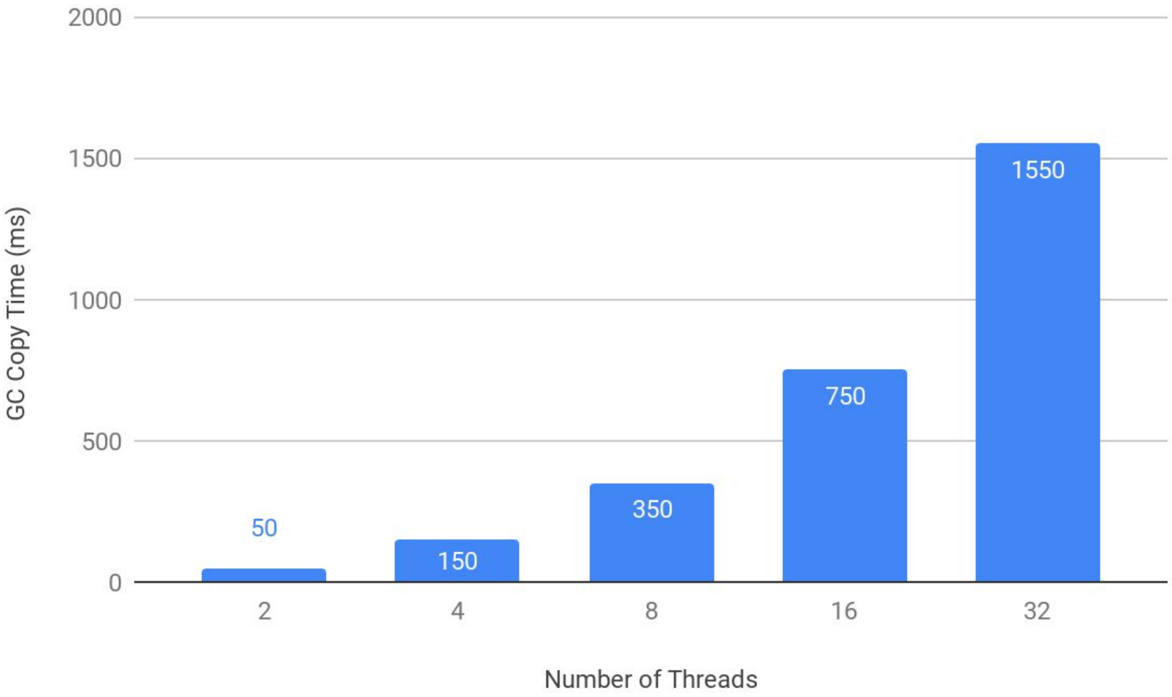

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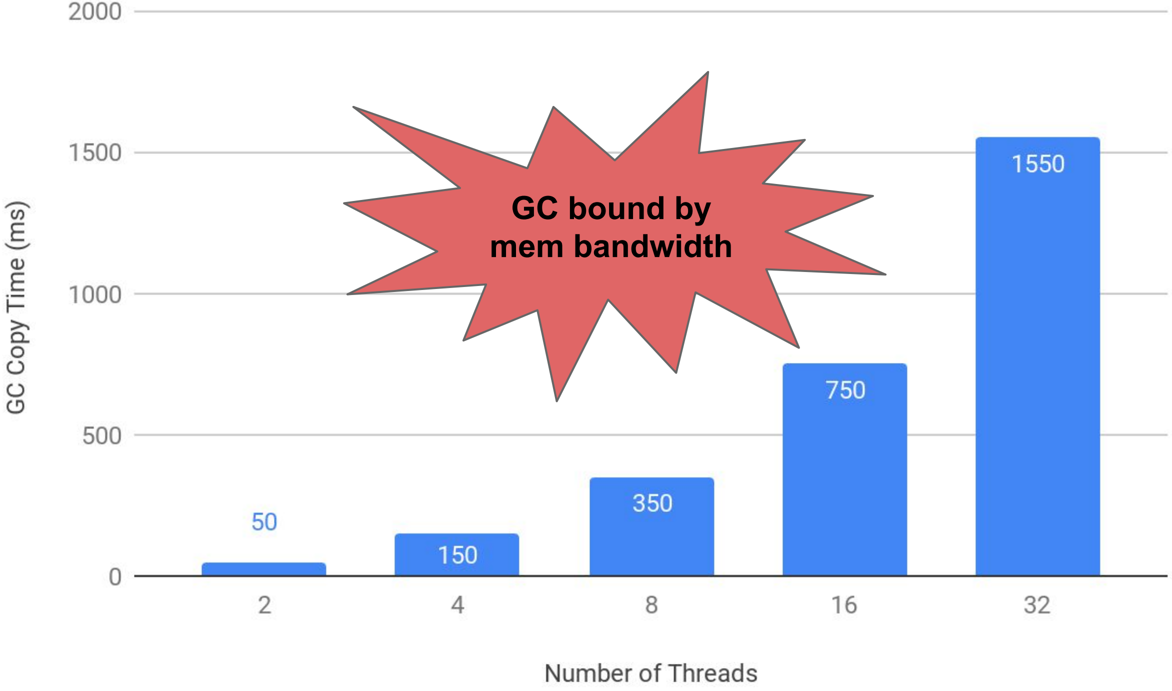
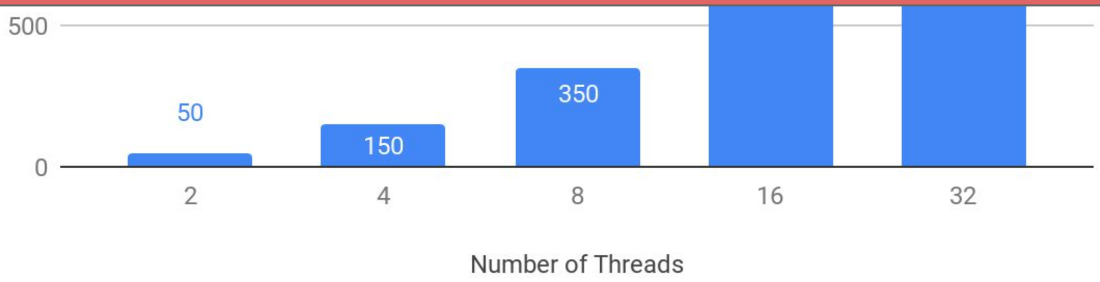


GC bound by
mem bandwidth

Big Data Application in HotSpot GCs

Goal: Reduce Application Pauses by reducing Object Copying

(no negative impact on throughput; no programmer effort)



How to Avoid en-masse Object Copying

- Attempt 1: Heap Resizing
  - ✓ Increase Young generation size giving more time for objects to die;
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- Attempt 3: Reuse data objects (object pooling)
  - ✓ Avoids allocating new memory for future Tasks;
  - ! Requires major rewriting of applications combined with very unnatural Java programming style.

How to Avoid en-masse Object Copying

- Attempt 4: Off-heap memory
  - ✓ Reduces GC effort as data objects can reside in off-heap
  - ! Objects describing data objects still reside in the GC-managed heap
  - ! Requires manual memory management (defeats the purpose of running inside a managed heap).

How to Avoid en-masse Object Copying

- Attempt 4: Off-heap memory
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- Attempt 5: Region-based/Scope-based memory allocation
  - ✓ Limits object's reachability by scope/region;
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- Attempt 6: Completely Concurrent Collectors (C4, Shenandoah, ZGC)
  - ✓ Greatly reduced pause times
  - ! High throughput overhead (~30% for Cassandra workloads)

How to Avoid en-masse Object Copying

Takeaway:

- Avoiding massive object copying is non-trivial!
- Existing solutions only alleviate the problem!
- Existing solutions might work in some scenarios but do not provide a general solution.

Proposed Solution

- **Solution**:
  - Allocate objects with similar lifetimes close to each other
    - Reducing memory fragmentation
    - Reducing object promotion
  - As a consequence, object copying is reduced!

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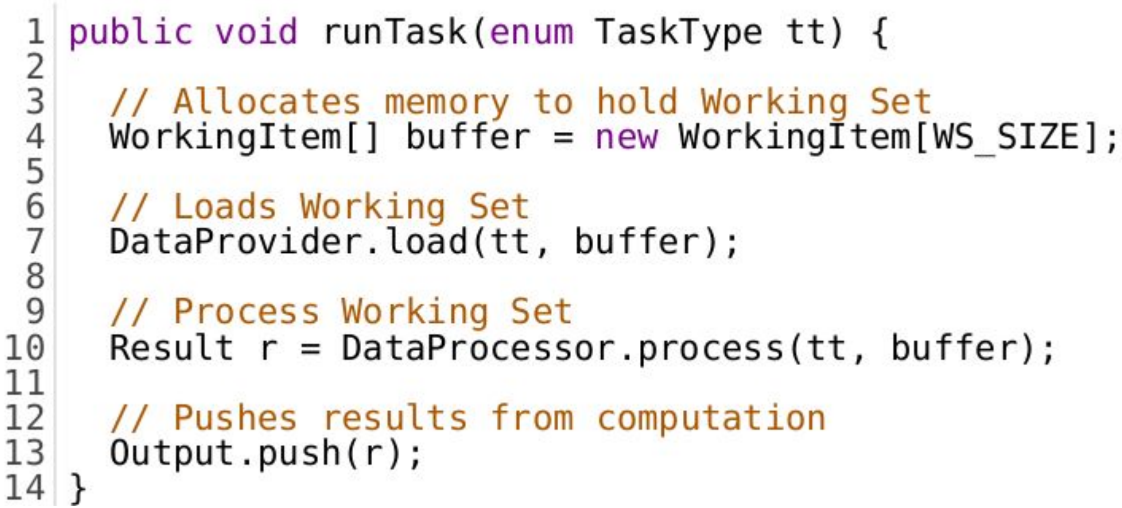
- **Hypothesis**:
  - Objects allocated through the same allocation context have similar lifetimes;
  - Allocation context is a tuple of:
    - Allocation site (line of bytecode)
    - Call graph state (stack state)

Big Data Application (simplification)



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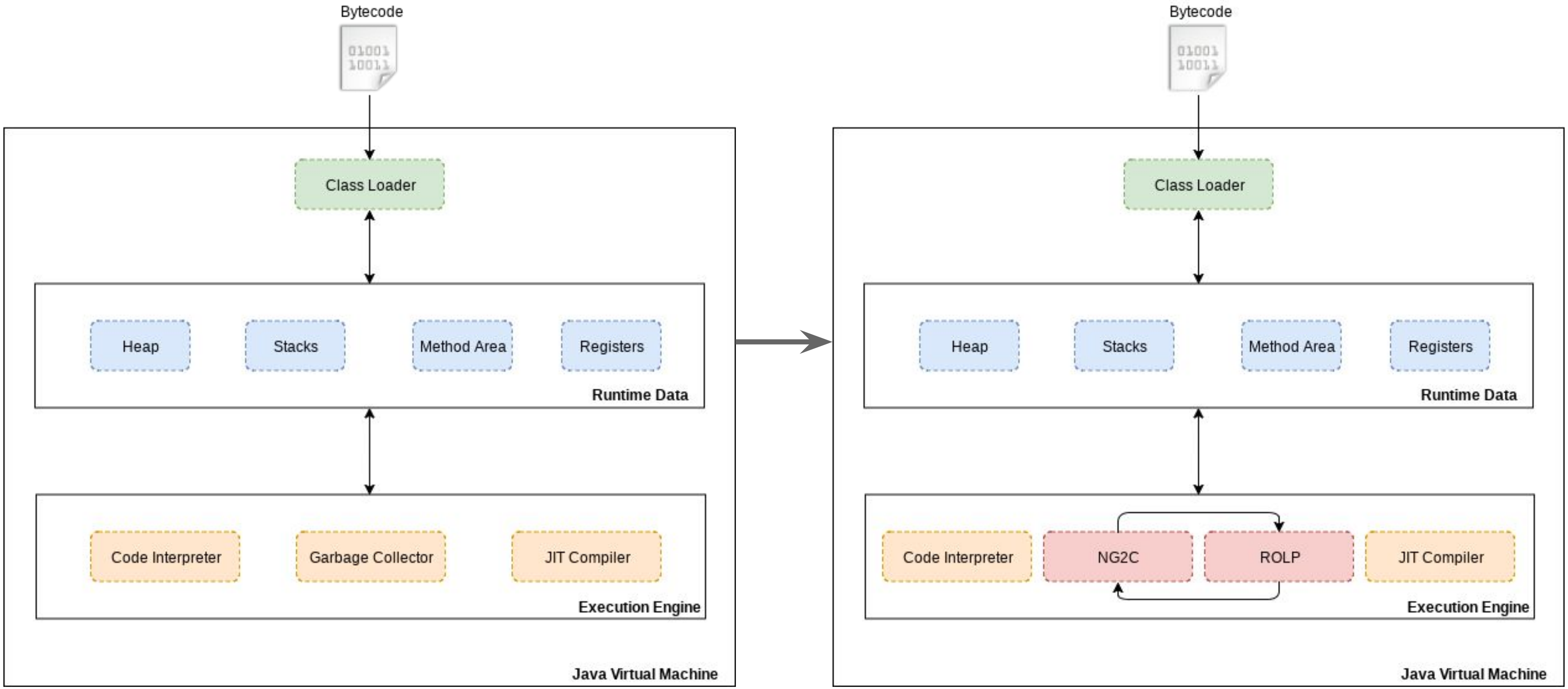
Solution - NG2C + ROLP



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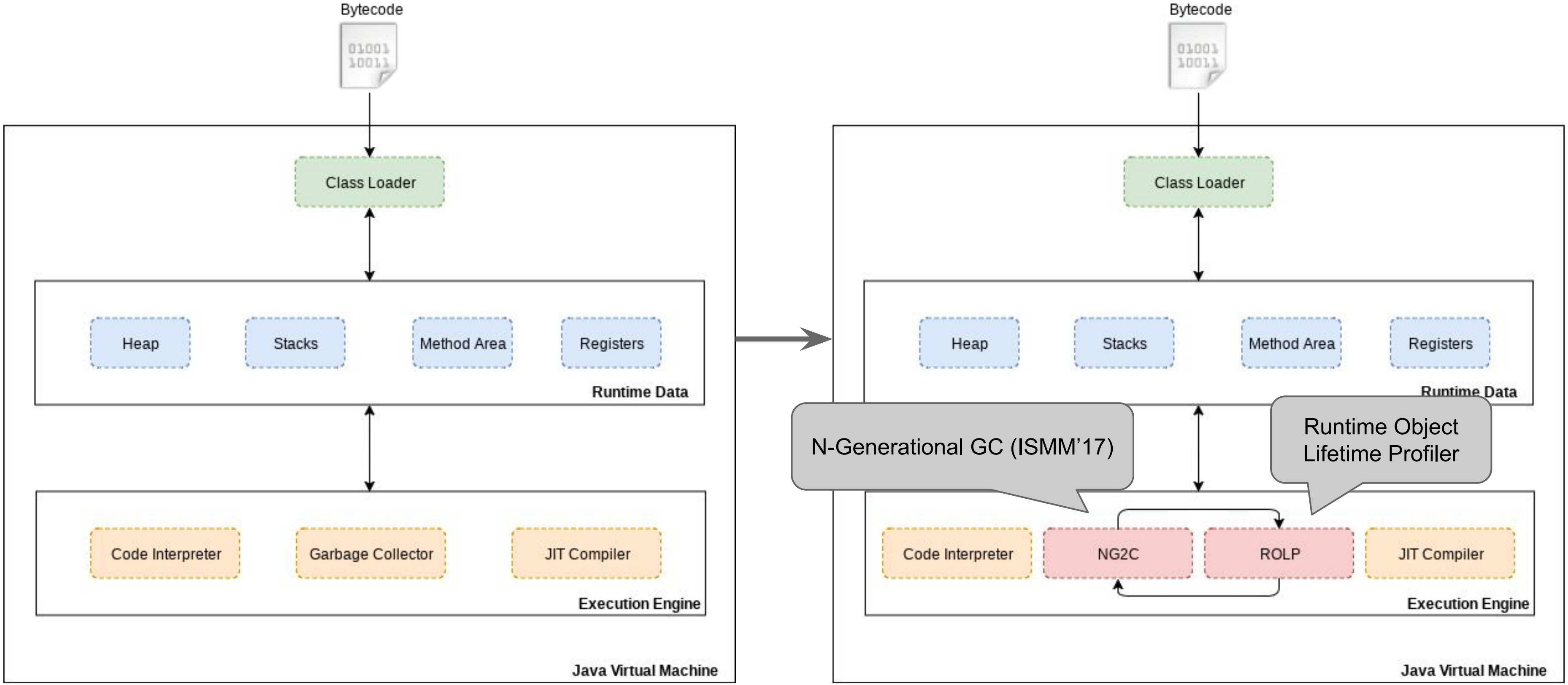
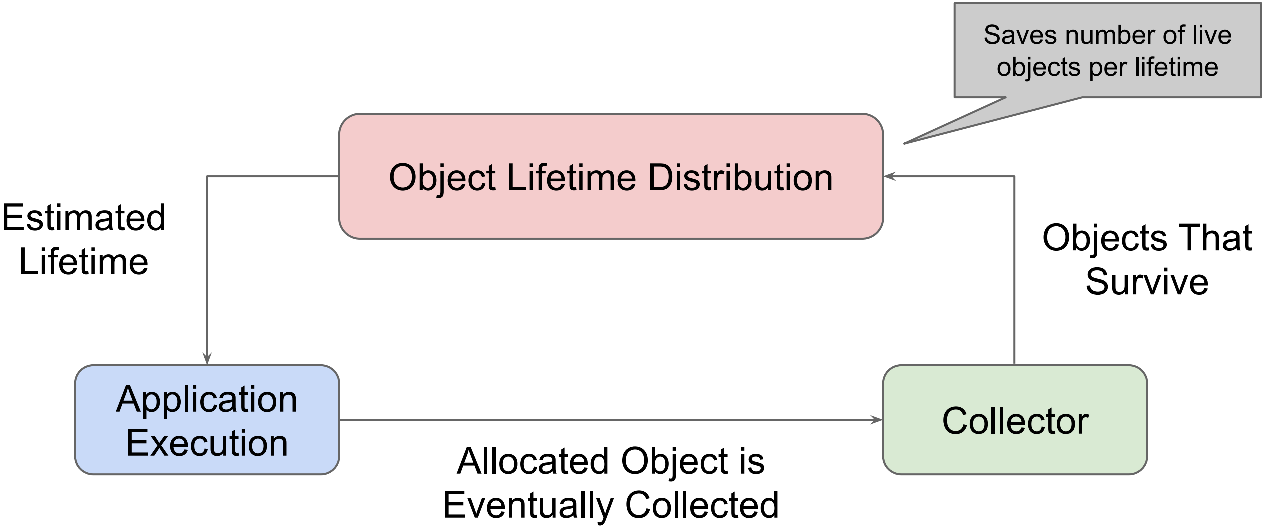


Runtime Object Lifetime Profiler (overview)

- Profiler needs to answer a single question
  - How long will objects allocated through a particular allocation context live?



Saves number of live objects per lifetime

Object Lifetime Distribution

Estimated Lifetime

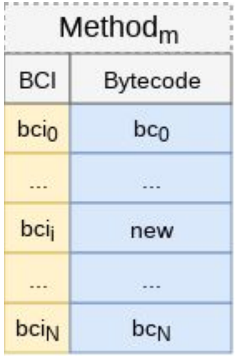
Objects That Survive

Application Execution

Collector

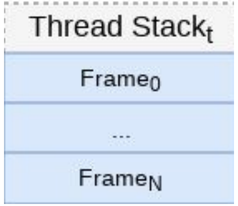
Allocated Object is Eventually Collected

Runtime Object Lifetime Profiler (workflow)



Method_m

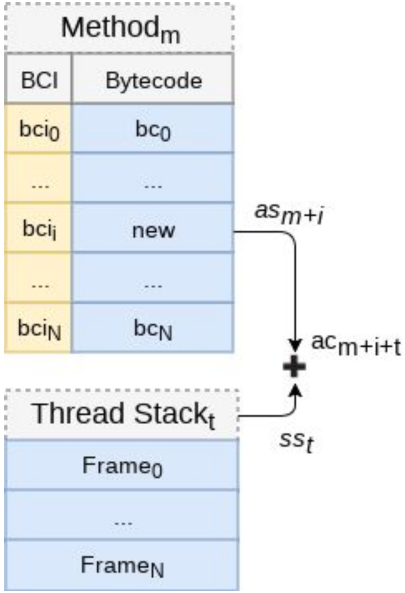
BCI	Bytecode
bci_0	bc_0
...	...
bci_i	new
...	...
bci_N	bc_N



Thread Stack_t

Frame_0
...
Frame_N

Runtime Object Lifetime Profiler (workflow)



Method$_m$

BCI	Bytecode
bci$_0$	bc$_0$
...	...
bci$_i$	new
...	...
bci$_N$	bc$_N$

Thread Stack$_t$

Frame$_0$
...
Frame$_N$

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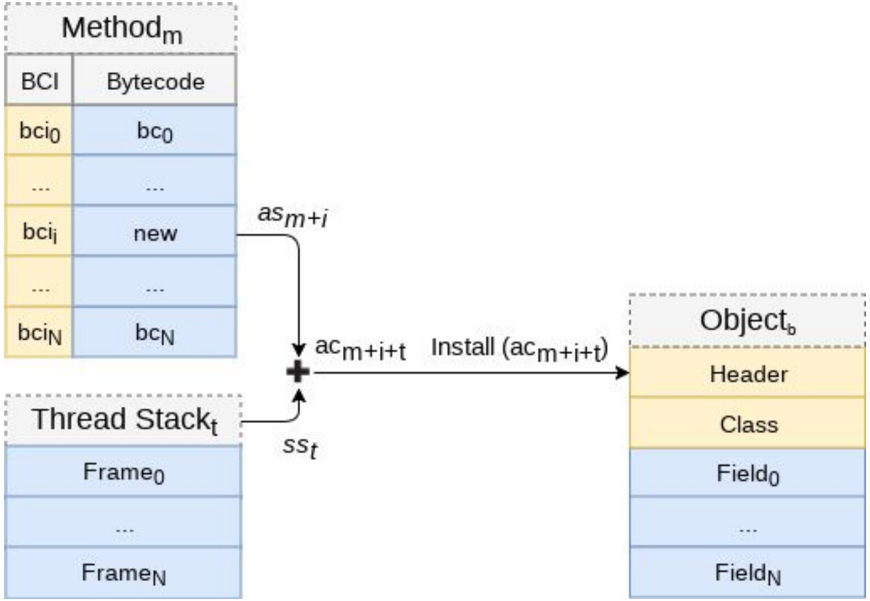
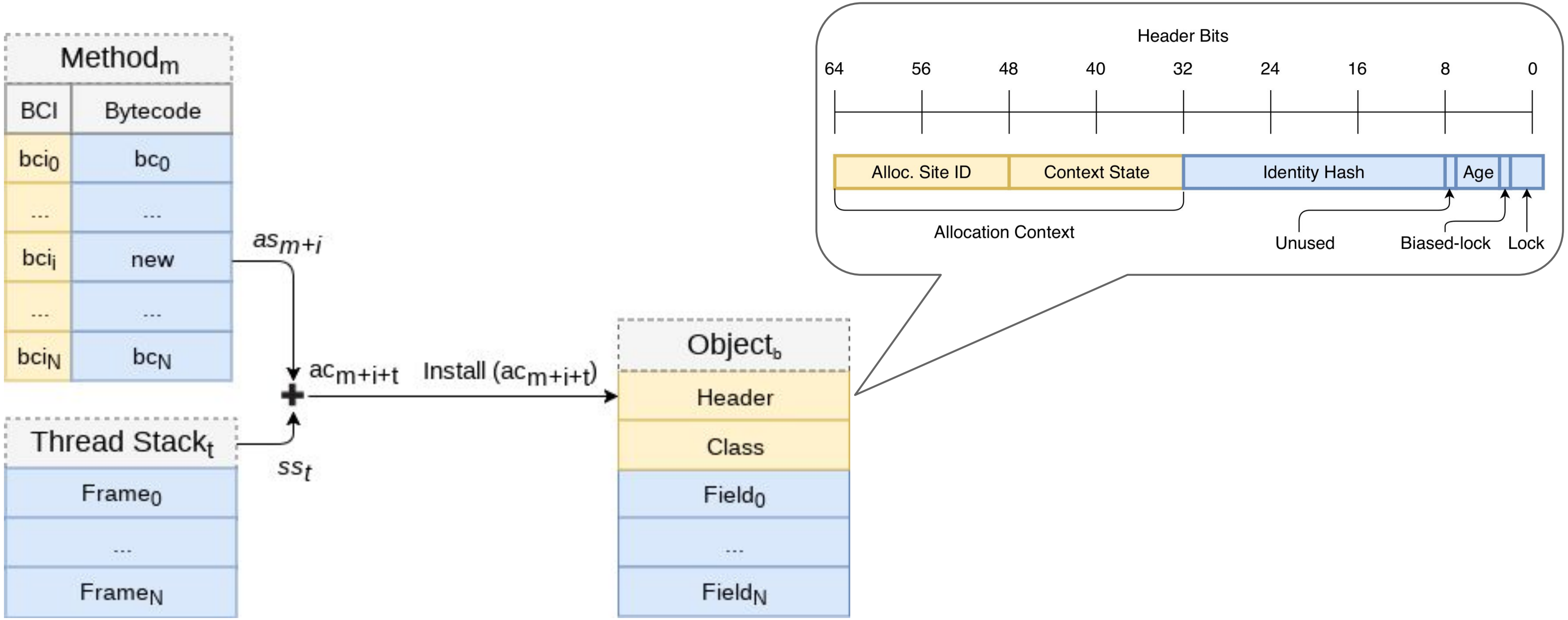


Runtime Object Lifetime Profiler (workflow)



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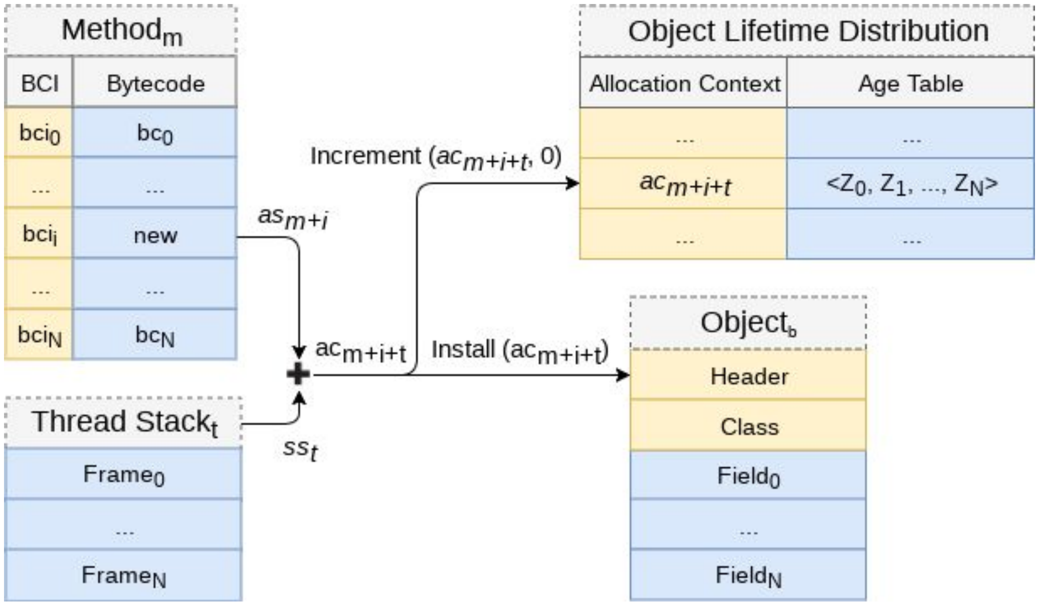

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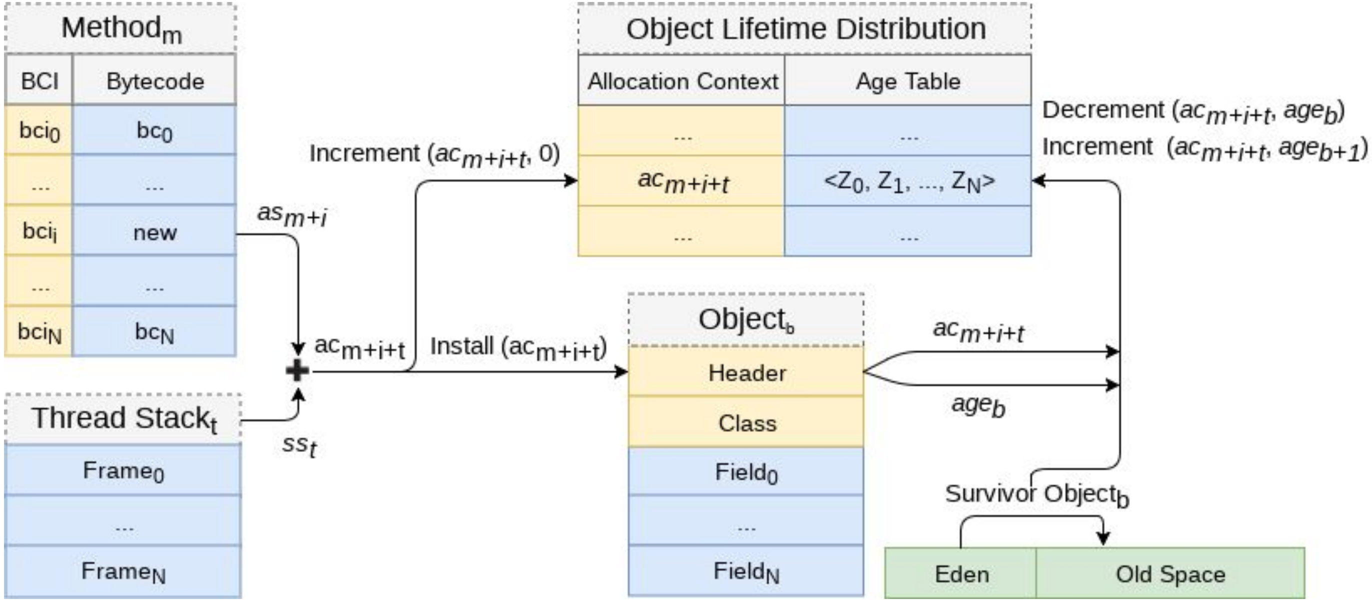


Method_m

BCI	Bytecode
bci_0	bc_0
...	...
bci_i	new
...	...
bci_N	bc_N

Thread Stack_t

Frame_0
...
Frame_N

Object Lifetime Distribution

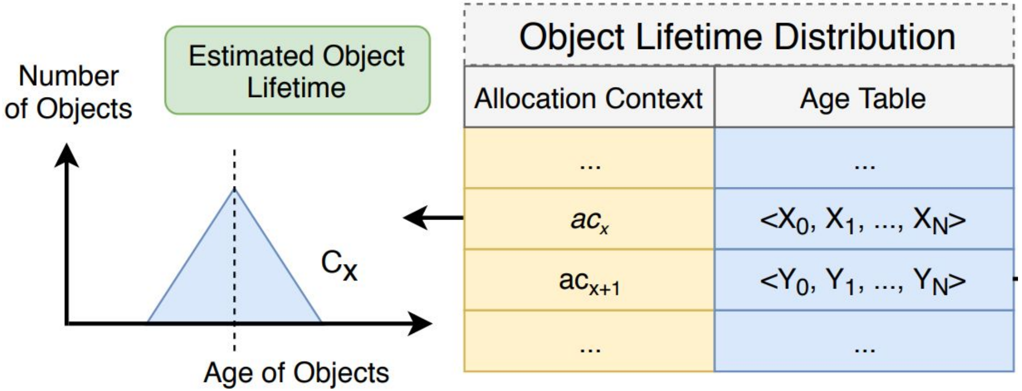
Allocation Context	Age Table
...	...
ac_{m+i+t}	$<Z_0, Z_1, ..., Z_N>$
...	...

Object_b

Header
Class
Field_0
...
Field_N

Eden	Old Space

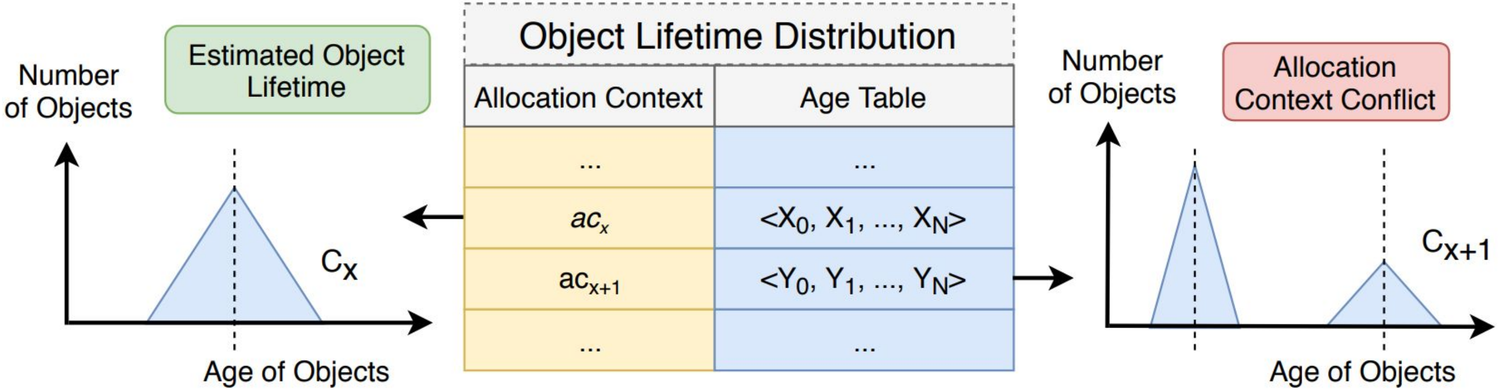
Runtime Object Lifetime Profiler (conflicts)



Object Lifetime Distribution

Allocation Context	Age Table
...	...
ac_x	$<X_0, X_1, ..., X_N>$
ac_{x+1}	$<Y_0, Y_1, ..., Y_N>$
...	...

Runtime Object Lifetime Profiler (conflicts)



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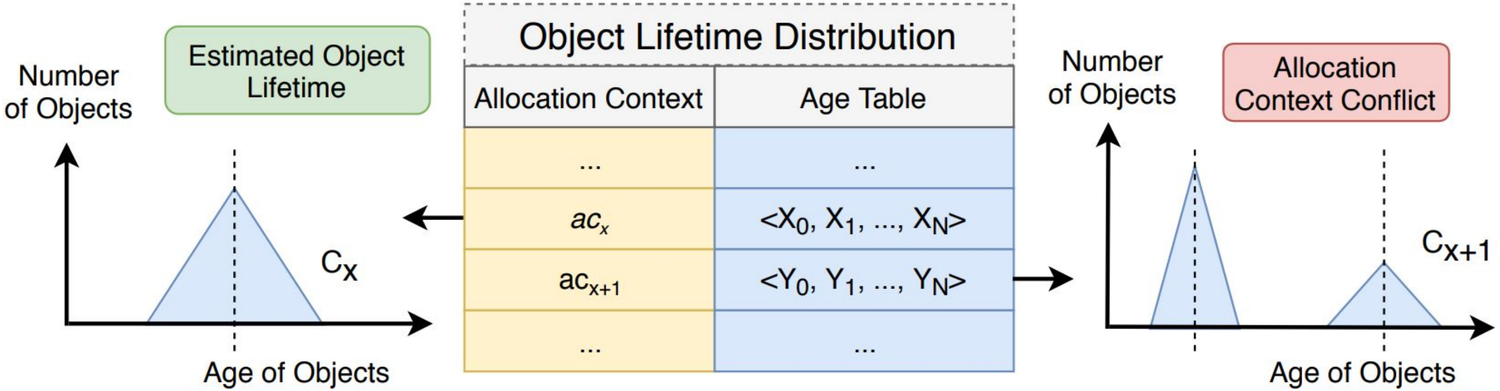

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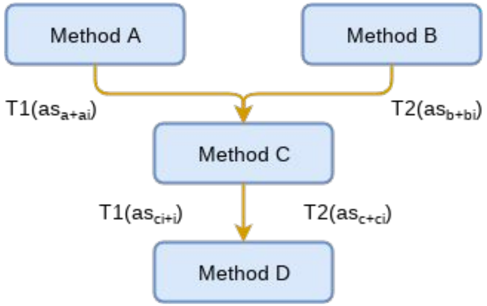

Runtime Object Lifetime Profiler (context tracking)

- Method calls are wrapped with context tracking code (update thread stack state)
- Context tracking is very expensive
  - Only method calls that can resolve conflicts are profiled (next slide)
  - Jitted code can dynamically enable or disable profiling

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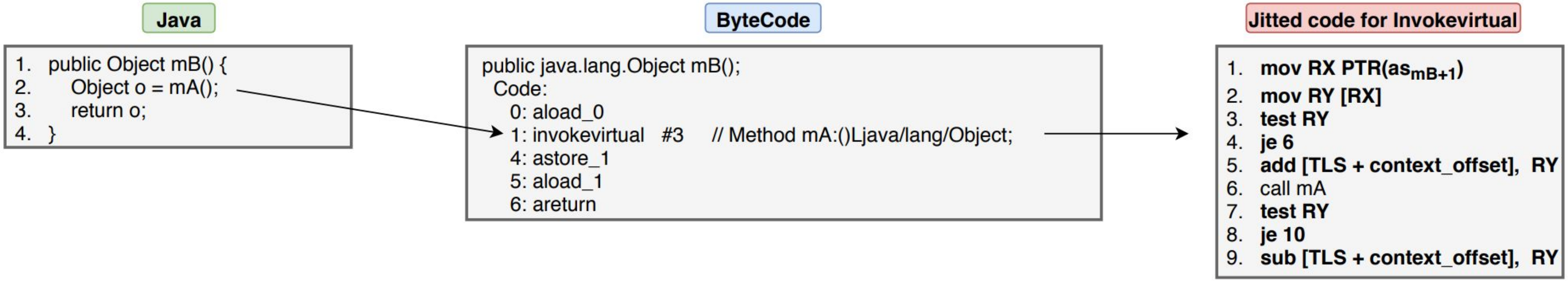

Java

```
public Object mB() {
    Object o = mA();
    return o;
}
```

ByteCode

```
public java.lang.Object mB();
  Code:
    0: aload_0
    1: invokevirtual   #3      // Method mA:()Ljava/lang/Object;
    4: astore_1
    5: aload_1
    6: areturn
```

Jitted code for Invokevirtual

1. **mov RX PTR(as$_{mB+1}$)**
2. **mov RY [RX]**
3. **test RY**
4. **je 6**
5. **add [TLS + context_offset], RY**
6. call mA
7. **test RY**
8. **je 10**
9. **sub [TLS + context_offset], RY**

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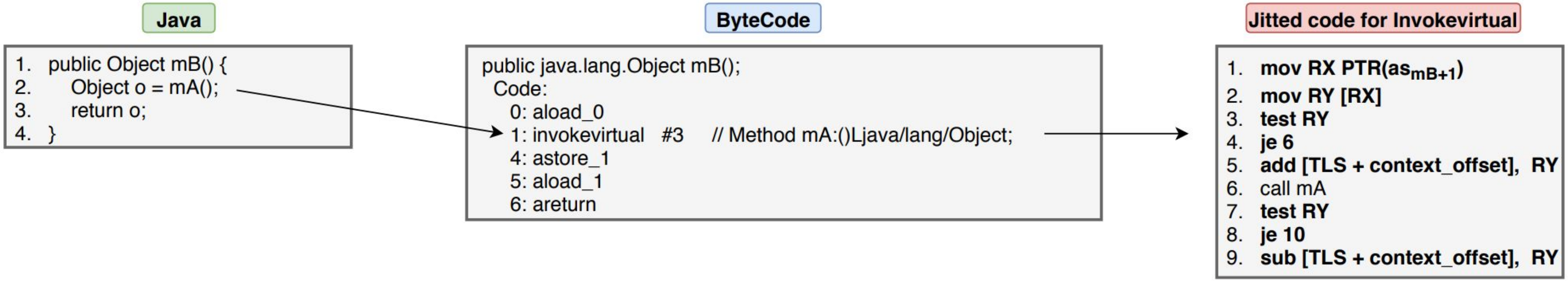

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Method call profiling can be dynamically turned on or off!

Runtime Object Lifetime Profiler (implementation)

- ROLP is implemented on OpenJDK HotSpot 8
  - Industrial JVM

- ROLP is integrated with NG2C

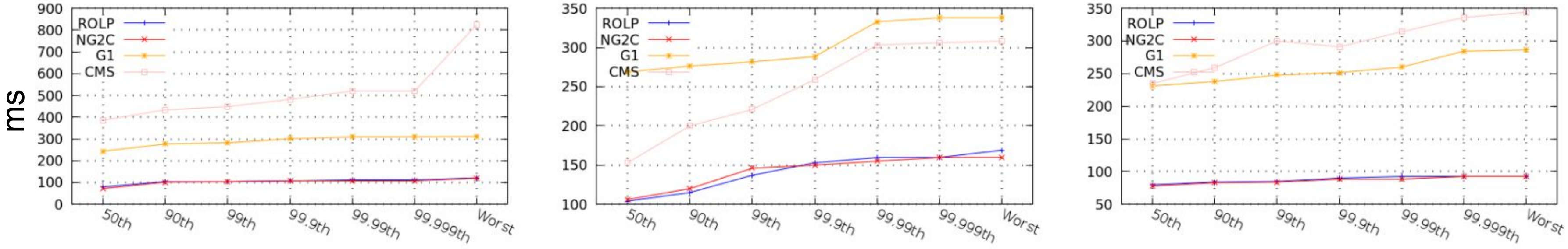
- ROLP is meant to be running in production workloads
  - Several of implementation/performance optimizations
    - Avoid inlined methods
    - Properly Handling Exceptions
    - Properly Handling On-Stack Replacement
    - Reducing Profiling Overhead for very large applications
    - Shutdown survivor tracking code to reduce overhead
    - Improving the scalability of the Object Lifetime Distribution table
    - ...

Runtime Object Lifetime Profiler (evaluation)

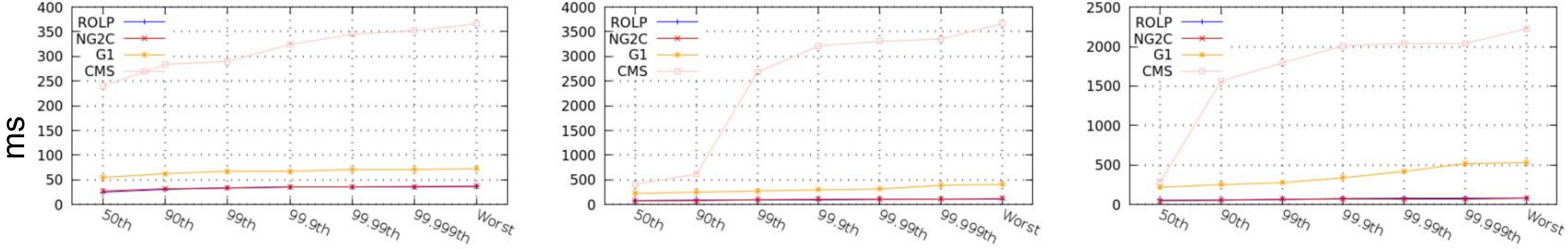
- Evaluate ROLP’s performance compared to:
  - G1 - best solution in OpenJDK, current default GC (ISMM’04)
  - NG2C - multi-generational GC (ISMM’17) - requires programmer effort and knowledge
  - CMS - concurrent mark-sweep - throughput oriented

- Big Data Platforms & Workloads:
  - Cassandra (**Key-Value Store**)
    - YCSB: Write-Intensive (75% writes), Read-Write (50% writes), Read-Intensive (75% reads)
  - Lucene (**In-Memory Indexing Tool**)
    - Read/Write transactions on Wikipedia dump (33M documents): Write-intensive (80% writes)
  - GraphChi (**Graph Processing Engine**)
    - Twitter graph dump (42M vertexes, 1.5B edges): PageRank, Connected Components
  - Environment:
    - Intel Xeon E5505, 16GB RAM
    - Heap/Young Size: 12/2GB

Runtime Object Lifetime Profiler (pausetime percentiles)



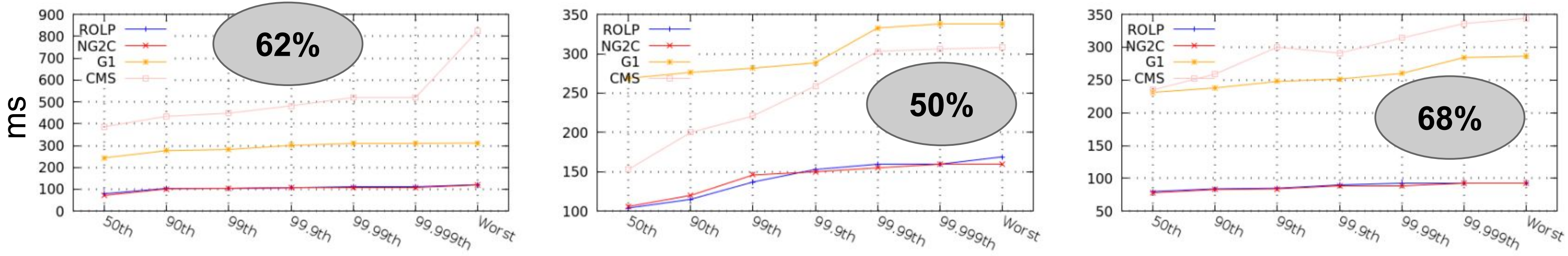
(a) Cassandra WI **(b)** Cassandra WR **(c)** Cassandra RI



(d) Lucene **(e)** GraphChi CC **(f)** GraphChi PR

Lower is Better

Runtime Object Lifetime Profiler (pausetime percentiles)



62%

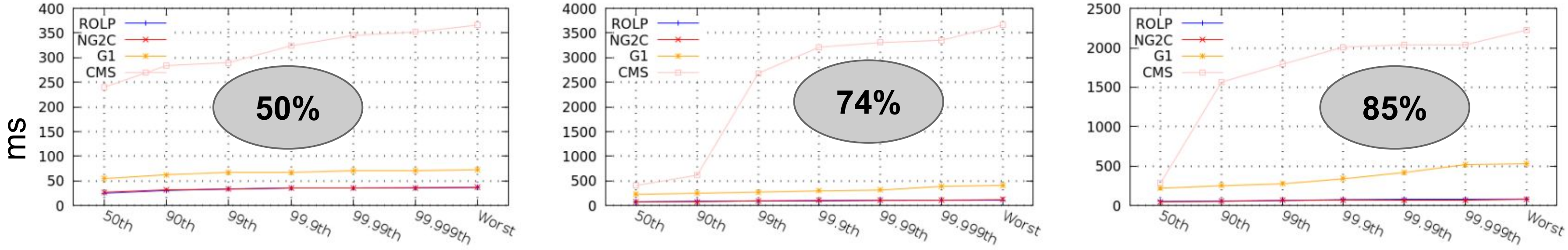
50%

68%

(a) Cassandra WI

(b) Cassandra WR

(c) Cassandra RI



50%

74%

85%

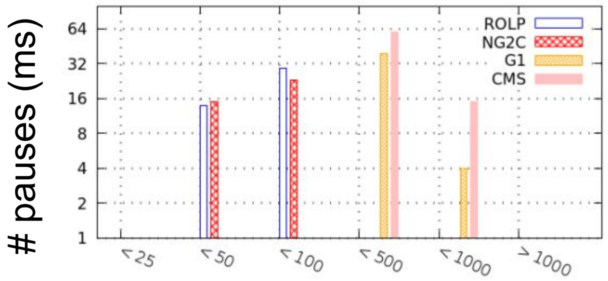
(d) Lucene

(e) GraphChi CC

(f) GraphChi PR

Lower is Better

Runtime Object Lifetime Profiler (pausetime distribution)



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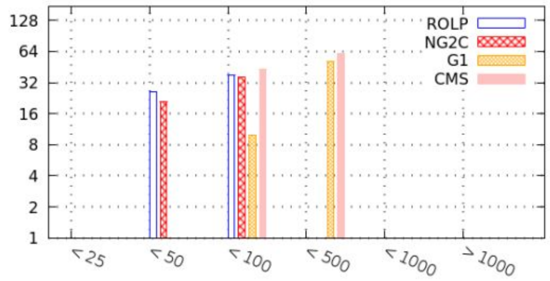
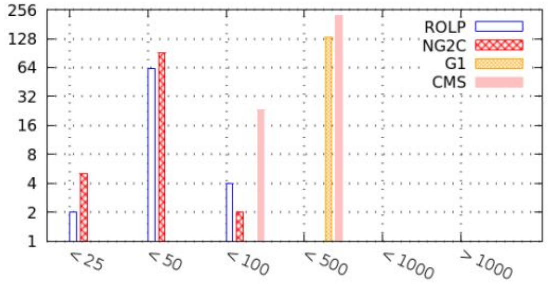
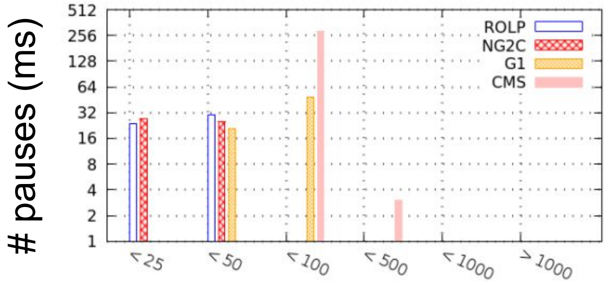


(b) Cassandra WR



(c) Cassandra RI



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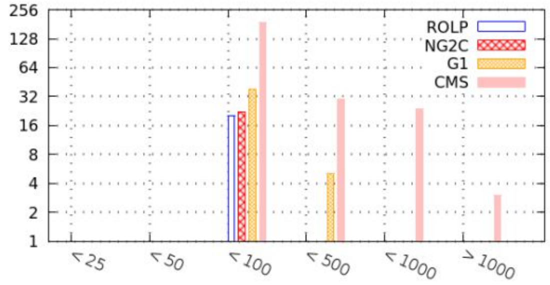

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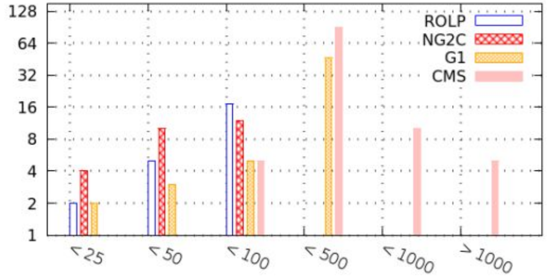
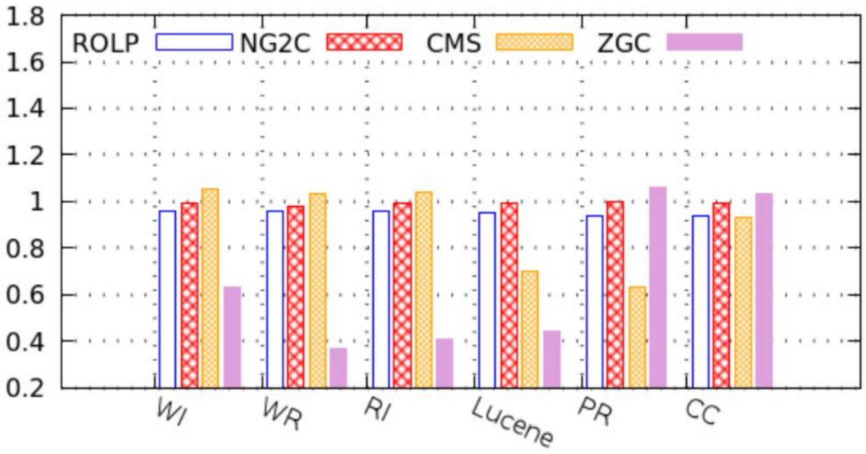


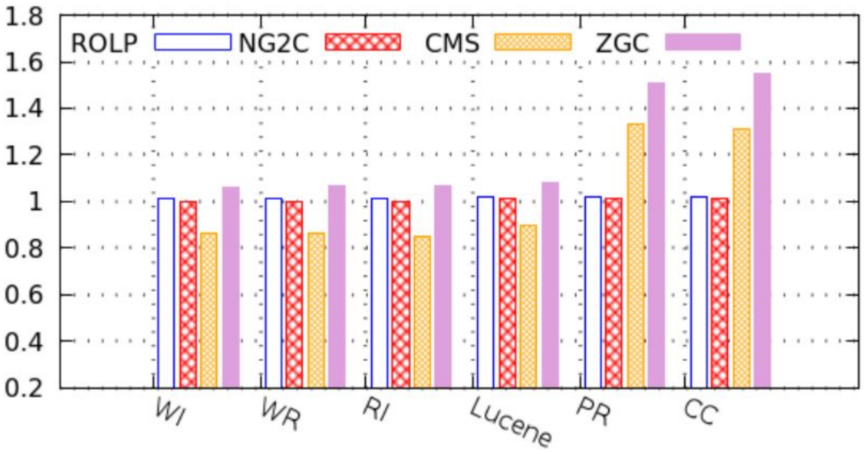
(f) GraphChi PR

Left and Lower is Better

Runtime Object Lifetime Profiler (throughput & memory)



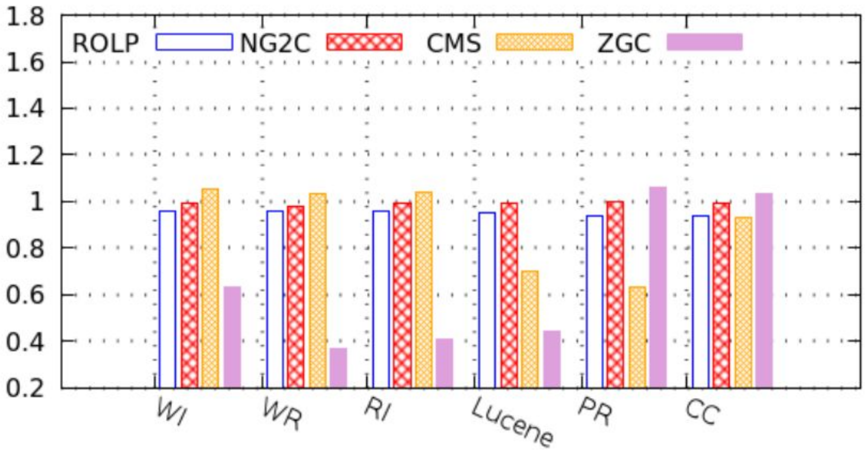
Throughput normalized to G1



Max Memory normalized to G1

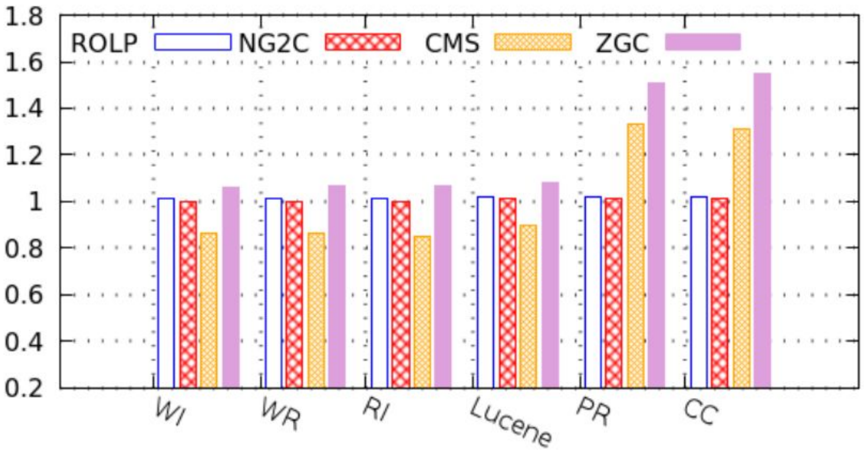
Lower is Better

Runtime Object Lifetime Profiler (throughput & memory)



Throughput normalized to G1

Up to 6%



Max Memory normalized to G1

Up to 2%

Lower is Better

Conclusions

- Big Data applications suffer from high long tail latencies
- Taking advantage of the proposed hypothesis leads to great reductions in pause times
  - More detailed results in the paper
- ROLP can significantly reduce application pauses with
  - Negligible throughput and memory overhead
  - No code access necessary
  - No programmer effort
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Thank you for your time. Questions?

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webpage: rodrigo-bruno.github.io
code: github.com/rodrigo-bruno/rolp