Cooperative Memory Management in Embedded Systems

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TECHNISCHE FAKULTÄT

Motivation

- Automated memory management
  - Safety-critical systems
  - Challenge: Resource-efficiency
- Embedded microcontrollers are heterogeneous, for example:
  - Memories (e.g. ROM, RAM)
  - Memory layout
  - Occurrence of random soft errors (bit flips)

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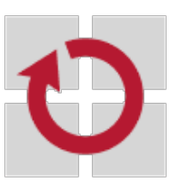
Motivation

Static knowledge about the employed operating system and hardware characteristics is useful for application-tailored automated memory management!

- Memory layout
- Occurrence of random soft errors (bit flips)



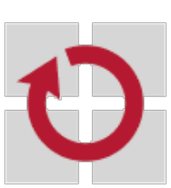
Agenda

How can static knowledge about the application, operating system and hardware-specifics be used to create an automated memory management in embedded systems?

Can automated and safe memory management efficiently be applied in resource-constraint embedded systems?

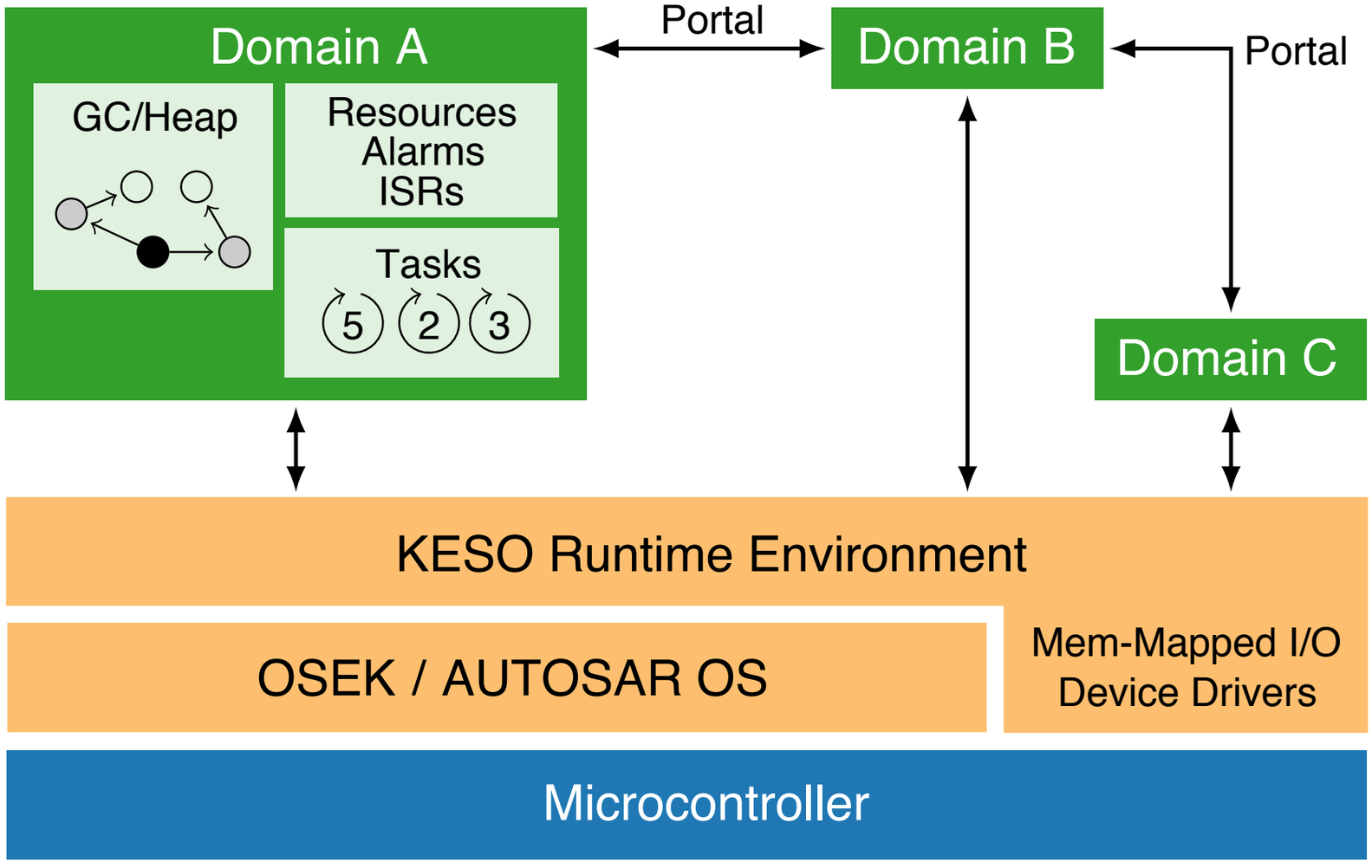
Case study with the embedded KESO Java Virtual Machine

- Cooperative Memory Management
  - Compiler Support
  - Safe and Latency-Aware Garbage Collection
- Evaluation



The KESO JVM

- Java-to-C ahead-of-time compiler
- VM tailoring, static configuration

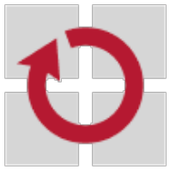


Memory Safety

```
public class Average {

  protected int sum, count;

  public synchronized void addValues( int values[] ) {
    for(int i=0; i < values.length; i++) {
      sum += values[i];
    }
    count += values.length;
  }

  public synchronized int average() {
    return (sum / count);
  }
}
```

"Memory safety ensures the **validity of memory references** by preventing `null` pointer references, references outside an array's bounds, or references to deallocated memory."

Aiken et. al (Microsoft Research)



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    }
    count += values.length;
  }

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    return (sum / count);
  }
}
```

null != values

null != values

0 <= i < values.length

null != values

count != 0

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Type Safety

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```
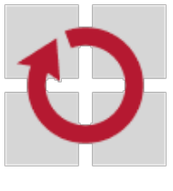

Value of an instance of *Average*

Operations on type *Average*



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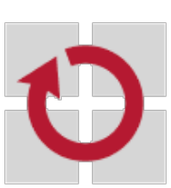
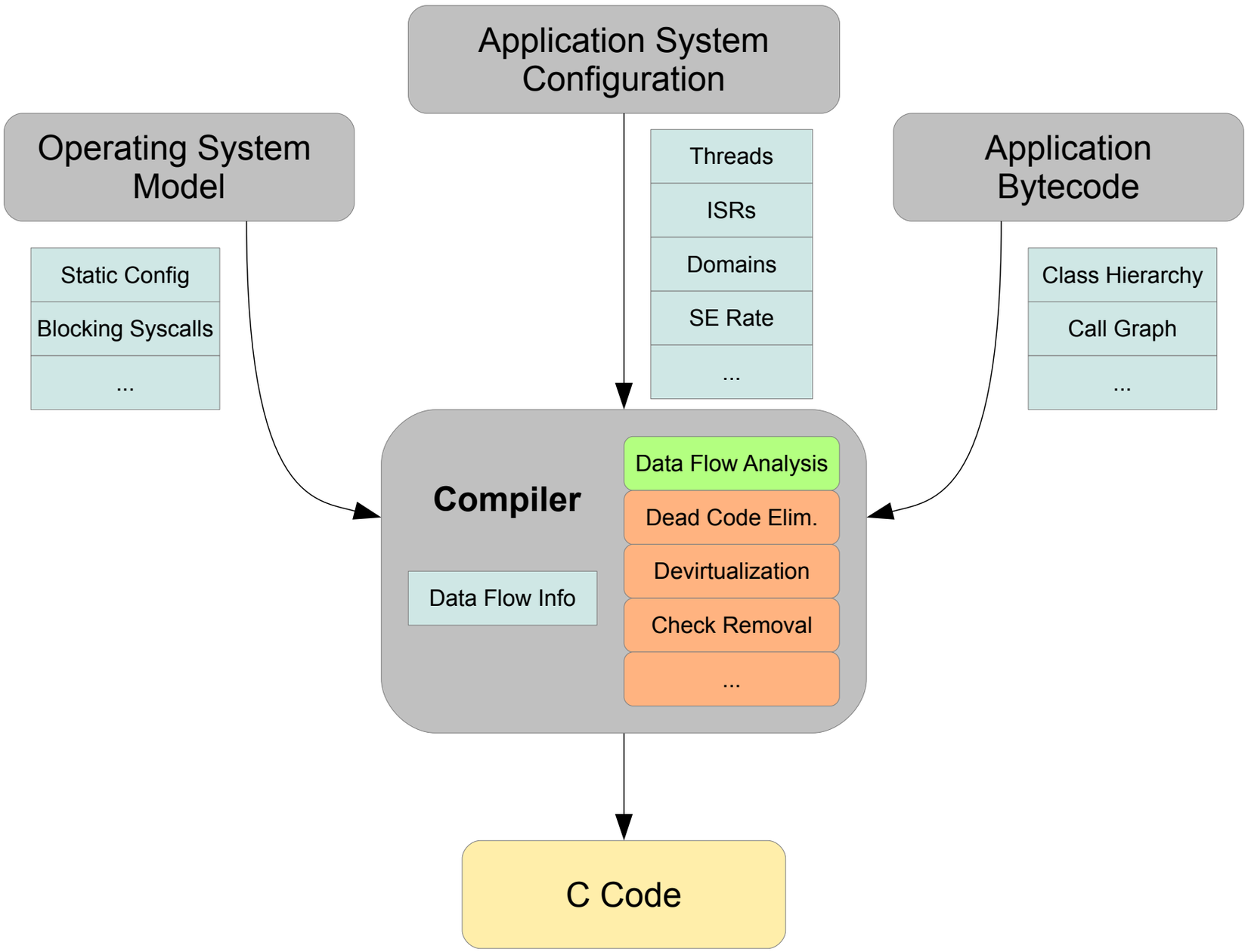


Cooperative Memory Management



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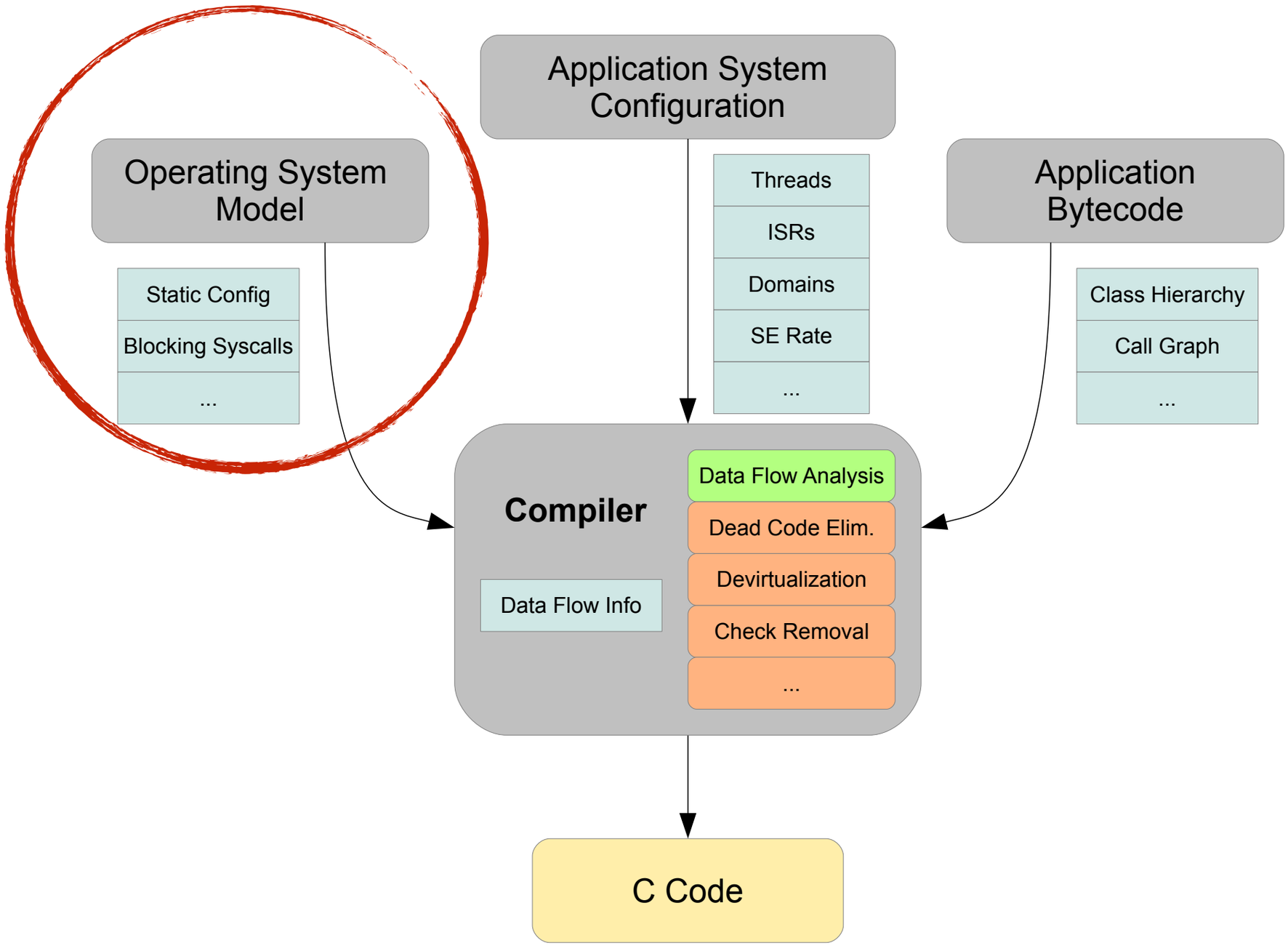

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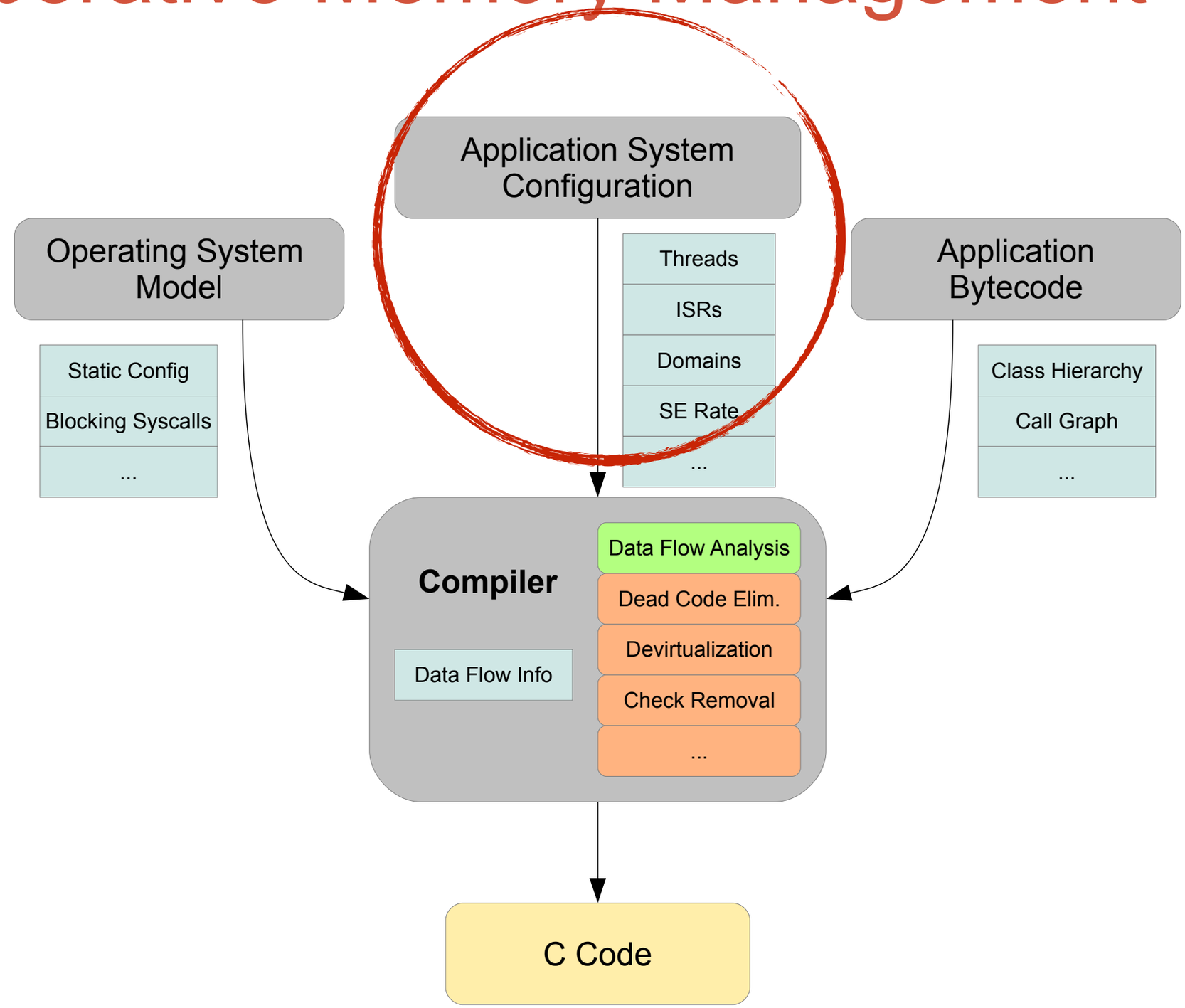

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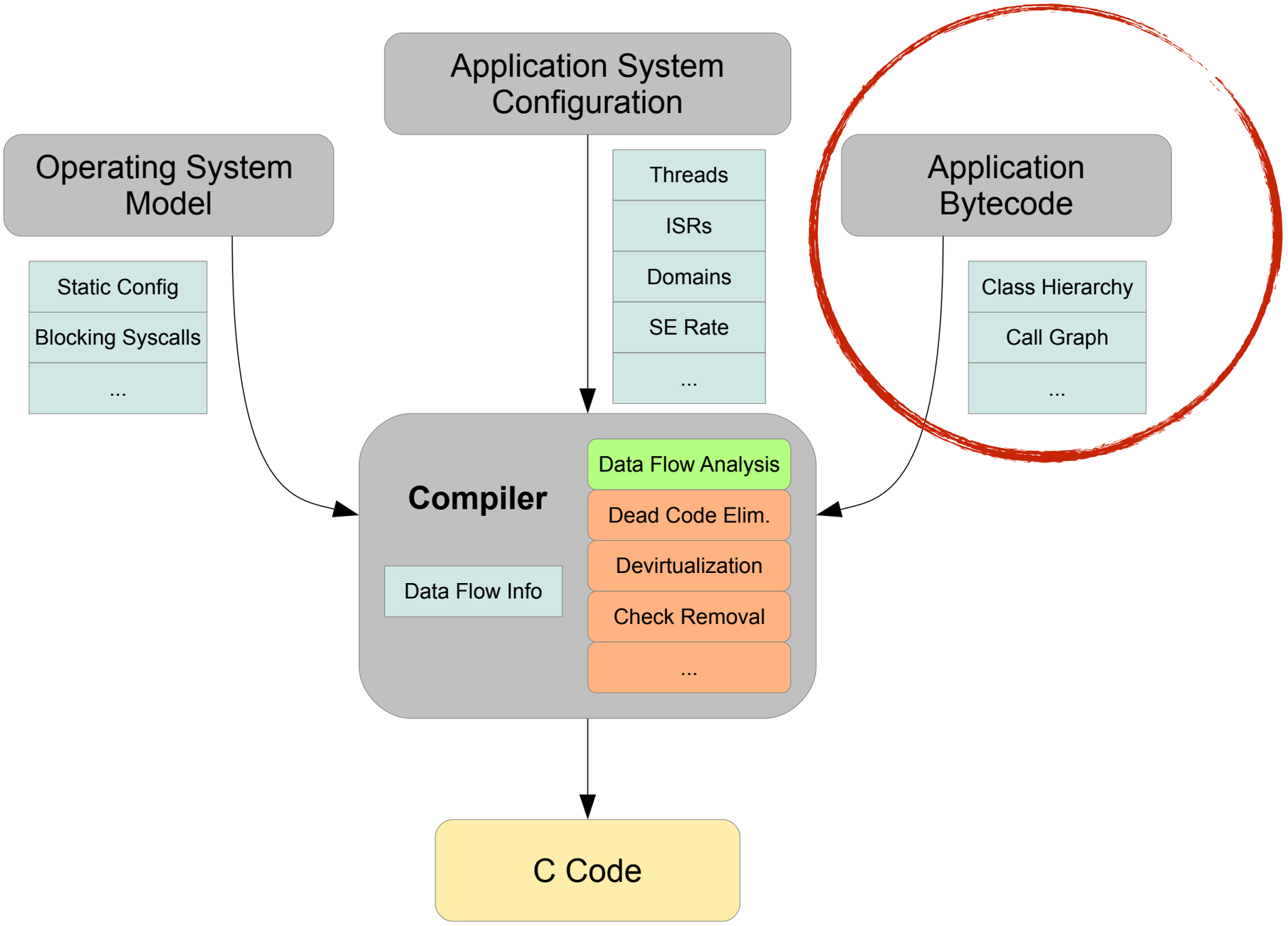

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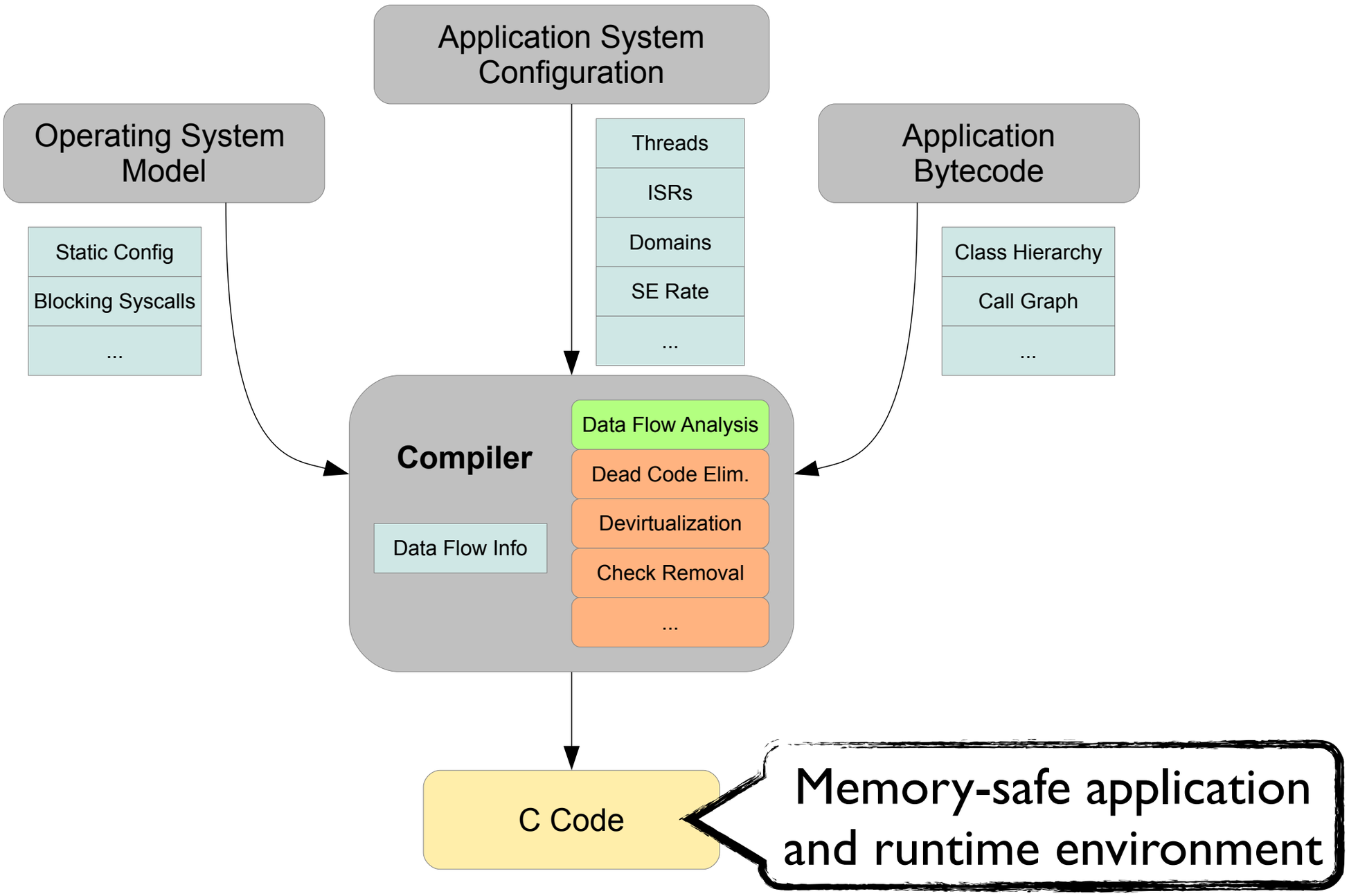

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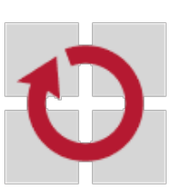
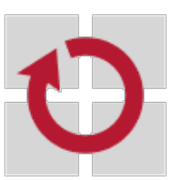


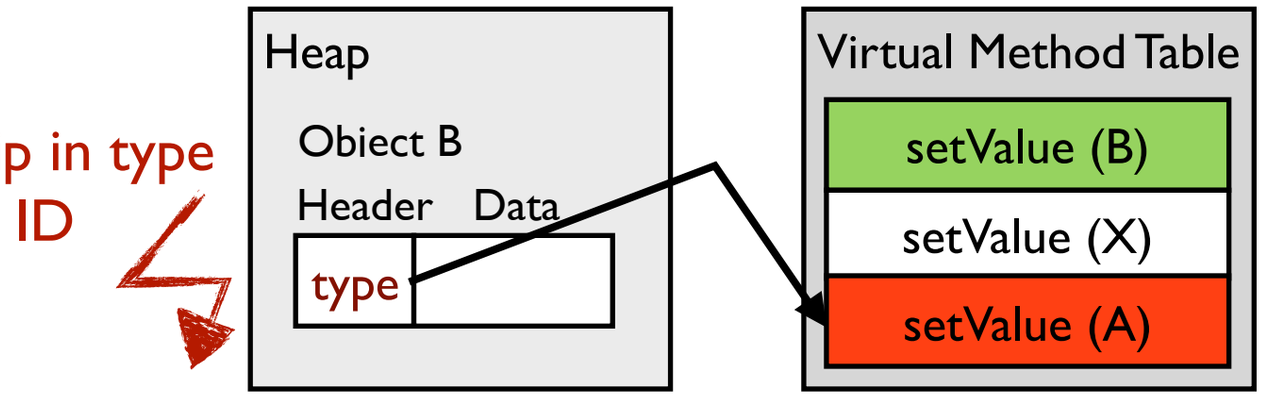
Escape Analysis

- Escape analysis is used to determine the escape state of an object
  - By using information from alias analysis and reachability of references
- Analysis results prove useful in the context of cooperative approach
  - Stack allocation and region inference
  - Allocation and deallocation is very efficient
  - Estimation of GC effort (real-time systems)
  - In the context of soft errors
    - Reduction of replication sphere
    - Efficient protection of type system via reference checking



Reference Integrity Checks

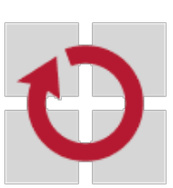
- Bit flips can break the soundness of the type system!
- Preserve software-based isolation via integrity checks of references
  - A controlflow-sensitive analysis determines the insertion of checks
  - Dereference check (**DRC**)
- Integrity check is two-fold
  - Validity of address
  - Check of header information (e.g. dynamic type)
  - **No wild references!**
- Protection information can be incorporated in the reference
  - Attack surface of the program is not increased
  - Protection information size is depended on the used hardware device



Immortal Data / Runtime-Final Analyses

- *Automatic inference of constant and runtime-final data (alias info)*

1. Determination of constant data is essential
   - Data can automatically be placed in read-only memory (ROM) e.g. flash
   - Flash memory is much less susceptible to soft errors
   - Garbage collection overhead can be reduced
2. Runtime-final analysis
   - Constant folding
   - Null checks on effectively-final data can be eliminated



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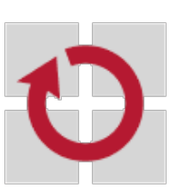
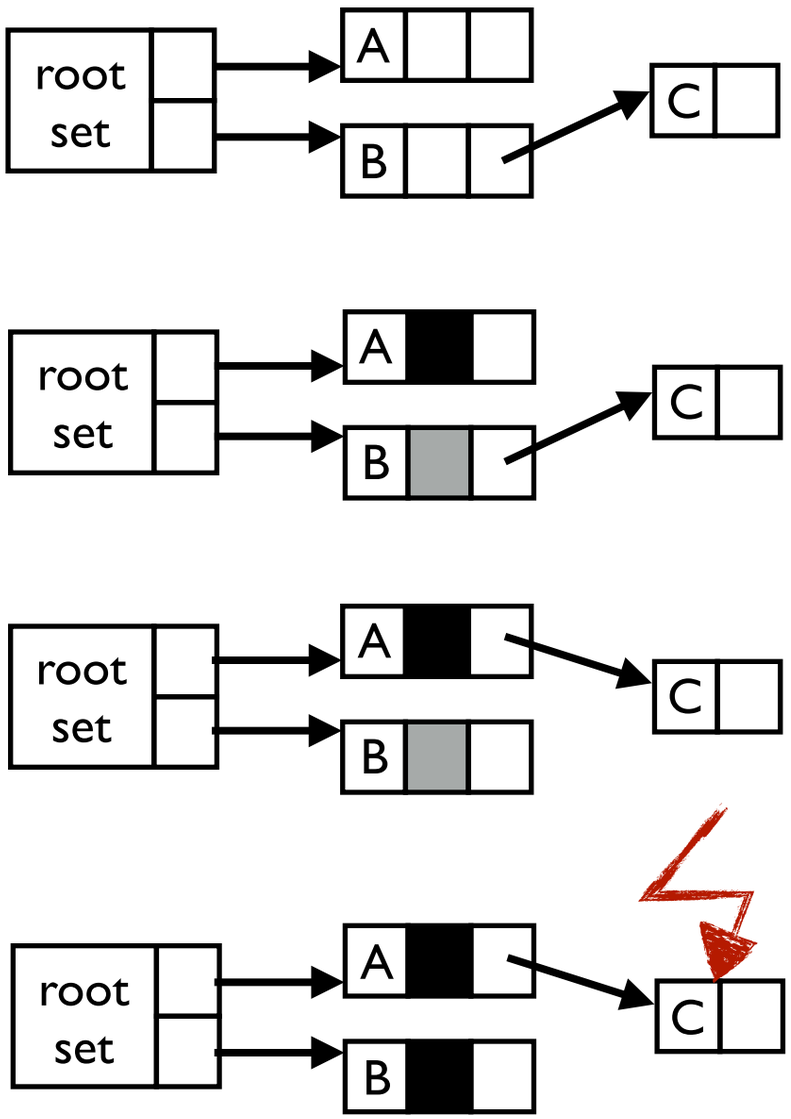


Latency-Aware Garbage Collection (LAGC)

- Incremental and slack-based *mark-and-sweep* GC algorithm
- Restrict each critical section to constant complexity
- Dedicated (low-priority) thread for garbage collection
- ***Scan-and-mark***:
  - Traditional tricolor scheme for marking (white, grey, black)
  - Reference scanning: start at root set
    - Static references: global array
    - Local references: linked stack frames
    - Object layout: grouping of references
- Sweep:
  - Memory of unreachable (white) objects is inserted into free memory list

Synchronization Needed

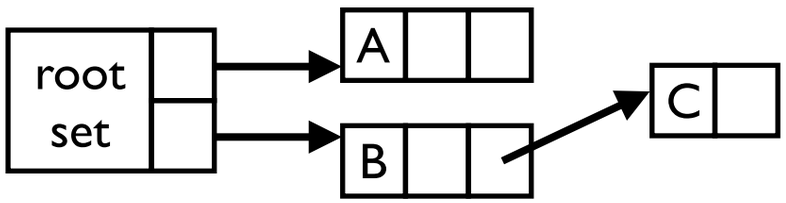


Scanned Reachable object

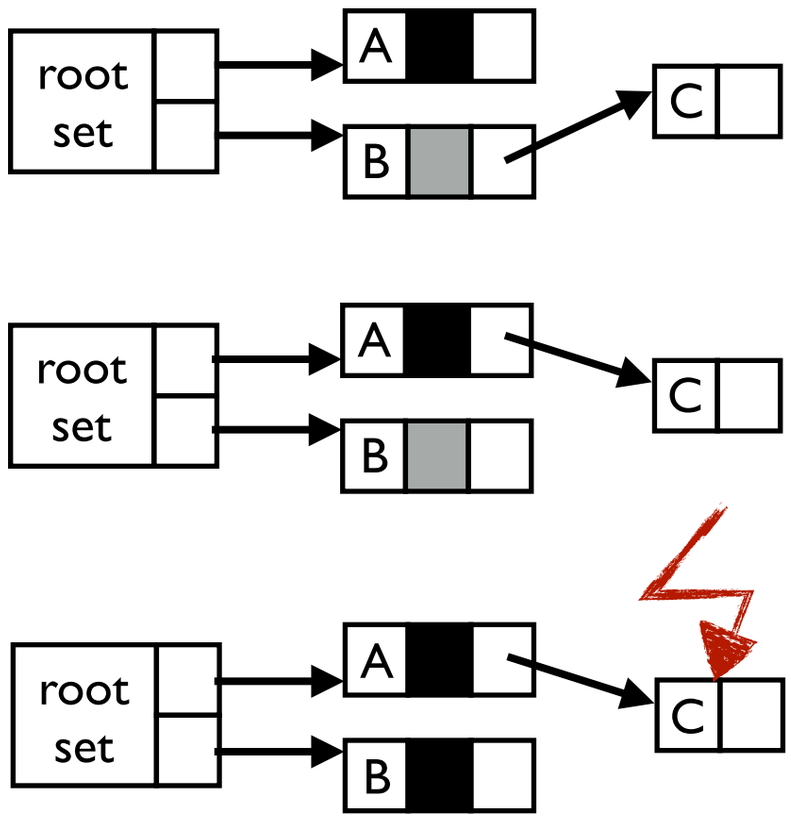
Unvisited/unreachable object

Unscanned reachable object

Synchronization Needed



Objects A, B and C are reachable via root set
Garbage Collector (GC) starts marking



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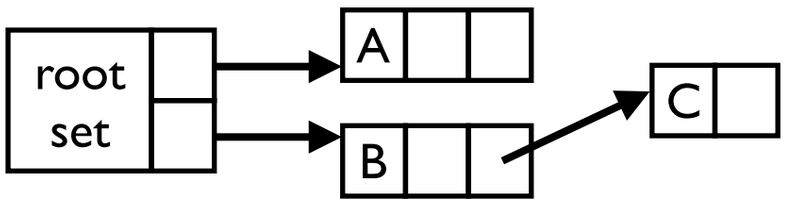
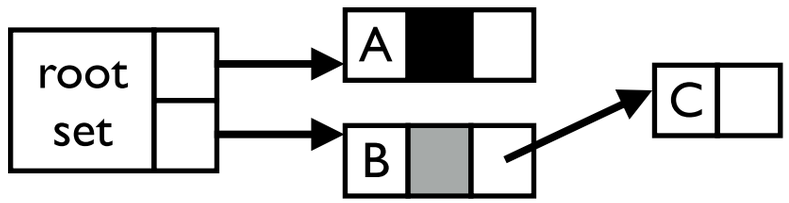
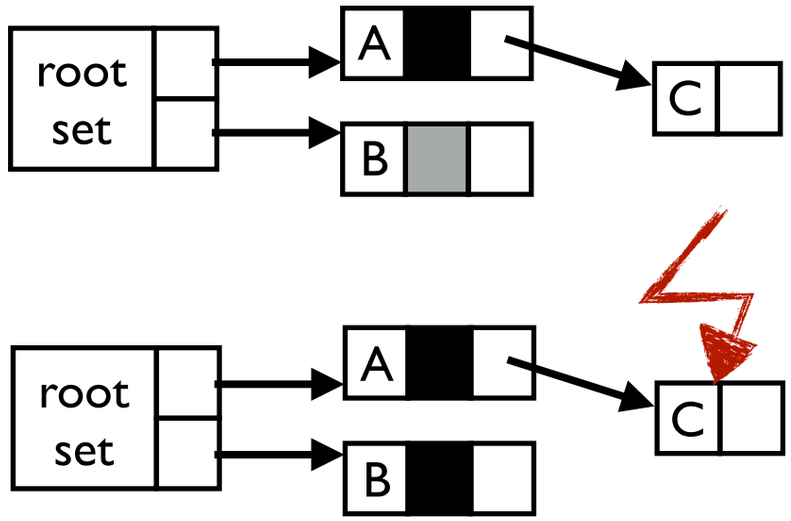
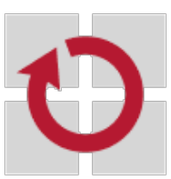




A is marked reachable (black)





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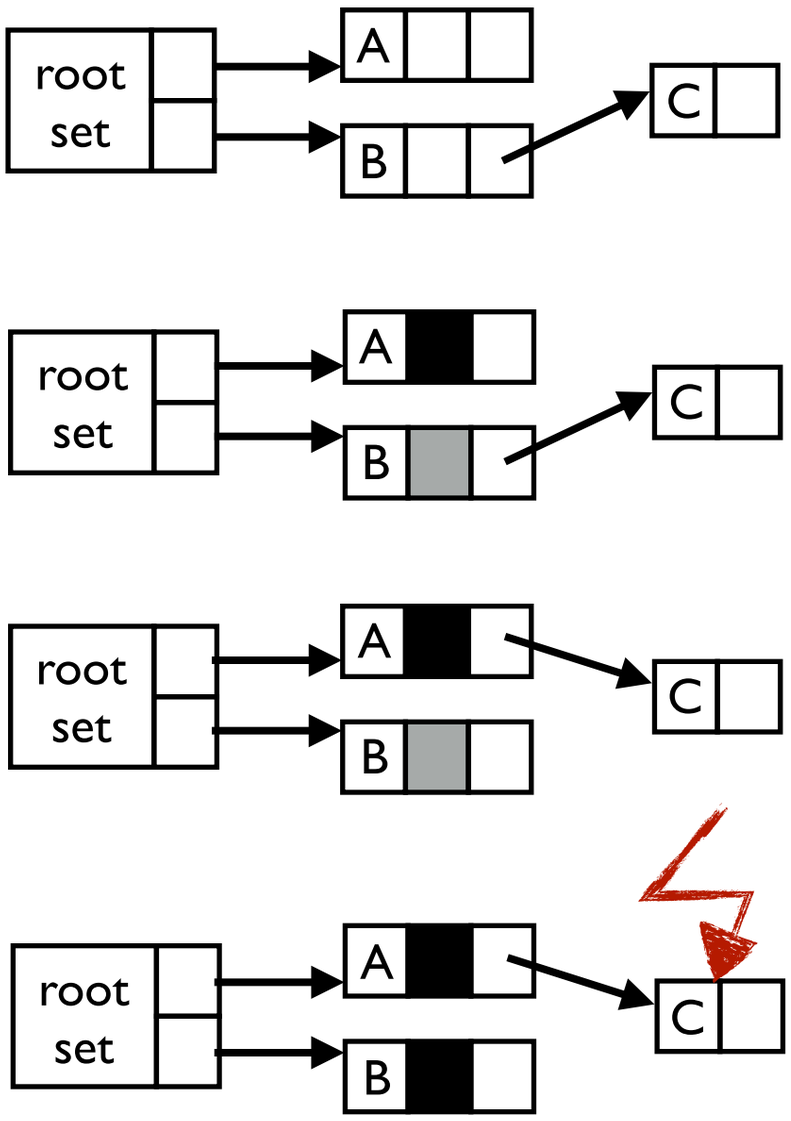


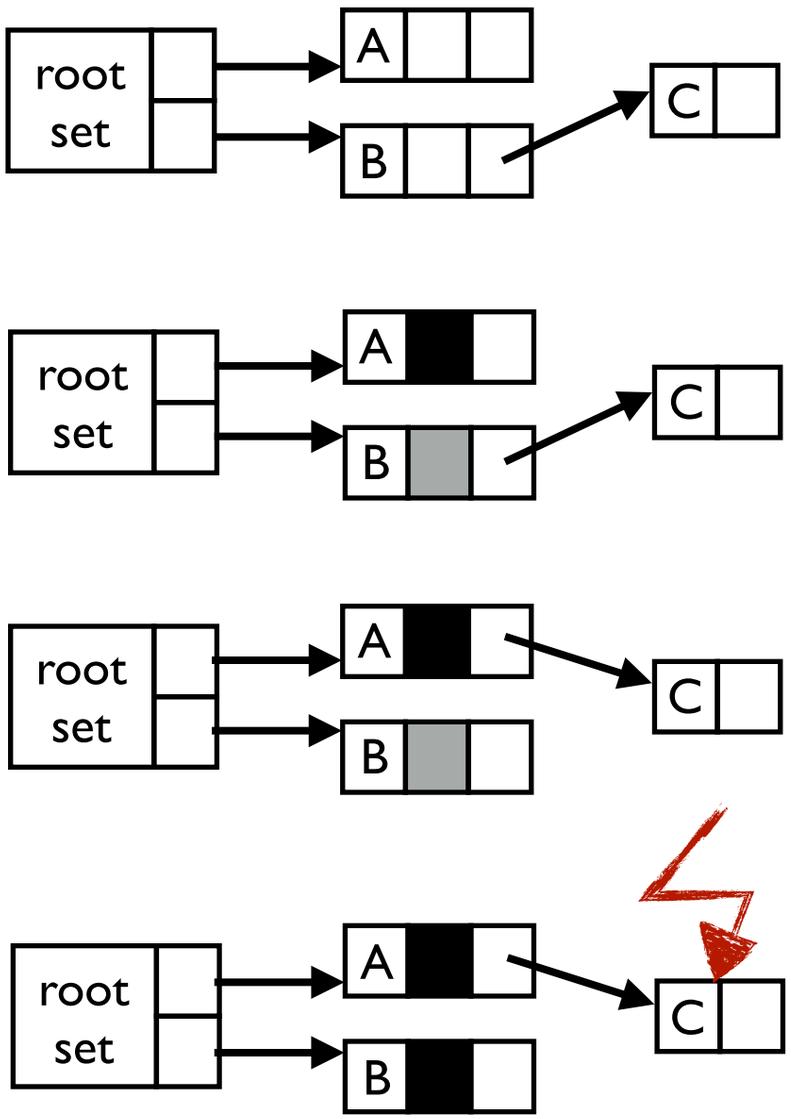
After marking A reachable, the GC is preempted by the higher-priority application, which sets a reference from A to C. The interrupted GC marking is resumed

Scanned Reachable object

Unvisited/unreachable object

Unscanned reachable object

Synchronization Needed



C is not marked reachable by the GC, though it is used by the application. A dangling reference has been forged

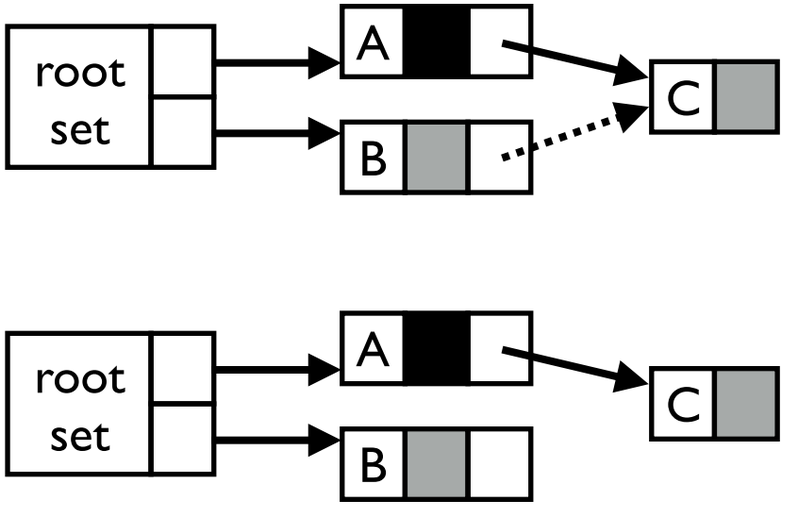
Scanned Reachable object

Unvisited/unreachable object

Unscanned reachable object

Write Barriers

- Whenever a reference to a white object is overwritten, no matter if the reference field was already scanned or not, the object referenced by the overwritten reference is colored gray



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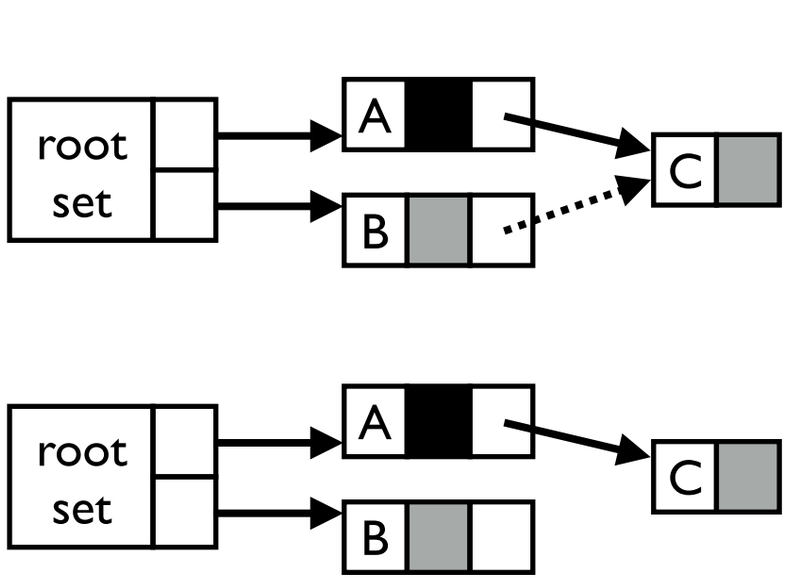
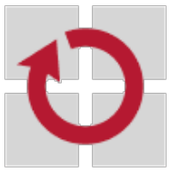


Object B's reference shall be overwritten with null, but currently it refers to object C. C is colored gray by the barrier



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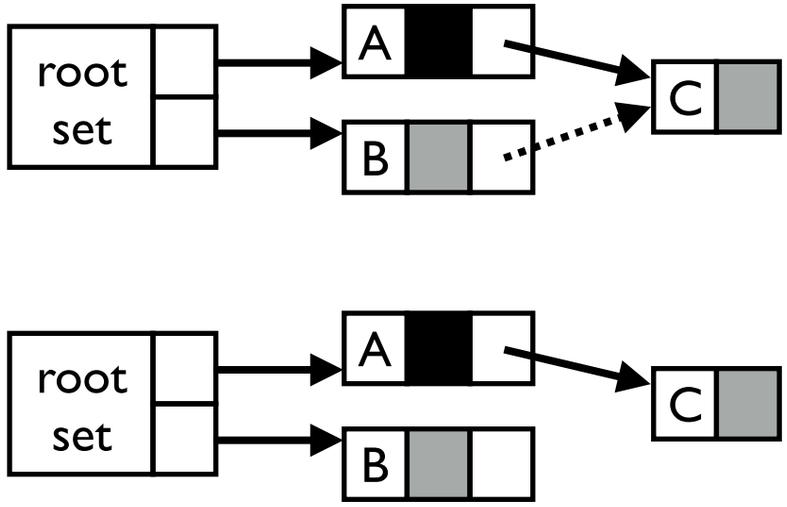

Scanned Reachable object Unvisited/Unreachable object Unscanned reachable object

Latency-Aware Scan-and-Mark

- Write barriers are activated by the GC
- Write barriers are expensive, inserted by the compiler only for
  - Static references
  - Reference fields
  - Field writes to references of object array
- Atomic scanning of task stacks
  - Blocked tasks
  - Complexity linear in its stack size
  - The task currently being scanned is delayed
  - Discovered references are colored gray (reachable, unscanned)

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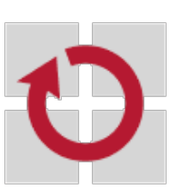


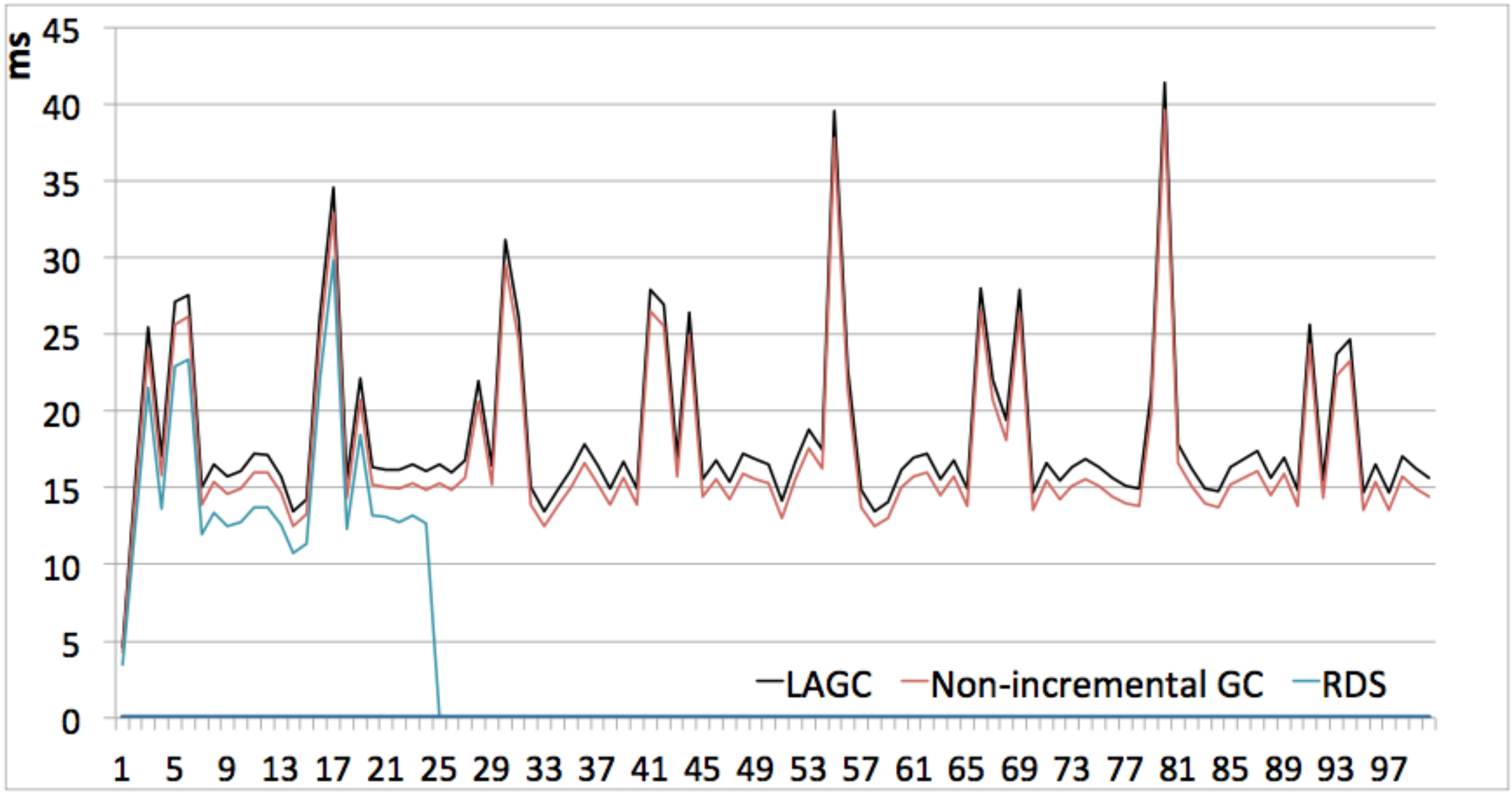
Evaluation

- Real-time Java application benchmark Collision Detector (CDx)
- Built KESO CDj variants
  - Incremental LAGC
  - **Incremental Safe-LAGC** (Protection against soft errors)
- Influence of compiler-assisted memory management
- Effectiveness of integrity checks
- Measured overhead of Safe-LAGC in contrast to LAGC
  - TriCore TC1796 (32-bit, 1 MiB SRAM, 2 MiB ROM)
  - Heap usage at runtime
  - Runtime

Compiler-Assisted Memory Management

- Escape analysis
  - 30% of all allocations are eligible for stack allocation
  - Reduces heap usage by 45%
  - Application runtime is boosted by 9.5%
- Immortal and runtime final analyses
  - Reduces segment sizes: .text (-14%), .data (-41%)
  - Reduces runtime of application by 12%
  - Placing immortal data in flash: runtime increases by 8%

Runtime


ms
45
40
35
30
25
20
15
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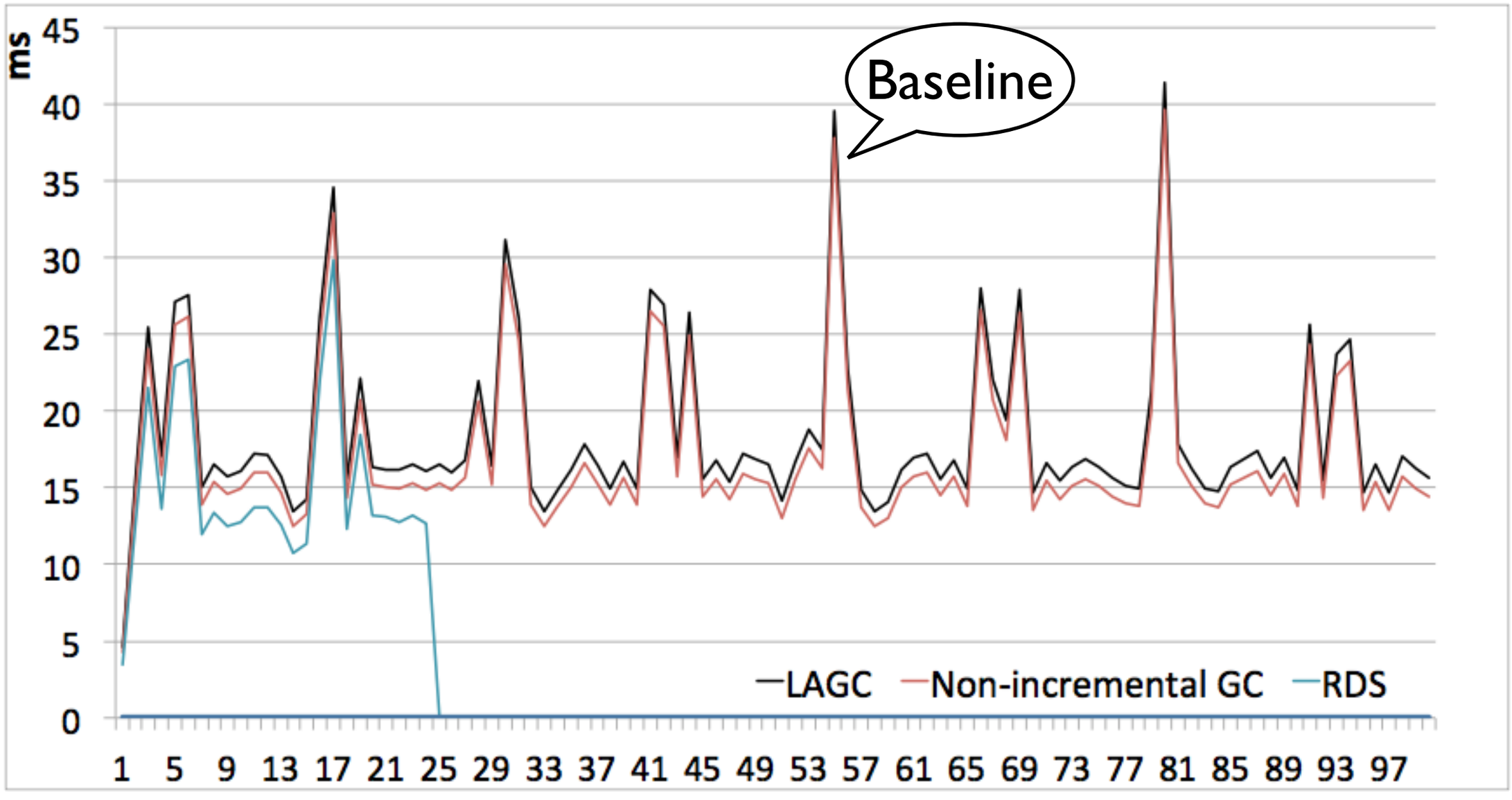
5
0
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77 81 85 89 93 97
LAGC
Non-incremental GC
RDS

Runtime


ms
45
40
35
30
25
20
15
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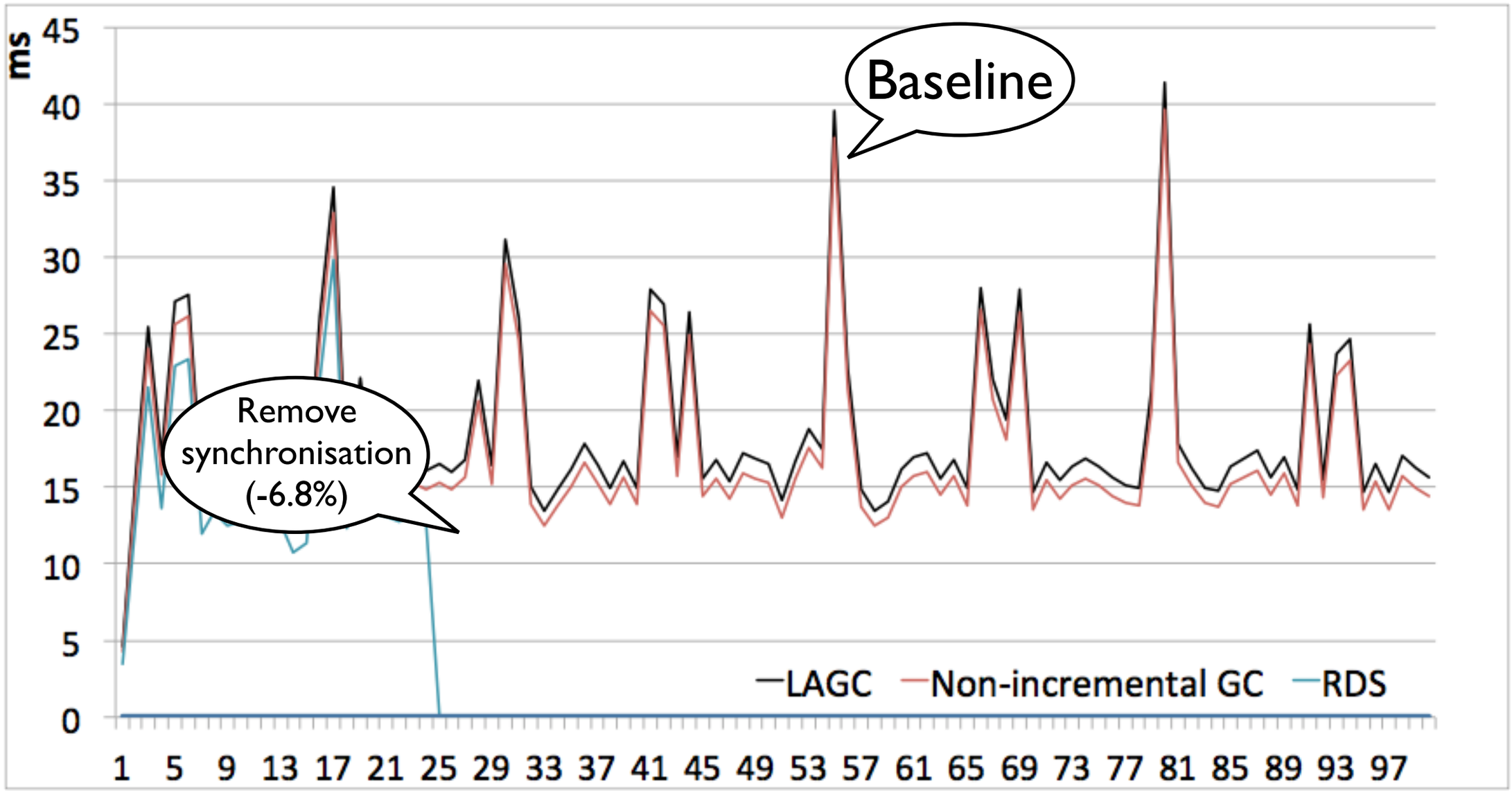
0
Baseline
LAGC
Non-incremental GC
RDS
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77 81 85 89 93 97

Runtime


ms
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40
35
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20
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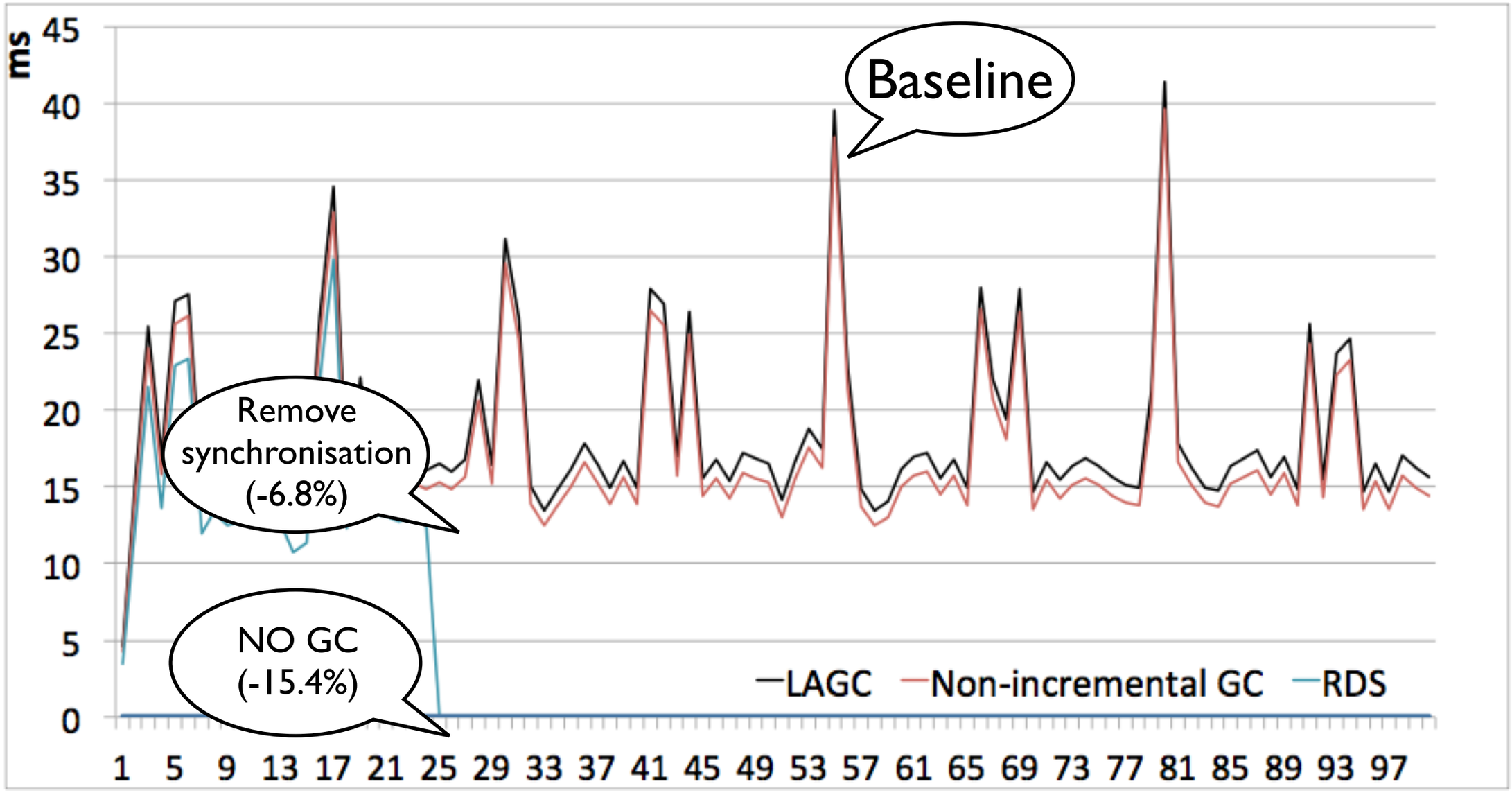
0
Baseline
Remove synchronisation (-6.8%)
LAGC
Non-incremental GC
RDS
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77 81 85 89 93 97

Runtime


ms
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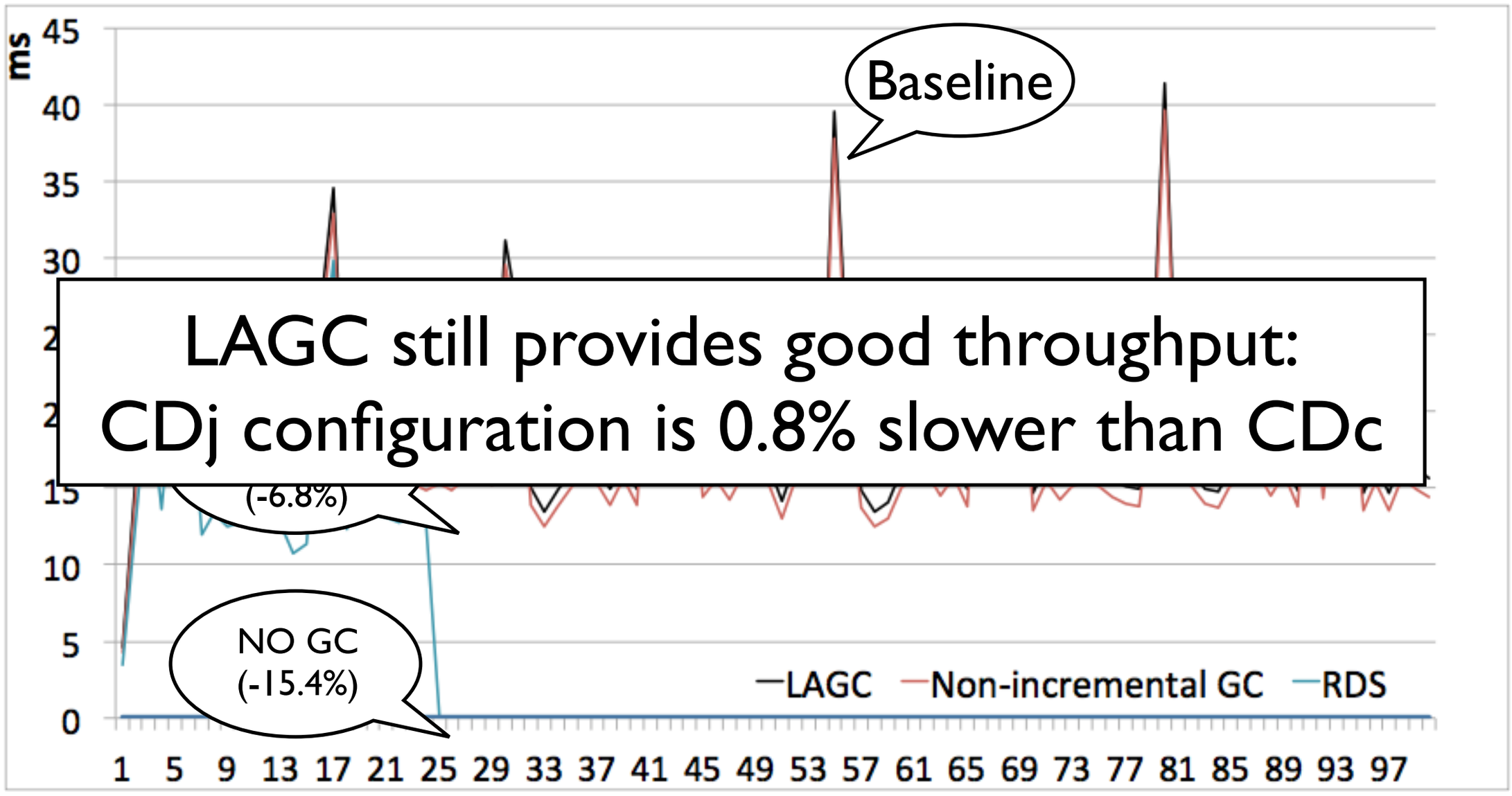
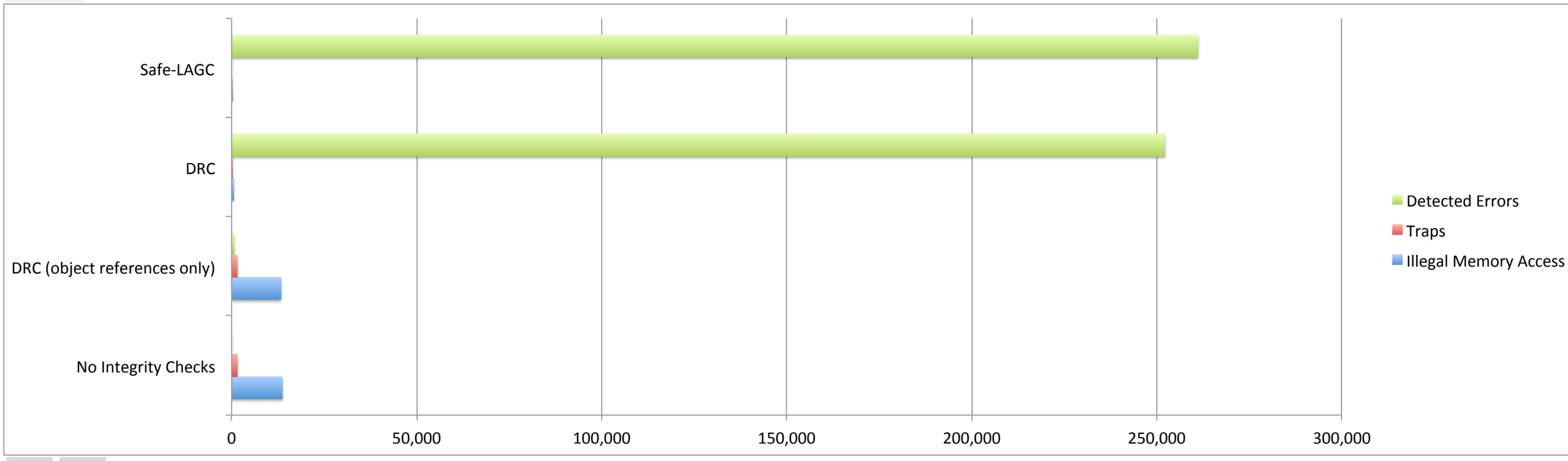
40
35
30
25
20
15
10
5
0
Baseline
Remove synchronisation (-6.8%)
NO GC (-15.4%)
LAGC
Non-incremental GC
RDS
1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77 81 85 89 93 97

Runtime


ms
45
40
35
30
15
10
5
0
Baseline
(-6.8%)
NO GC
(-15.4%)
LAGC
Non-incremental GC
RDS
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
LAGC still provides good throughput:
CDj configuration is 0.8% slower than CDc

Effectiveness of Integrity Checks

- FAIL*: Fault injection tool, application of fault space pruning
- Injected bit flips into each position of a memory word
- Application data is physically grouped by KESO's reachability analysis



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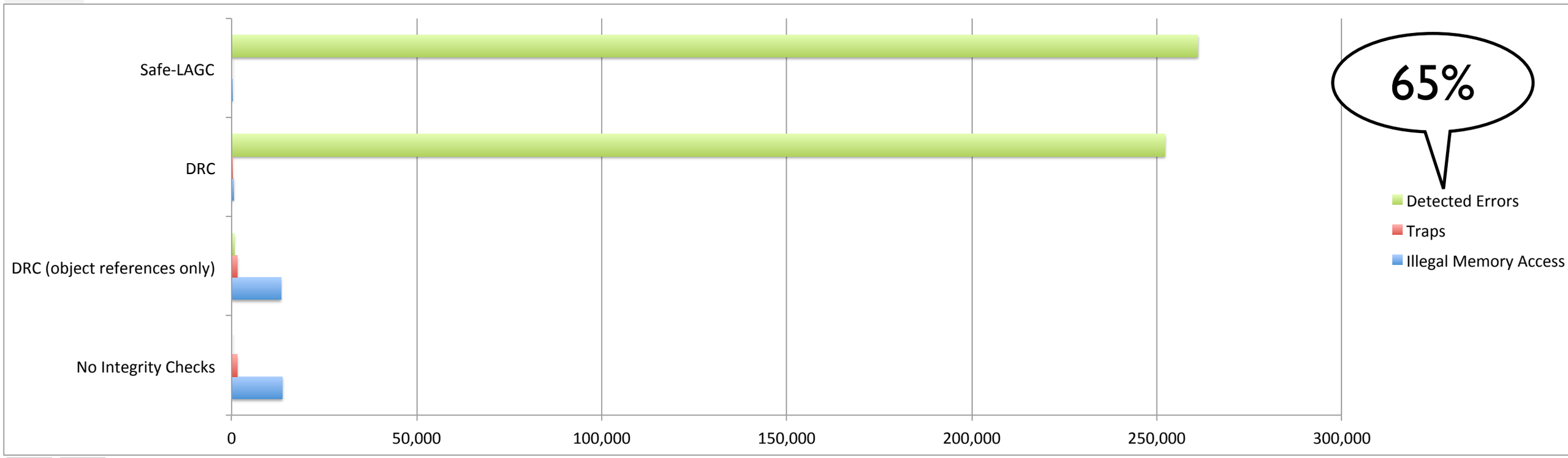

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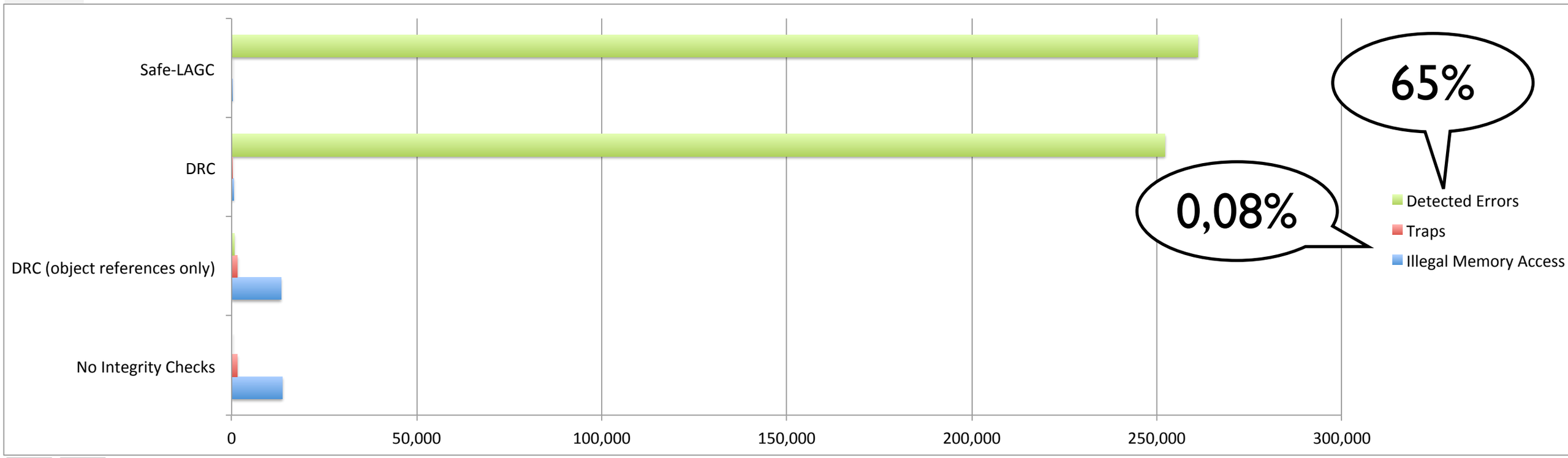
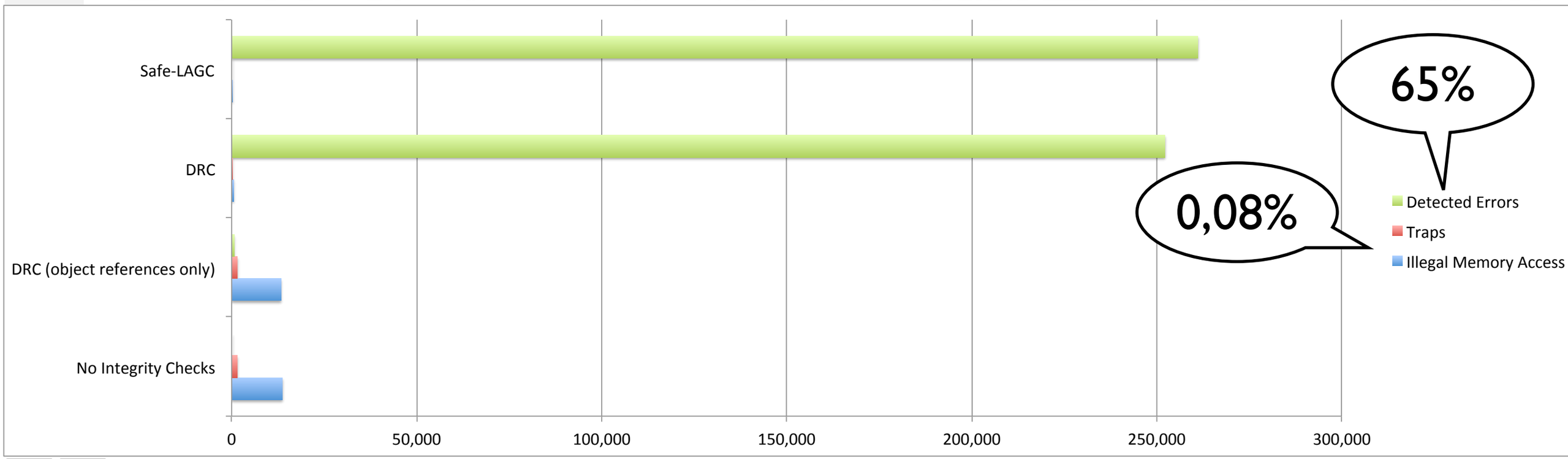
- FAIL*: Fault injection tool, application of fault space pruning
- Injected bit flips into each position of a memory word
- Application data is physically grouped by KESO's reachability analysis



Effectiveness of Integrity Checks

Establishment of software-based memory protection: Foundation to built replication for the protection of application data



Overhead of Protection

- Runtime:
  - Safe-LAGC
    - 55%(DRC)-95%(full protection) for one GC execution instance
    - GC's execution time is short in contrast to application's
  - Application
    - 44% increase
- Memory needed at runtime: no increase

Conclusion

How can static knowledge about the application, operating system and hardware-specifics be used to create an automated memory management in embedded systems?

- Cooperative approach
  - Type-safe language and compiler assistance
  - Assistance of the application developer during the integration
  - Incorporation of application, OS model and hardware specifics
  - Latency-aware and safe garbage collection

Can automated and safe memory management efficiently be applied in resource-constraint embedded systems?

- Evaluation results show that generated system can compete with unsafe and manual approaches

Questions?

- http://www4.cs.fau.de/Research/KESO/
- KESO: distributed under the terms of the GNU LGPL, version 3