M3: End-to-End Memory Management in Elastic System Software Stacks

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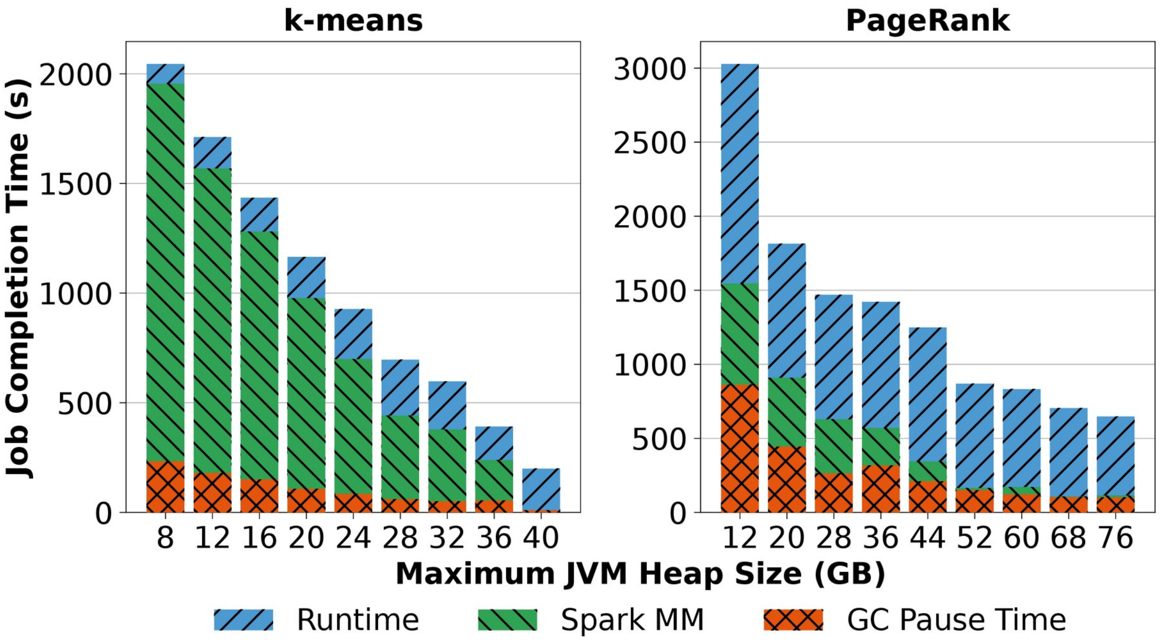
Traditional Memory Provisioning

- Traditional working set model [Denning, 1968]
  - Requires a set of pages in memory to avoid thrashing
- Forced to provision for peak memory usage
  - Memory wasted outside the peak usage

Elastic Applications

- Performance continuously improves with additional memory



Provisioning Elastic Applications

- Potential to improve throughput by utilizing more memory
- Dynamically adjust application memory usage to availability
- Adjust memory usage in the OS?
  - OS lacks domain knowledge of memory usage
- Adjust memory directly in the application?
  - Memory abstractions hinder application memory management

Abstraction Problems

- Static settings forced to control physical memory usage
  - i.e. JVM heap size

Layer	Abstracts	Issue
OS	Physical Memory	Require Static Settings

Abstraction Problems

- Physical memory optimistically retained
  - Not returned to the OS

Layer	Abstracts	Issue
OS	Physical Memory	Require Static Settings
JVM	Allocation + Reclamation	Retain Physical Memory

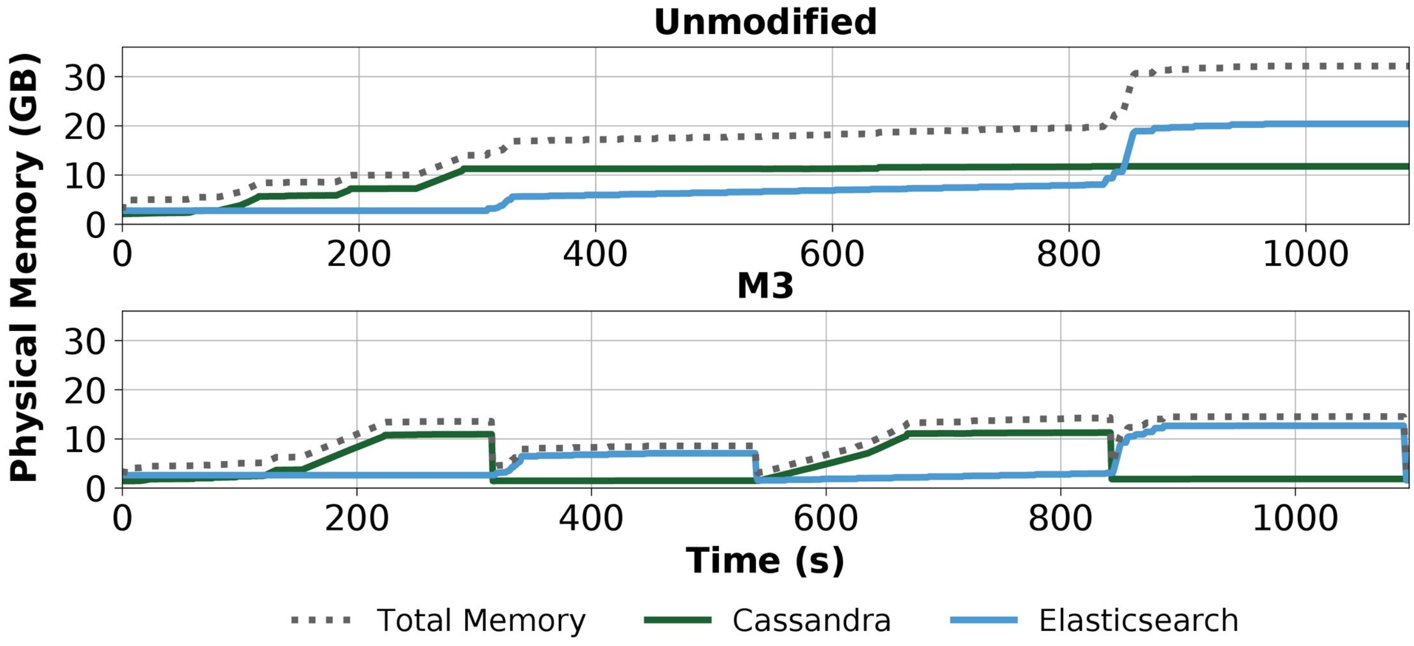
Abstraction Problems

- Evicted memory sits unusable as garbage

Layer	Abstracts	Issue
OS	Physical Memory	Require Static Settings
JVM	Allocation + Reclamation	Retain Physical Memory
Spark	Partition Input Data + Eviction	Uncoordinated Reclamation

Abstraction Problems: Example

- Cannot adapt to changes in memory demand
  - Must provision for peak usage



Summary

- Memory abstractions unnecessarily limit elastic applications
  - Static settings unable to adapt
  - Problem made worse by multiple layers of abstraction

Summary

- Memory abstractions unnecessarily limit elastic applications
  - Static settings unable to adapt
  - Problem made worse by multiple layers of abstraction
- M3 Goal: improve throughput and memory utilization
  - Bridge memory abstractions
  - React to memory demand and availability

Outline

- Memory Management Issues in Elastic System Stacks
- M3 Design
  - Signal handling
  - Adaptive allocation protocol
  - Monitor
- Evaluation
- Conclusion

M3 Design Overview

- Remove static memory settings
- Monitor: send signals when memory reaches a threshold
  - Low threshold: early warning, return what you can
  - High threshold: nearing memory exhaustion
- Signal handler: reclaim and return memory
- Adaptive allocation protocol: slow application memory growth

Practical Approach

- End-to-end argument [Saltzer, 1984]
  - Applications implement all policy
- Utilize existing memory reclamation mechanisms
  - GC, cache eviction, etc

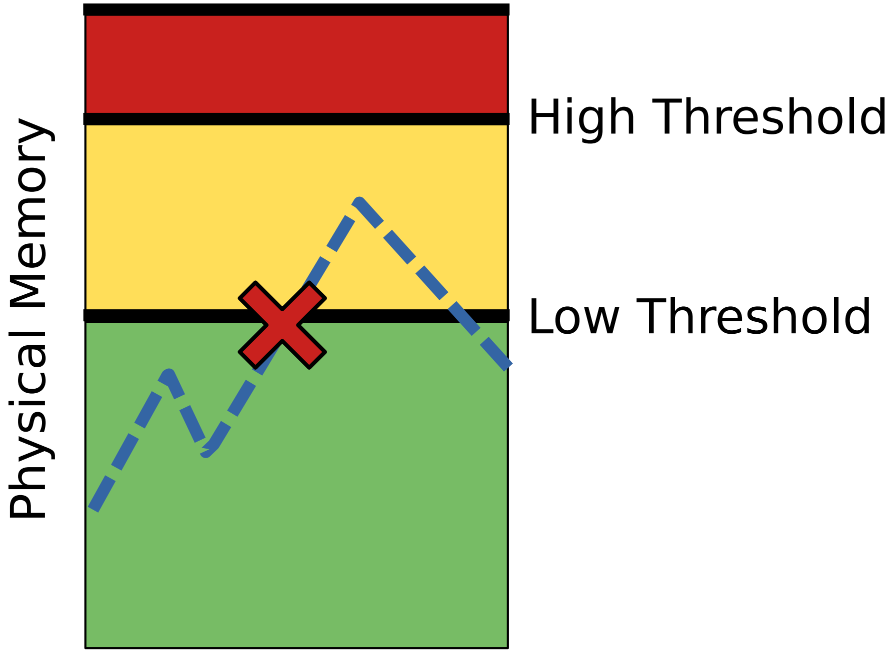
	JVM	Go Runtime	Spark	Memcached
LOC Modified	220	50	250	170

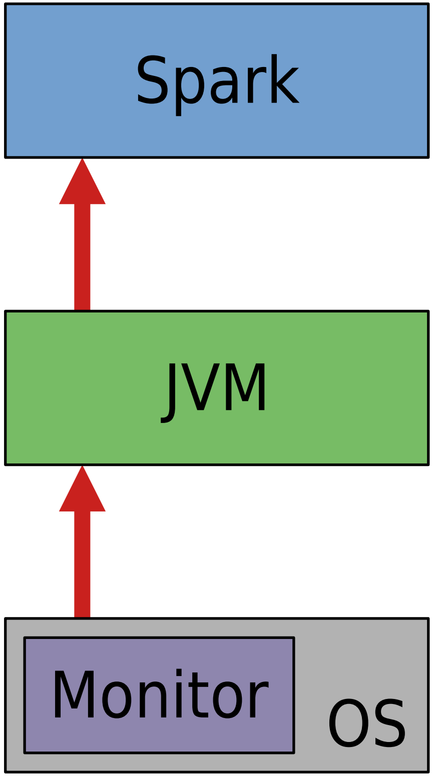
Signal Handling

- Applications register signal handler

Signal Handling

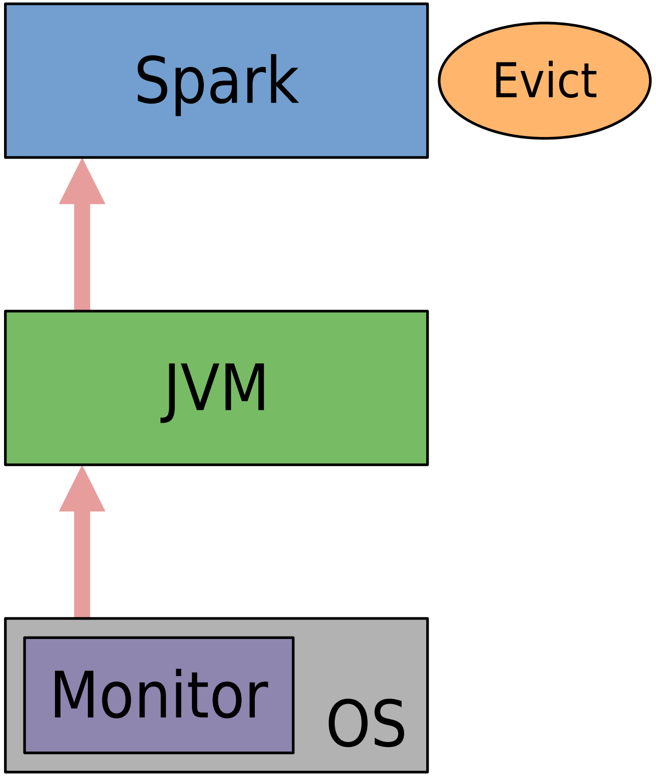
- Monitor sends out signal





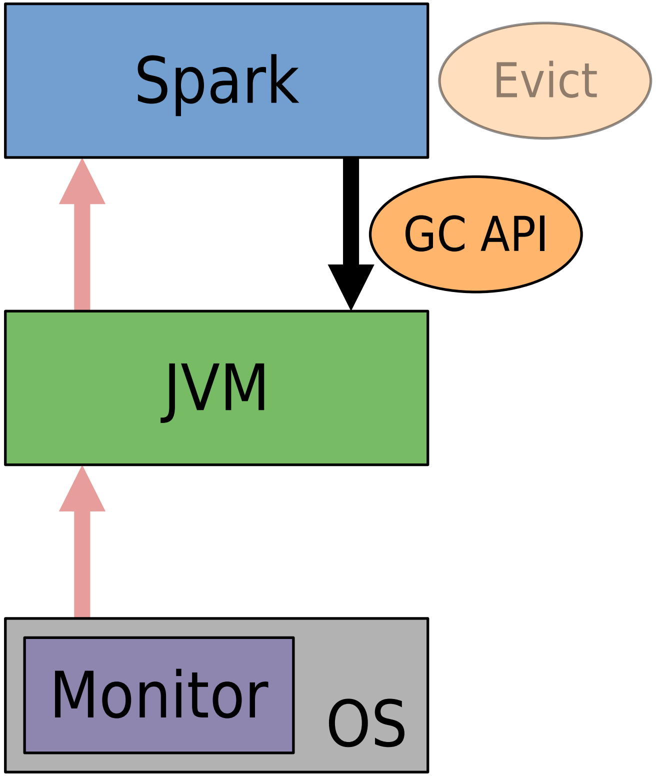
Signal Handling

- Application reclaims memory
  - Spark evicts data blocks



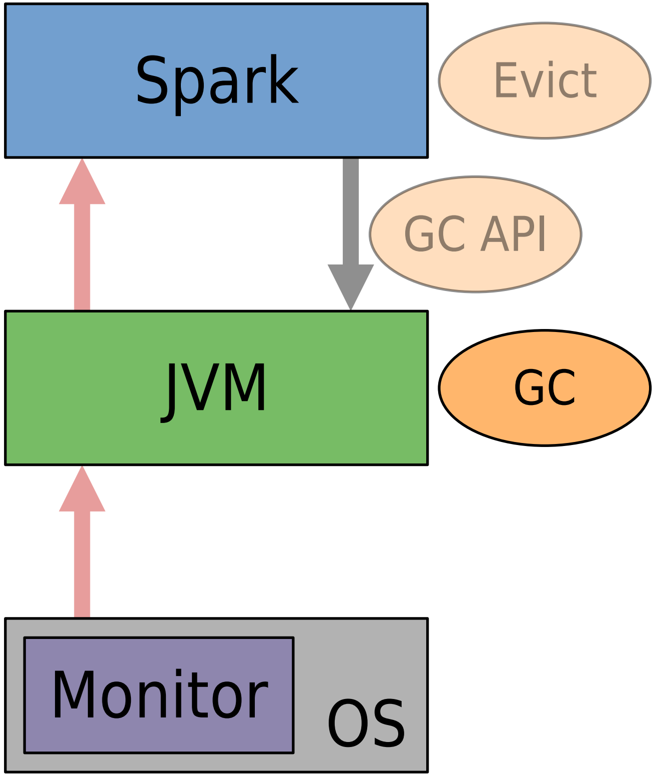
Signal Handling

- Notify lower layer when memory reclamation completes
  - Spark calls JVM GC API



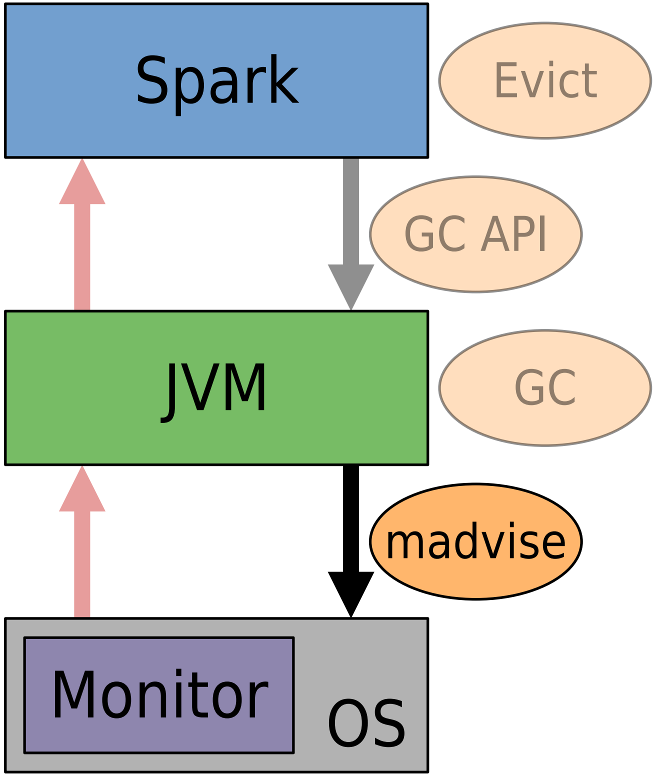
Signal Handling

- Lower layer reclaims memory
  - JVM runs a GC cycle



Signal Handling

- Return memory to OS
  - JVM uses **`madvise`** syscall



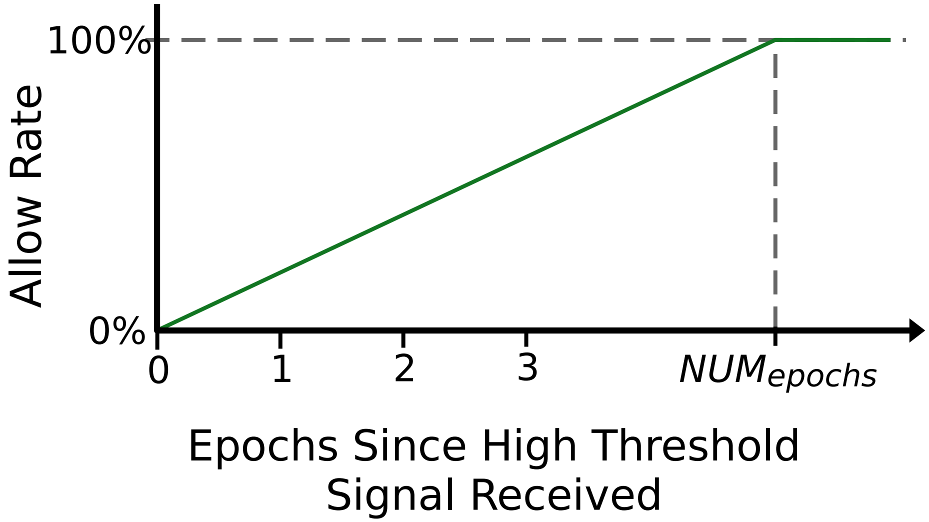
Adaptive Allocation Protocol

- Goal: slow memory growth to prevent exhaustion
- Dynamically adjust allowed allocation rate
  - Allowed allocations grow memory
- Disallowed allocations reclaim memory before continuing
  - No correctness issues or complex modifications

```
int alloc(size_t size) {
  if (!allow()) {
    evict(size);
  }
  // continue allocation path
}
```

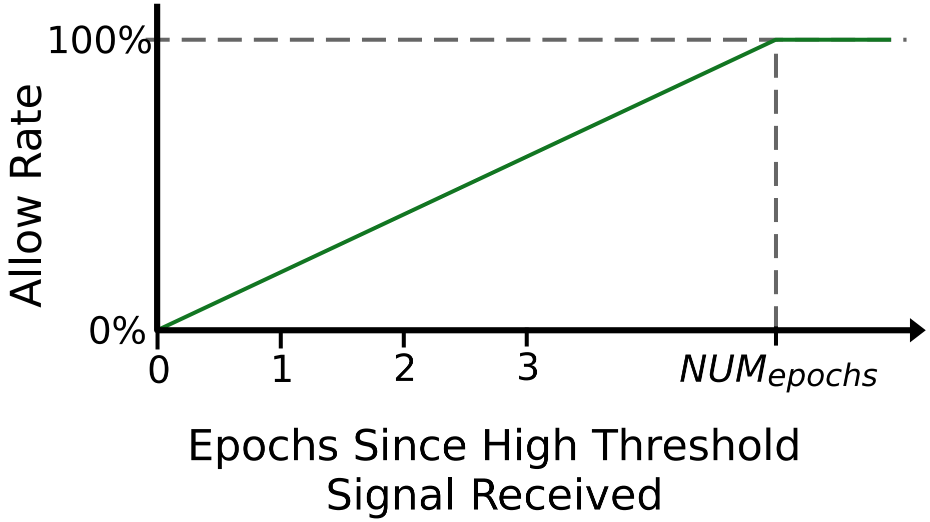
Adaptive Allocation Protocol

- Upon receiving a high signal allow rate is set to 0%
- Epoch: time taken to handle a signal
- NUM_{epochs}: user parameter to control recovery



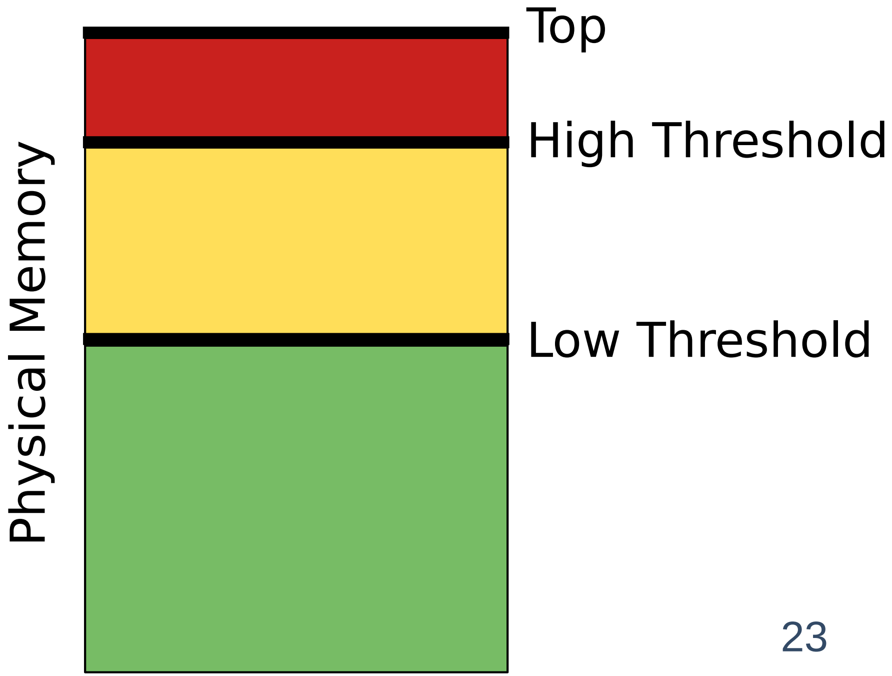
Adaptive Allocation Protocol

- Reward efficient reclamation
  - Fast reclamation → small epoch → more allocations allowed
- Memory demand is respected
  - More allocations → more allowed allocations → memory growth



Monitor

- Goal: maximize memory utilization while avoiding exhaustion
- Dynamically adjust high and low thresholds
- Lower when usage stays high
  - Slow reclamation requires earlier signals
- Raise when usage stays low
  - Later signals allow for higher memory utilization



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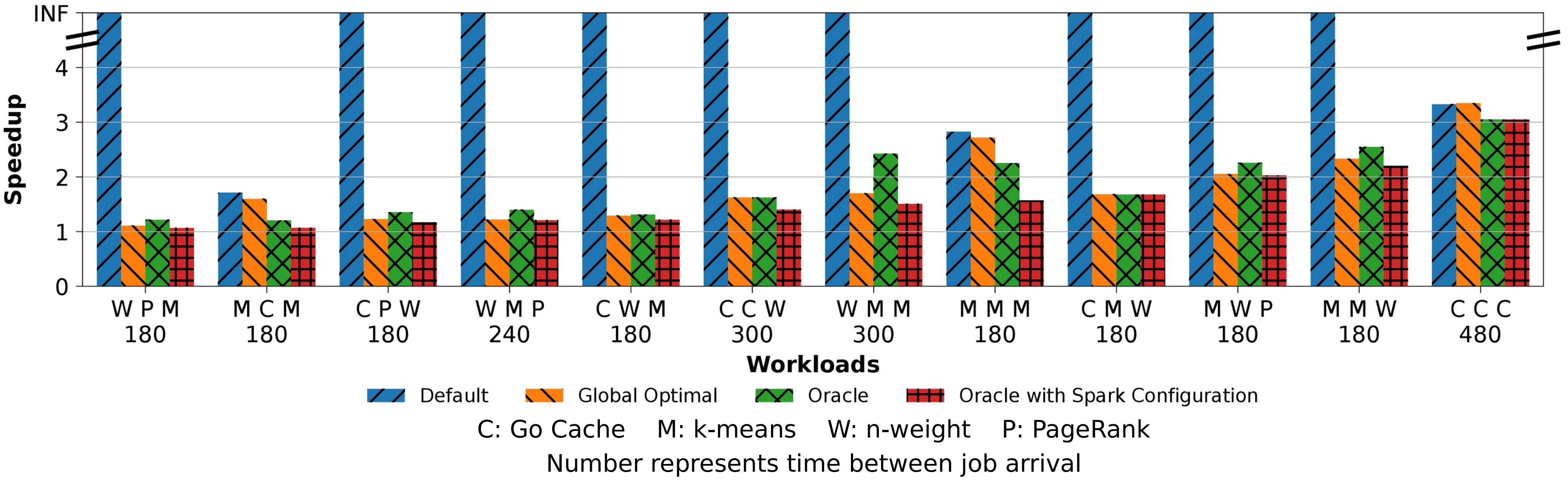
Evaluation Methodology

- Cluster of 9 servers, each with 64GB memory and 16 cores
- Spark + JVM : PageRank, n-weight, k-means
  - HiBench [Huang et al. 10]
- Go Cache: runs a mixed read and write benchmark
- 16 Workloads
  - Combination of jobs with different scheduling
- Measure average speedup of each application’s completion time

Configurations

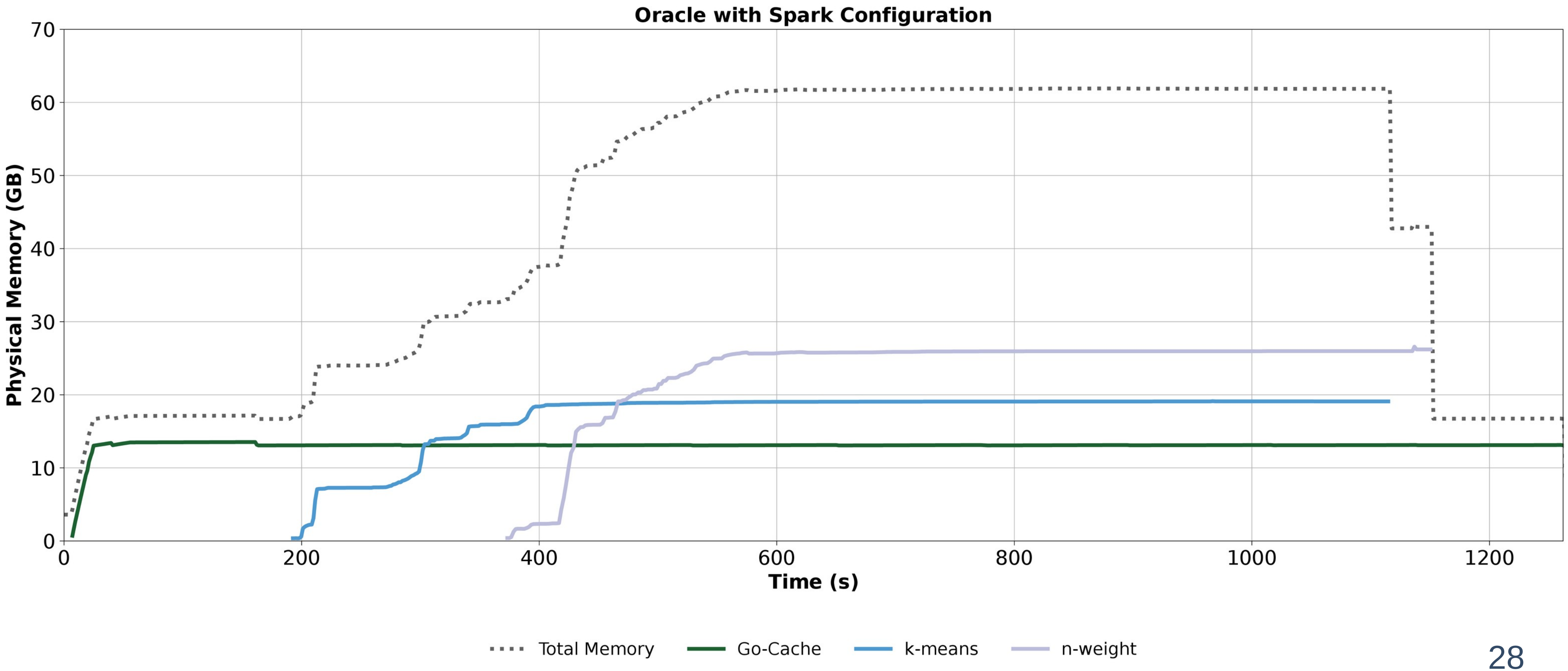
- Default
  - All parameters set to default values
- Global Optimal
  - Minimize average throughput of all workloads
  - Knowledge and tuning of all possible job combinations
- Oracle
  - Optimize jobs individually for each workload
  - Individual tuning and reconfiguration for each job scheduling
- Oracle with Spark Parameters
  - Further tune unadvised parameters

Results

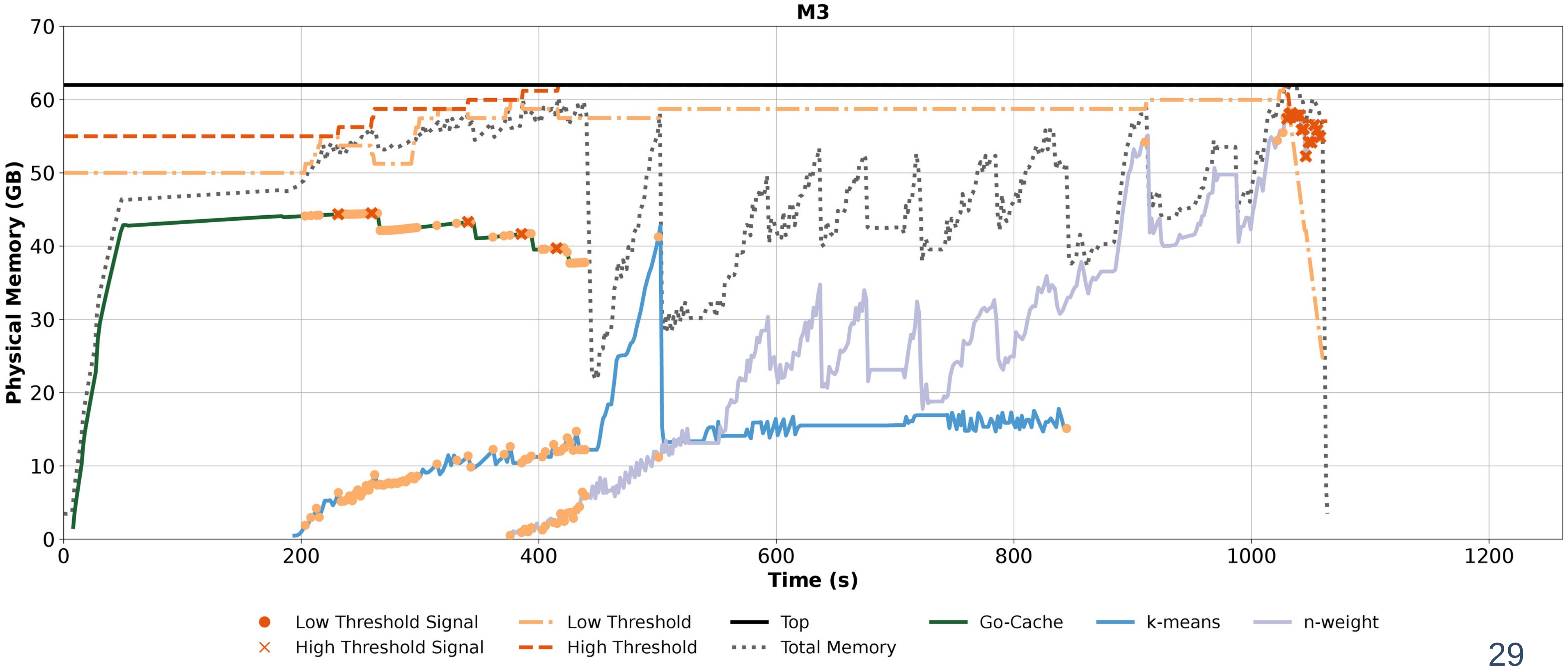


- Oracle with Spark Conf: 1.6x average, 3.1x best case
- Global Optimal: 1.9x average, 3.4x best case

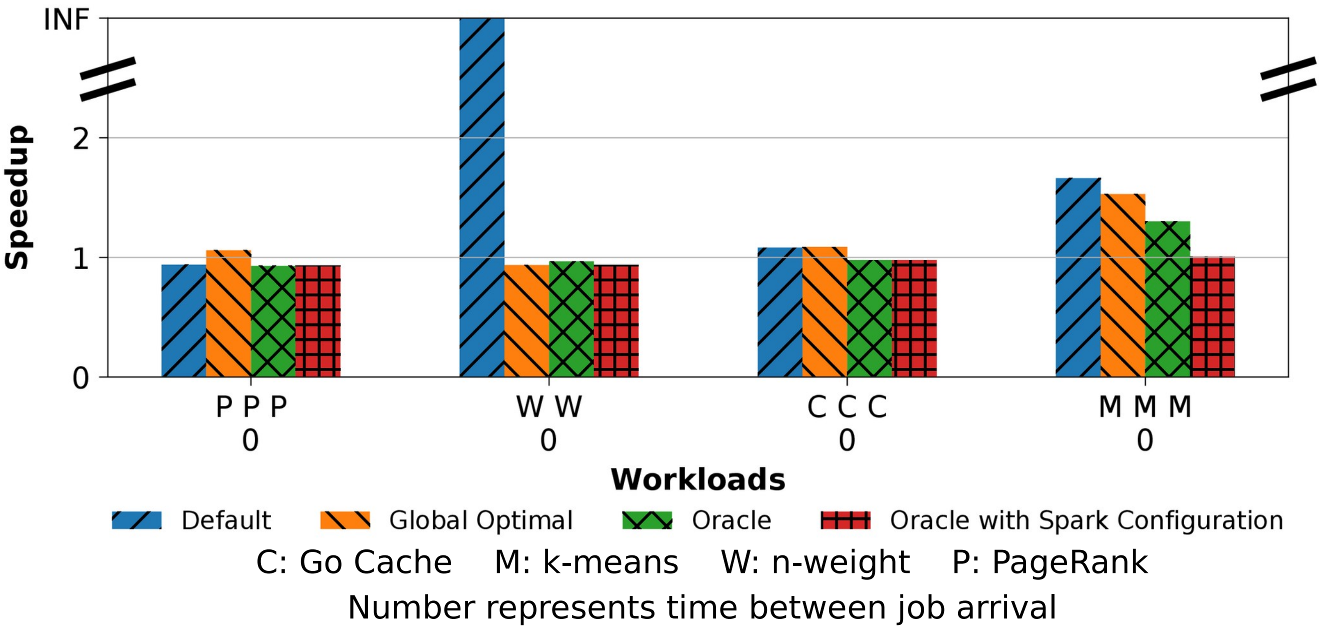
Unmodified Execution



M3 Execution



Worst Case



- Oracle with Spark Configuration
  - 3.8% slower on average, 7.0% worst case

Limitations

- Cannot guarantee optimal memory distribution
  - Distribution is decentralized
- Requires cooperative applications
  - Faithful implementation of policies
  - Not withholding memory after recieving a signal

Related Work

- Memory Distribution among Virtual Machines
  - Ballooning [Waldspurger 02], App. Ballooning [Salomie et al. 13]
  - Resource deflation [Sharma et al. 19]
  - MemOpLight: among containers [Laniel et al. 20]
- MM coordination
  - JVM resizing: [Alonso & Appel 90], CRAMM [Yang et al. 06]
  - GC coordination: Taurus [Maas et al. 16]
- Uniqueness of M3:
  - Cross all memory abstractions in elastic applications
  - End-to-end design

Concluding Remarks

- Data center applications suffer due to abstractions
  - Multiple uncoordinated layers
  - Fall back to static settings
- M3 bridges memory abstractions
  - Coordinates memory management
  - Dynamically adjusts to changes in memory demand
- Open sourced at: https://github.com/dsrg-uoft