# RT-LAGC: Fragmentation-Tolerant Real-Time Memory Management Revisited

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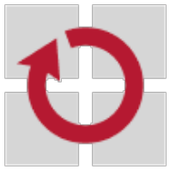
# Real-Time Embedded Java

- **Productivity**
- **Safety**
  - Software-based memory protection
- **Efficiency**
  - Ahead-of-time compilation
  - Static configuration
- **… Memory management?**
  - In particular: predictability?



# Real-Time Memory Management

- **Pseudo-static allocation** (`ImmortalMemory`)
  - Bump pointer
  - No memory release
- **Region-based allocation** (`ScopedMemory`)
  - Bump pointer
  - Region released as a whole

} Simple, predictable, special-purpose

- **Automatic memory management**
  - Complex, list-like heap structure
  - Garbage collection

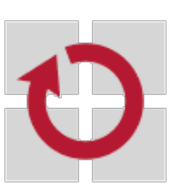
→ Heap fragmentation, unpredictable allocation times

→ Unpredictable latencies

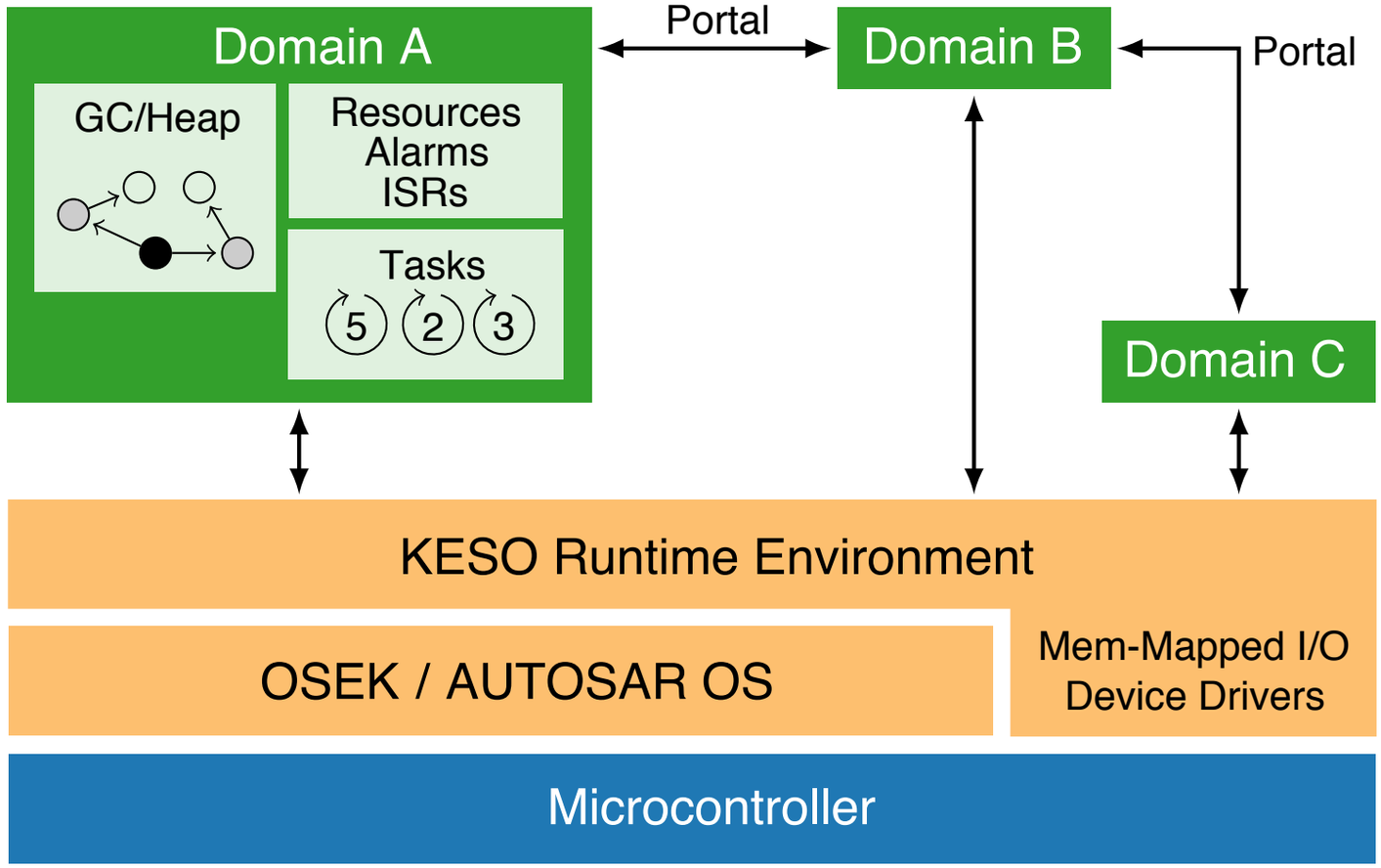
# Agenda

- **Goal: real-time-capable automatic memory management**
  - Bounded allocation times
  - Bounded latencies
  - Good throughput

- **Implementation in the KESO JVM**
  - ***R**eal-**T**ime **L**atency-**A**ware **G**arbage **C**ollection*
- **Evaluation**



# The KESO JVM

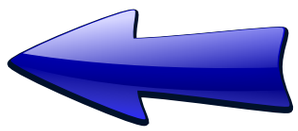



- Ahead-of-time compilation to C code
- Static configuration
- “Pay only for what you use”

# Garbage Collectors in KESO

1. **No GC**
2. **Slack-based mark-and-sweep GC**
   a) Stop-the-world
   - Not preemptible

   b) Incremental
   - Preemptible by application tasks
   - Synchronisation, write barriers

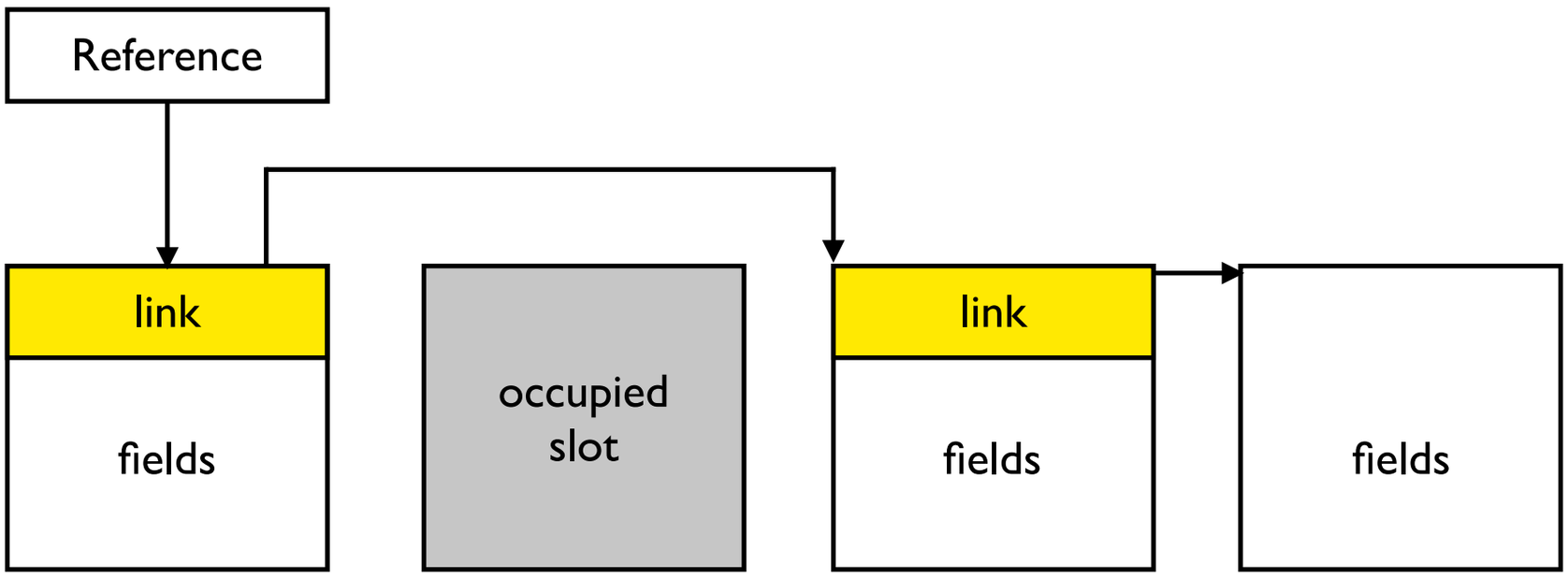


Extend for better predictability

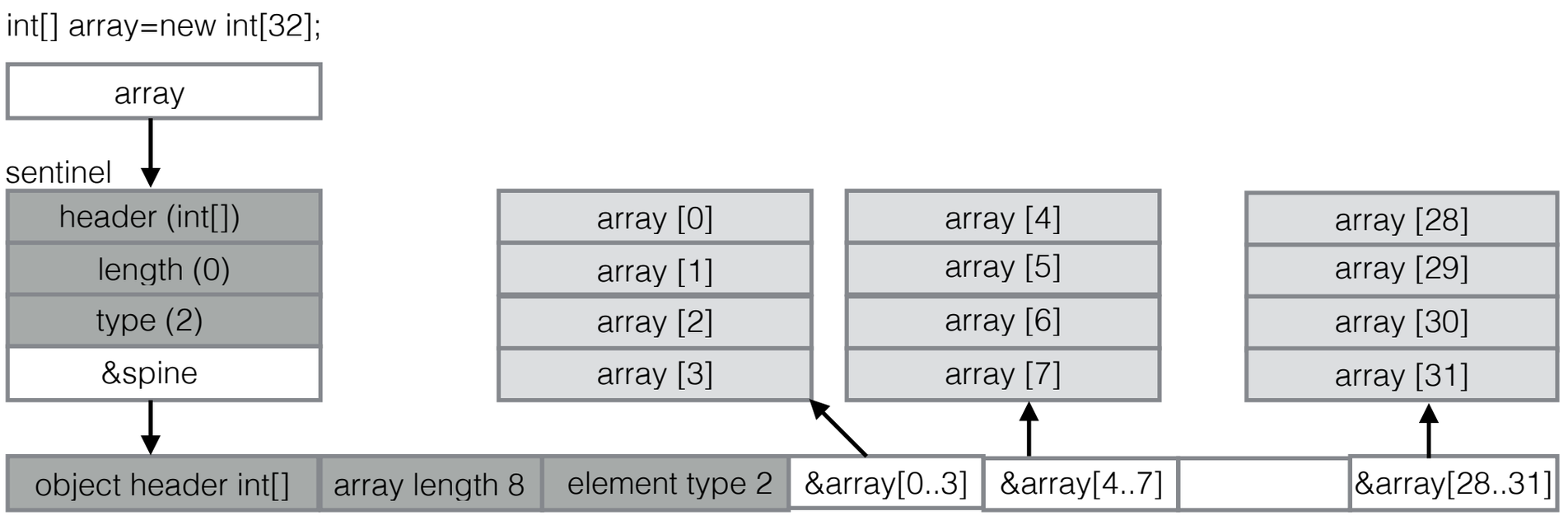
- **Configurable per domain**

# Fragmented Objects

- **Traditional heap**
  - Variable-size chunks → heap fragmentation
  - Unpredictable allocation time
- **Fragmented allocation**
  - Fixed-size slots → no heap fragmentation possible
  - Fragmented objects
  - Predictable allocation time

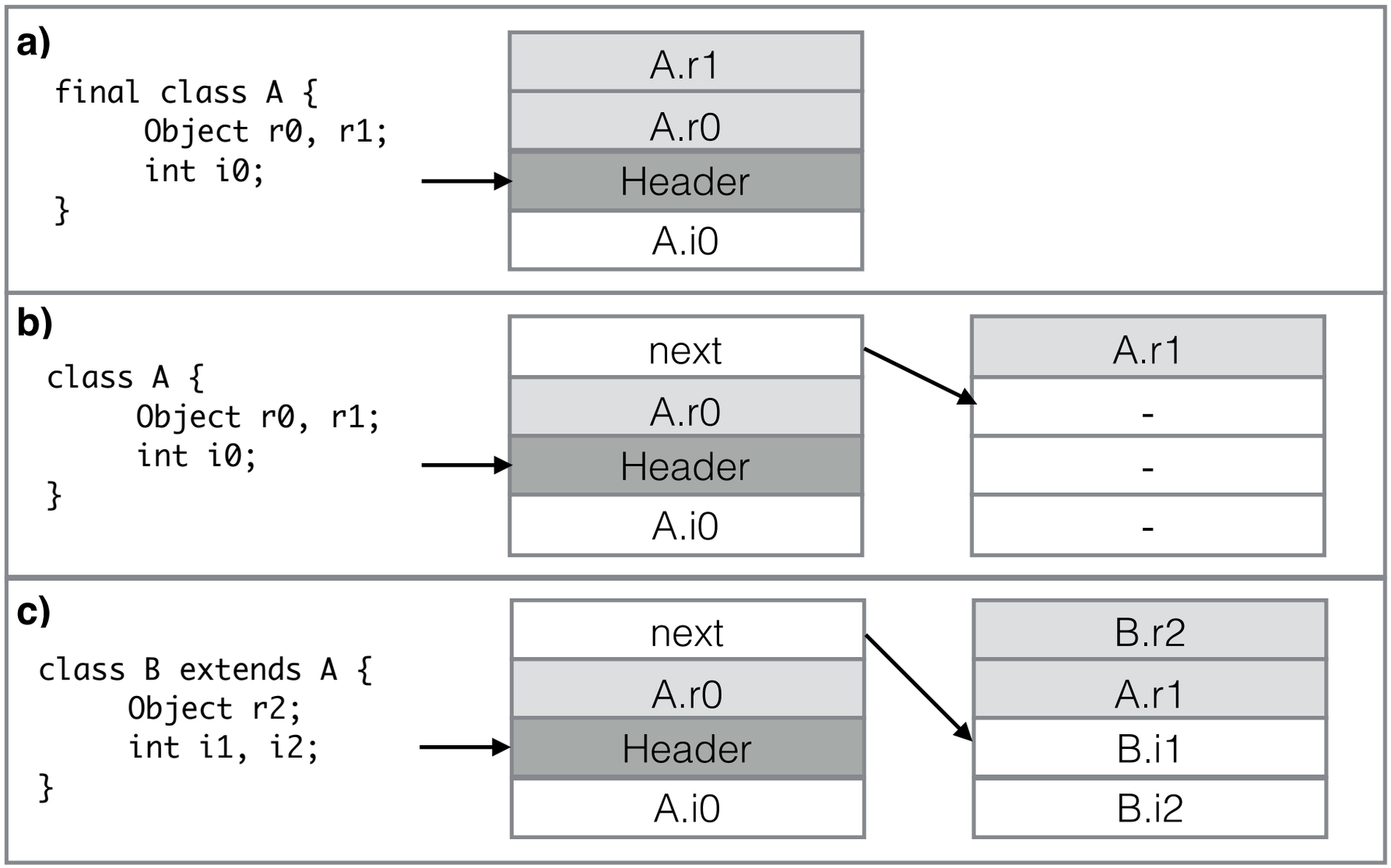



# Fragmented Arrays

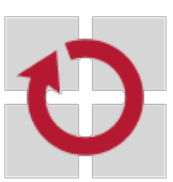



- **Spines**
  - Constant access complexity
  - Allocated in separate heap space
    - Bump pointer
    - Replicating or generational GC
- **Optimisation: omit spine if all fragments are contiguous**

# Object Layout




- Reference grouping for efficient scanning by GC
- ***F**ragmented **B**idirectional **O**bject **L**ayout*



# Scanning the Object Graph

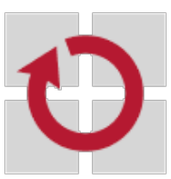
- **Static references**
  - Grouped together in `.data` section
- **Non-static reference fields**
  - Grouped together in object fragments
- **Local references**
  - Henderson’s linked stack frames
    - Only generated for blocking methods
  - Only scan stacks of currently blocked tasks

# Write Barriers

- **Whenever a reference is written, mark its pointee grey**
  - Significant application overhead
- **Trade-off: latency vs. performance**
  - Omit write barriers for local references
  - During stack scanning, raise GC's priority above stack owner's
    - Short, bounded time (sans recursion)
    - GC still preemptible by higher-priority tasks
  - Also possible: omit write barriers for static fields

# Improving GC Predictability

- **Observation: GC runtime dominated by mark phase**
  - Object-graph traversal expensive
  - Only surviving heap objects contribute
- **Survivability analysis**
  - Per-object lifespan categorisation
  - Based on escape analysis and call-graph analysis
  - Object may survive GC if reference …
    - … escapes globally
    - … is live beyond blocking system calls



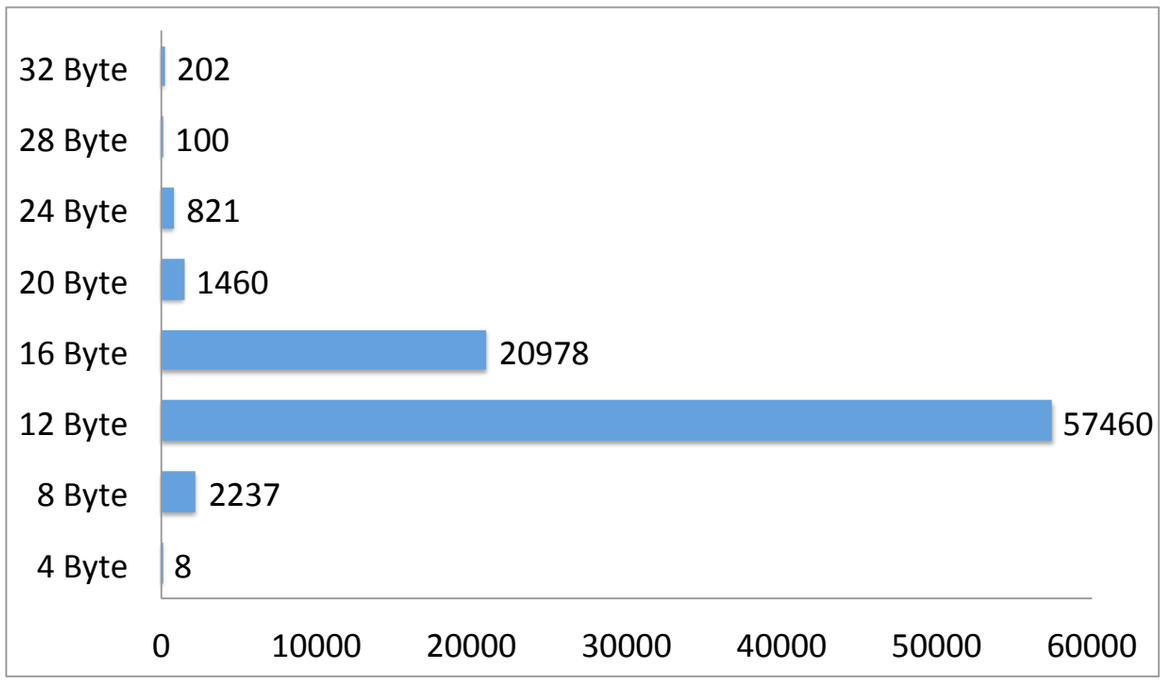
# Survivability Classification

- **Method-local**
  - Automatic stack allocation
- **Region-local**
  - Automatic region-based allocation
- **Task-local**
  - Per-task heaps
- **Task-escaping**
  - Regular heap

# Evaluation

- **Collision Detector ($CD_j$) 1.2**
  - Real-time air-traffic simulator and collision detector
  - CiAO OS
  - TriCore TC1796 @ 150 MHz

- **Object sizes**
  - Regular objects are small due to by-reference semantics
  - Chain length determines execution time of
    - Allocation
    - Field access



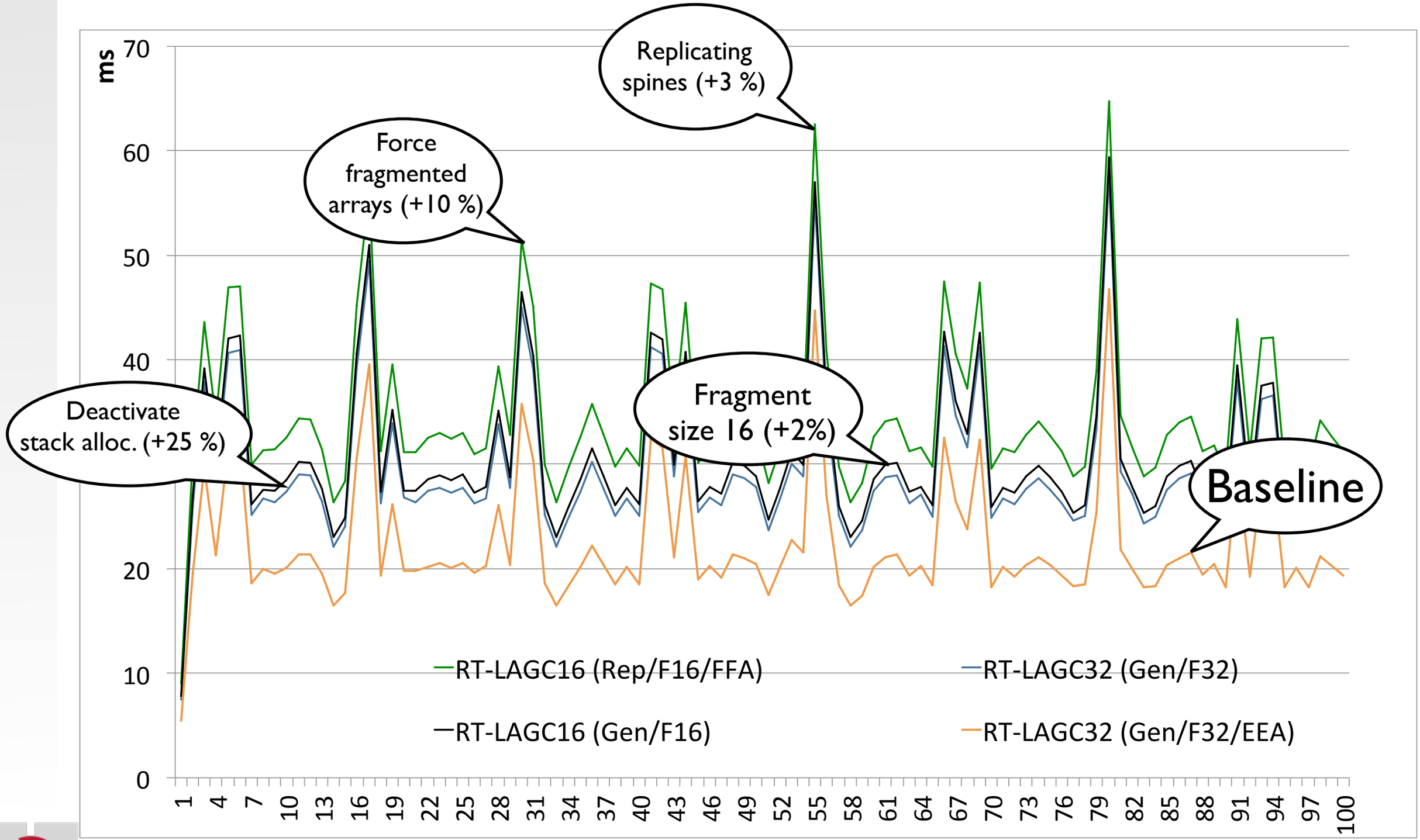
# Memory Footprint / Heap Usage

- **Memory footprint**

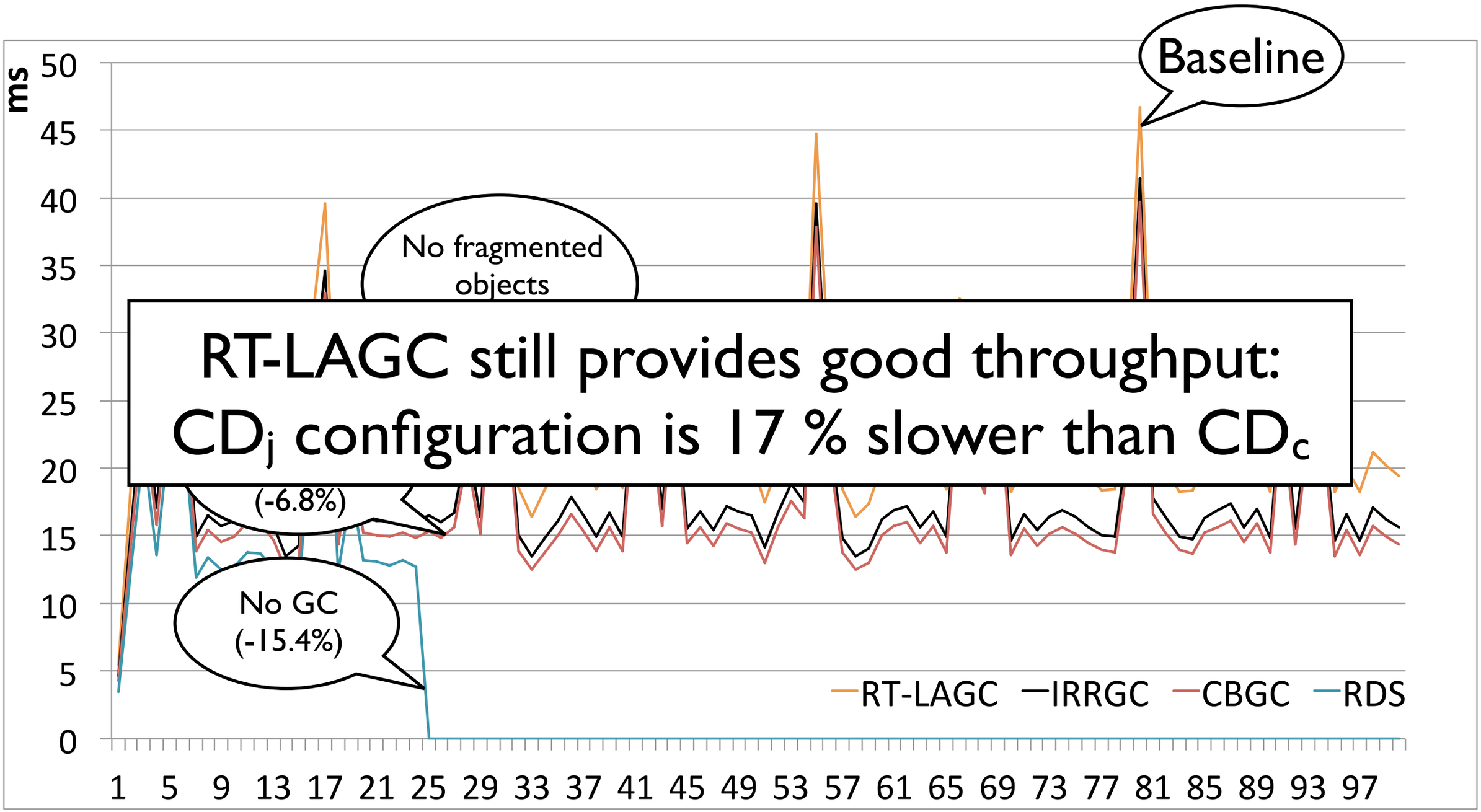
| | `.text` | `.data + .bss` |
|---|---|---|
| **Incremental** | 50 KiB | 660 KiB |
| **RT-LAGC** | 58-60 KiB | 820 KiB |
| ***Δ*** | *+ 16-20 %* | *+ 23 %* |

- **Heap usage**
  - Generational vs. replicating spines: spine memory reduced by 50 %
  - Stack allocation reduces heap usage by 43 %
  - 32-byte vs. 16-byte fragments: usage raised by 45 % (internal fragmentation)

# Runtime


ms
70
60
50
40
20
10
0
Replicating spines (+3 %)
Force fragmented arrays (+10 %)
Deactivate stack alloc. (+25 %)
Fragment size 16 (+2%)
Baseline
RT-LAGC16 (Rep/F16/FFA)
RT-LAGC32 (Gen/F32)
RT-LAGC16 (Gen/F16)
RT-LAGC32 (Gen/F32/EEA)
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58 61 64 67 70 73 76 79 82 85 88 91 94 97 100

# Runtime


ms
50
45
40
35
30
25
20
15
10
5
0
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77 81 85 89 93 97
Baseline
No fragmented objects
(-6.8%)
No GC
(-15.4%)
RT-LAGC
IRRGC
CBGC
RDS
RT-LAGC still provides good throughput:
CDj configuration is 17 % slower than CDc

# Conclusion

- **RT-LAGC in KESO**
  - Cooperative approach
  - Predictable allocation times
  - Fine-grained synchronisation code
  - Low reaction time to external events
  - Good throughput
- **Developer assistance during integration**
  - Survivability analysis
  - Object sizes