POLM2: Automatic Object Lifetime-aware Memory Management for Big Data Applications

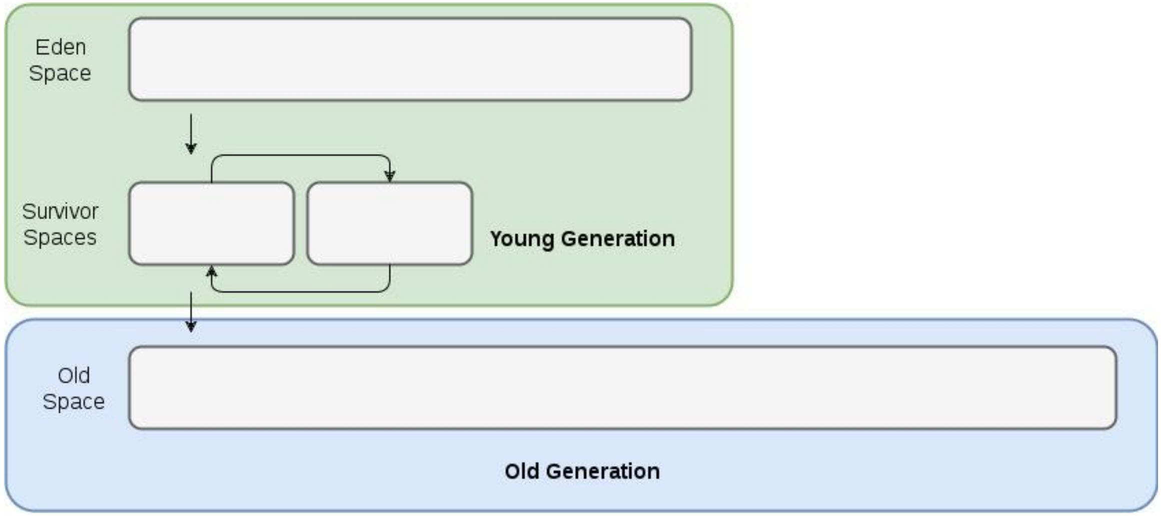
Rodrigo Bruno and Paulo Ferreira

rodrigo.bruno@tecnico.ulisboa.pt, paulo.ferreira@inesc-id.pt

INESC-ID - Instituto Superior Técnico, University of Lisbon, Portugal

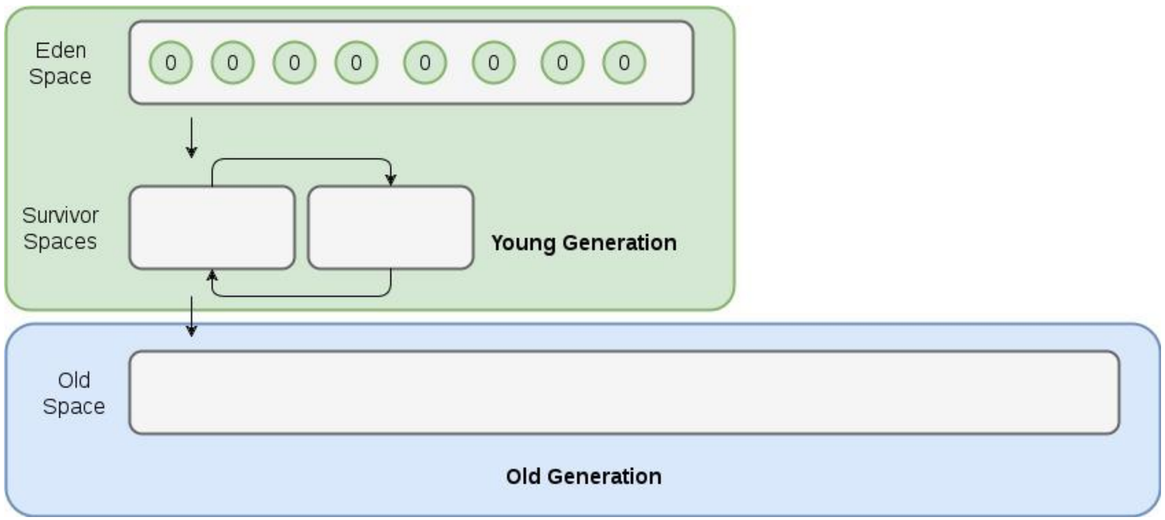
Middleware'17 @ Las Vegas

OpenJDK HotSpot Generational GCs (PS, CMS, G1)

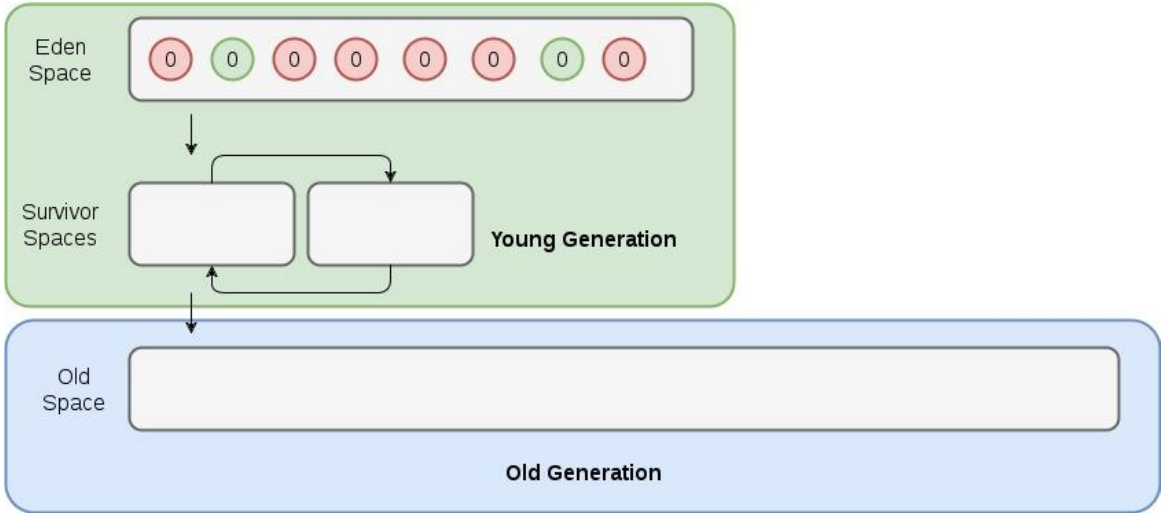


- Two generations:
  - **Young** and **Old**
- Surviving objects are copied to
  - **Survivor** spaces and then to
  - the **Old** generation.

OpenJDK HotSpot Generational GCs

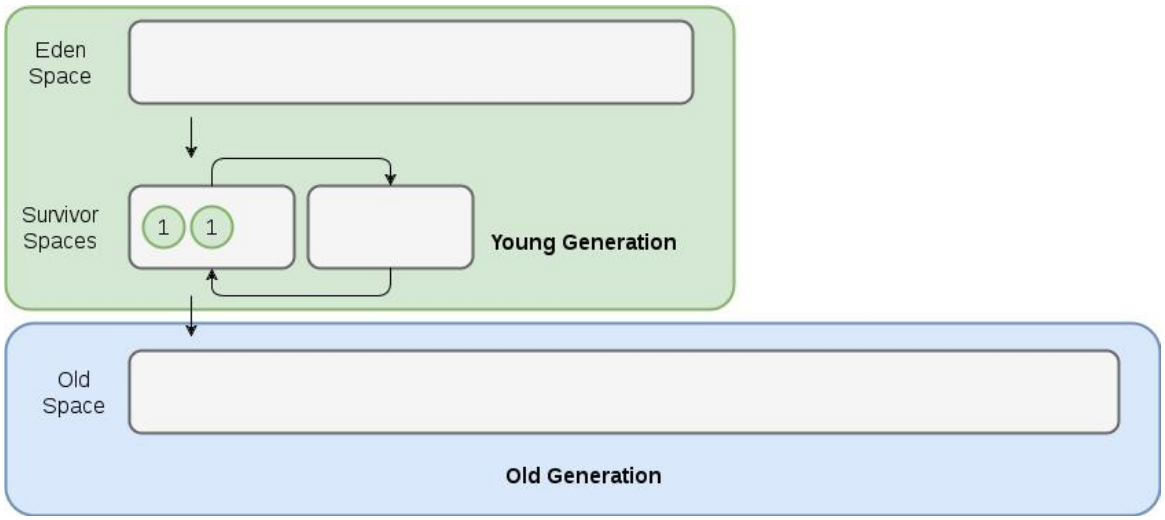


OpenJDK HotSpot Generational GCs



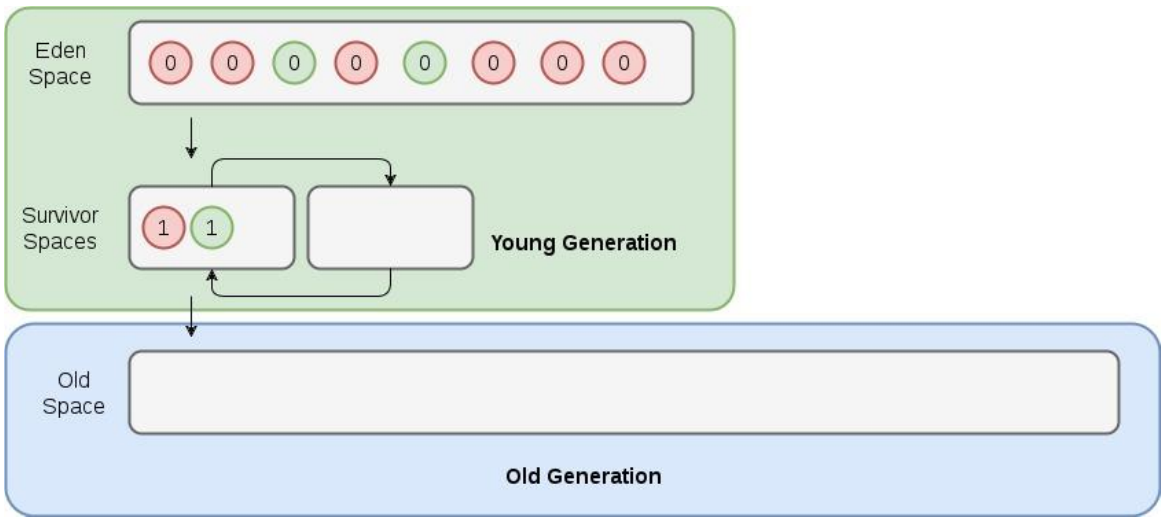
Before GC cycle 1

OpenJDK HotSpot Generational GCs



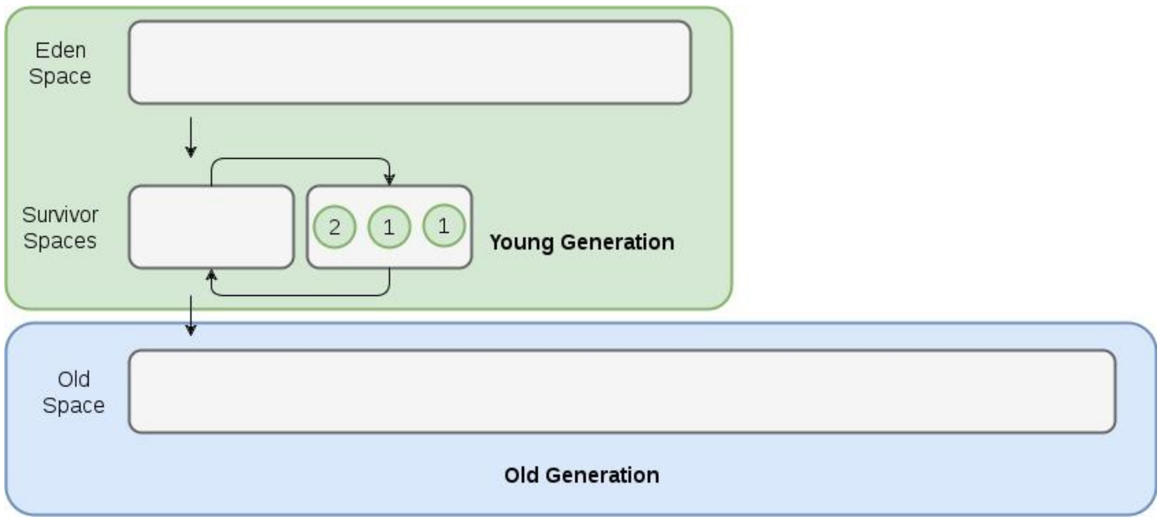
After GC cycle 1

OpenJDK HotSpot Generational GCs



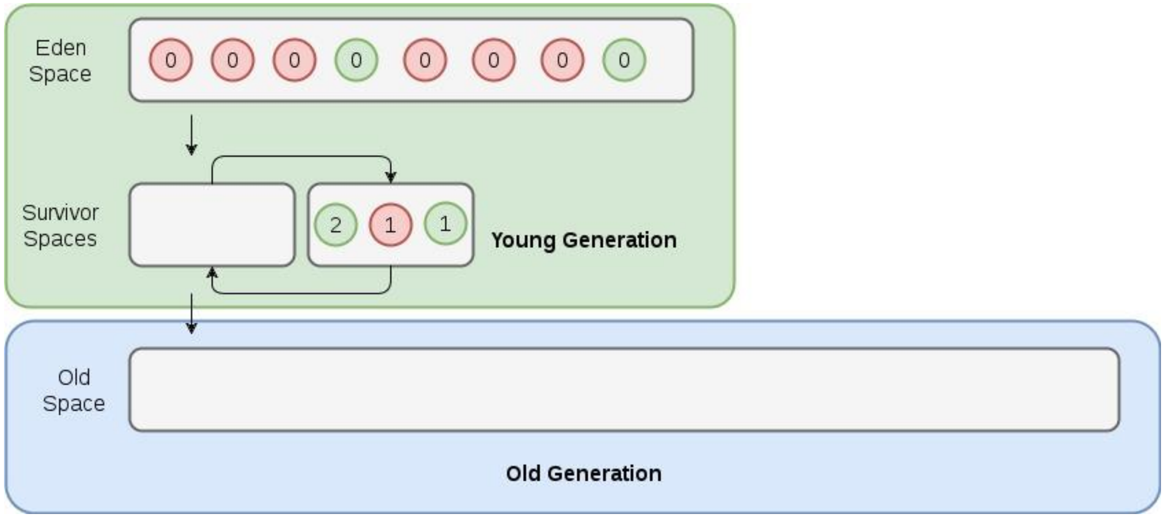
Before GC cycle 2

OpenJDK HotSpot Generational GCs



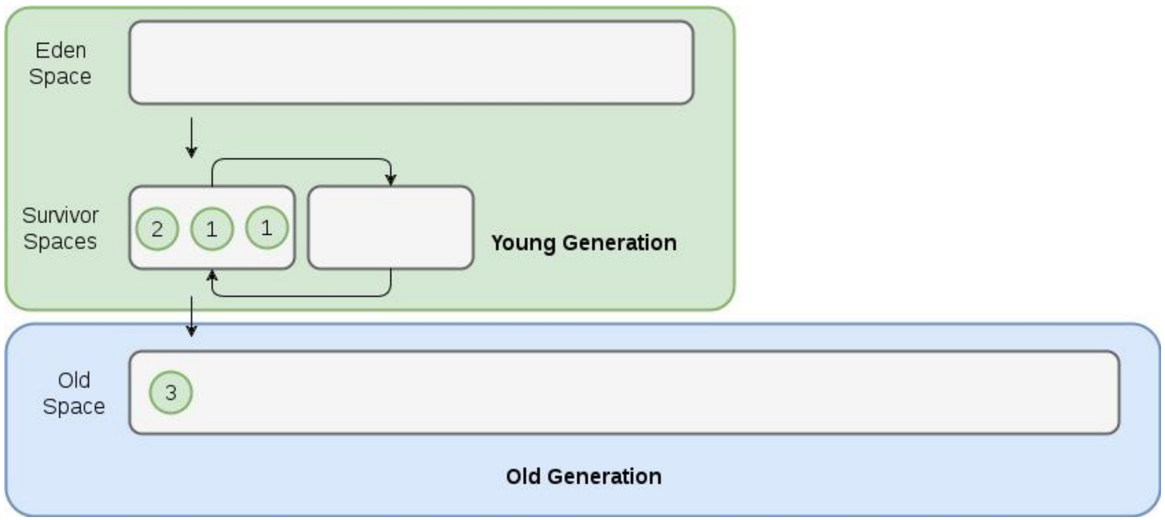
After GC cycle 2

OpenJDK HotSpot Generational GCs



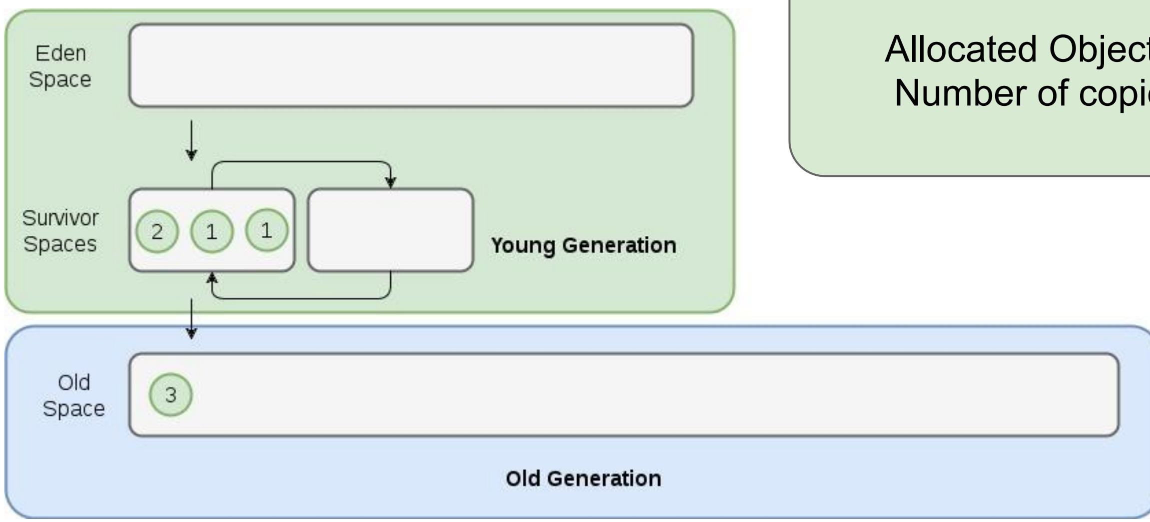
Before GC cycle 3

OpenJDK HotSpot Generational GCs



After GC cycle 3

OpenJDK HotSpot Generational GCs



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

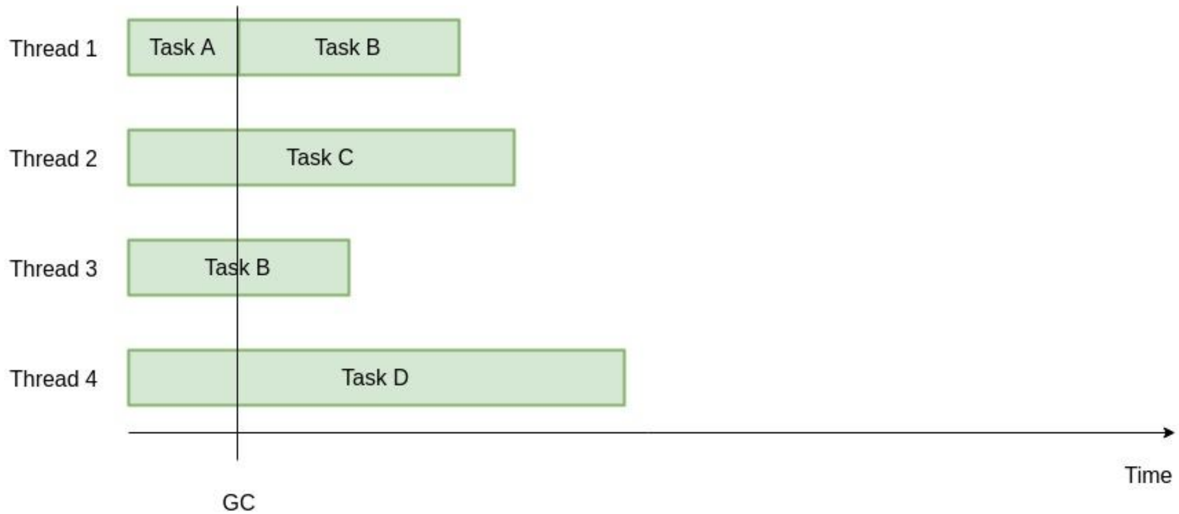
After GC cycle 3

Big Data Application (simplification)

```
public void runTask(enum TaskType tt) {

  // Allocates memory to hold Working Set
  WorkingItem[] buffer = new WorkingItem[WS_SIZE];

  // Loads Working Set
  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

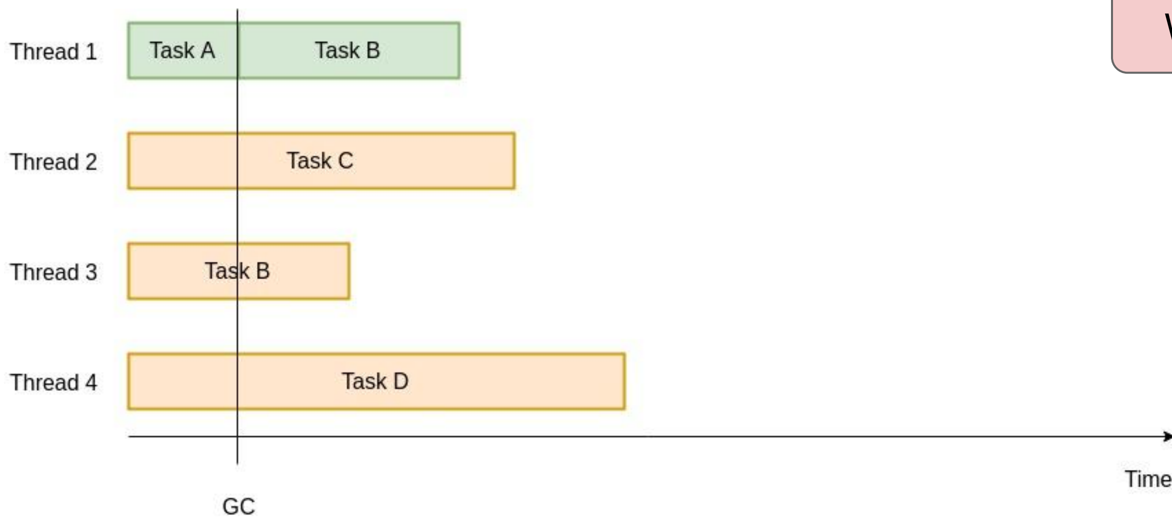


Big Data Application in HotSpot GCs

WS not copied

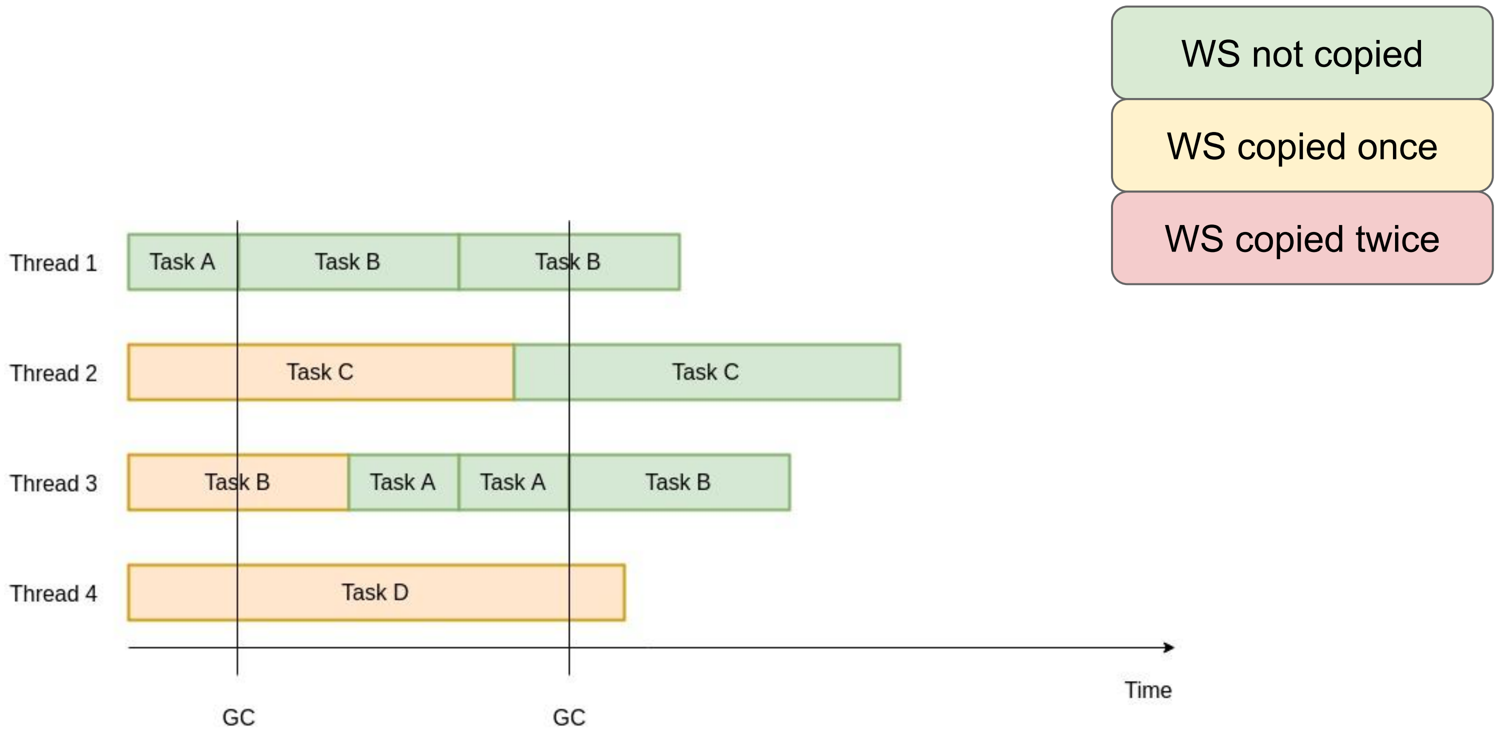
WS copied once

WS copied twice



Copies 3 WS = 1500 MB!

Big Data Application in HotSpot GCs

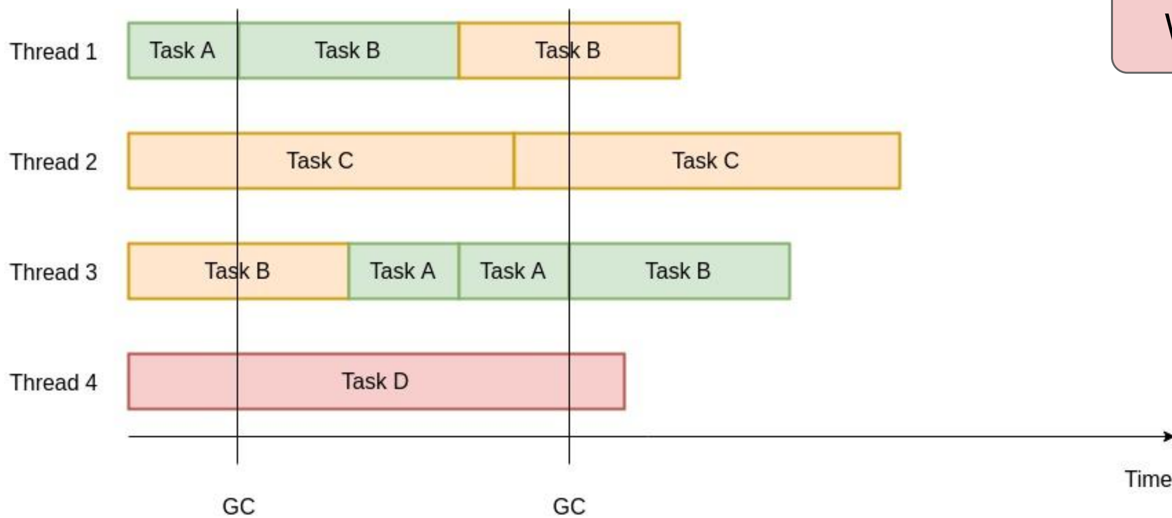


Big Data Application in HotSpot GCs

WS not copied

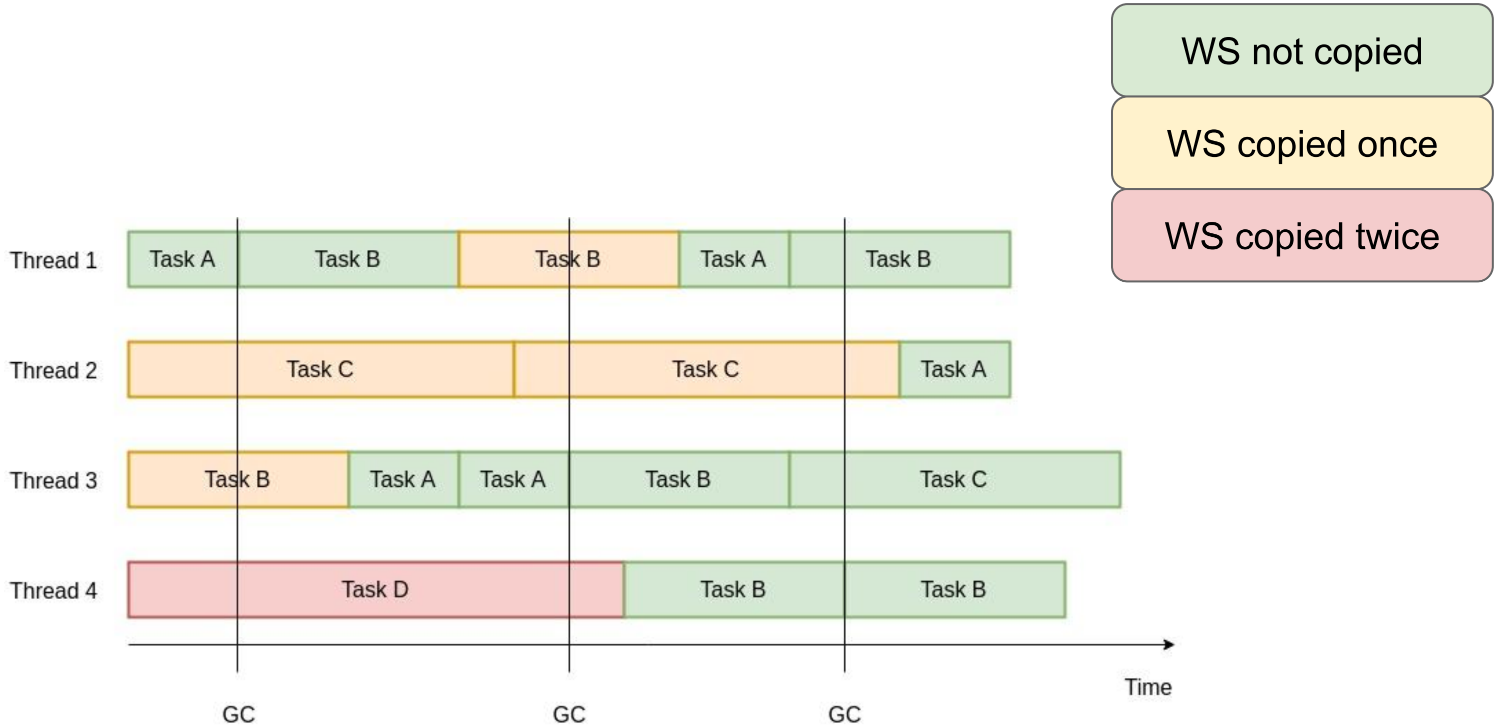
WS copied once

WS copied twice

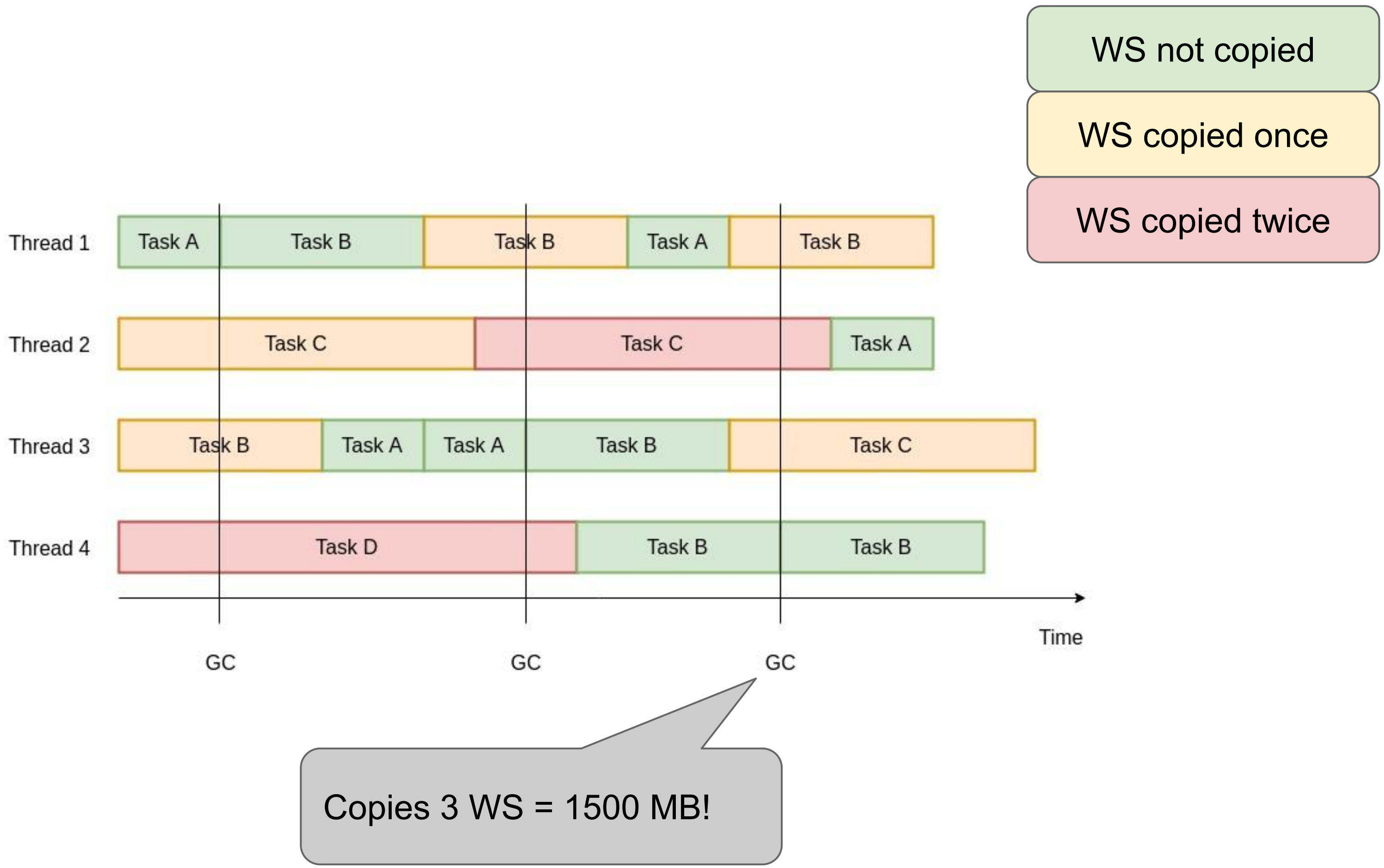


Copies 3 WS = 1500 MB!

Big Data Application in HotSpot GCs



Big Data Application in HotSpot GCs

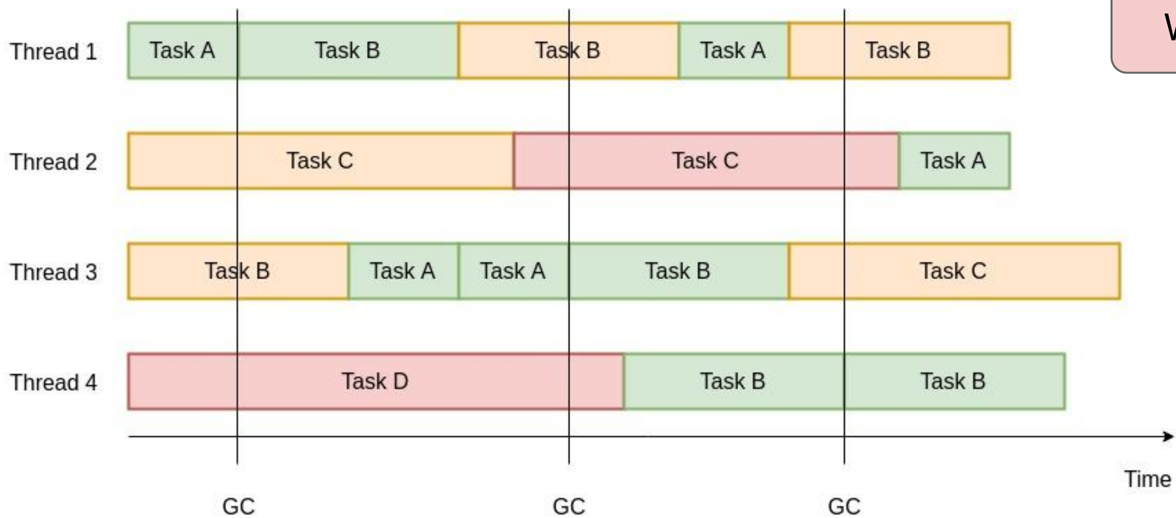


Big Data Application in HotSpot GCs

WS not copied

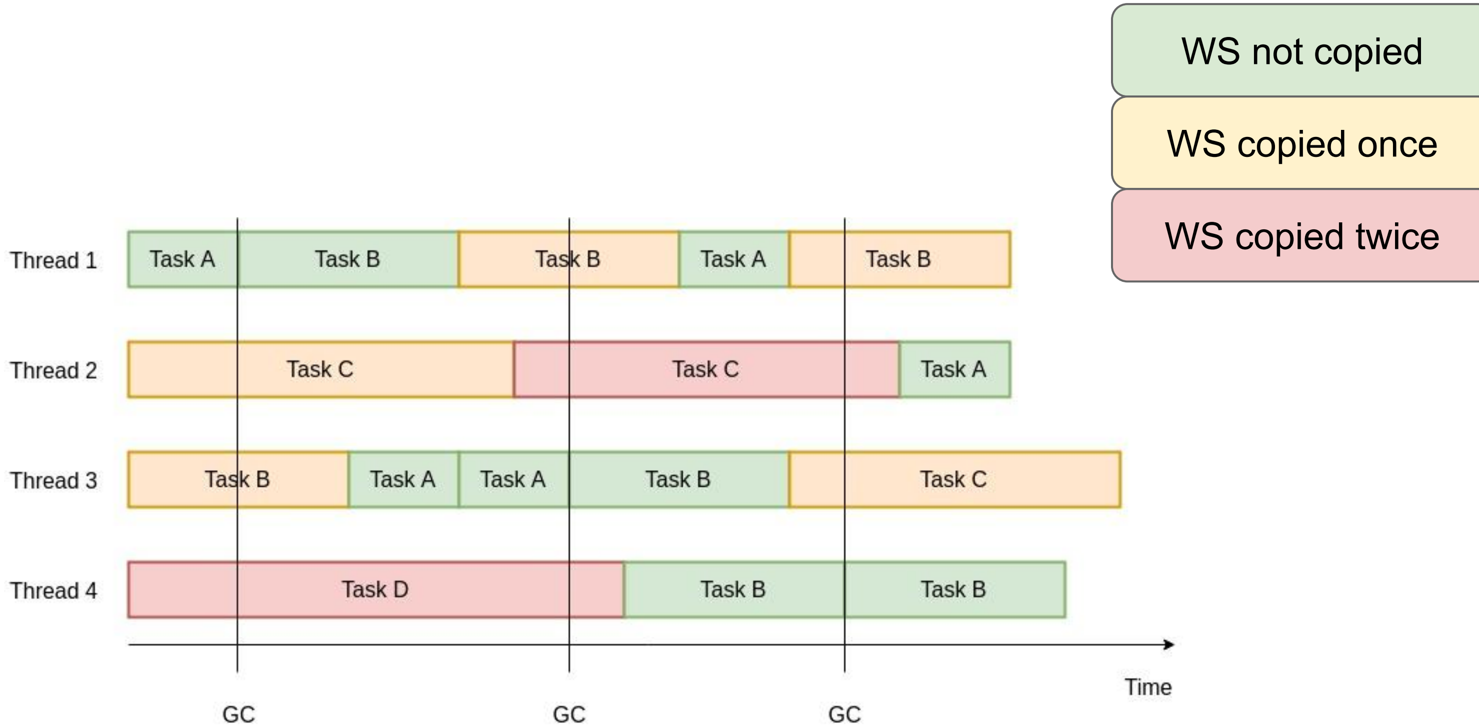
WS copied once

WS copied twice



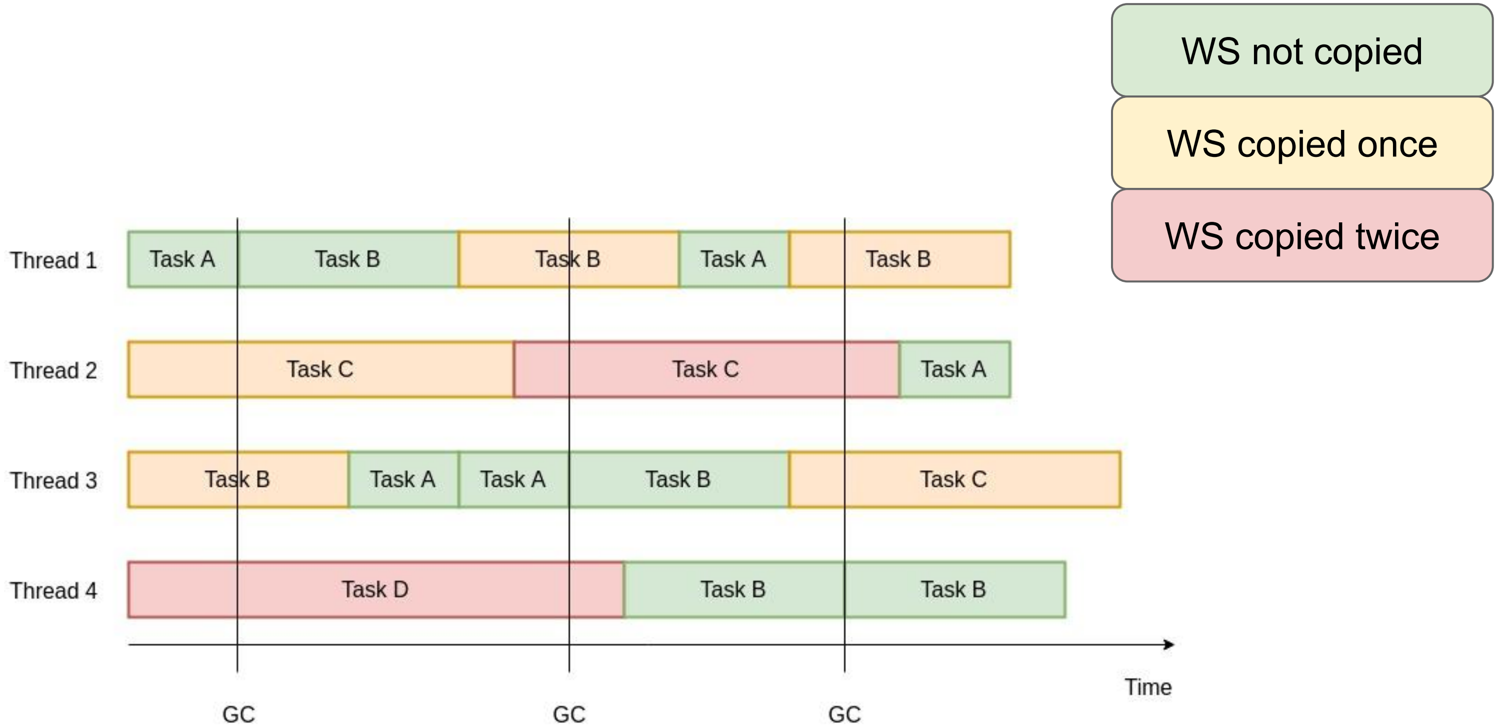
Object copy per GC cycle: 1500 MB
Total amount of object copy: 4500 MB

Big Data Application in HotSpot GCs



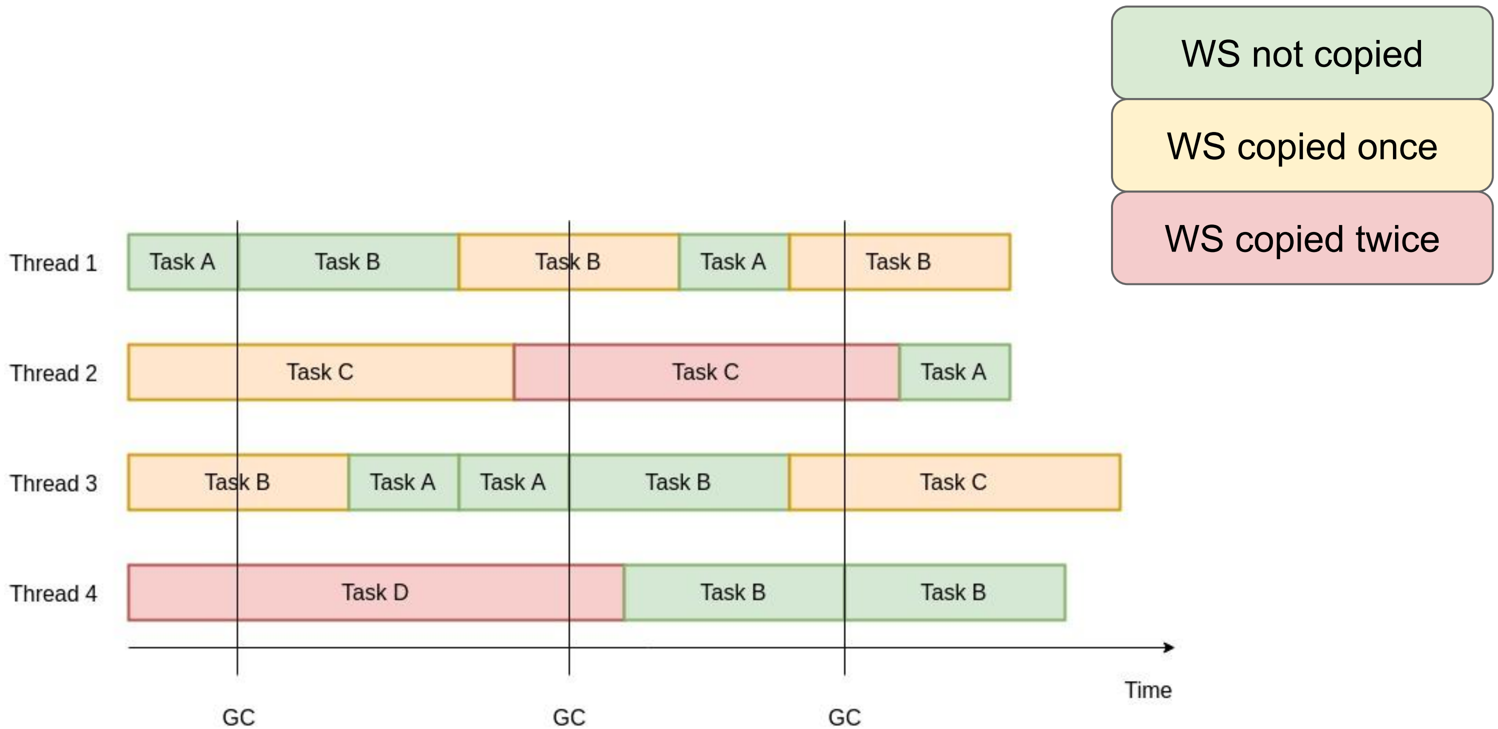
Object copy per GC cycle: 1500 MB
Total amount of object copy: 4500 MB
Assuming average RAM bandwidth of 10GB/s (DDR3)

Big Data Application in HotSpot GCs



Object copy per GC cycle: 1500 MB
Total amount of object copy: 4500 MB
Assuming average RAM bandwidth of 10GB/s (DDR3)
4 Threads, Eden 2GB = copy 3 tasks (1500 MB) ~= **300 ms**

Big Data Application in HotSpot GCs



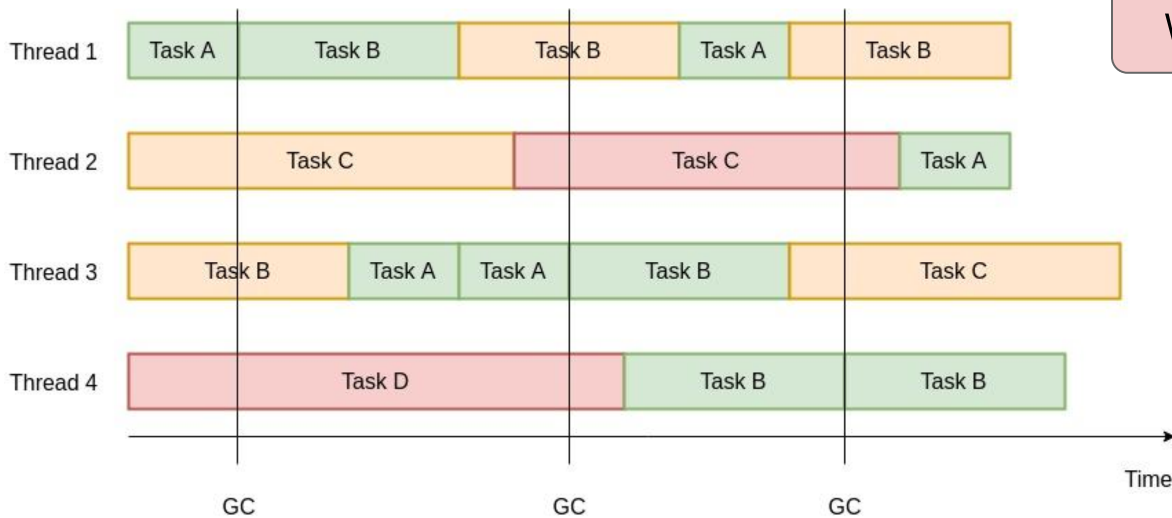
Object copy per GC cycle: 1500 MB
Total amount of object copy: 4500 MB
Assuming average RAM bandwidth of 10GB/s (DDR3)
4 Threads, Eden 2GB = copy 3 tasks (1500 MB) ~= **300 ms**
8 Threads, Eden 4GB = copy 7 tasks (3500 MB) ~= **700 ms**

Big Data Application in HotSpot GCs

WS not copied

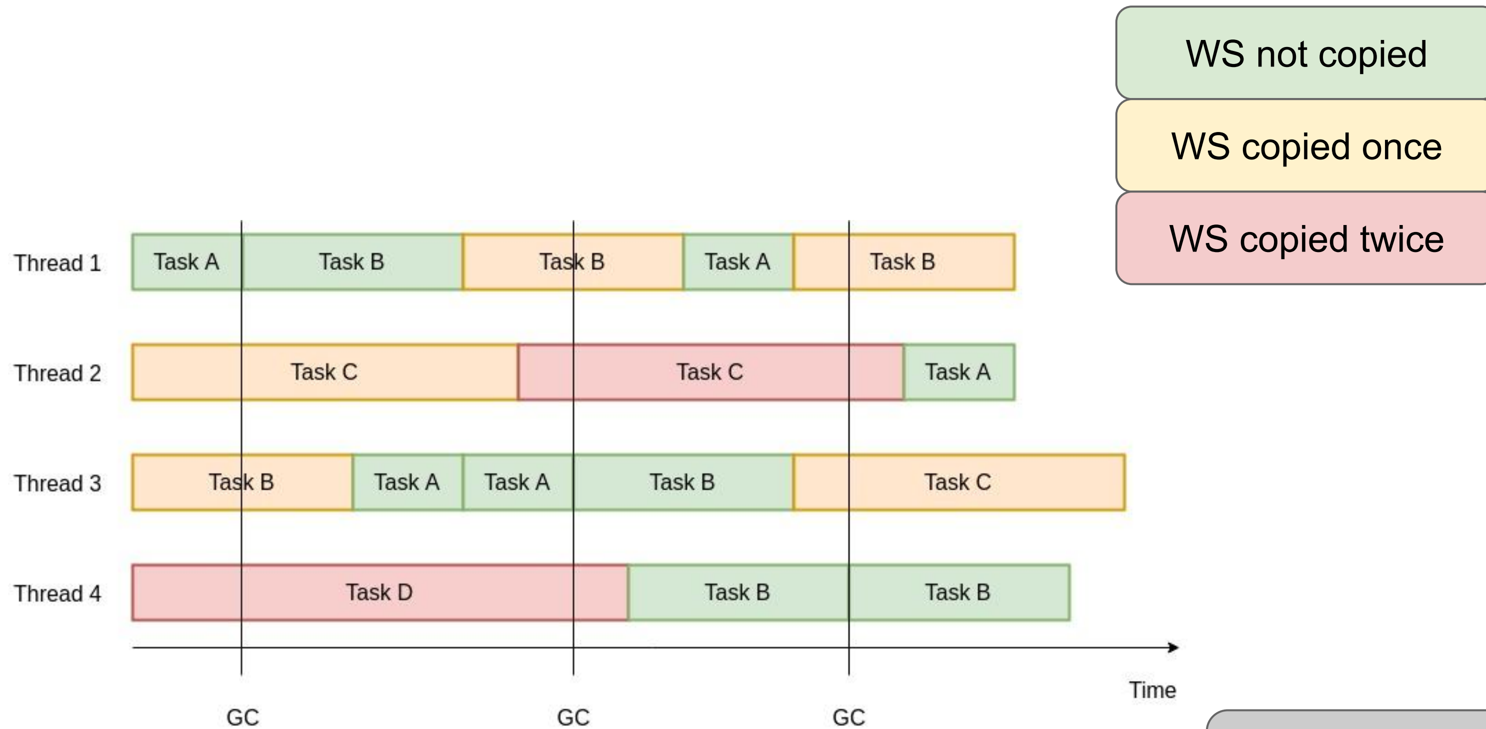
WS copied once

WS copied twice



Object copy per GC cycle: 1500 MB
Total amount of object copy: 4500 MB
Assuming average RAM bandwidth of 10GB/s (DDR3)
4 Threads, Eden 2GB = copy 3 tasks (1500 MB) ~= **300 ms**
8 Threads, Eden 4GB = copy 7 tasks (3500 MB) ~= **700 ms**
16 Threads, Eden 8GB = copy 15 task (7500 MB) ~= **1500 ms**

Big Data Application in HotSpot GCs



Object copy per GC cycle: 1500 MB
Total amount of object copy: 4500 MB
Assuming average RAM bandwidth of 10GB/s (DDR3)
4 Threads, Eden 2GB = copy 3 tasks (1500 MB) ~= **300 ms**
8 Threads, Eden 4GB = copy 7 tasks (3500 MB) ~= **700 ms**
16 Threads, Eden 8GB = copy 15 task (7500 MB) ~= **1500 ms**

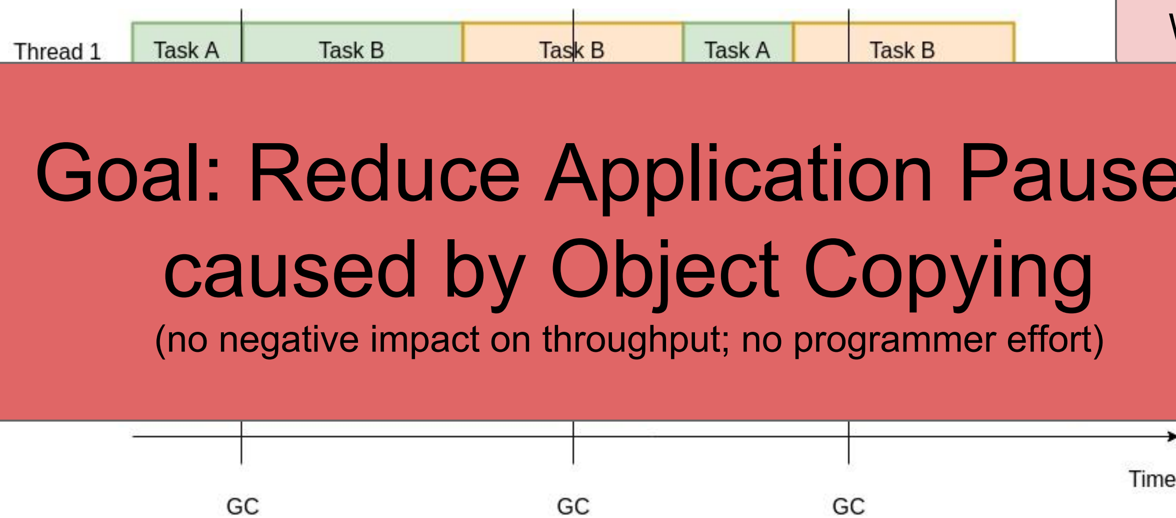
Long Pauses!
Not Scalable!

Big Data Application in HotSpot GCs

WS not copied

WS copied once

WS copied twice



Goal: Reduce Application Pauses caused by Object Copying

(no negative impact on throughput; no programmer effort)

Object copy per GC cycle: 1500 MB
Total amount of object copy: 4500 MB
Assuming average RAM bandwidth of 10GB/s (DDR3)
4 Threads, Eden 2GB = copy 3 tasks (1500 MB) ~= **300 ms**
8 Threads, Eden 4GB = copy 7 tasks (3500 MB) ~= **700 ms**
16 Threads, Eden 8GB = copy 15 task (7500 MB) ~= **1500 ms**

Long Pauses!
Not Scalable!

How to Avoid en-masse Object Copying

- Attempt 1: Heap Resizing
  - ✓ Increase Young generation size;
  - ✓ Gives more time for objects to die;
  - ! Does not solve the problem, eventually the Young gen will get full and objects will be copied.
- Attempt 2: Reduce Task/Working Set size
  - ✓ Reduces the amount of object copying since the WS is smaller;
  - ! Increases overhead as more tasks and coordination is necessary to process smaller tasks.
- Attempt 3: Reuse data objects (object pulling)
  - ✓ Avoids allocating new memory for future Tasks;
  - ✓ Limits GC effort;
  - ! Requires major rewriting of applications combined with very unnatural Java programming style.
- 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).
- Attempt 5: Region-based/Scope-based memory allocation
  - ✓ Limits object's reachability by scope/region;
  - ✓ Limits GC effort as objects are automatically collected once the scope/region is discarded;
  - ! Requires major rewriting of existing applications;
  - ! Does not allow objects to freely move between scopes. Fits only to bag of tasks model.

TÉCNICO LISBOA

gsd inesc id lisboa

How to Avoid en-masse Object Copying

- Attempt 1: Heap Resizing
  - ✓ Increase Young generation size;
  - ✓ Gives more time for objects to die;
  - ! Does not solve the problem, eventually the Young gen will get full and objects will be copied.

- Attempt 2: Re
  - ✓ Reduces th
  - ! Increases c ... aller tasks.

- Attempt 3: Re
  - ✓ Avoids allo
  - ✓ Limits GC e
  - ! Requires m ... gramming style.

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.

- Attempt 4: Off-
  - ✓ 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).

- Attempt 5: Region-based/Scope-based memory allocation
  - ✓ Limits object's reachability by scope/region;
  - ✓ Limits GC effort as objects are automatically collected once the scope/region is discarded;
  - ! Requires major rewriting of existing applications;
  - ! Does not allow objects to freely move between scopes. Fits only to bag of tasks model.

Proposed Solution: POLM2

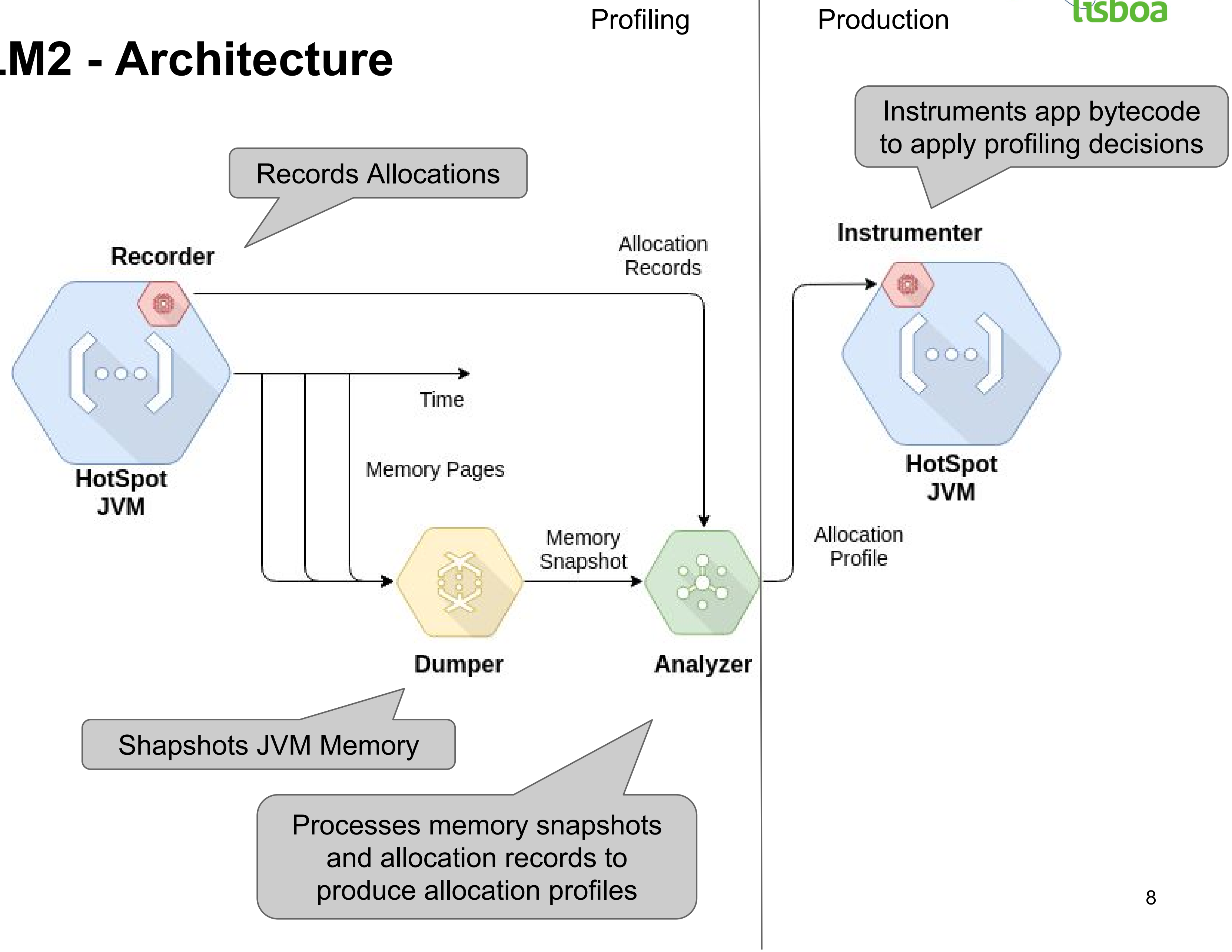
- Goals:
  - reduce long tail latencies (due to object copies)
  - avoid memory and/or throughput negative impact
  - require no programmer knowledge and effort.

- Overview:
  - Application execution is profiled (once, before going into production) and an application allocation profile is created (to be used in production)
  - Profile is used to automatically insert bytecode to
    - pretenure/allocate objects into different dynamic generations depending on their expected lifetime
    - Uses NG2C API
  - Profiles can then be used to improve performance in production environments

Outline

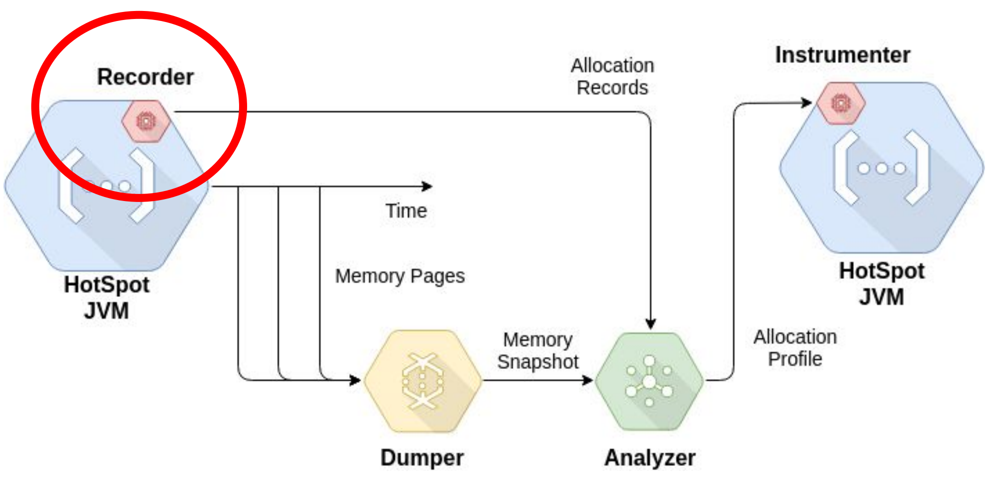
- **POLM2 - Automatic Object Lifetime-aware Memory Management**
- Implementation
- Evaluation
- Conclusions & Future Work

POLM2 - Architecture



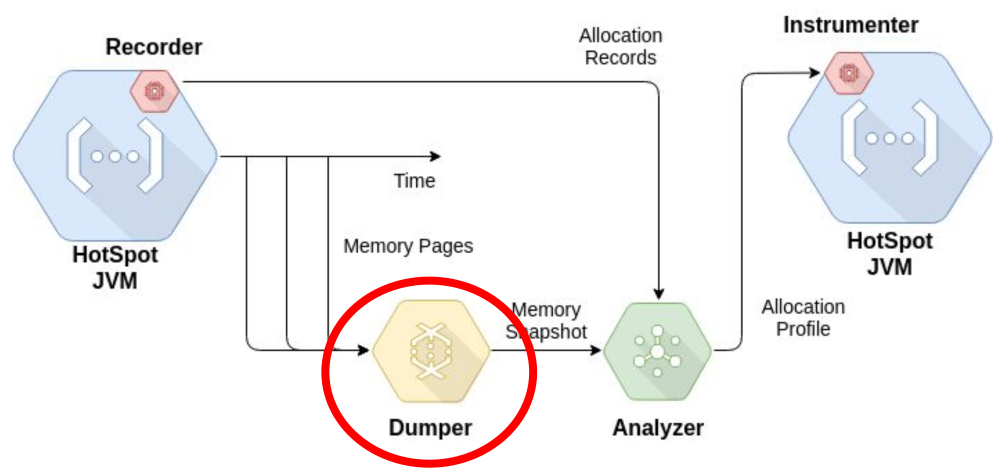
Object Allocation Recording (profiling phase)

- Recorder:
  - Java-agent that intercepts class loading to insert recording code on object allocation
  - Recording code produces a allocation records per object allocation:
    - strack-trace and
    - object unique identifier



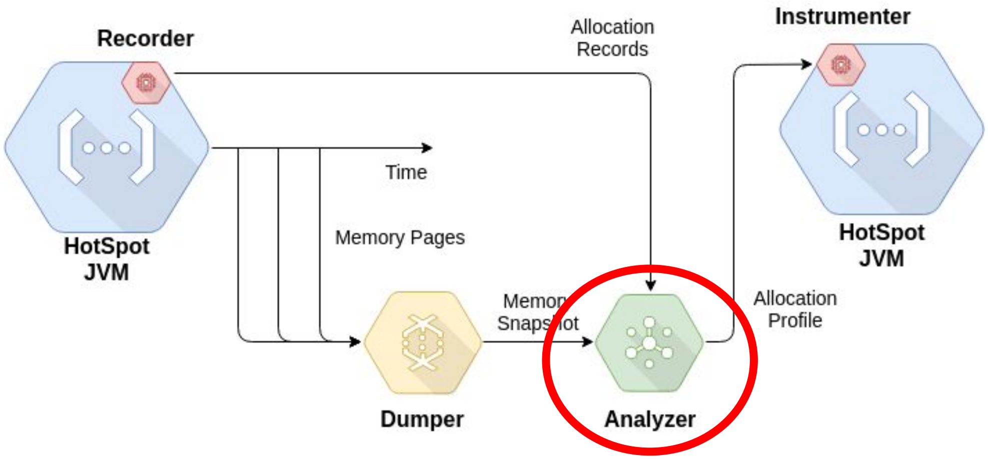
Object Allocation Recording (profiling phase)

- Dumper:
    - External process that creates a memory snapshot of the JVM
    - Memory snapshots are incremental (page dirty bit)
    - Memory pages with only garbage are not dumped
    - Heap dumps can be created offline
        - Reduces application interference (such as long app. pauses)



Object Allocation Recording (profiling phase)

- Analyzer:
  - Takes as input:
    - Allocation records (alloc. stack traces and object ids)
    - Heap dumps (live objects and live object ids)
  - Outputs
    - Which allocation sites should pretenure objects because produced objects live for too long

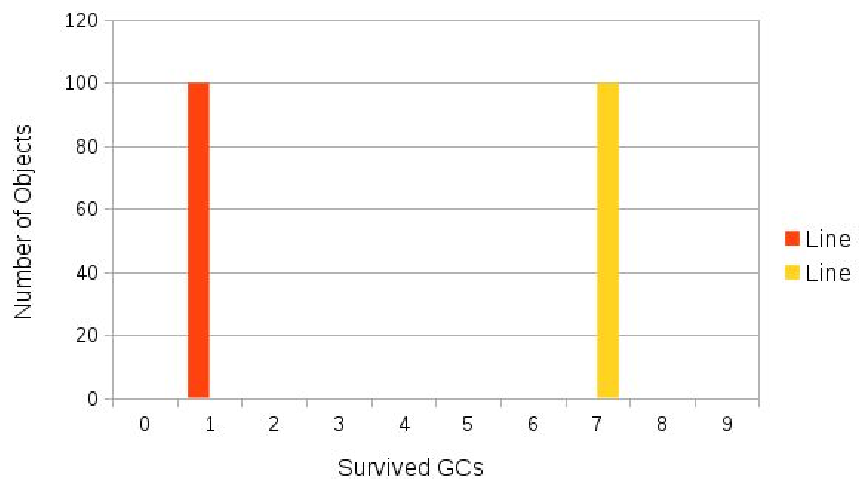


Estimating Object Lifetime (profiling phase)

```
public static void shortTermFactory() { return new int[1024]; }
public static void longTermFactory()  { return new int[1024]; }

public static void factory() {
    int[] arr;
    if (foo) arr = shortTermFactory();
    else     arr = longTermFactory();
}

public static void doWork() {
    if (bar) {
        ...
        factory();
        ...
    else {
        ...
        factory();
        ...
    }
    ...
}

public static void main(String[] args) { while(!stop) doWork(); }
```

Estimating Object Lifetime (profiling phase)

```
1   public static void shortTermFactory() { return new int[1024]; }
2   public static void longTermFactory()  { return new int[1024]; }
3
4   public static void factory() {
5       int[] arr;
6       if (foo) arr = shortTermFactory();
7       else     arr = longTermFactory();
8   }
9
10  public static void doWork() {
11      if (bar) {
12          ...
13          factory();
14          ...
15      else {
16          ...
17          factory();
18          ...
19      }
20      ...
21  }
22
23  public static void main(String[] args) { while(!stop) doWork(); }
```

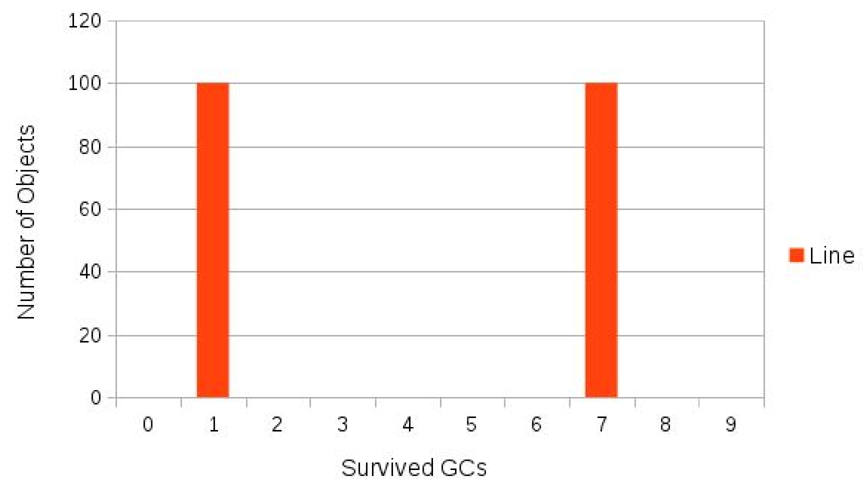


Estimating Object Lifetime (profiling phase)

```
public static int[] allocator()        { return new int[1024]; }

public static void shortTermFactory() { return allocator(); }
public static void longTermFactory()  { return allocator(); }

public static void factory() {
    int[] arr;
    if (foo) arr = shortTermFactory();
    else     arr = longTermFactory();
}

public static void doWork() {
    if (bar) {
        ...
        factory();
        ...
    else {
        ...
        factory();
        ...
    }
    ...
}

public static void main(String[] args) { while (!stop) doWork(); }
```

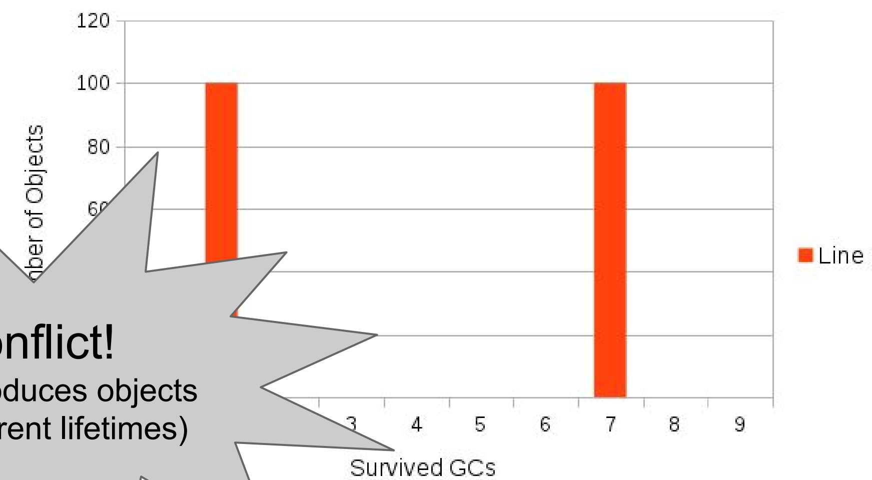
Estimating Object Lifetime (profiling phase)

```
public static int[] allocator()        { return new int[1024]; }

public static void shortTermFactory() { return allocator(); }
public static void longTermFactory()  { return allocator(); }

public static void factory() {
    int[] arr;
    if (foo) arr = shortTermFactory();
    else     arr = longTermFactory(
}

public static void doWork() {
    if (bar) {
        ...
        factory();
        ...
    else {
        ...
        factory();
        ...
    }
    ...
}

public static void main(String[] args) { while (!stop) doWork(); }
```



Estimating Object Lifetime (profiling phase)

```
1   public static int[] allocator()       { return new int[1024]; }
2
3   public static void shortTermFactory() { return allocator(); }
4   public static void longTermFactory()  { return allocator(); }
5
6   public static void factory() {
7       int[] arr;
8       if (foo) arr = shortTermFactory();
9       else     arr = longTermFactory(
10  }
11
12  public static void doWork() {
13      if (bar) {
14          ...
15          factory();
16          ...
17      else {
18          ...
19          factory();
20          ...
21      }
22      ...
23  }
24
25  public static void main(String[] args) { while (!stop) doWork(); }
```

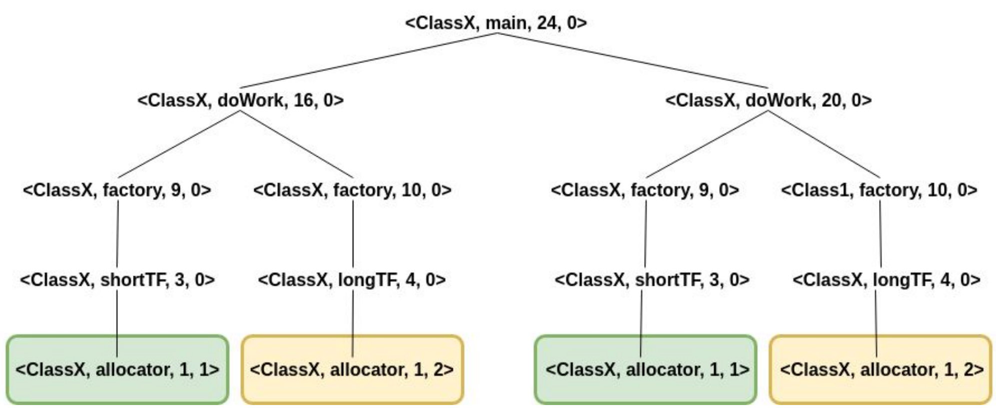


Conflict!
(line 1 produces objects with different lifetimes)

Estimating Object Lifetime (profiling phase)

```
public static int[] allocator()        { return new int[1024]; }

public static void shortTermFactory() { return allocator(); }
public static void longTermFactory()  { return allocator(); }

public static void factory() {
    int[] arr;
    if (foo) arr = shortTermFactory();
    else     arr = longTermFactory();
}

public static void doWork() {
    if (bar) {
        ...
        factory();
        ...
    else {
        ...
        factory();
        ...
    }
    ...
}

public static void main(String[] args) { while (!stop) doWork(); }
```

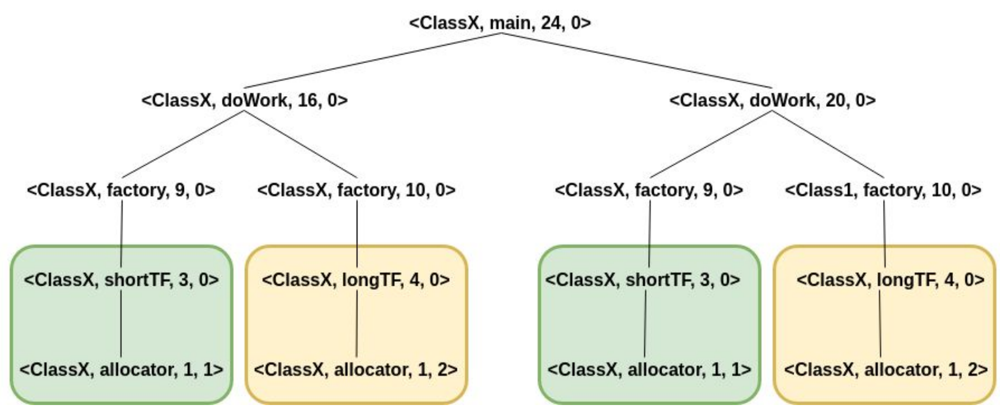
STTree to resolve conflicts



Estimating Object Lifetime (profiling phase)

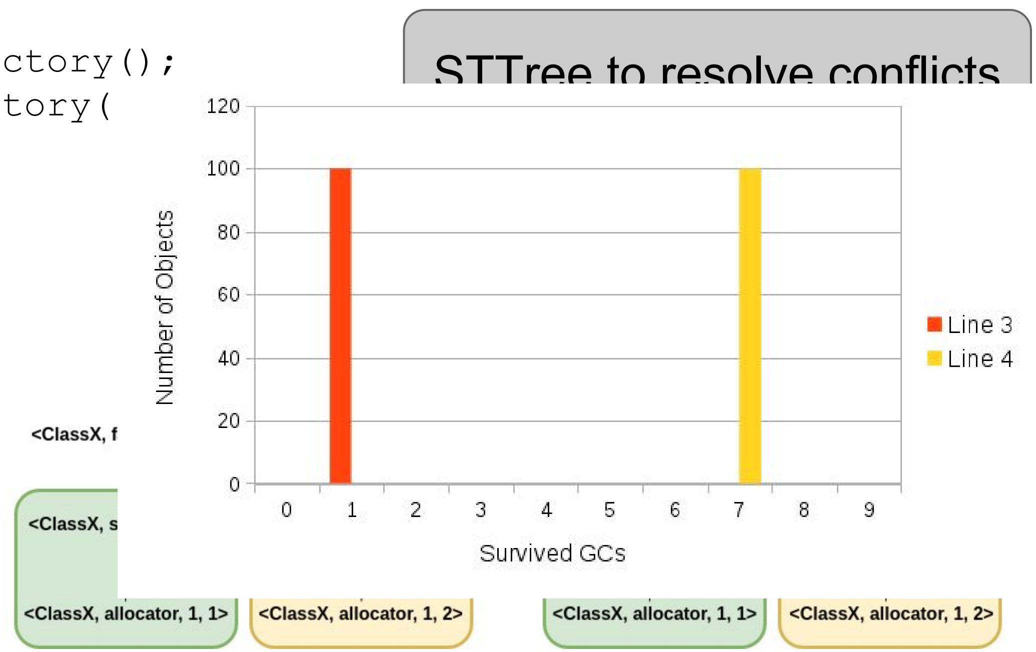
```
public static int[] allocator()          { return new int[1024]; }

public static void shortTermFactory() { return allocator(); }
public static void longTermFactory()  { return allocator(); }

public static void factory() {
    int[] arr;
    if (foo) arr = shortTermFactory();
    else     arr = longTermFactory();
}

public static void doWork() {
    if (bar) {
        ...
        factory();
        ...
    else {
        ...
        factory();
        ...
    }
    ...
}

public static void main(String[] args) { while (!stop) doWork(); }
```

STTree to resolve conflicts



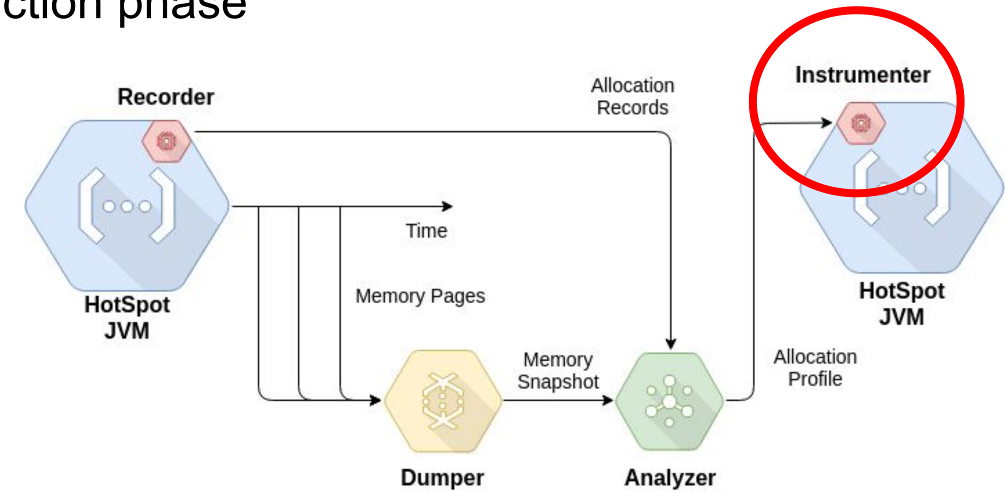
Estimating Object Lifetime (profiling phase)

```
1   public static int[] allocator()        { return new int[1024]; }
2
3   public static void shortTermFactory() { return allocator(); }
4   public static void longTermFactory()  { return allocator(); }
5
6   public static void factory() {
7       int[] arr;
8       if (foo) arr = shortTermFactory();
9       else     arr = longTermFactory(
10  }
11
12  public static void doWork() {
13      if (bar) {
14          ...
15          factory();
16          ...
17      else {
18          ...
19          factory();
20          ...
21      }
22      ...
23  }
24
25  public static void main(String[] args) { while (!stop) doWork(); }
```



Using Profiling Information (production phase)

- Instrumenter:
  - Takes as input an allocation profile
  - Intercepts class bytecode loading
  - Uses NG2C annotations and API to ensure that new objects are allocated in the correct generation
  - Profiling phase VS Production phase



Outline

- POLM2 - Automatic Object Lifetime-aware Memory Management
- **Implementation**
- Evaluation
- Conclusions & Future Work

Implementation

- POLM2 is implemented for the OpenJDK 8 HotSpot JVM
  - Using NG2C (ISMM'17)
  - You can try it with your own application
- Dumper is implemented using CRIU (checkpoint-restore for Linux)
- Recorder implemented using
  - Allocation-instrumenter (uses the Java Instrumentation API)
- Instrumented implemented using
  - ASM bytecode instrumented (low-level bytecode management API)

Outline

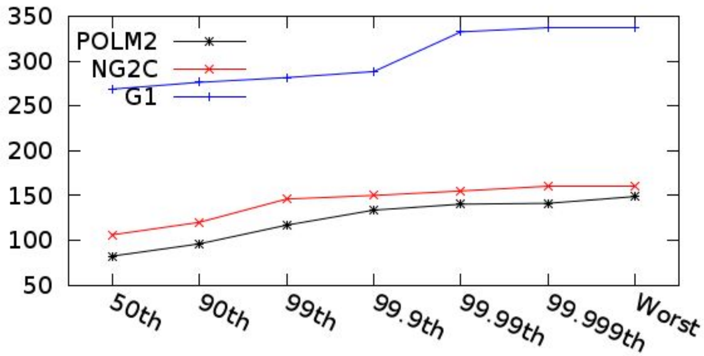
- POLM2 - Automatic Object Lifetime-aware Memory Management
- Implementation
- **Evaluation**
- Conclusions & Future Work

Evaluation

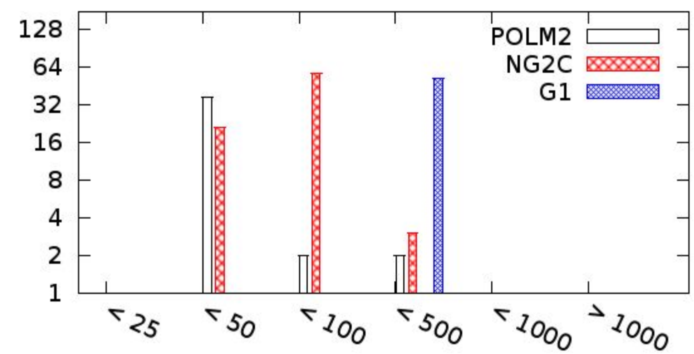
- Evaluate POLM2's performance compared to:
  - G1 - popular OpenJDK GCs (ISMM'04)
  - NG2C - multi-generational GC (ISMM'17)
    - requires programmer effort and knowledge

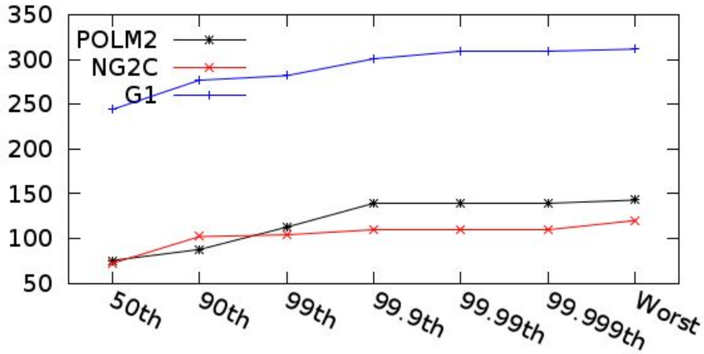
- Big Data Platforms & Workloads:
  - Cassandra (**Key-Value Store**)
    - YCSB workloads
      - Write-Intensive (75% writes), Read-Intensive (75% reads)
  - Lucene (**In-Memory Indexing Tool**)
    - Read/Write transactions on Wikipedia dump (33M documents)
      - Write-intensive (80% writes)
  -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

Evaluation - Pause Times for Cassandra (ms)

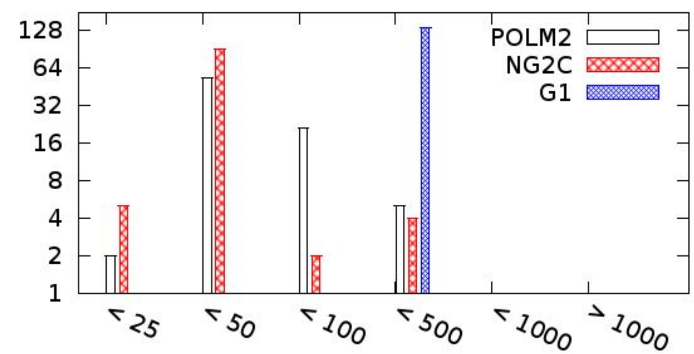


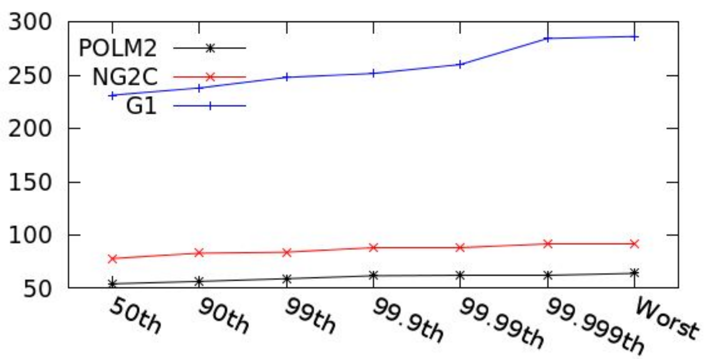
Read-Write



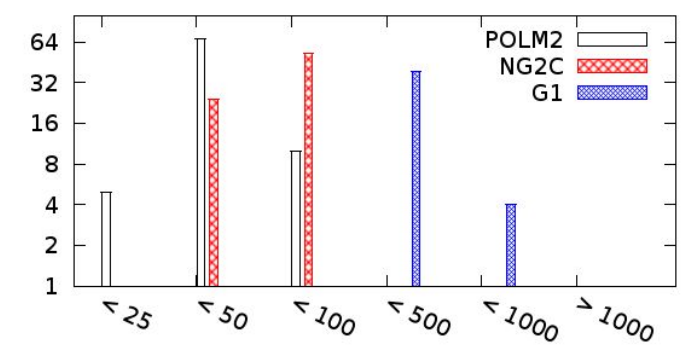


Write-Intensive

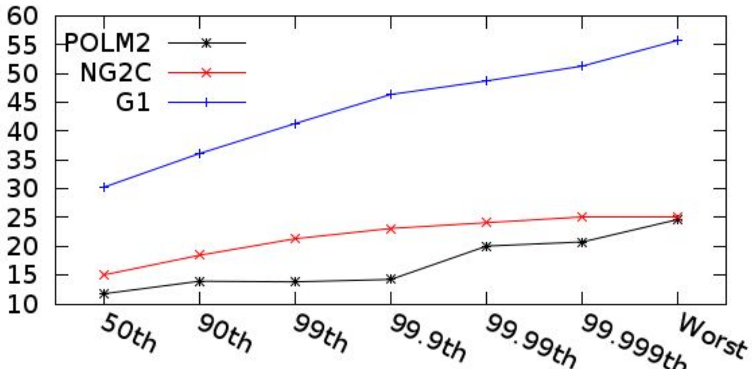




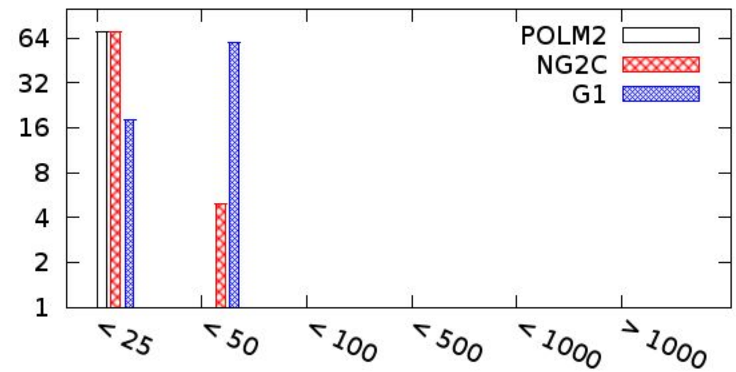
Read-Intensive

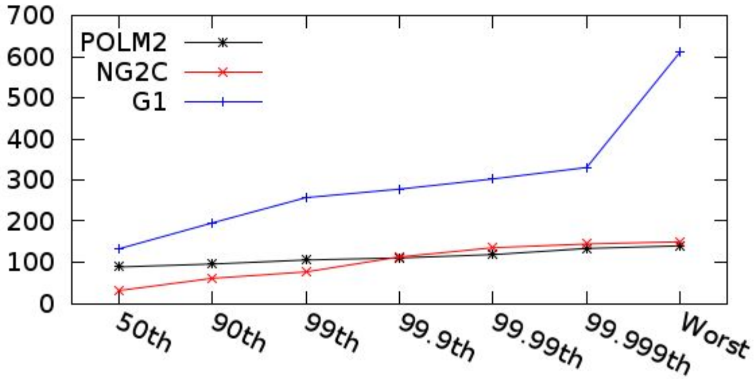


Evaluation - Pause Times for Lucene and GraphChi (ms)

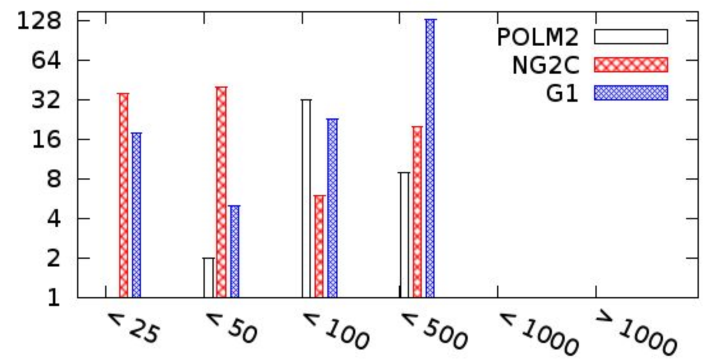


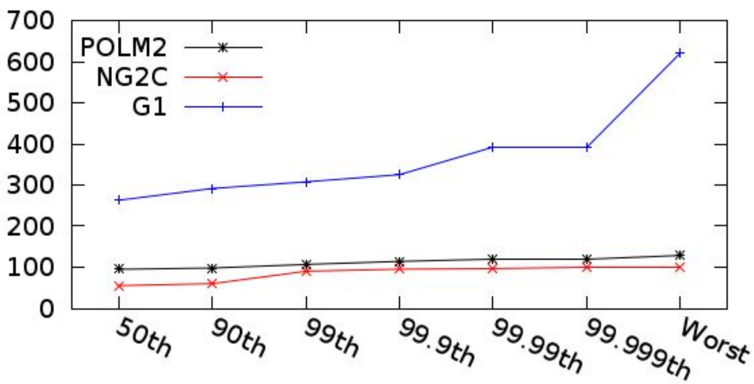
Lucene



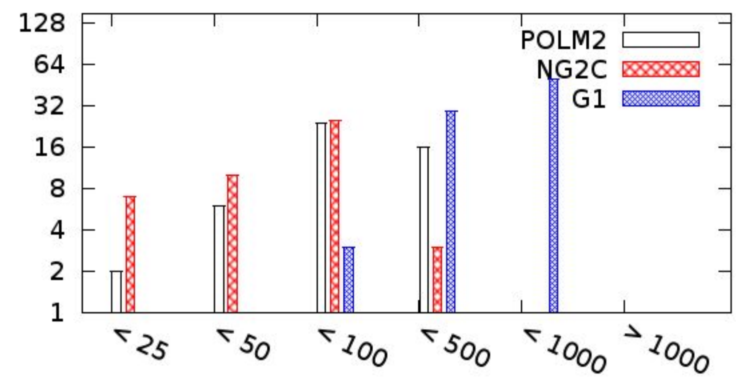


GraphChi CC

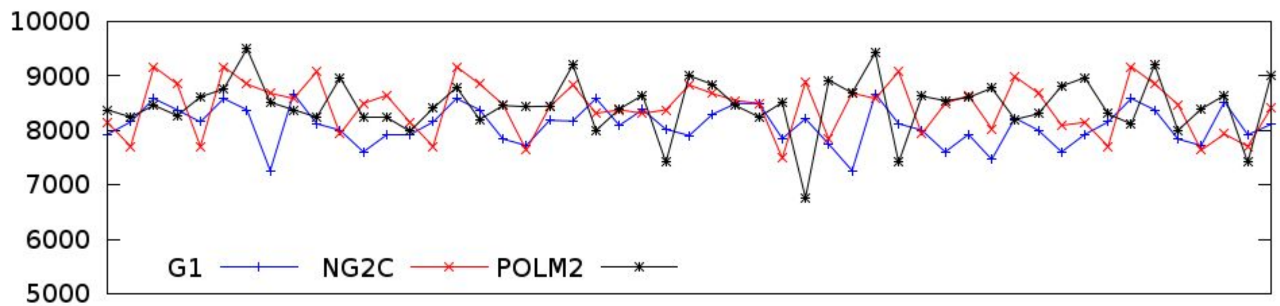




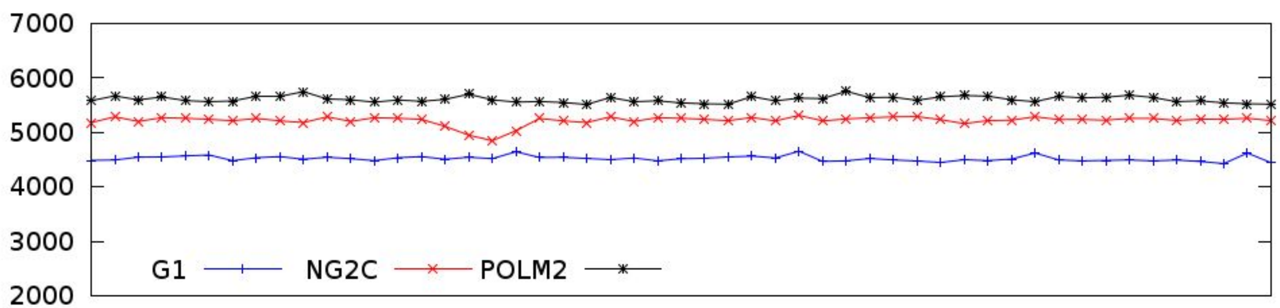
GraphChi PR



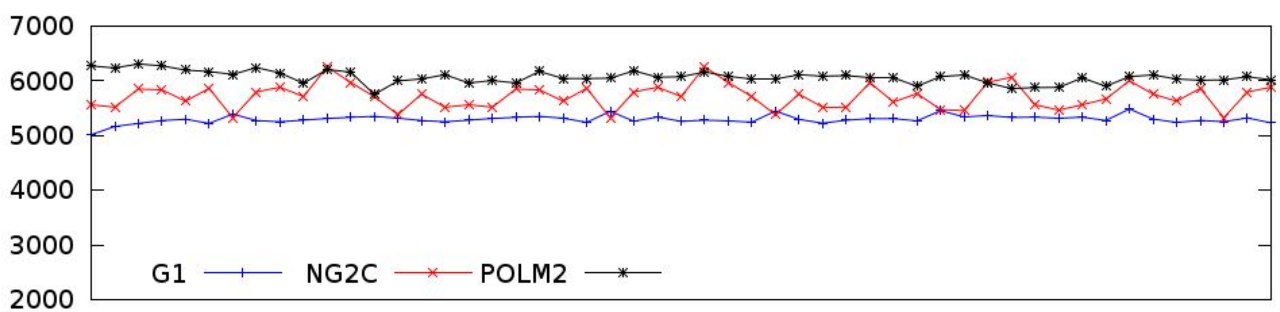
Evaluation - Throughput (Cassandra) - 10 min sample



Write-Intensive



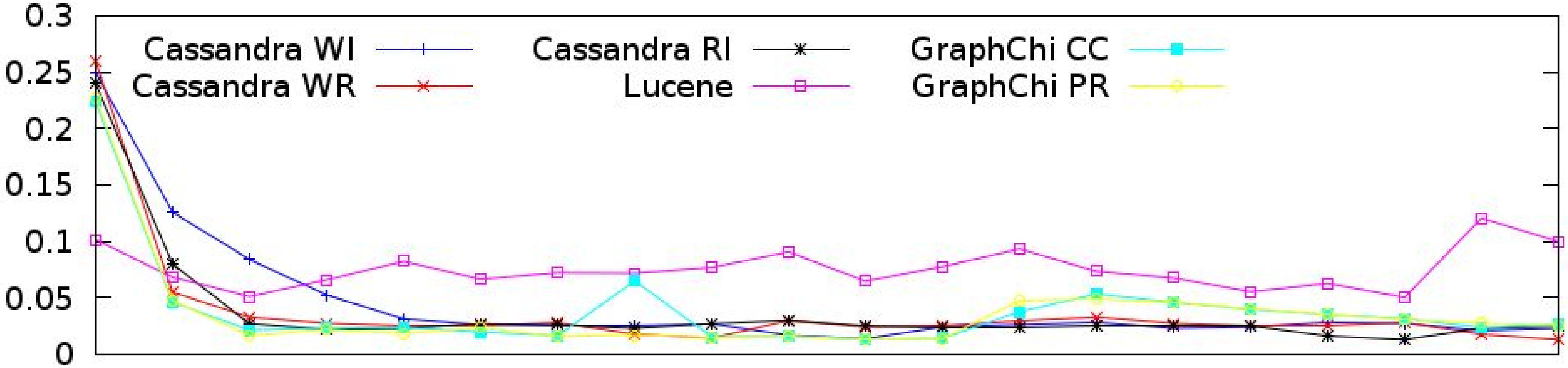
Read-Intensive



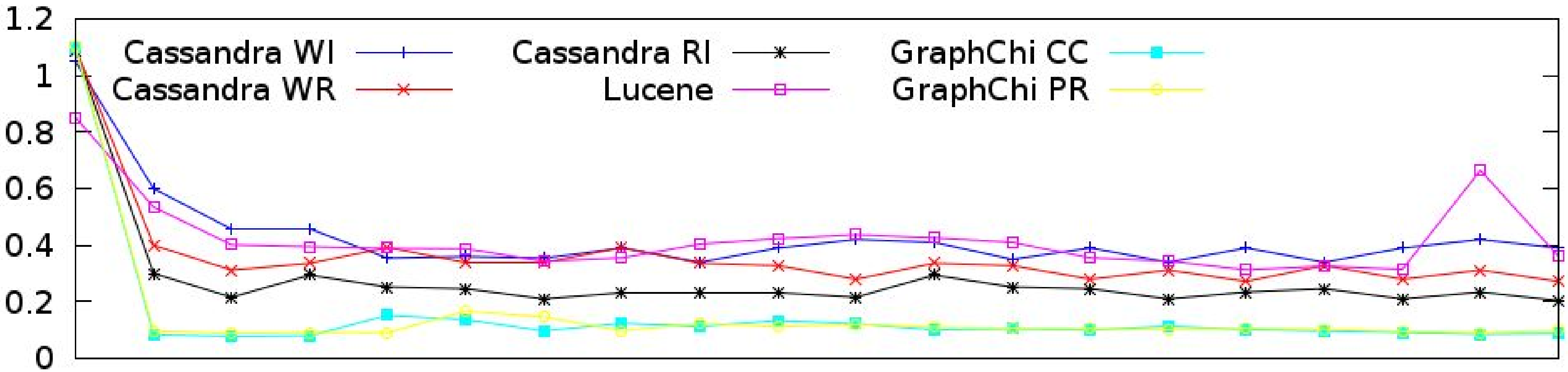
Read-Write

More results in the paper

Evaluation - Dumper vs jmap



Snapshot time (norm to jmap)



Snapshot size (norm to jmap)

Outline

- POLM2 - Automatic Object Lifetime-aware Memory Management
- Implementation
- Evaluation
- **Conclusions & Future Work**

Conclusions

- POLM2 provides a realistic approach to improve Big Data application memory management in HotSpot
  - It decreases pause times by avoiding object copying
  - It requires no programmer effort and knowledge
  - It does not compromise throughput
- Results are very encouraging
- Code is available at github.com/rodrigo-bruno/polm2

Future Work

- Provide in-JVM support for dynamic generations and pretenuring
  - JVM must internally estimate the appropriate generation for each alloc. site
  - JVM must dynamically change the target generation for each alloc. site
  - Work in progress
    - Current prototype leads to up to 8% throughput degradation for Cassandra
    - There are still several performance improvements to be done.

Thank you for your time.
Questions?

Rodrigo Bruno
email: rodrigo.bruno@tecnico.ulisboa.pt
webpage: www.gsd.inesc-id.pt/~rbruno
github: github.com/rodrigo-bruno