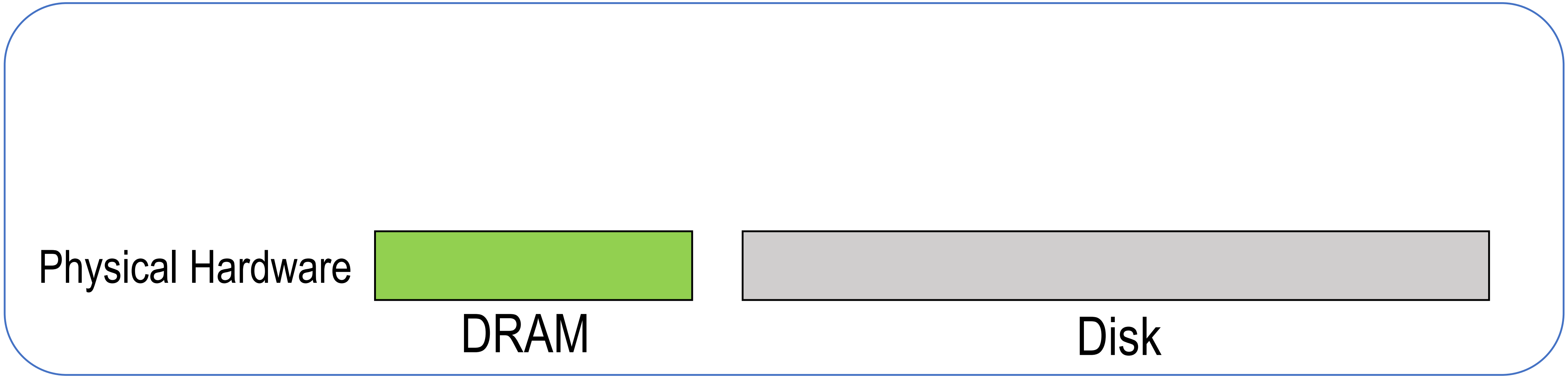
An Evolutionary Study of Linux Memory Management for Fun and Profit

Jian Huang

Moinuddin K. Qureshi Karsten Schwan

Virtual Memory: A Long History



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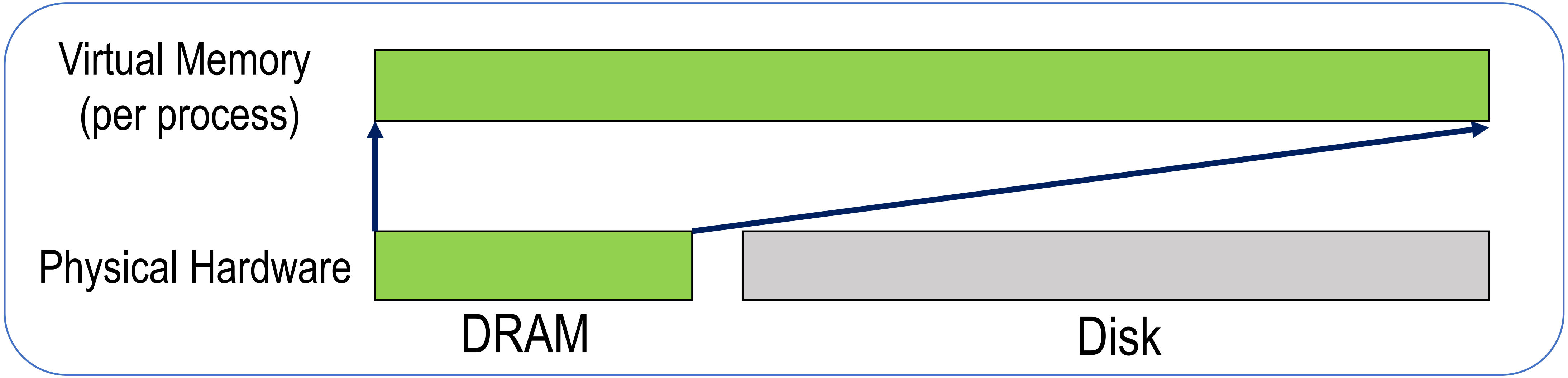

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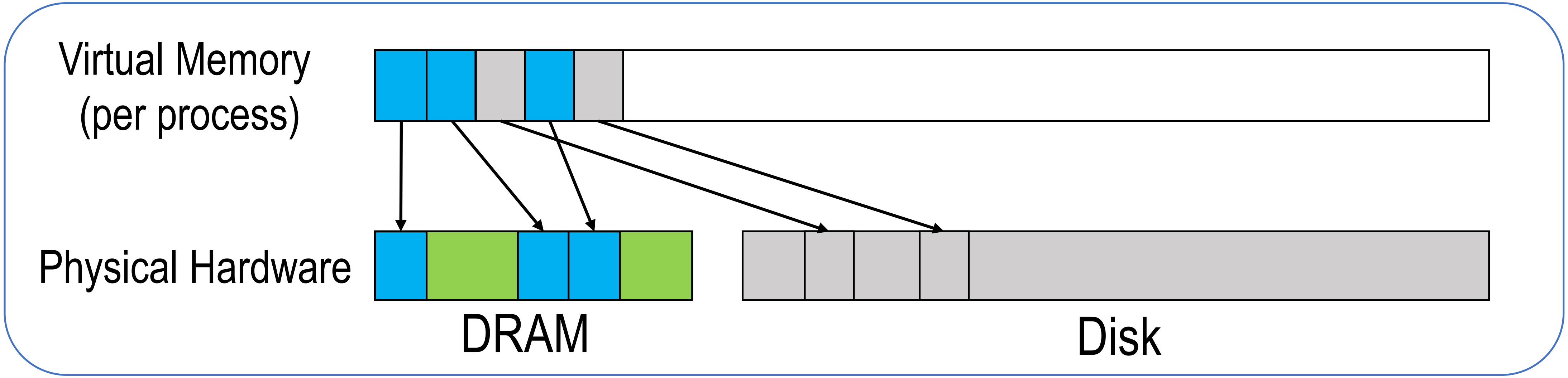

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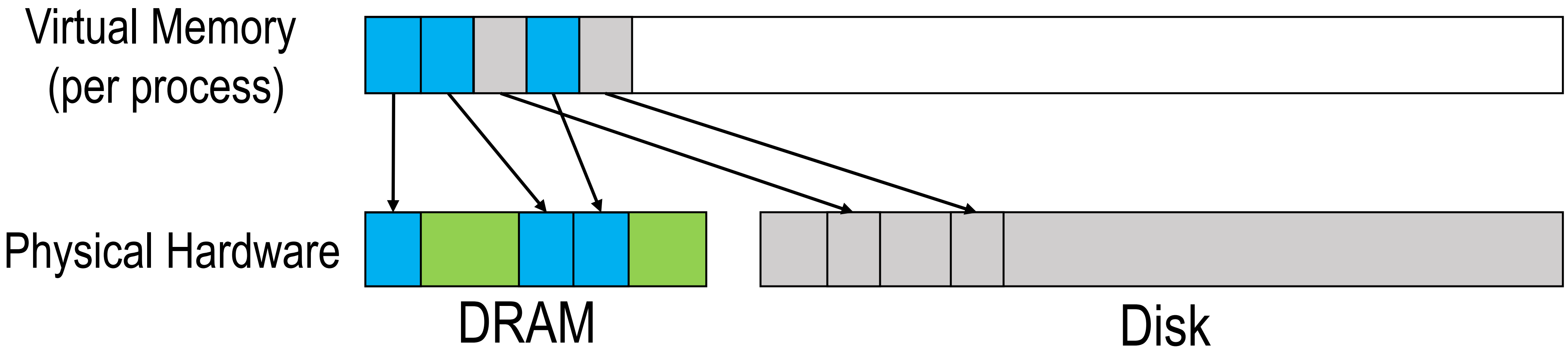

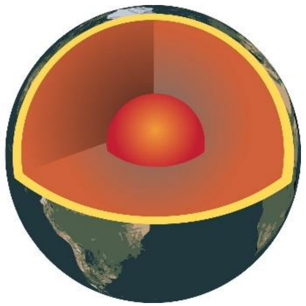

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60 YEARS

OS Core Component

Development

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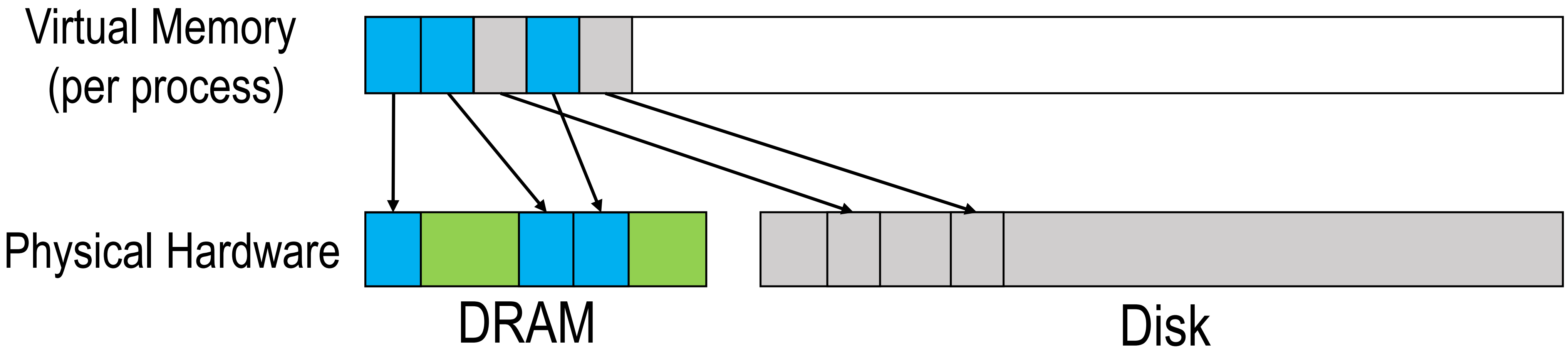

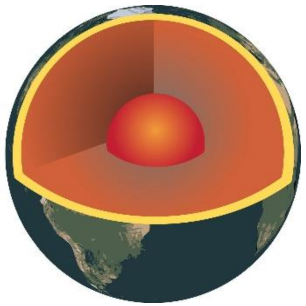

OS Core Component

+

Development

Pervasively Used

Why Memory Manager Study Matters?

Features & Functions

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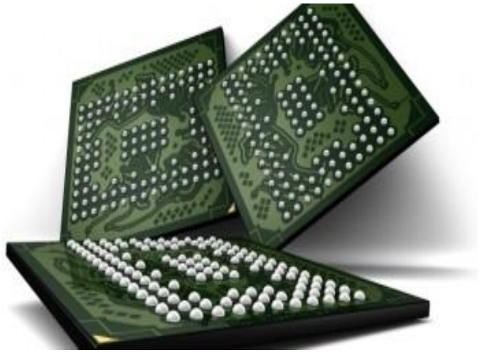
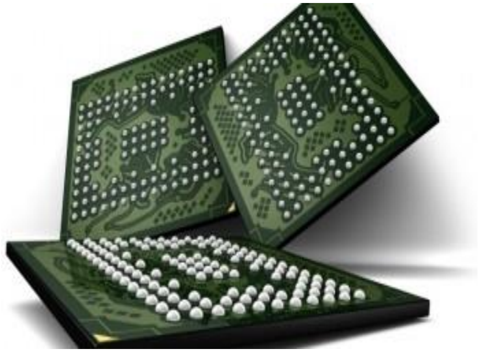


Hardware Support

Why Memory Manager Study Matters?

Features & Functions



Hardware Support

System Reliability

Why Memory Manager Study Matters?

Features & Functions

Hardware Support

System Reliability

Study on Memory Manager

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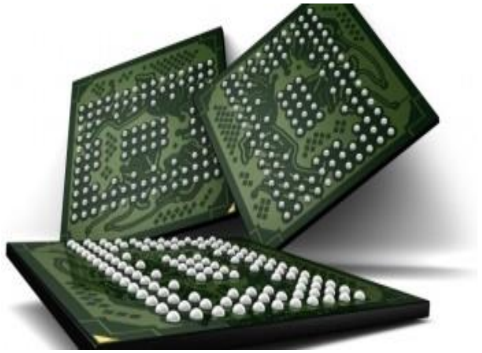


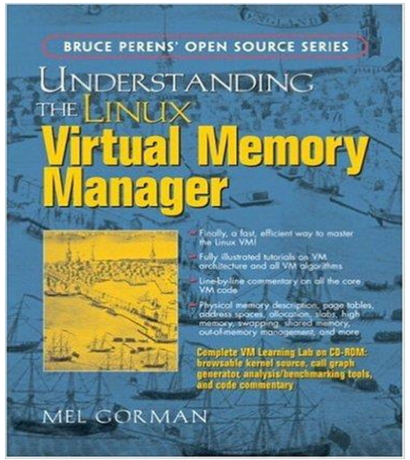
Hardware Support

System Reliability

Study on Memory Manager

Building Better Memory Manager

On the Study of Memory Management



Understanding the Linux Virtual Memory Manager

[Mel Gorman, July 9, 2007]

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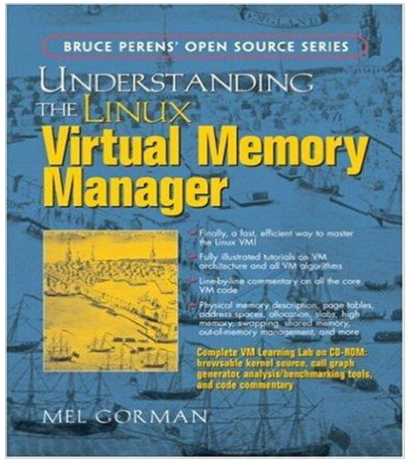

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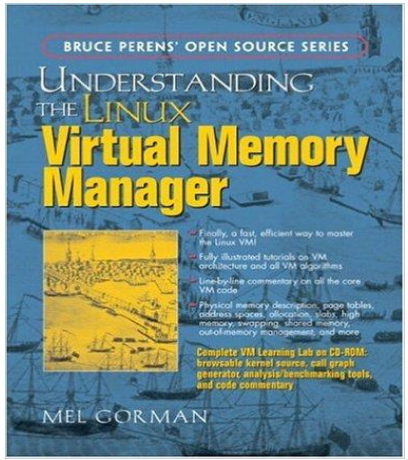

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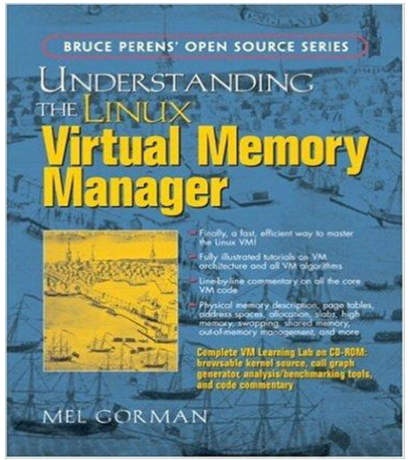

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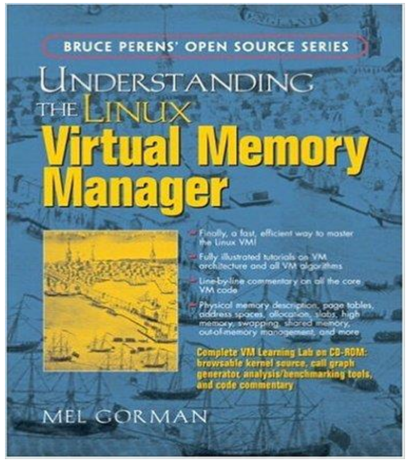

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Pattern

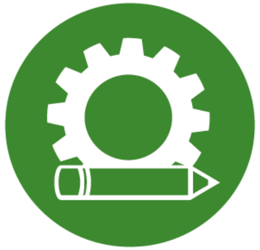
+

Memory Bug

+

Optimization

+



Semantic

Preview of Our Findings

- Code changes are highly concentrated around the key functions
- 80% of patches → 25% of its source code
- ......

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- Data structures -- Policy trade-off -- Fast path
- 4 data structures, 5 design trade-offs, 8 types of fast paths
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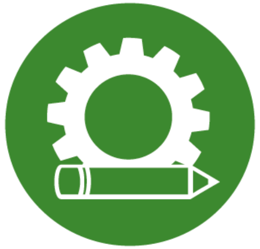


- 35 key functionalities in 13 hot files
- The well-developed memory allocators still have many checking & lock bugs
- ......

Methodology Used in Our Study

Memory Allocation | Resource Controller | Garbage Collection | Page Cache & Write-back

Virtual Memory Management | Swapping | Exception Handling | Misc (e.g., data structure)

8 components

Methodology Used in Our Study

Memory Allocation

Resource Controller

Garbage Collection

Page Cache & Write-back

Virtual Memory Management

Swapping

Exception Handling

Misc (e.g., data structure)

8 components

2.6.32 (2009)

2.6.33 (2010)

2.6.38 (2011)

3.2 (2012)

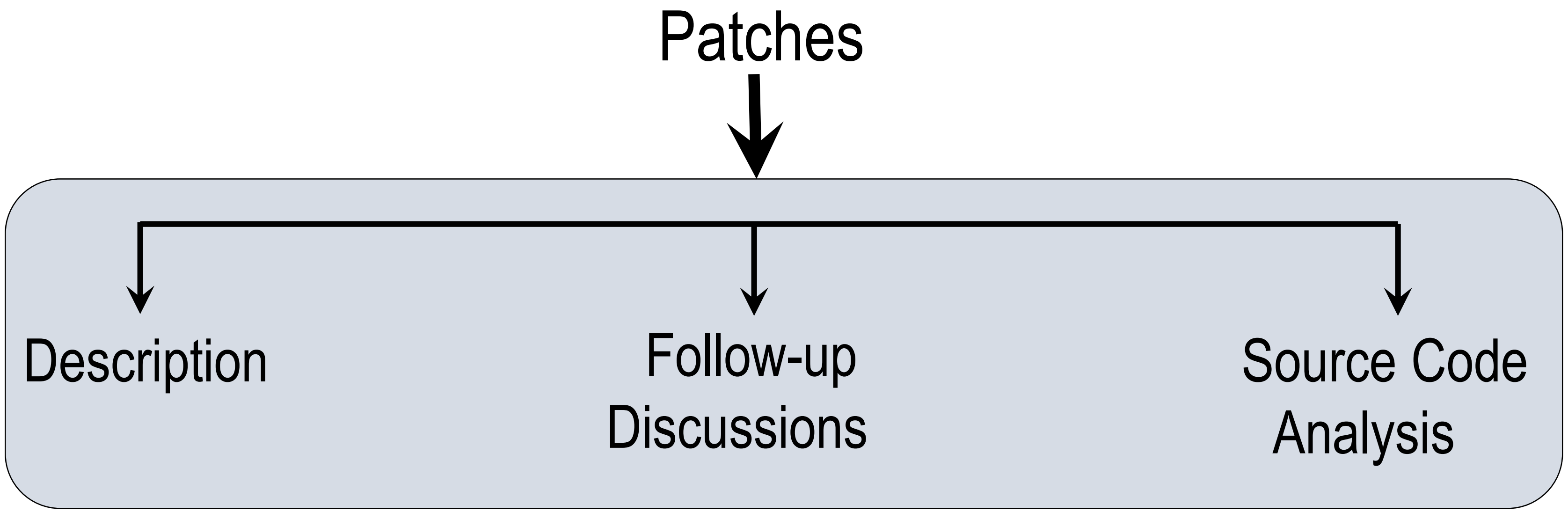
3.10 (2013)

3.14 (2014)

4.0-rc4 (2015)

4587 patches in 5 years

Methodology Used in Our Study



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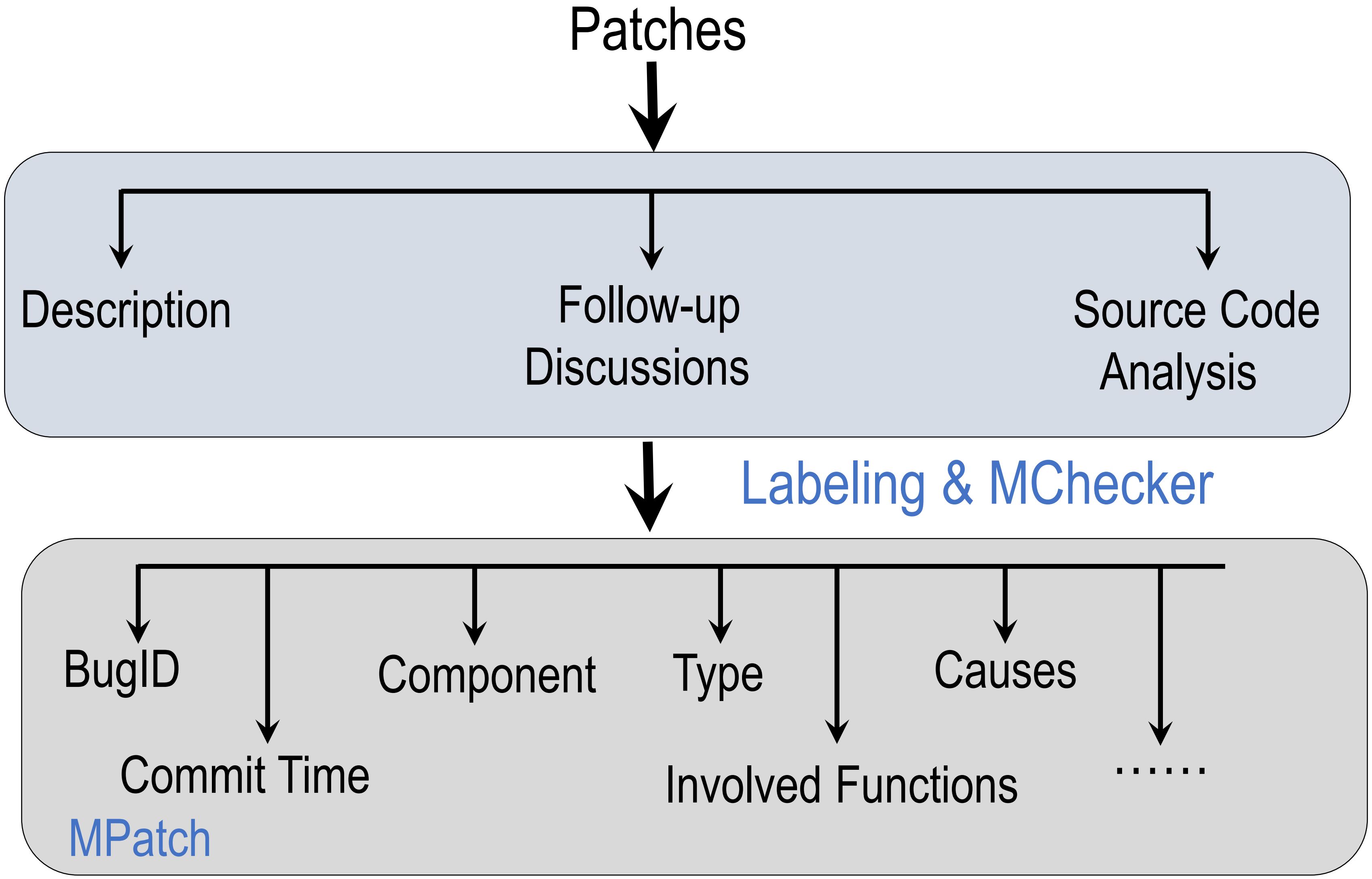

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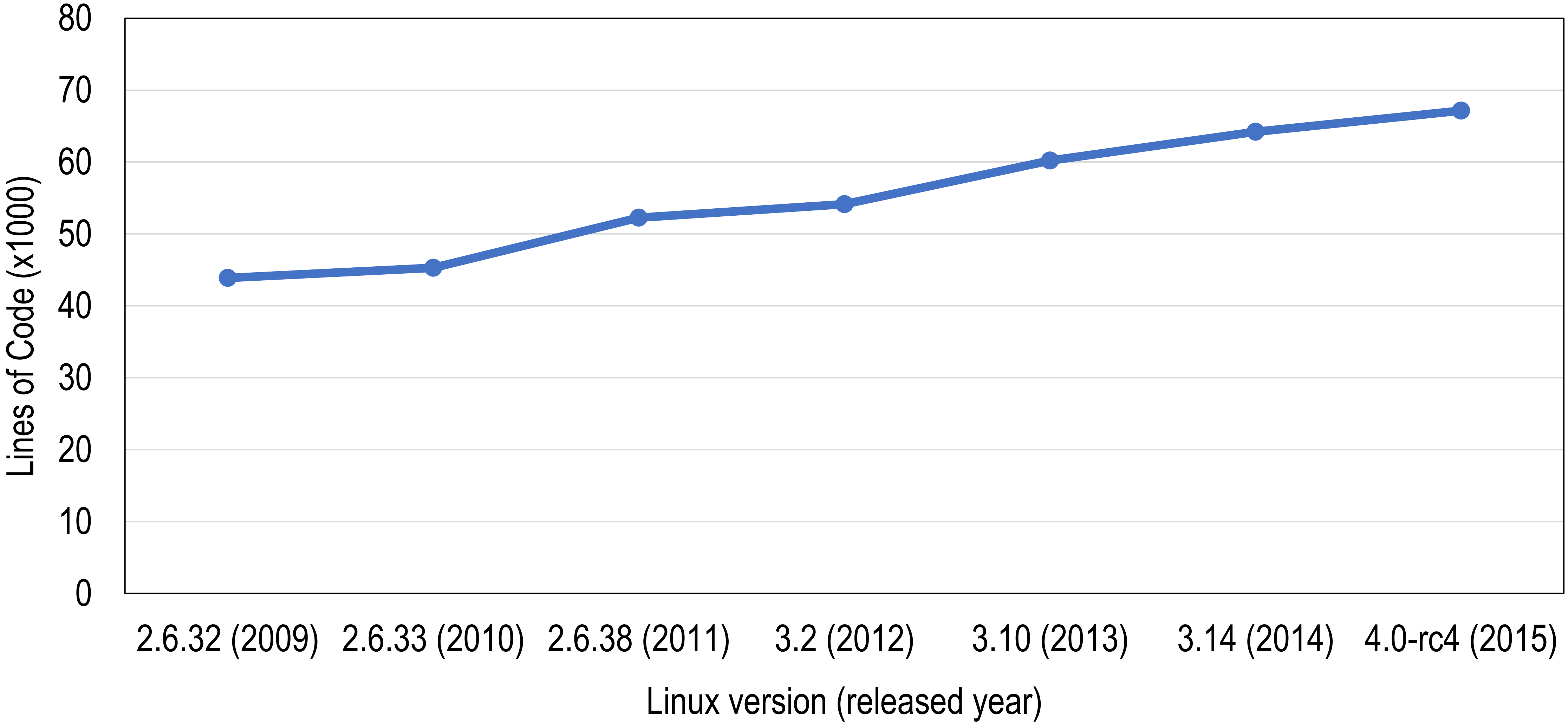

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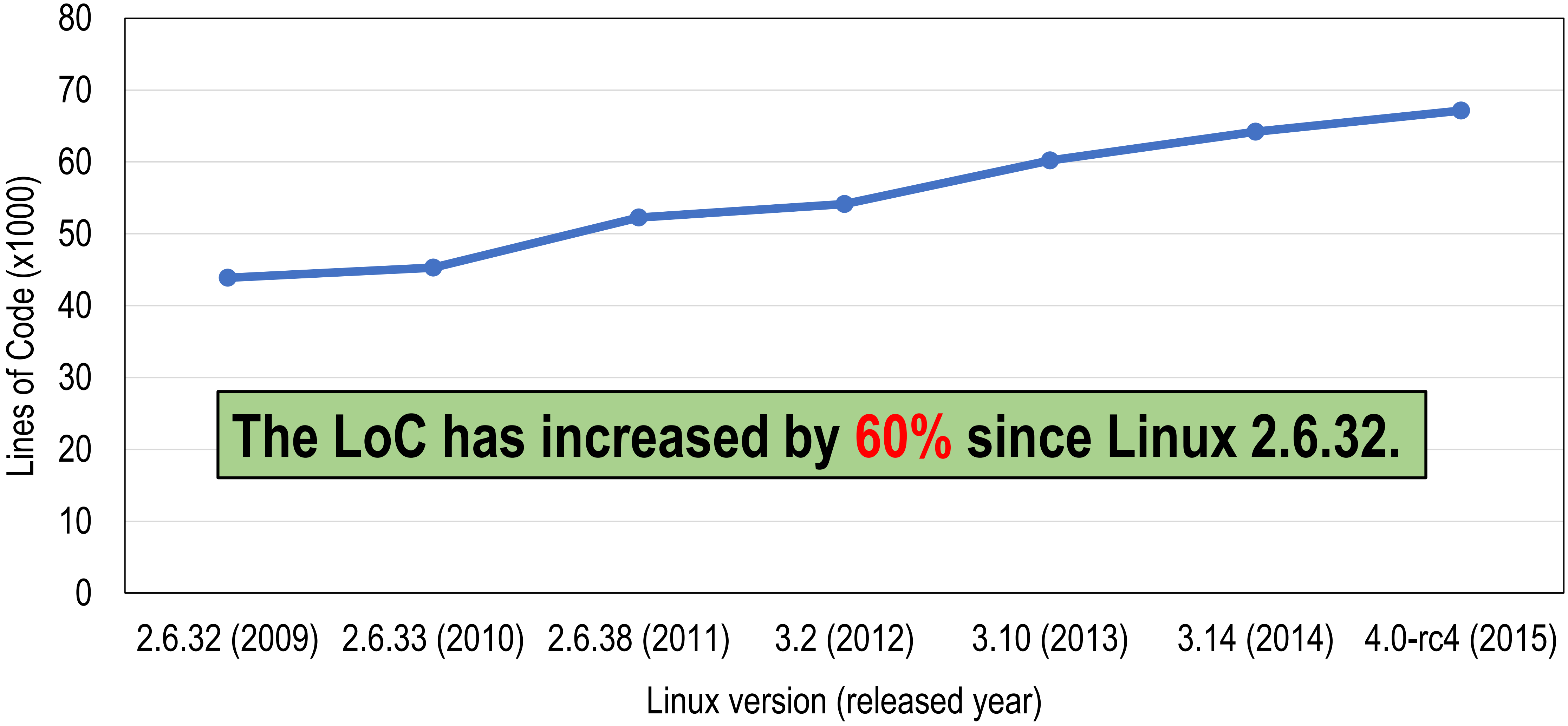

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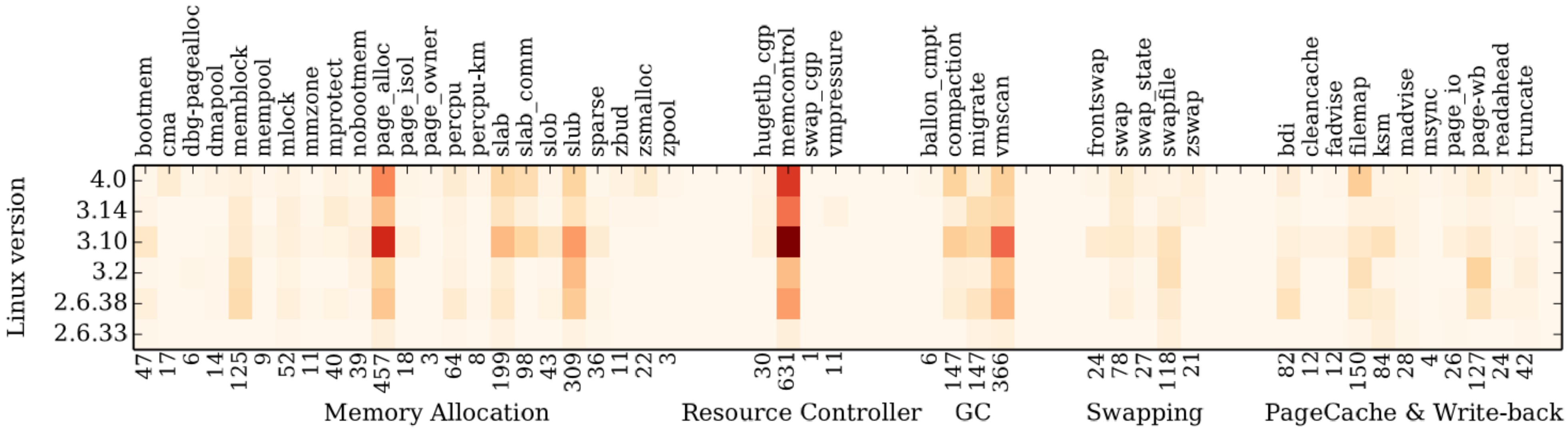

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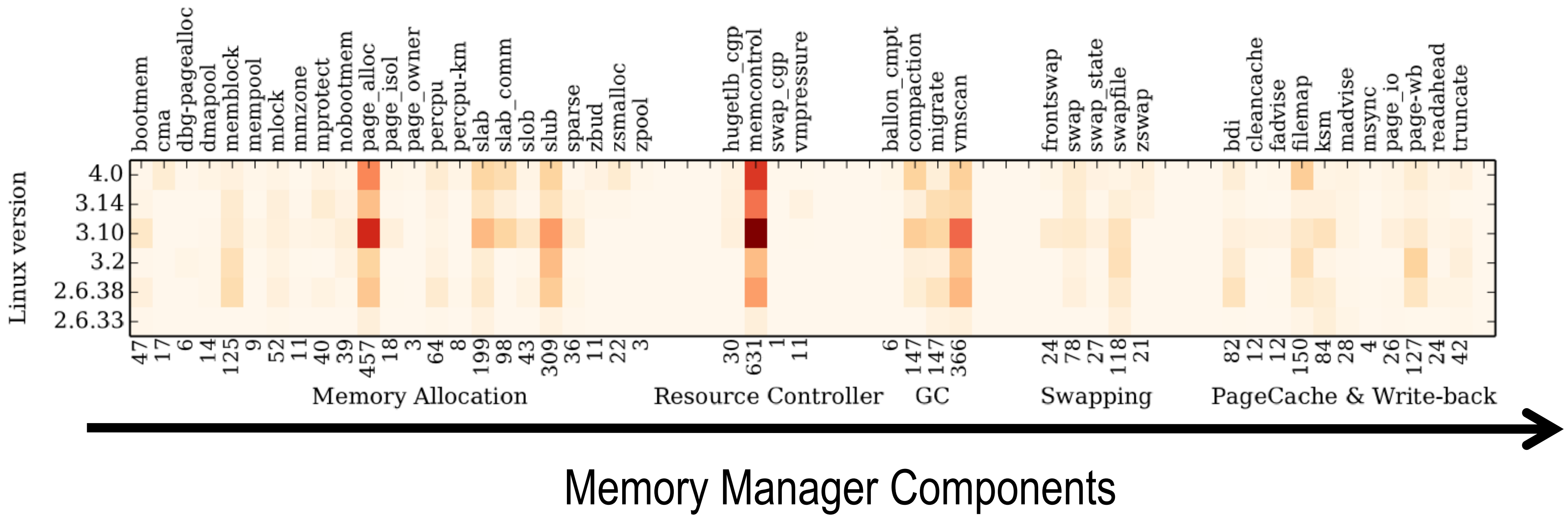

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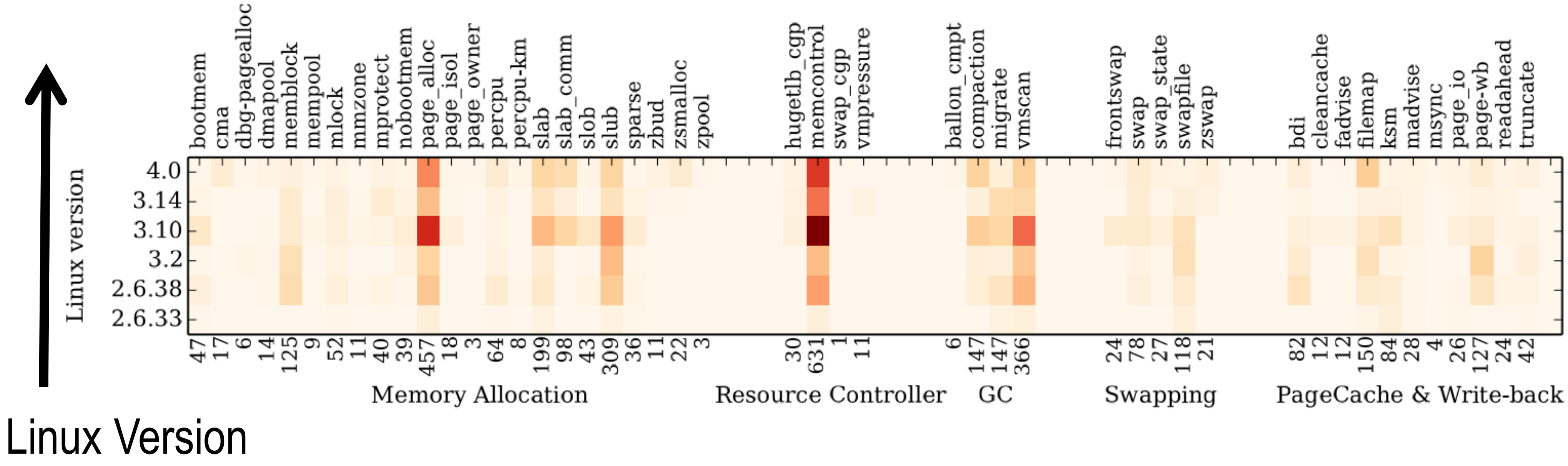

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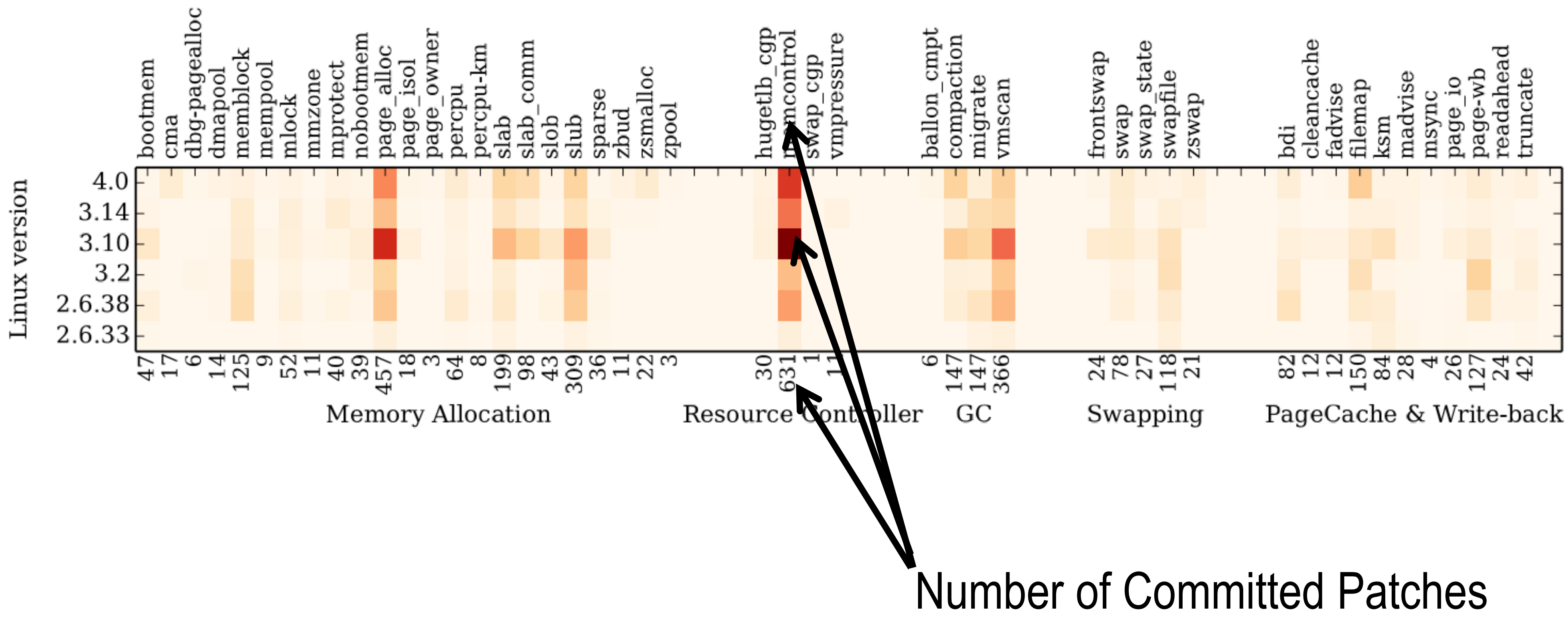

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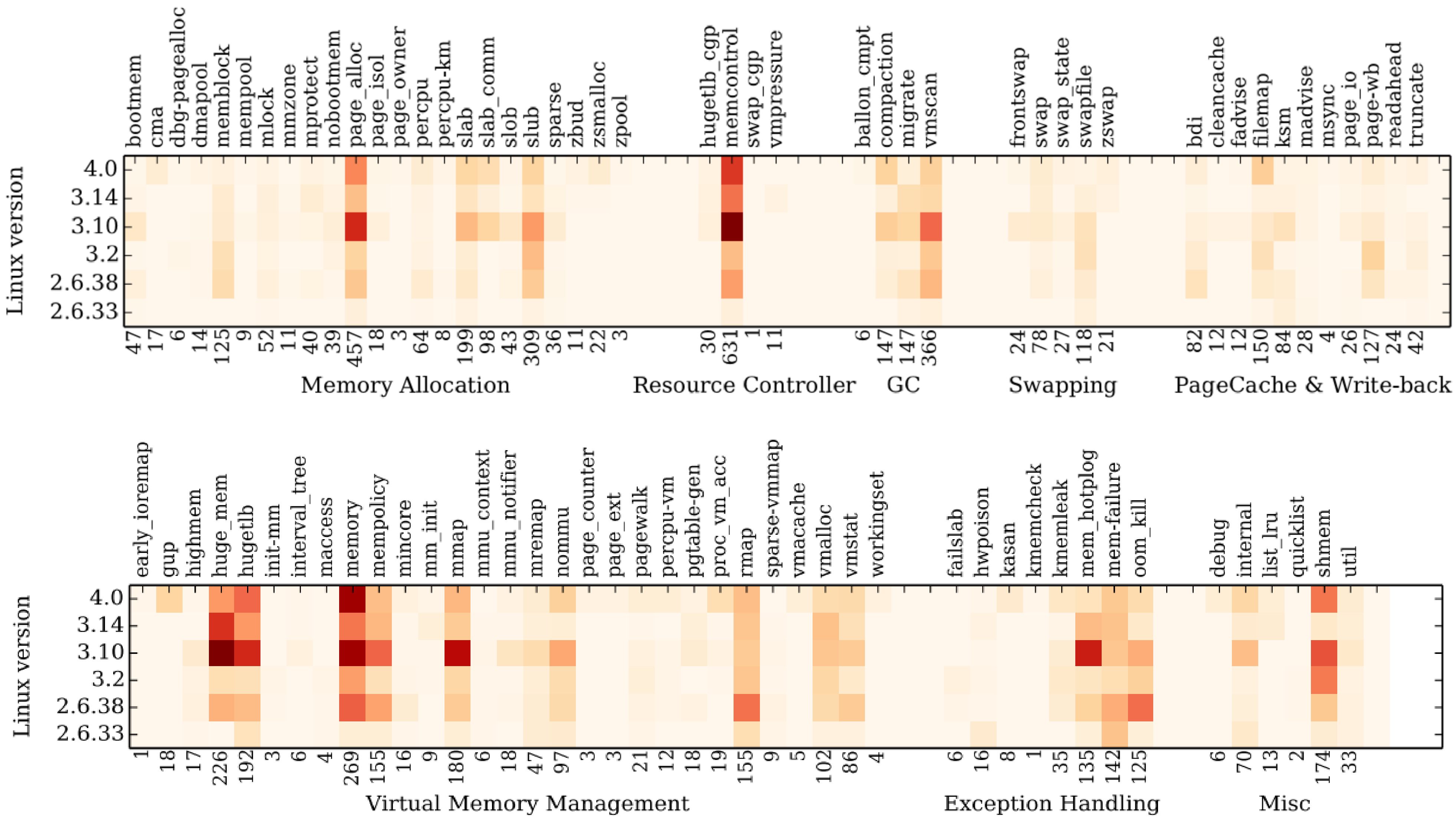

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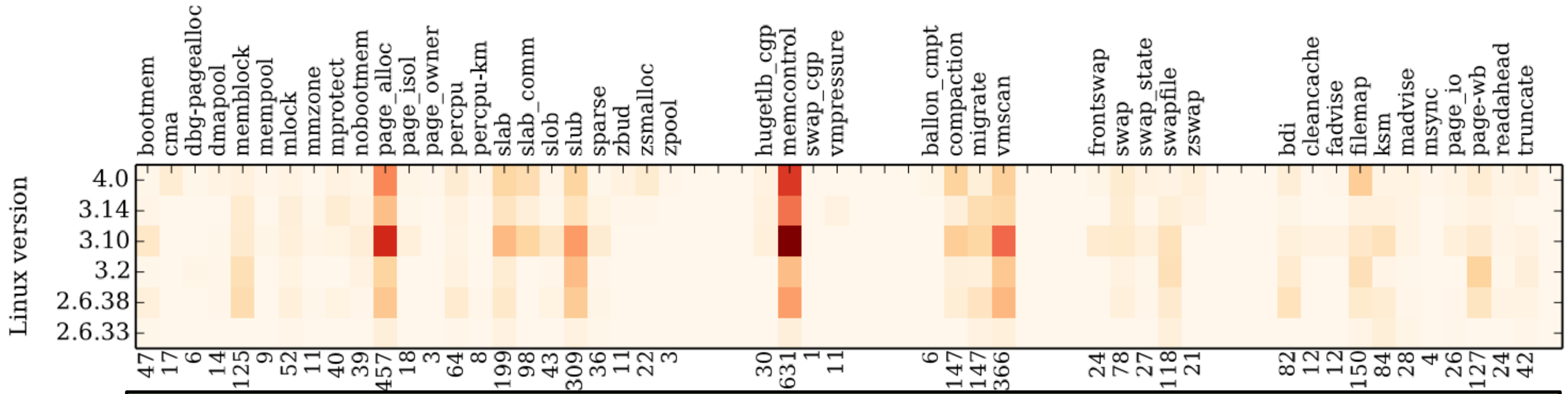
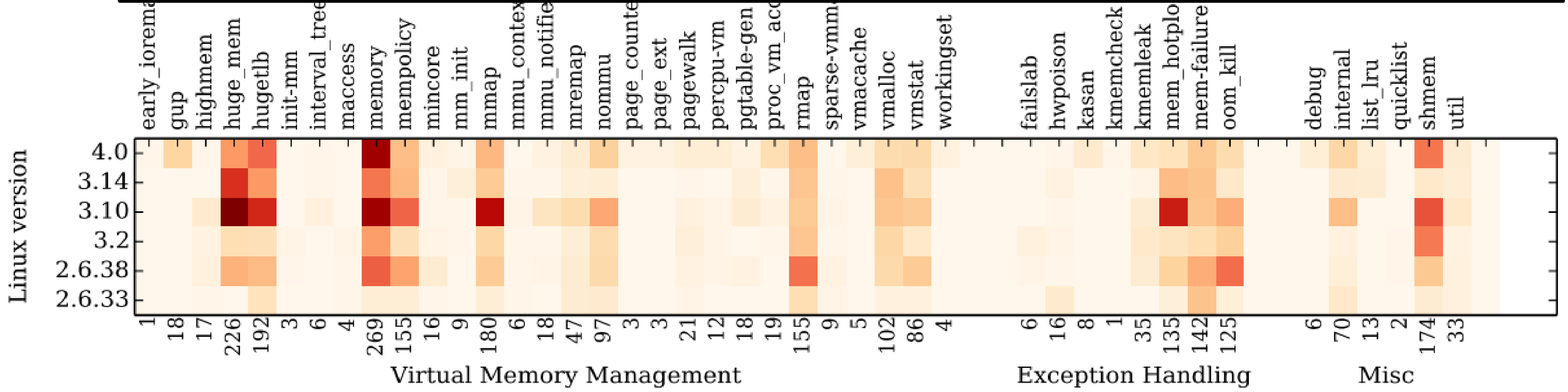


80% of the code changes → 25% of the source code



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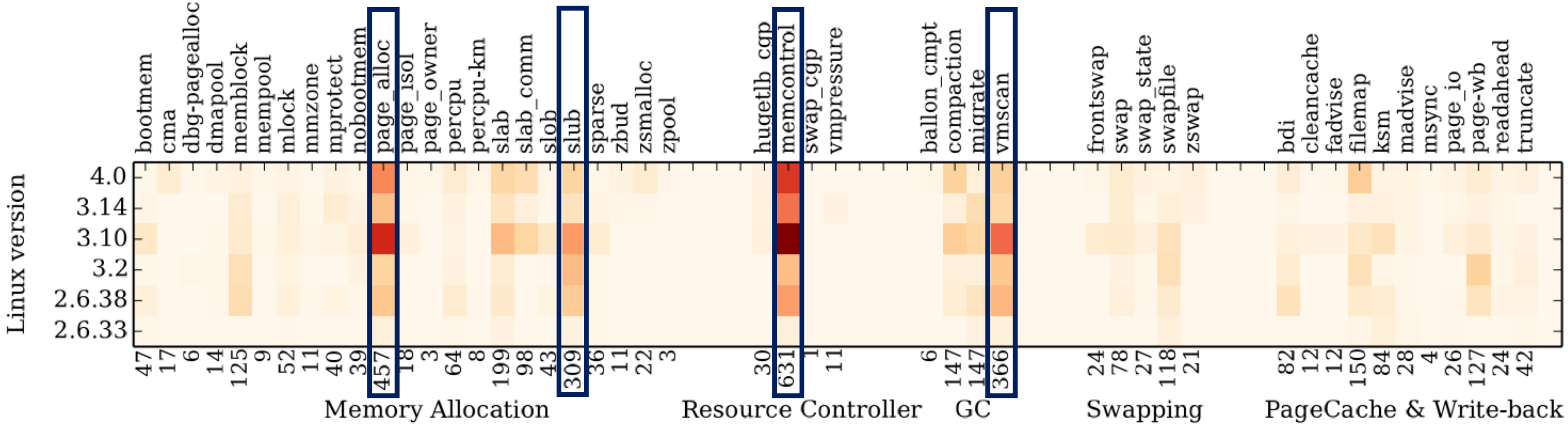

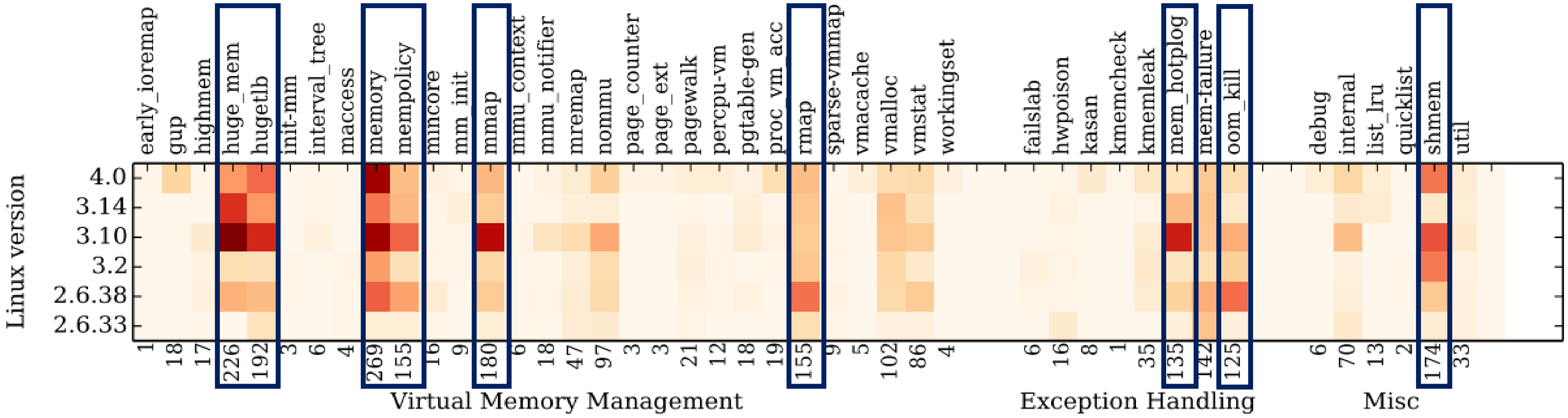

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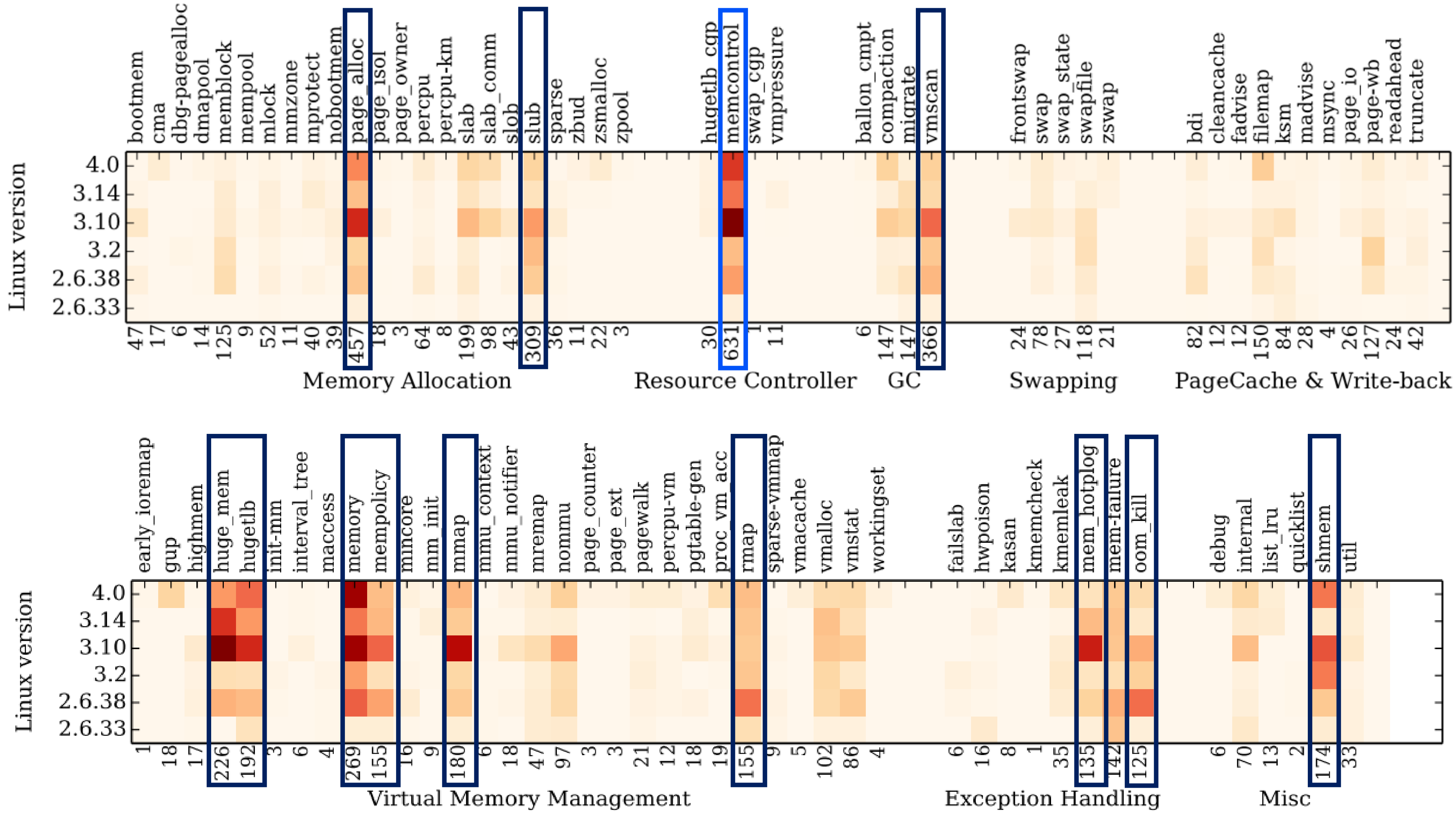

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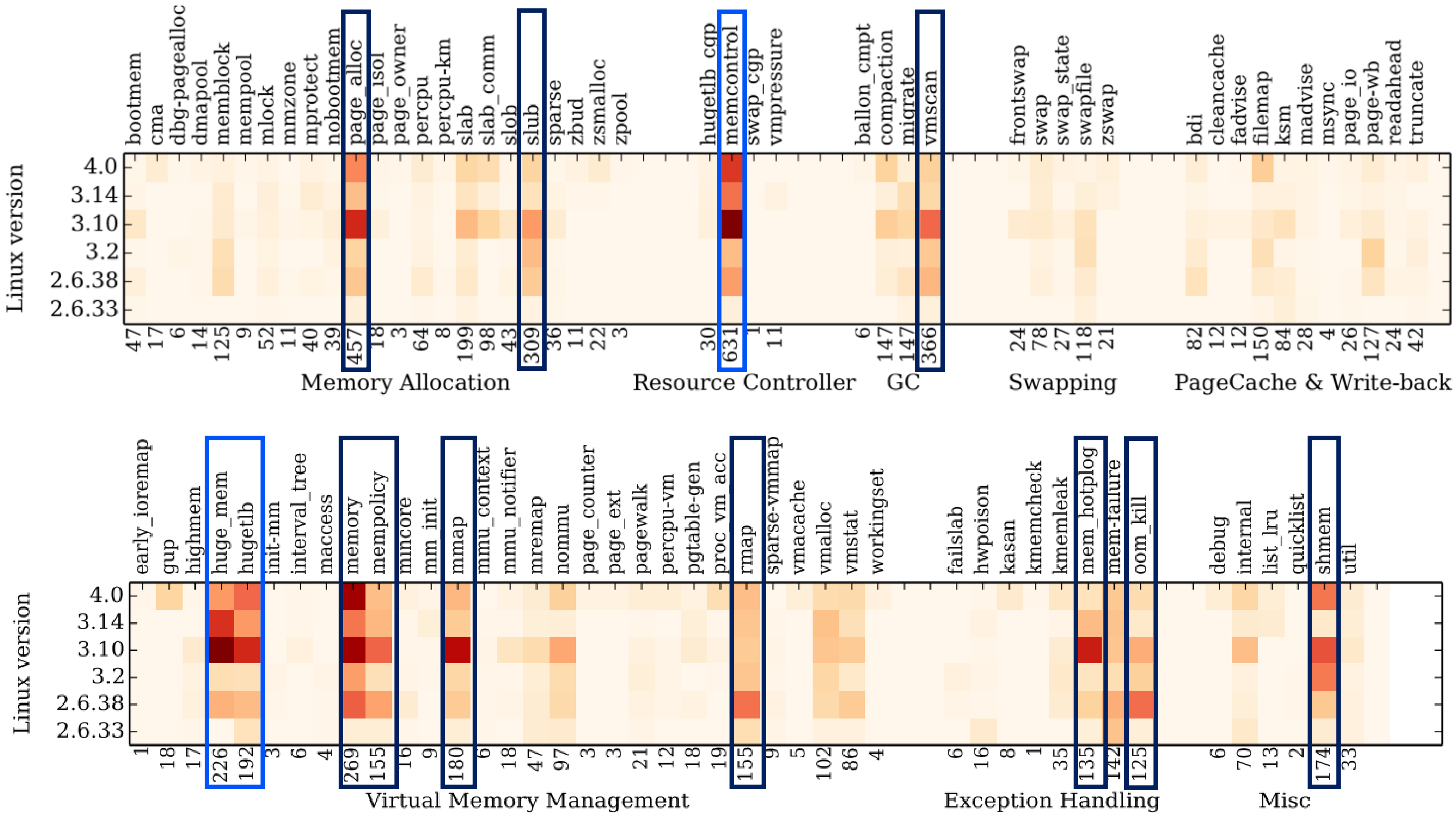

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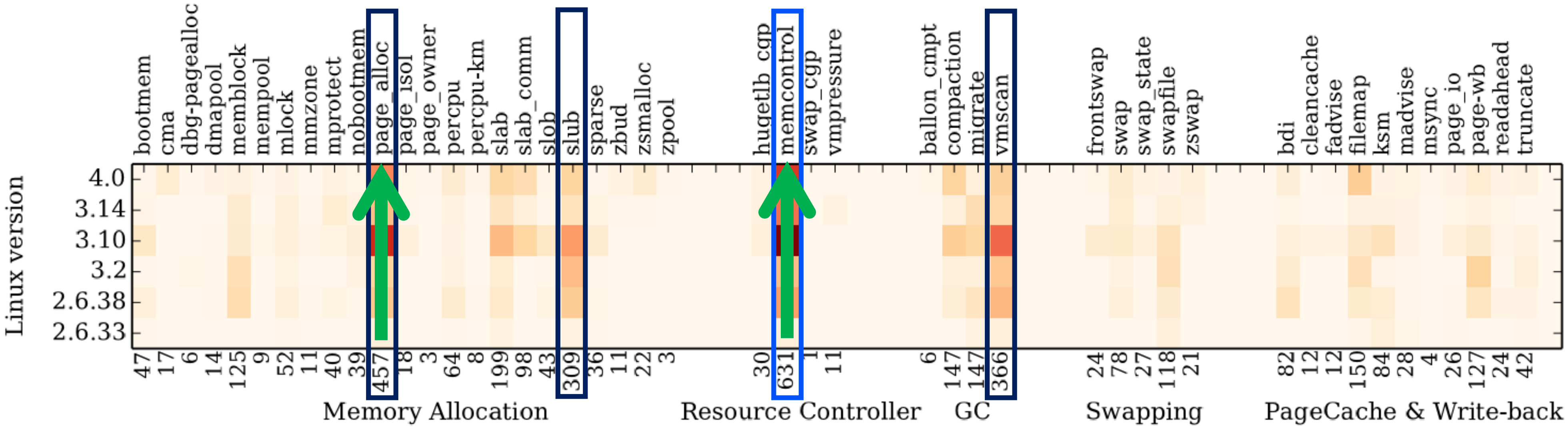

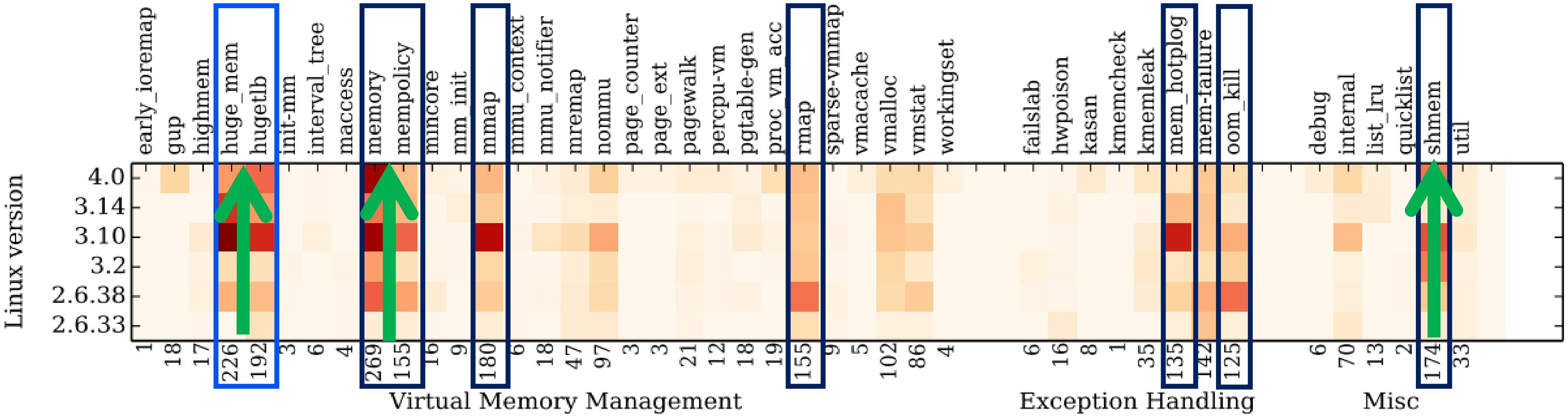

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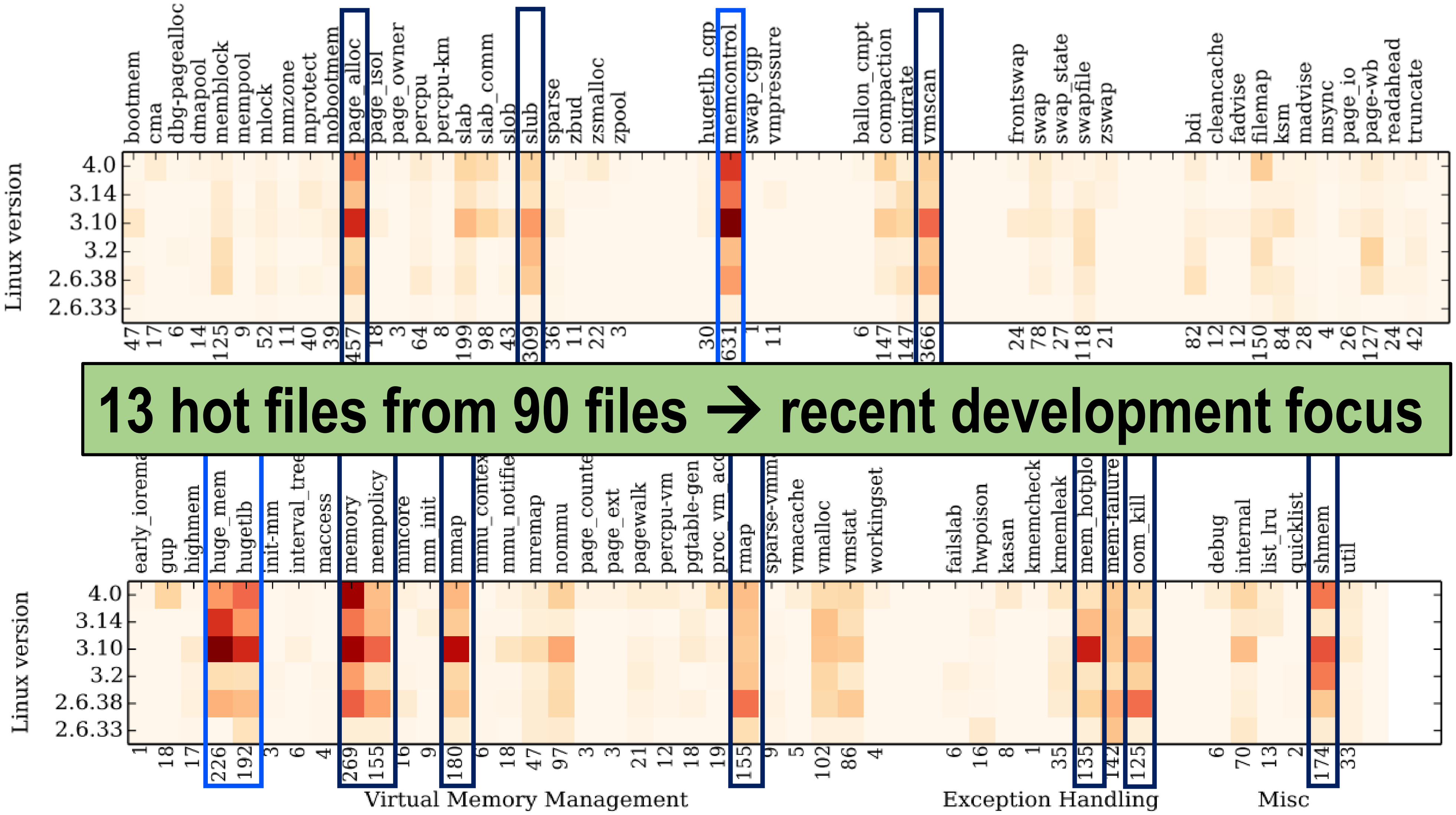
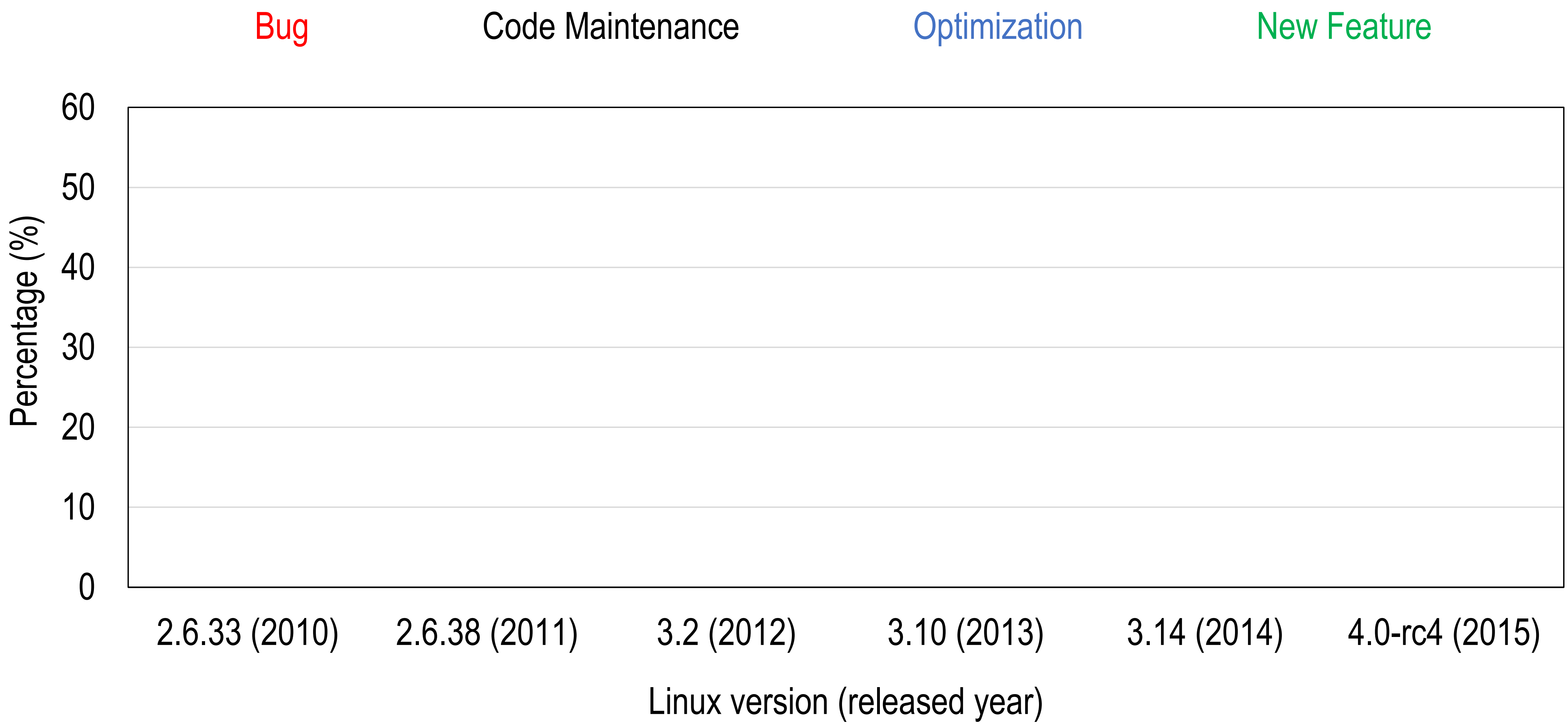


13 hot files from 90 files → recent development focus

Why Is the Memory Manager Changed?



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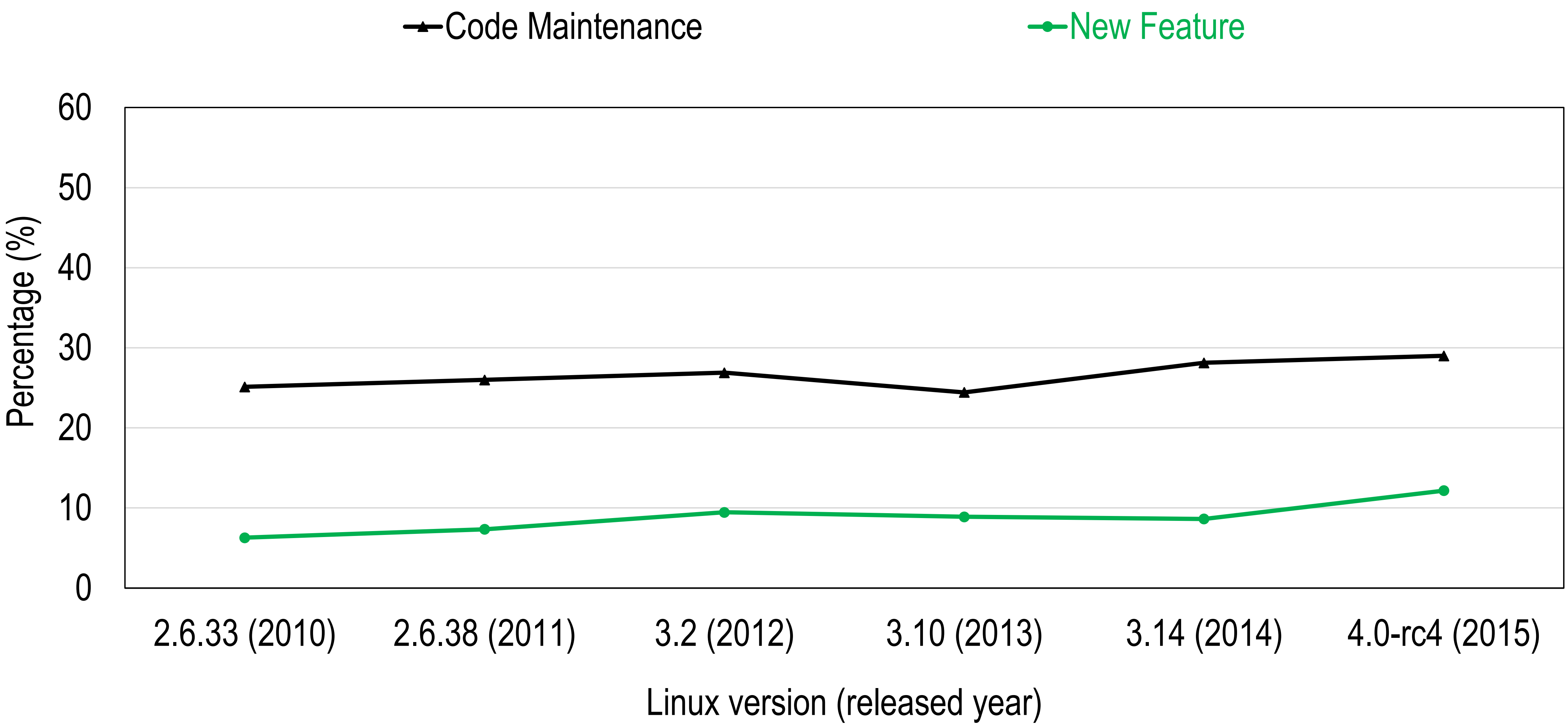

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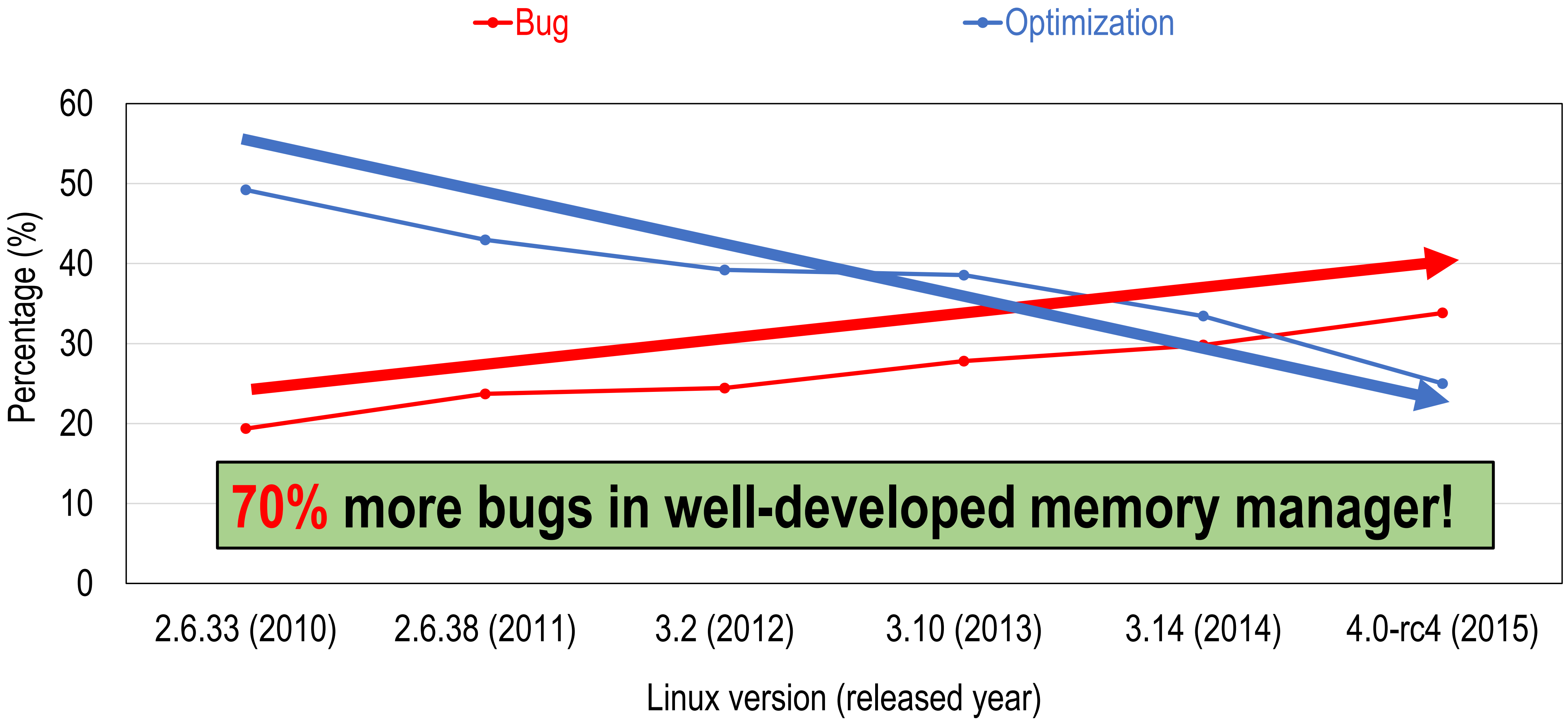

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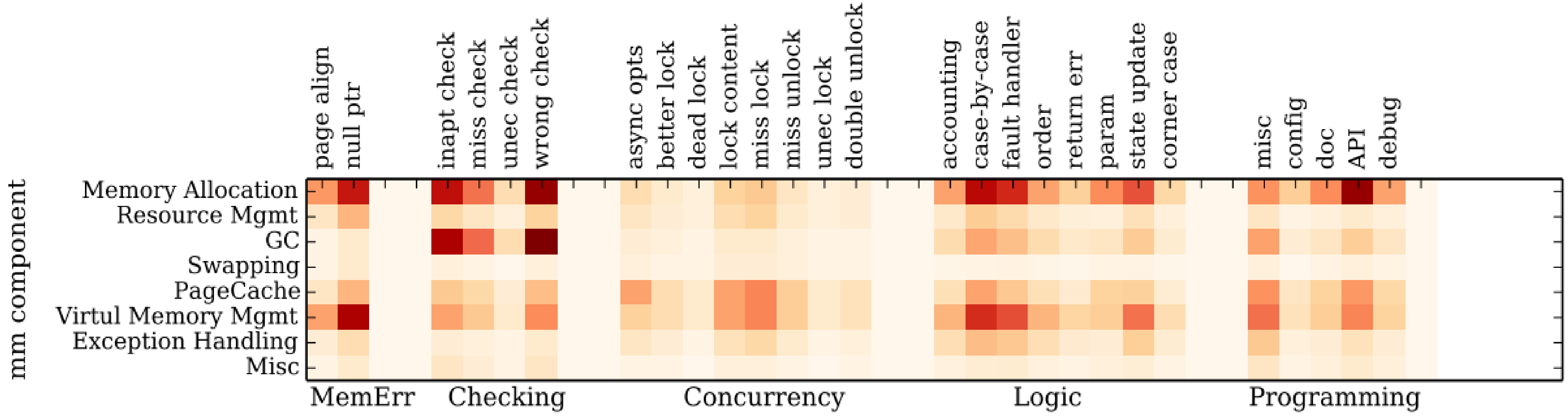

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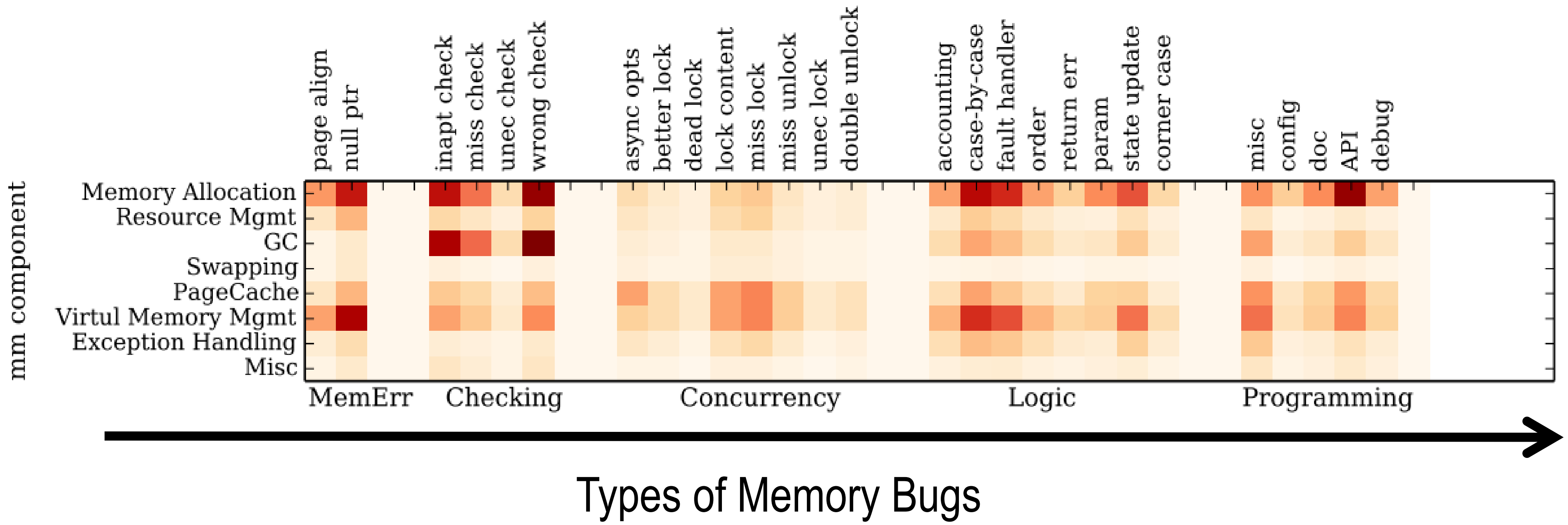

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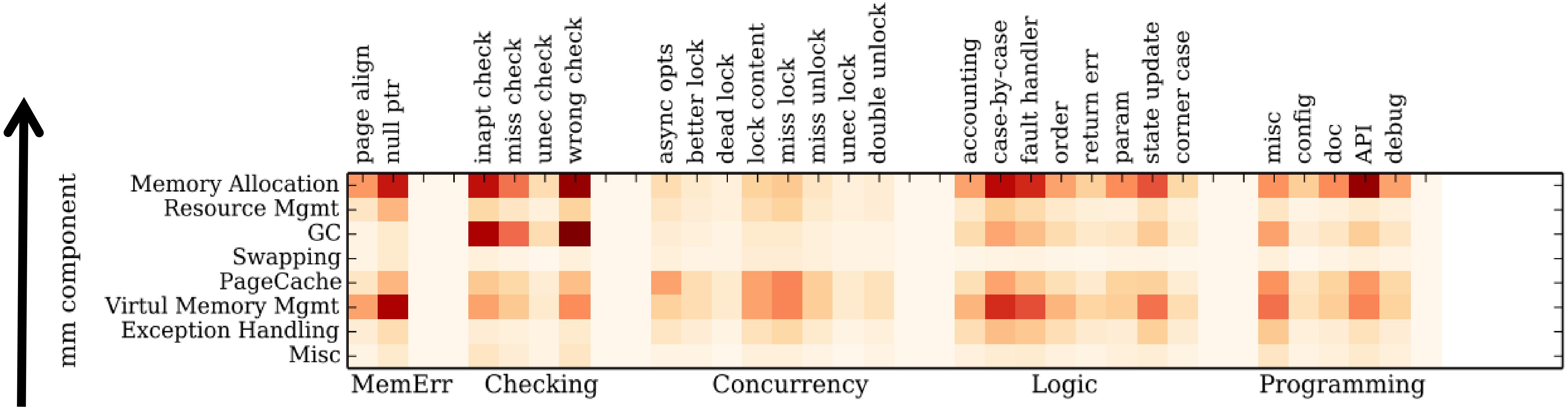

Memory Manager Component

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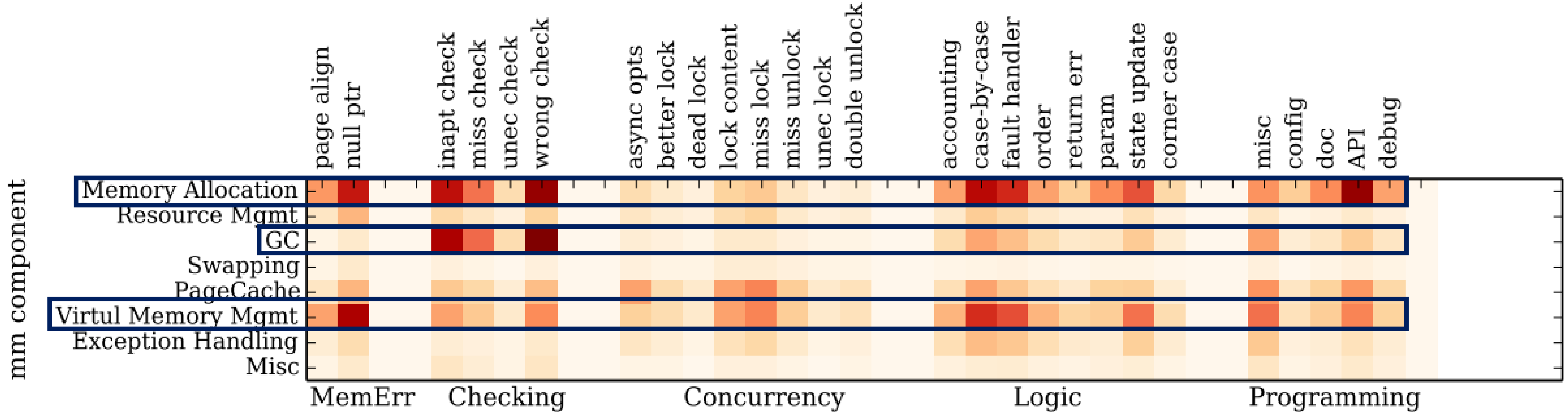

Memory Allocation: 26%, Virtual Memory Management: 22%, GC: 14%

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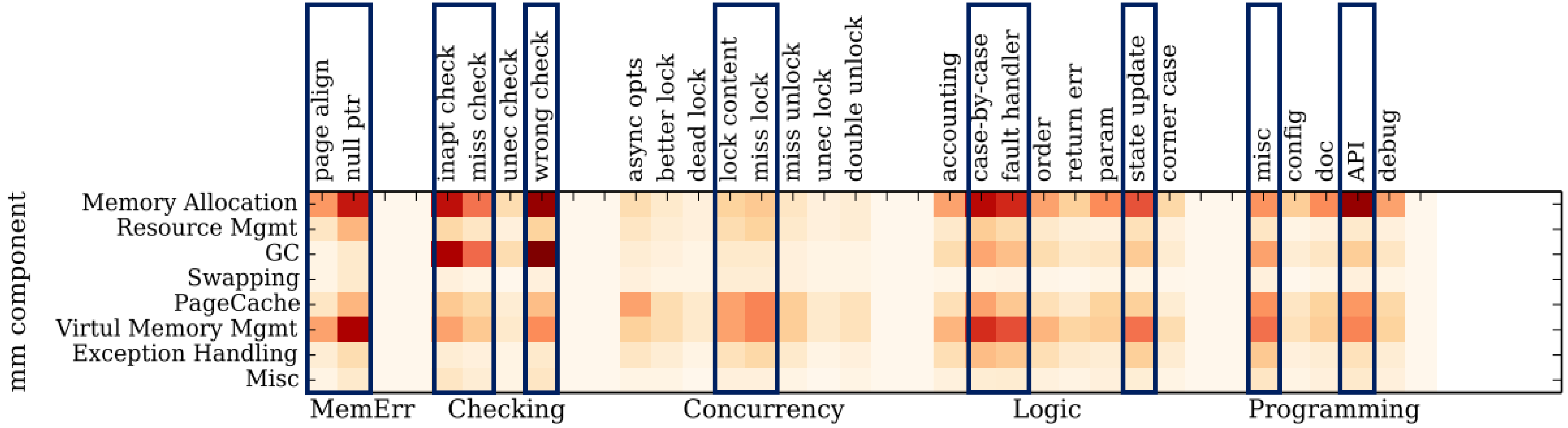

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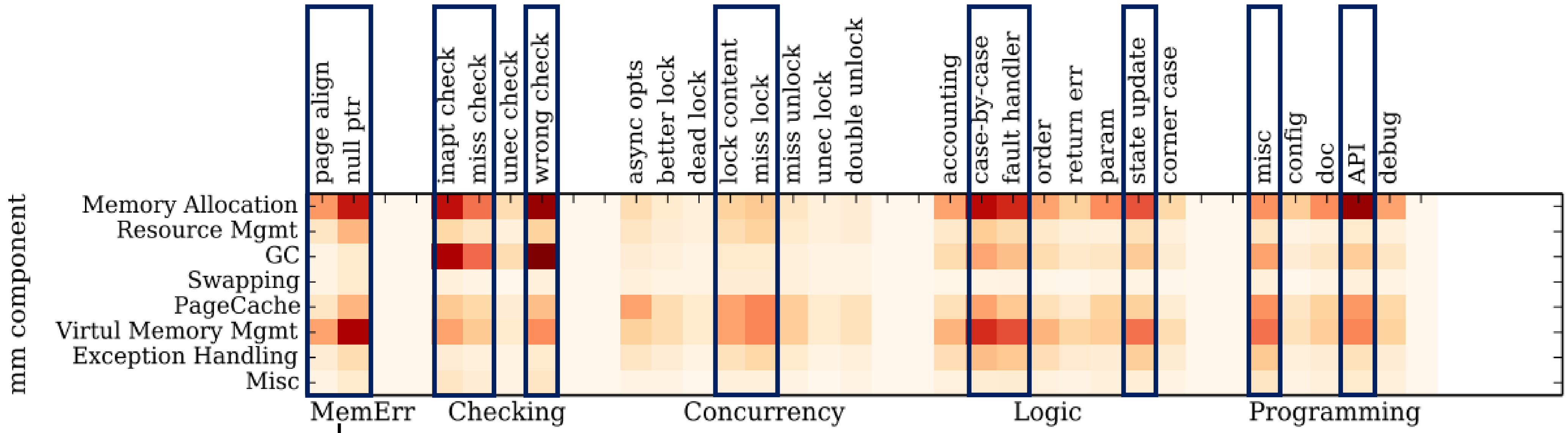

- Page alignment
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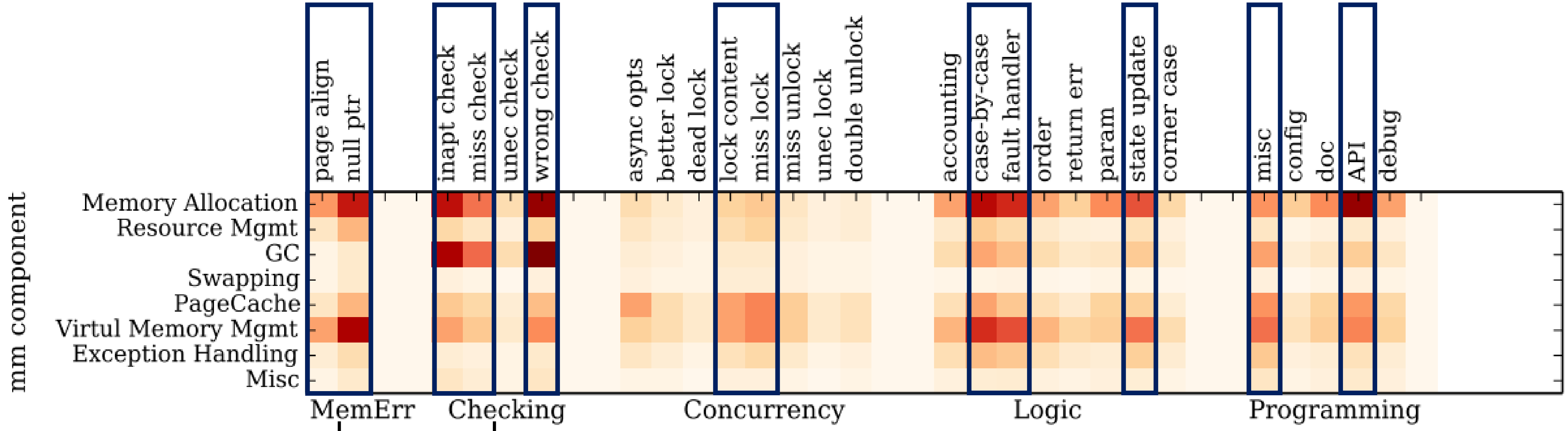

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- Inappropriate check
- Missing check
- Wrong check

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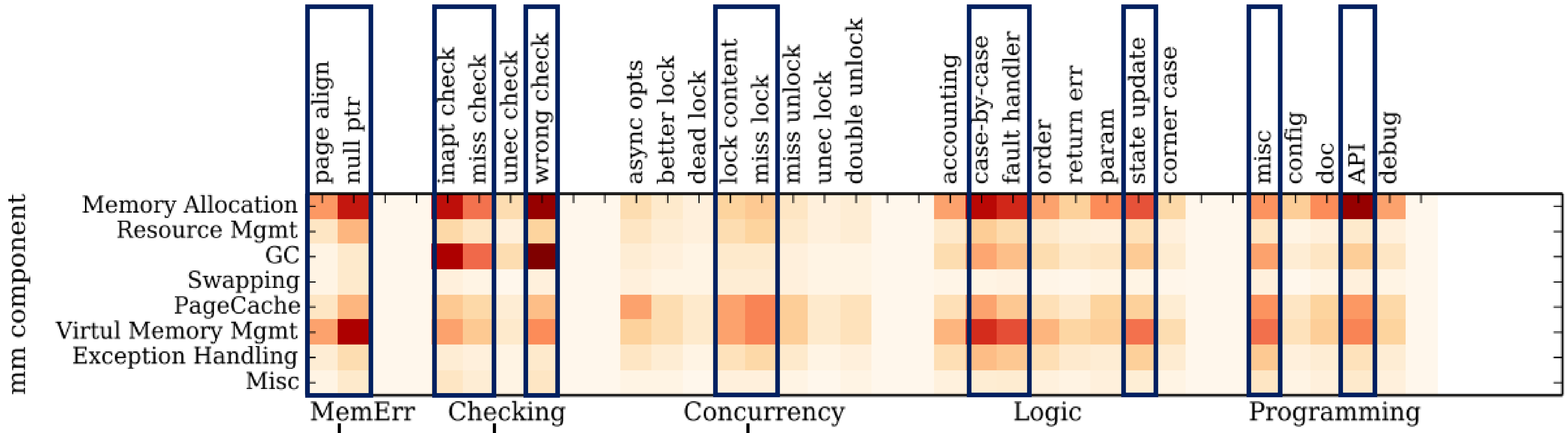

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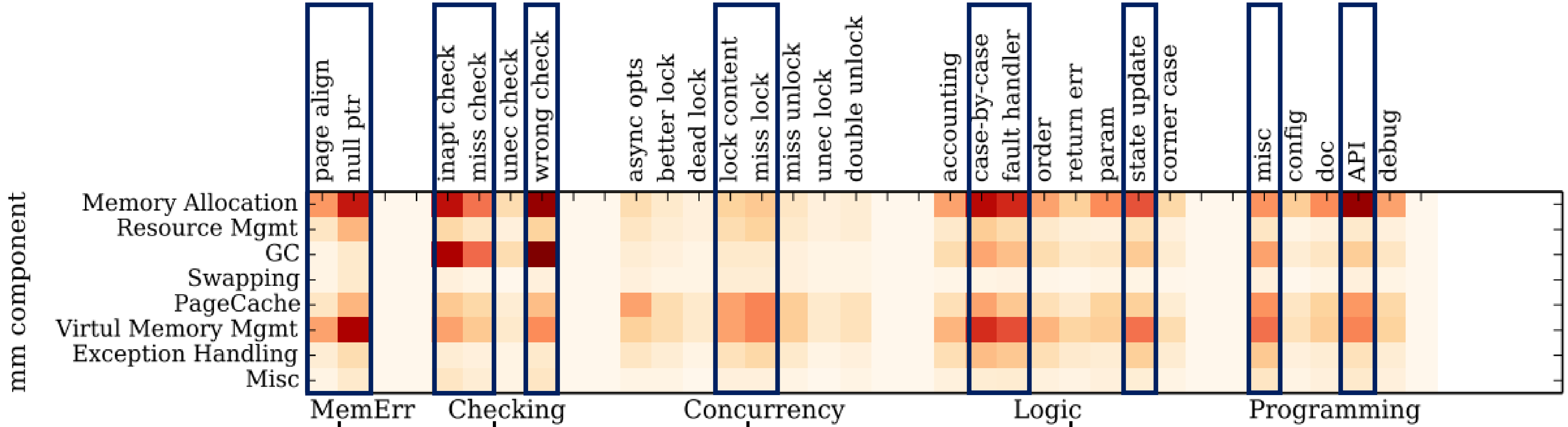

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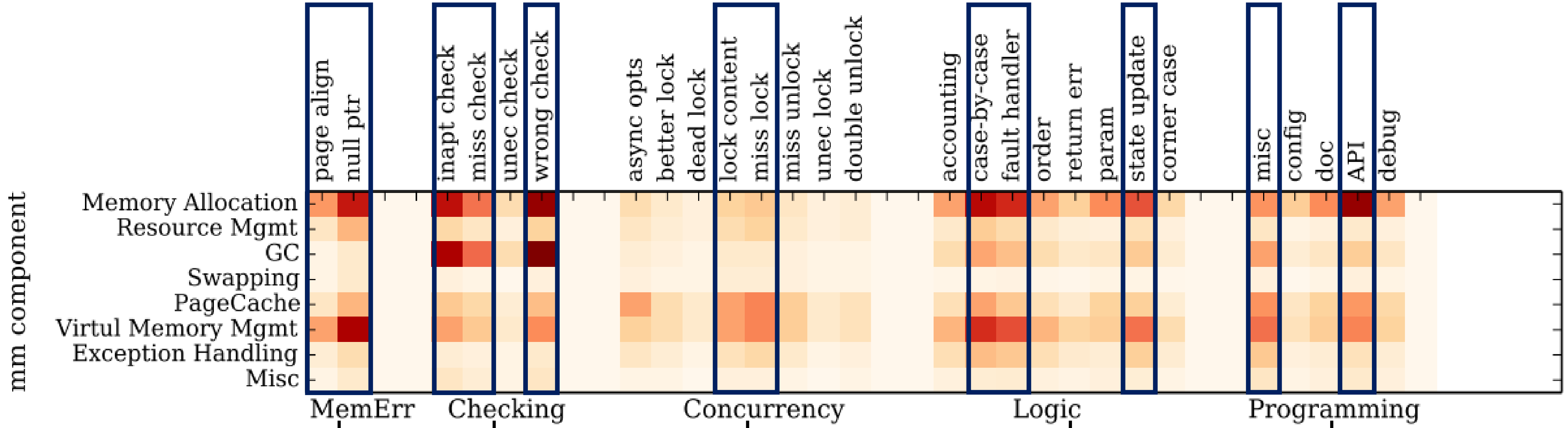

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- Fault handler
- State update
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- API
- Misc

Memory Bugs: Case Studies

Page Alignment

```
mm/nommu.c

@@ -1762,6 +1765,8 @@ unsigned long do_mremap(unsigned long addr,
struct vm_area_struct *vma;

        /* insanity checks first */


        if (old_len == 0 || new_len == 0)
                return (unsigned long) -EINVAL;
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Bug: device drivers' mmap() failed.
Cause: NOMMU does not do page_align(), which is inconsistent with MMU arch.

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Checking

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free_bootmem_core(bootmem_data_t *bdata, unsigned long addr,
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@@ -156,21 +157,31 @@ static void __init
free_bootmem_core(bootmem_data_t *bdata, unsigned long addr,

+        BUG_ON(!size);
+
+        /* out range */
+        if (addr + size < bdata->node_boot_start ||
+                PFN_DOWN(addr) > bdata->node_low_pfn)
+                return;
```

Bug: free pages wrongly.
Cause: miss boundary checking.

Memory Optimizations

4 Data Structures

Radix Tree | Red-black Tree | Bitmap | List

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Decentralize data structures: per-core/per-node/per-device approaches.

Memory Optimizations

4 Data Structures

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- Red-black Tree
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5 Policy Trade-offs

- Latency Vs. Throughput
- Synchronous Vs. Asynchronous
- Lazy Vs. Non-lazy
- Local Vs. Global
- Fairness Vs. Performance

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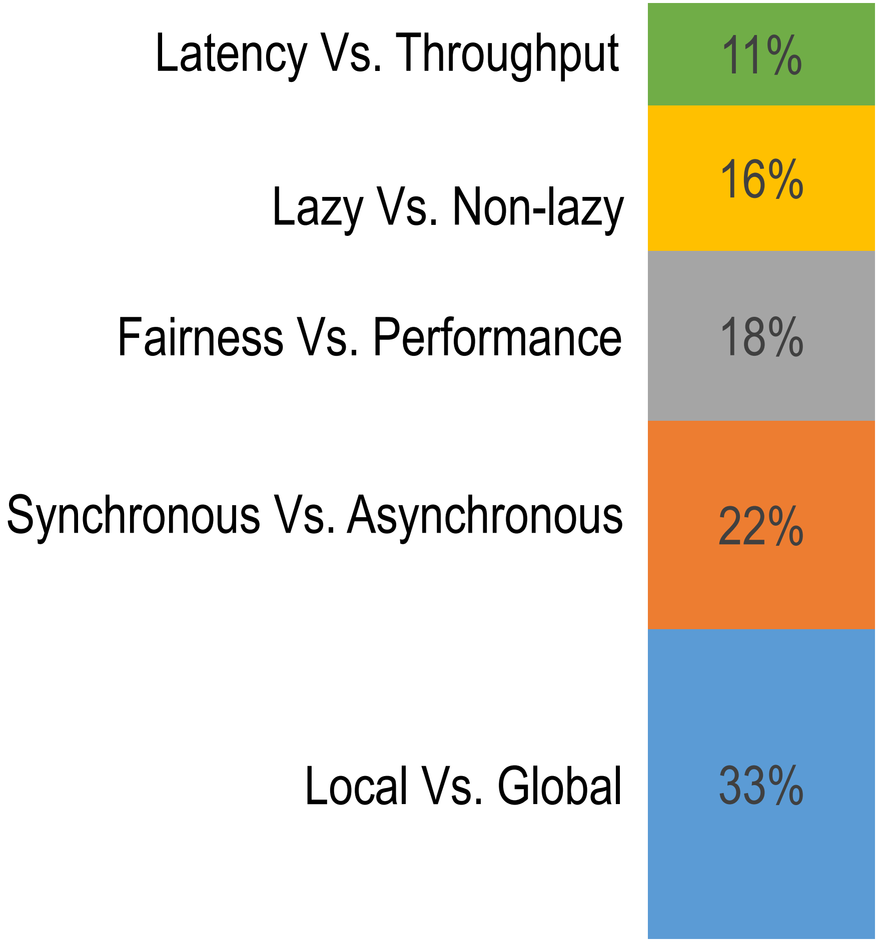
8 Fast Paths

- Code Reduction
- Lockless Optimization
- New Function
- Inline
- State Caching
- Code Shifting
- Group Execution
- Optimistic Barrier

Memory Optimizations: Policy Trade-offs



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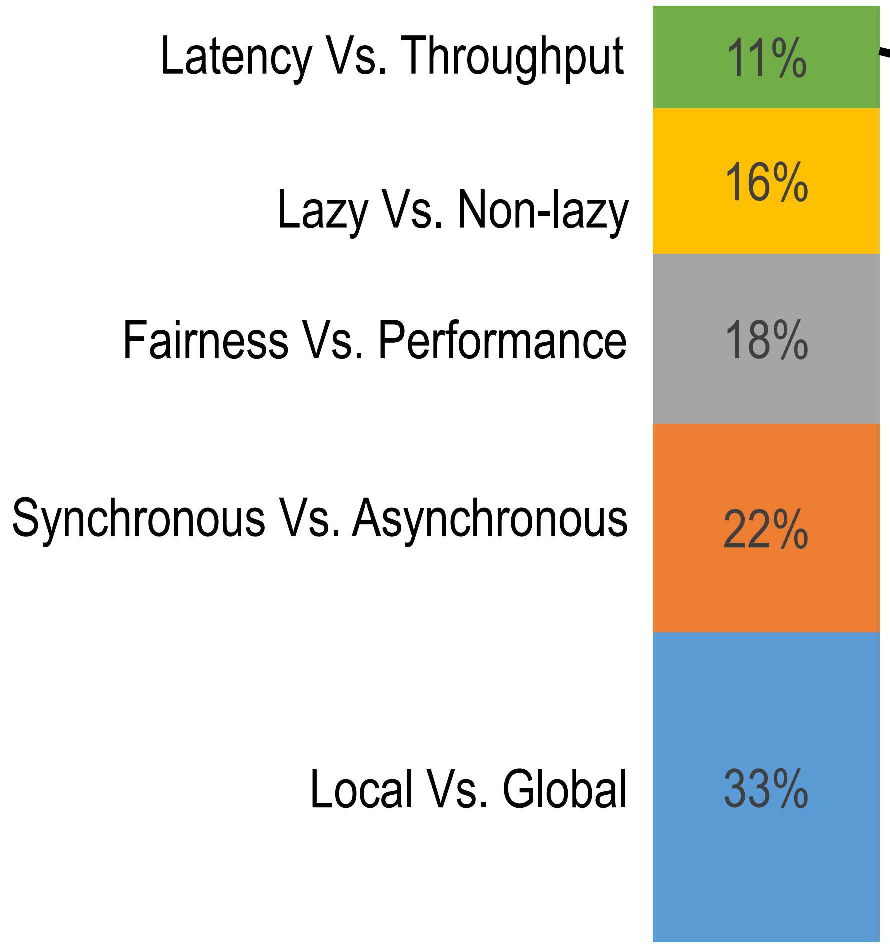
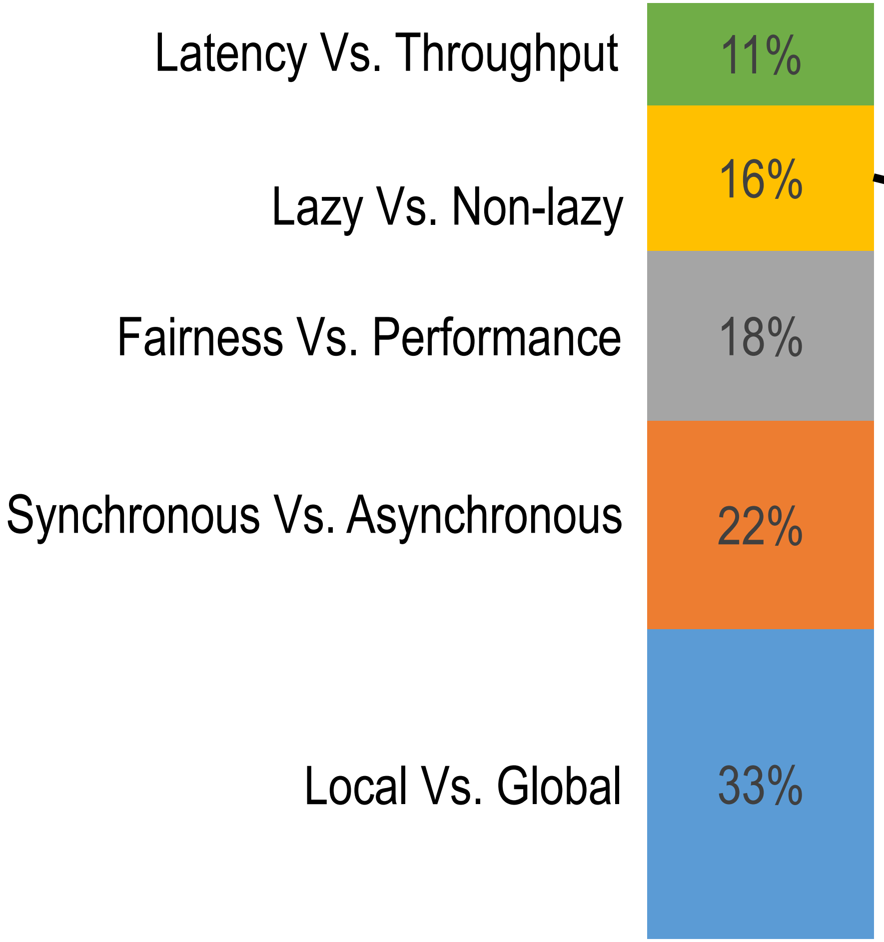


137 patches committed especially for reducing the latencies of memory operations.

Memory Optimizations: Policy Trade-offs



Lazy policy: delay expensive operations.
May change the execution order of functions.

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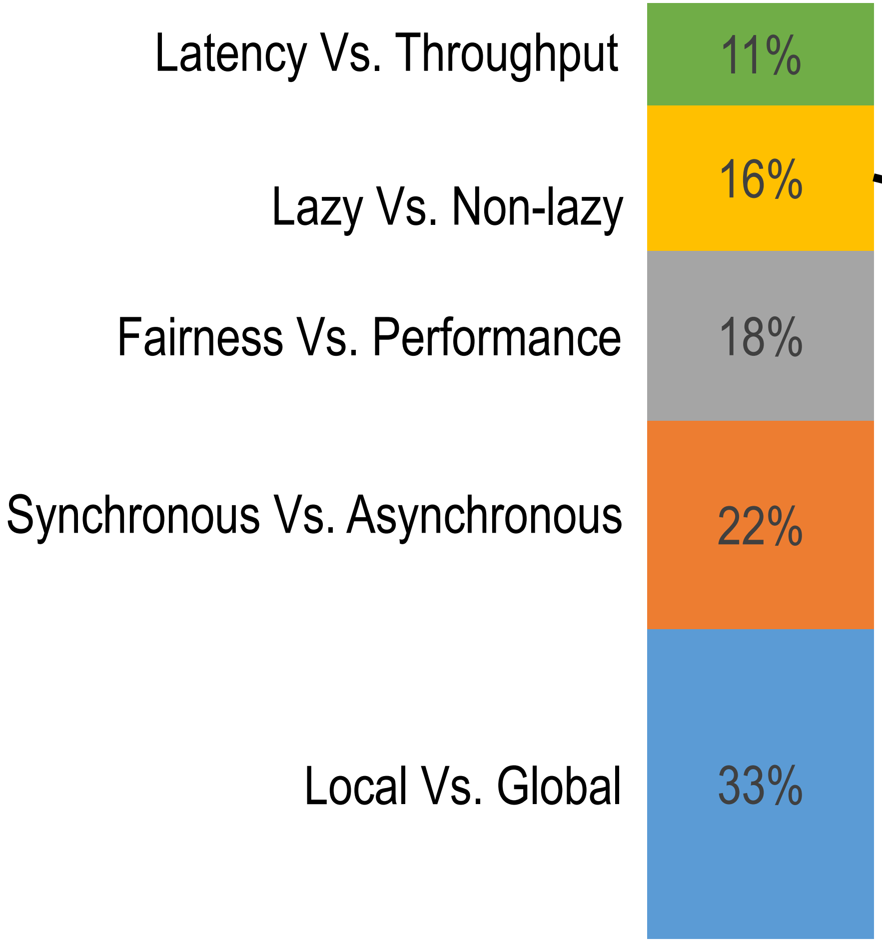

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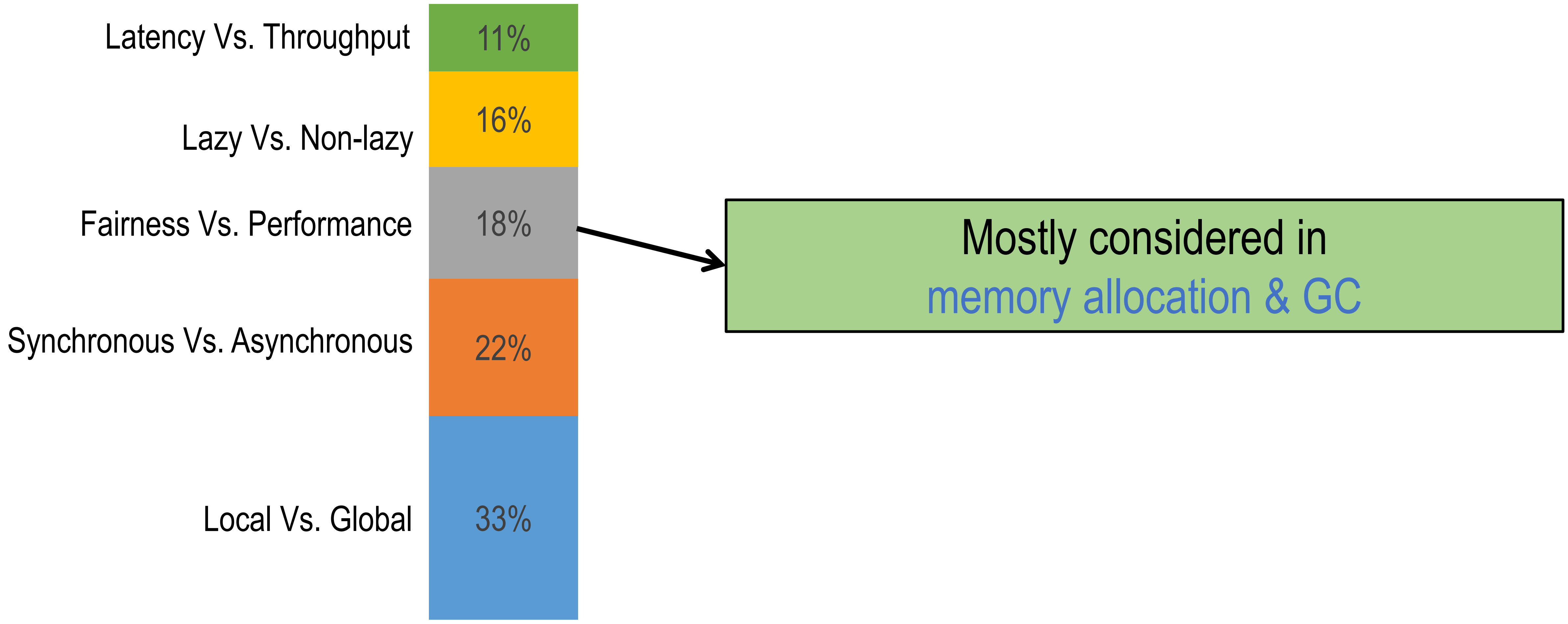
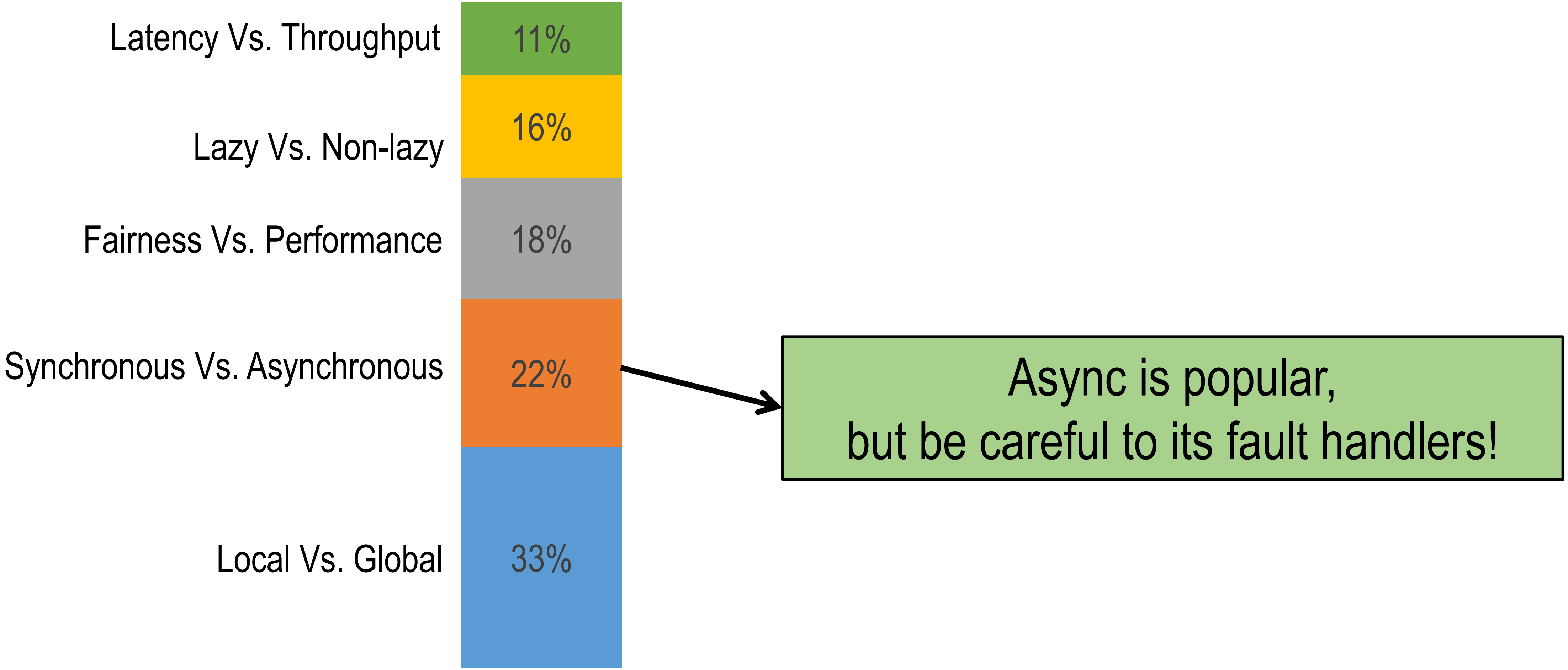
vmalloc	Lazy TLB flush, lazy unmapping
mempolicy	Lazy page migration between nodes
huge_memory	Lazy huge zero page allocation

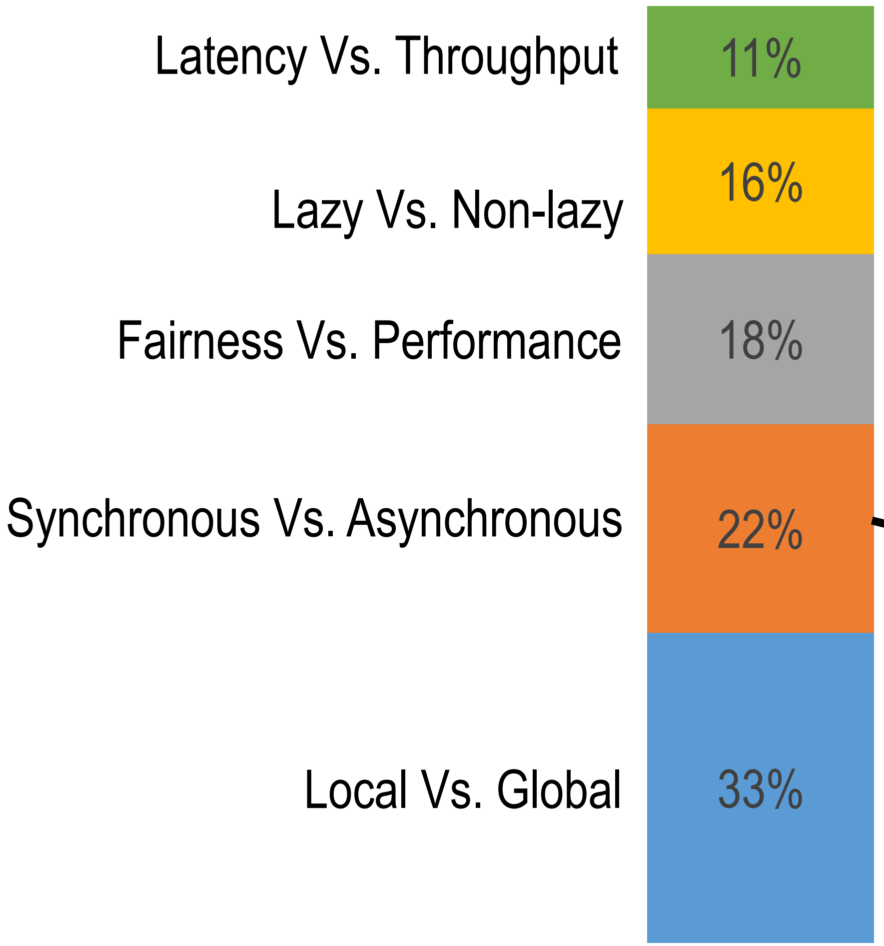
Memory Optimizations: Policy Trade-offs



Memory Optimizations: Policy Trade-offs



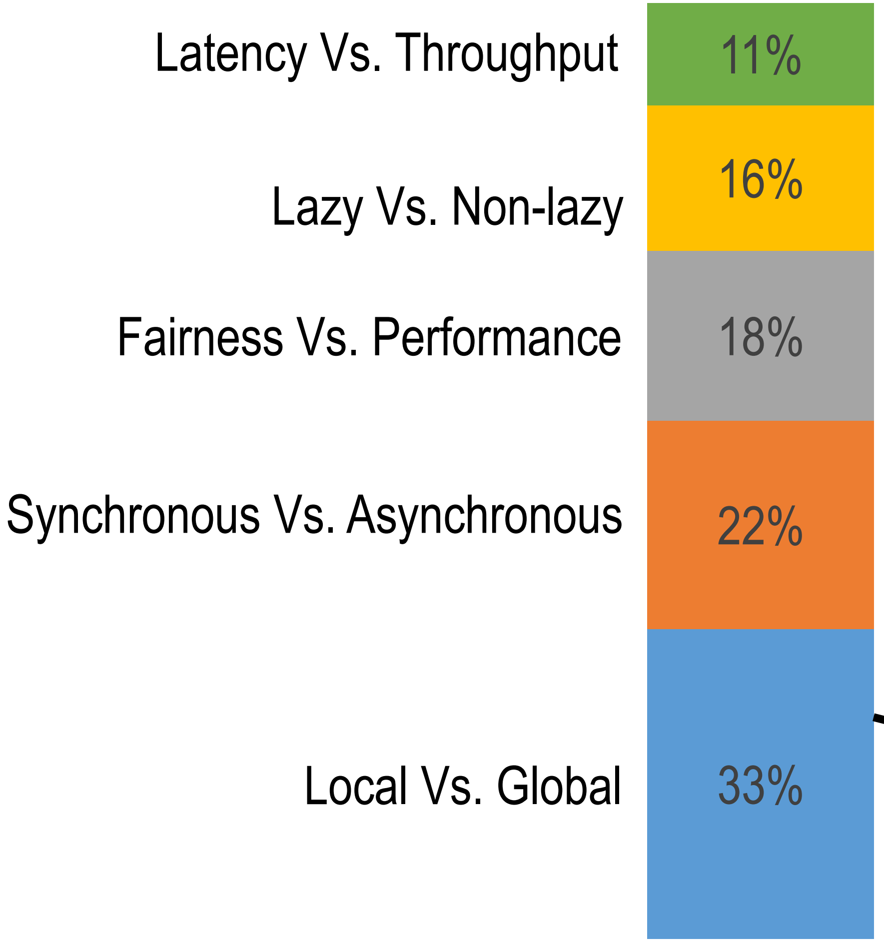
Memory Optimizations: Policy Trade-offs



Async is popular,
but be careful to its fault handlers!

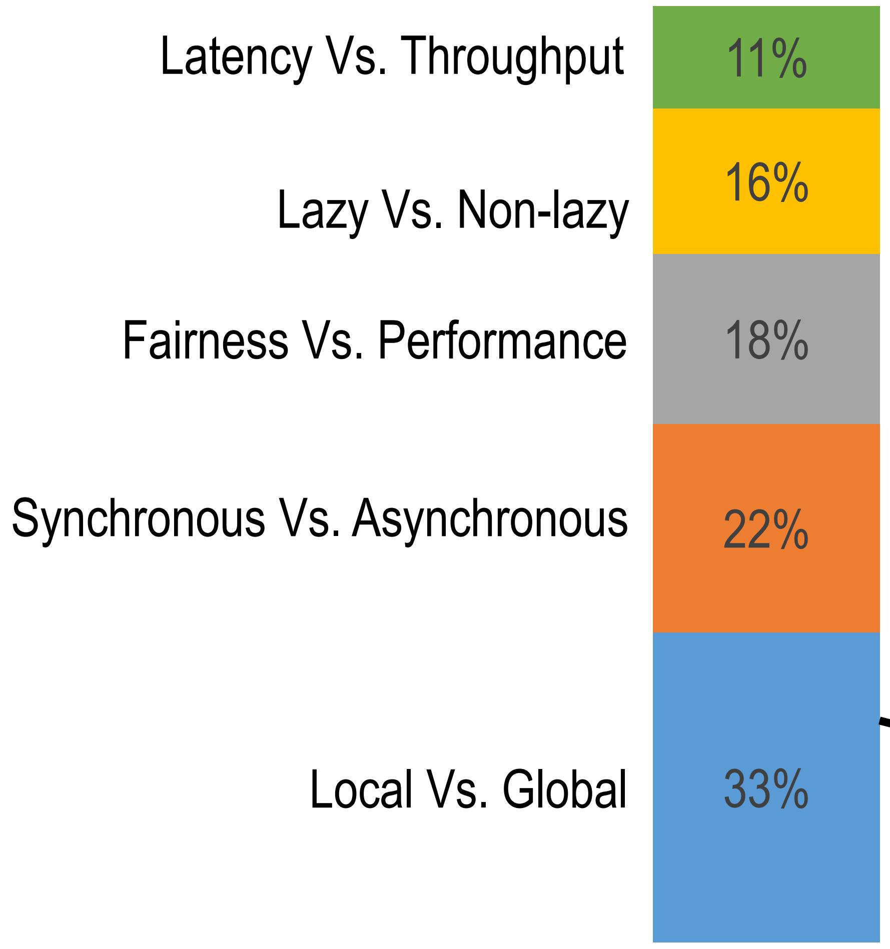
E.g., early termination

Memory Optimizations: Policy Trade-offs



Decentralizing global structures for better scalability

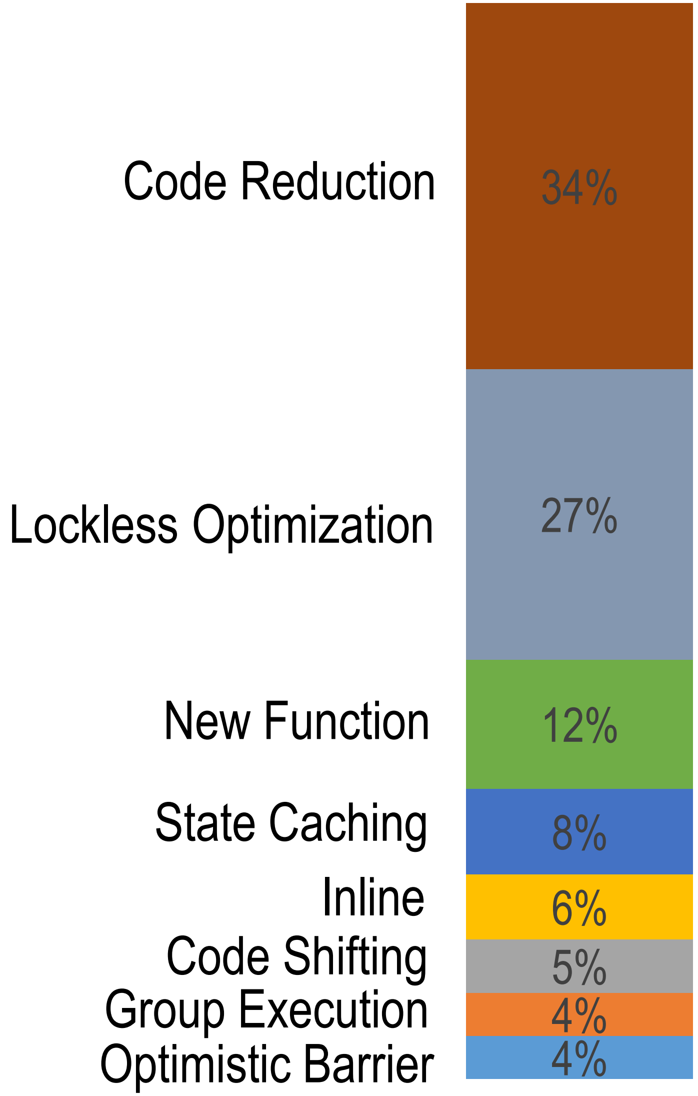
Memory Optimizations: Policy Trade-offs



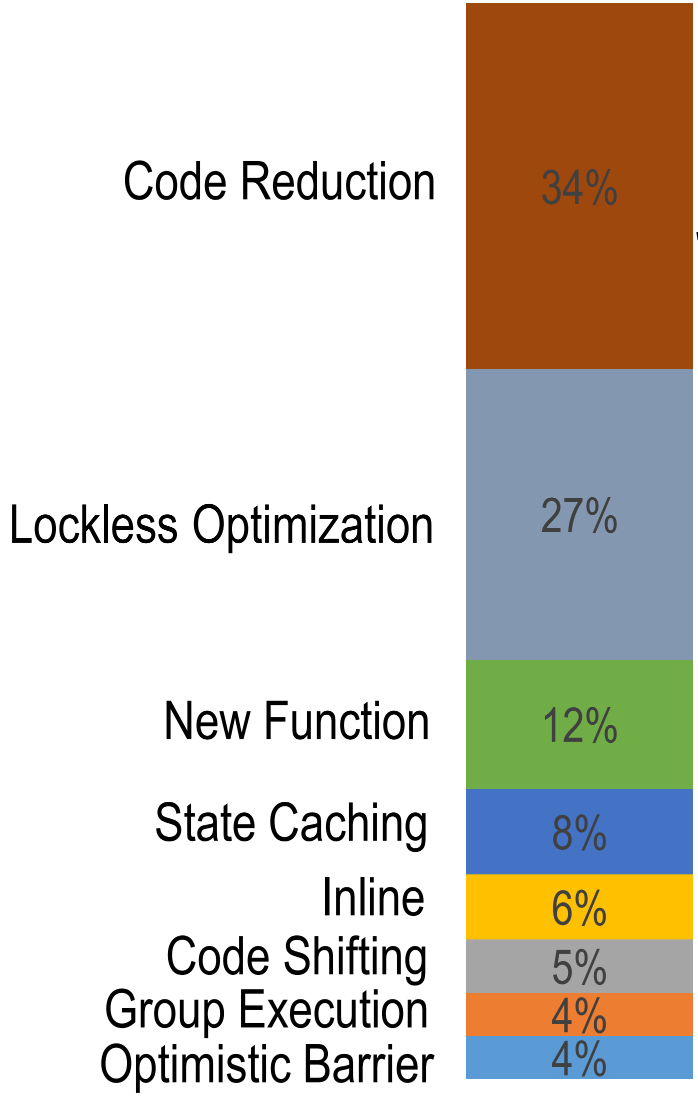
Decentralizing global structures for better scalability

E.g., dynamic per-cpu allocator.

Memory Optimizations: Fast Path

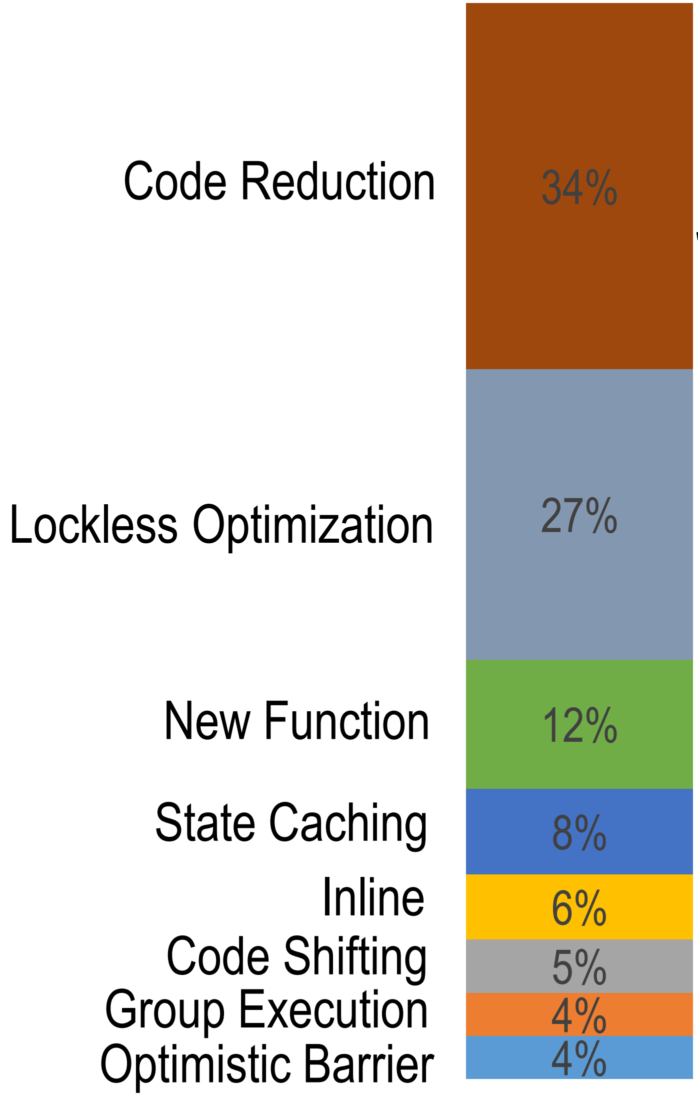


Memory Optimizations: Fast Path



Simplify the slow path logic

Memory Optimizations: Fast Path

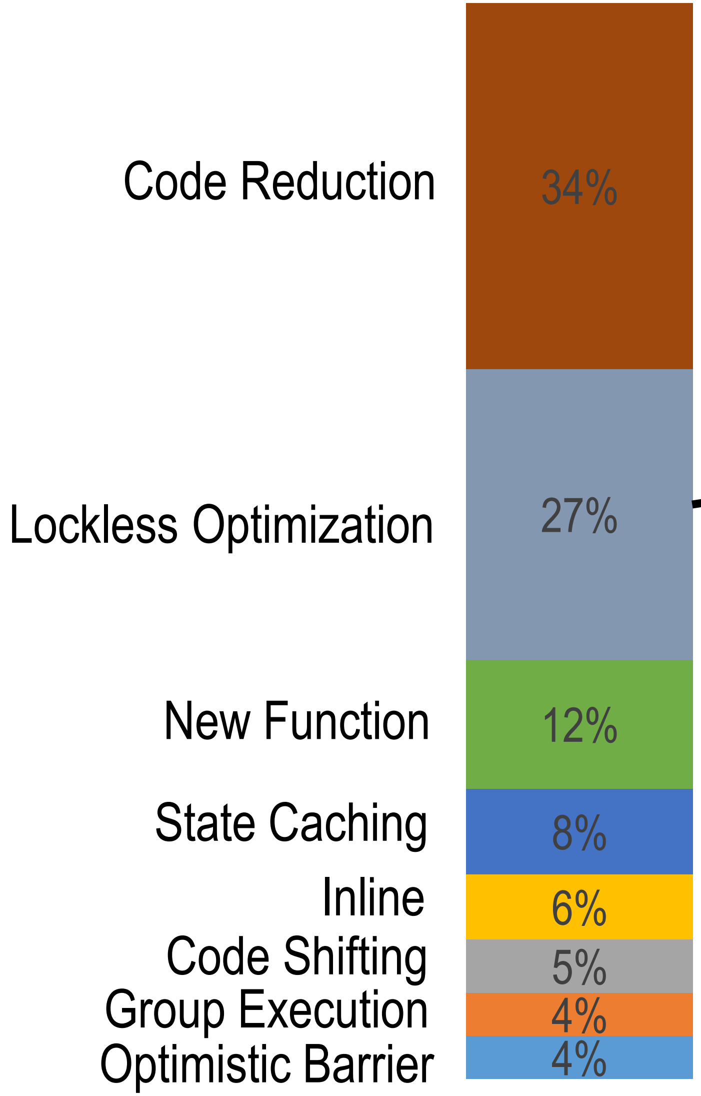


Simplify the slow path logic

E.g., Avoid redundant get/put_page in munlock_vma_range as pages will not be referred anymore.

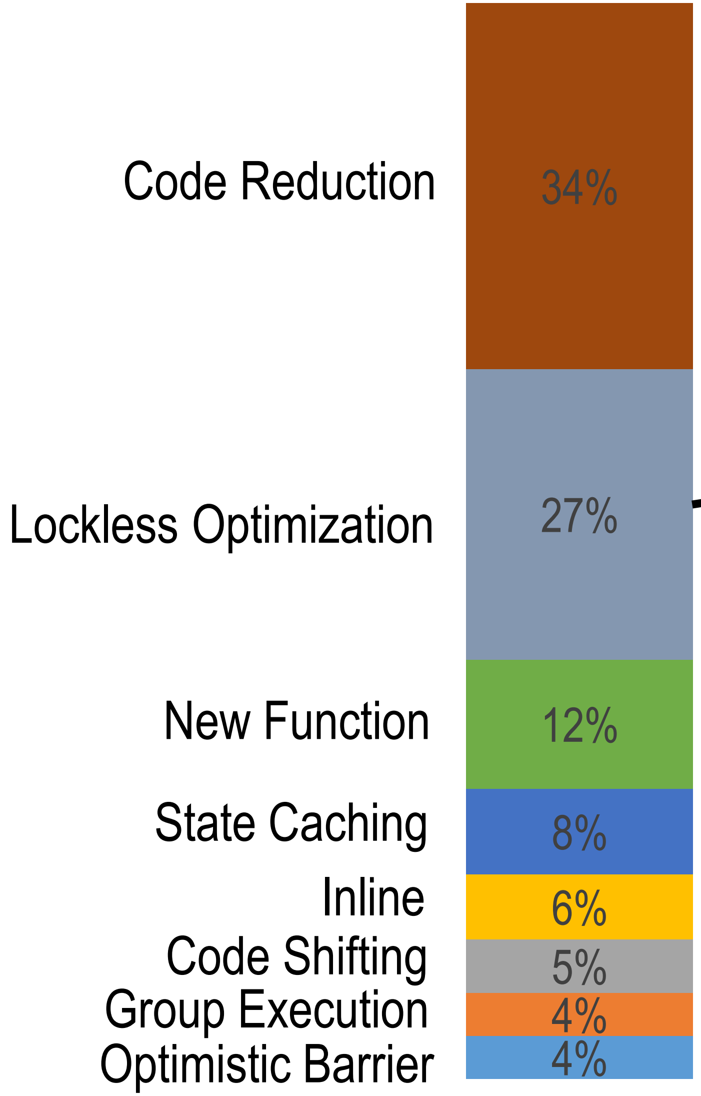
```
mm/memory.c
@@ -303,8 +303,10 @@ static void __munlock_pagevec(
if (PageLRU(page)) {
        lruvec = mem_cgroup_page_lruvec(page, zone);
        lru = page_lru(page);
-
-       get_page(page);
+      /*
+       * We already have pin from follow_page_mask()
+       * so we can spare the get_page() here.
+       */
```

Memory Optimizations: Fast Path



Reduce the usage of lock and atomic operations

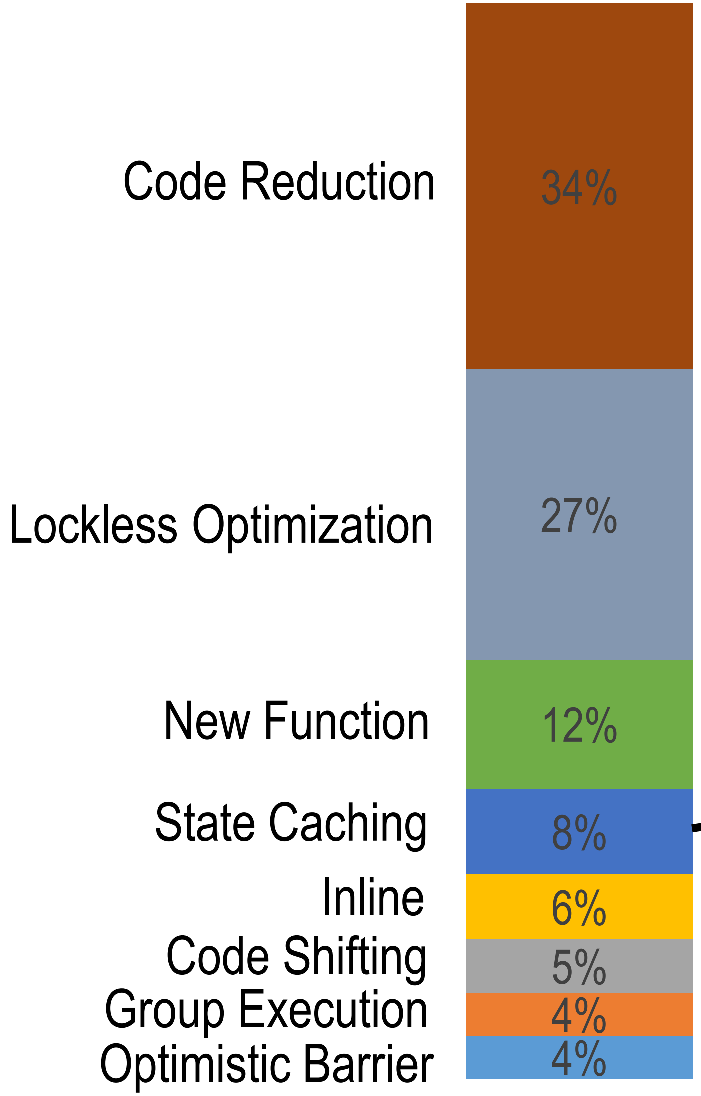
Memory Optimizations: Fast Path



Reduce the usage of lock and atomic operations

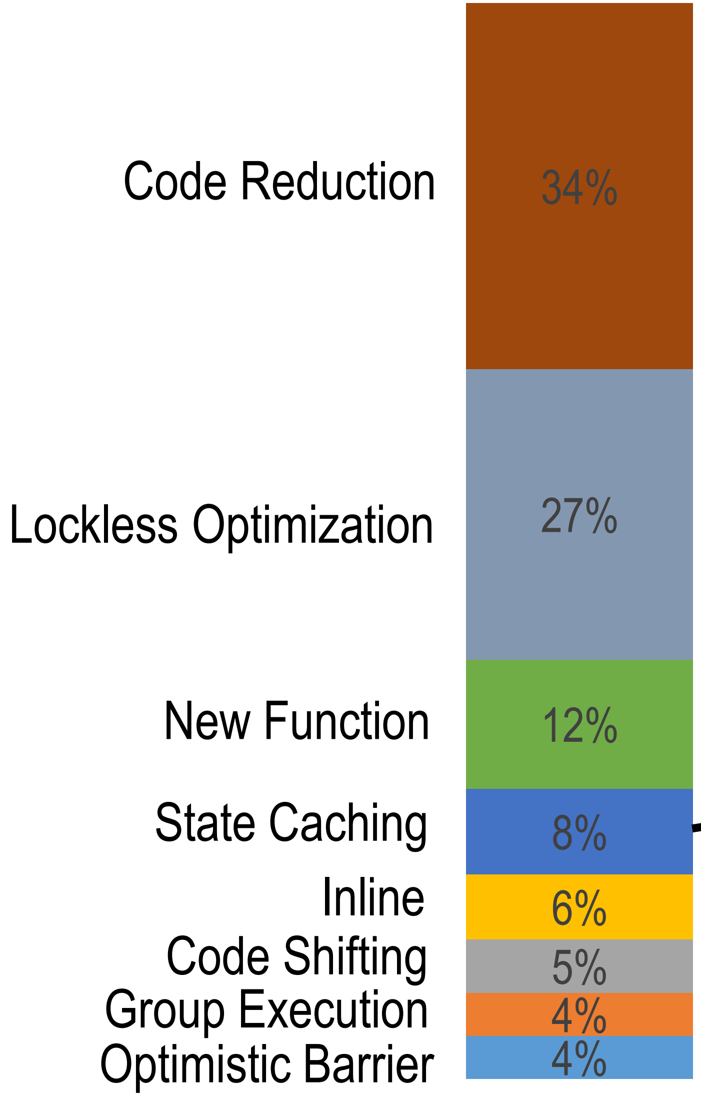
E.g., lockless memory allocator in SLUB

Memory Optimizations: Fast Path



Cache states to avoid expensive operations

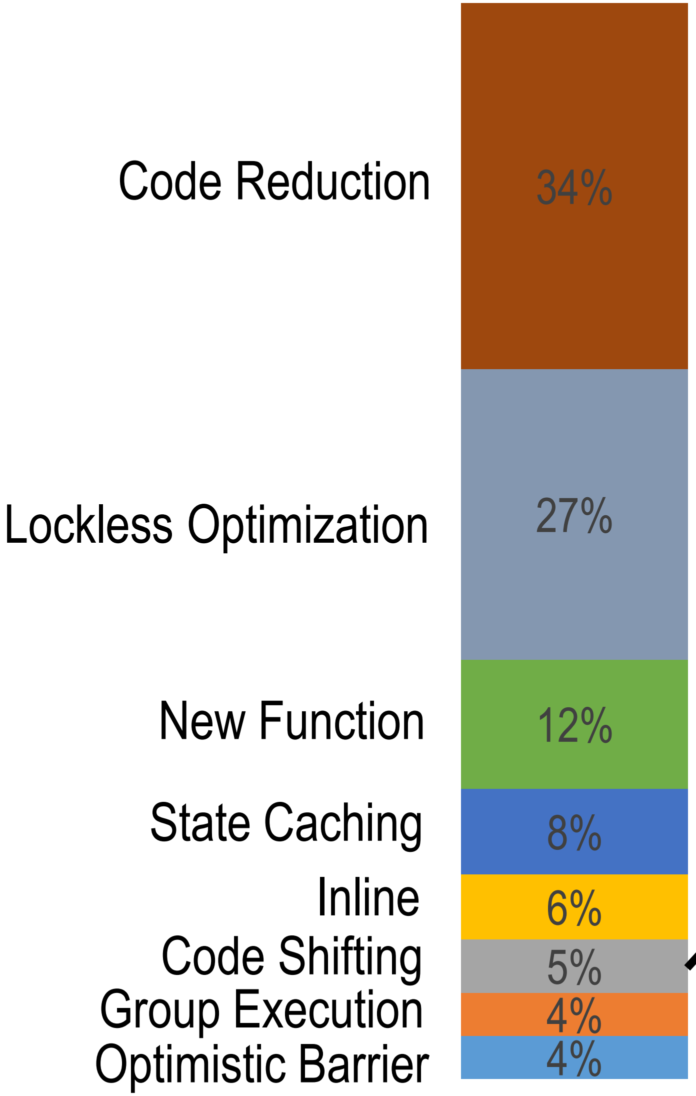
Memory Optimizations: Fast Path



Cache states to avoid expensive operations

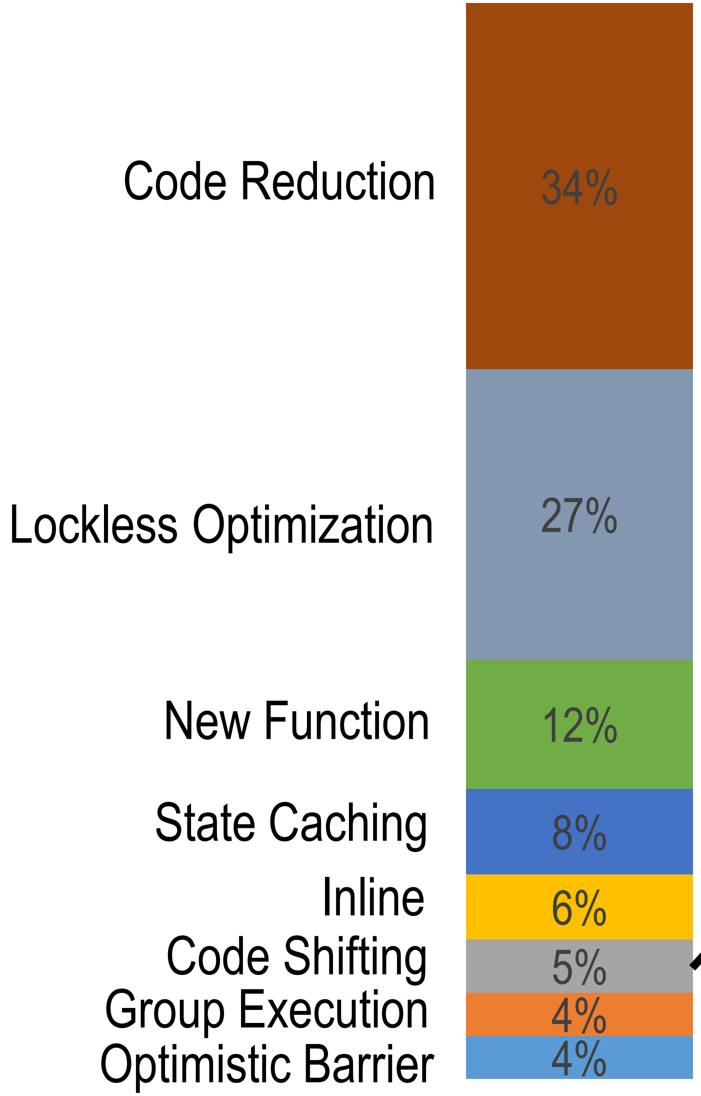
E.g., pre-calculate the number of online nodes vs. always calling expensive num_online_nodes

Memory Optimizations: Fast Path



Move infrequently executed code from fast path to slow path

Memory Optimizations: Fast Path

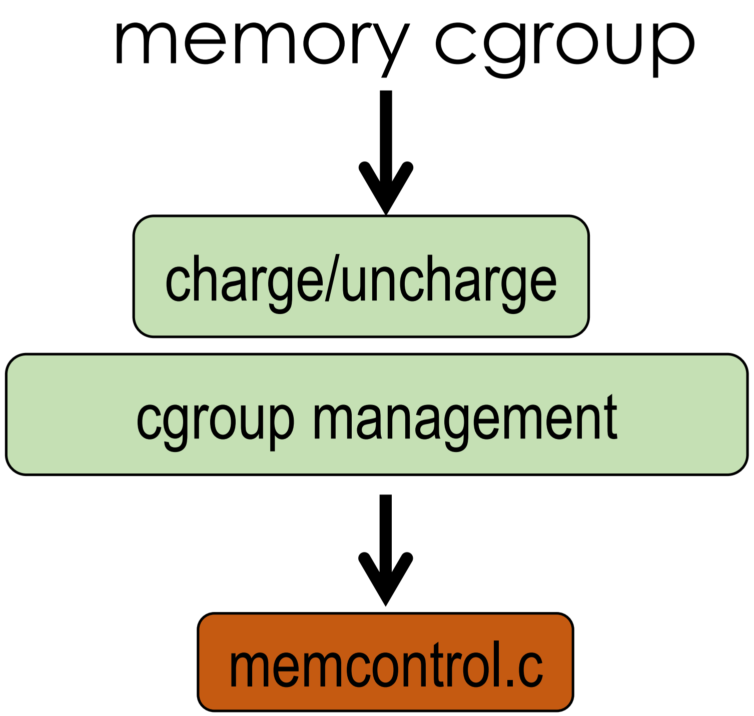


Move infrequently executed code from fast path to slow path

E.g., in SLUB allocator, slow path executes the interrupt enable/disable handlers, fast path executes them only at fallback

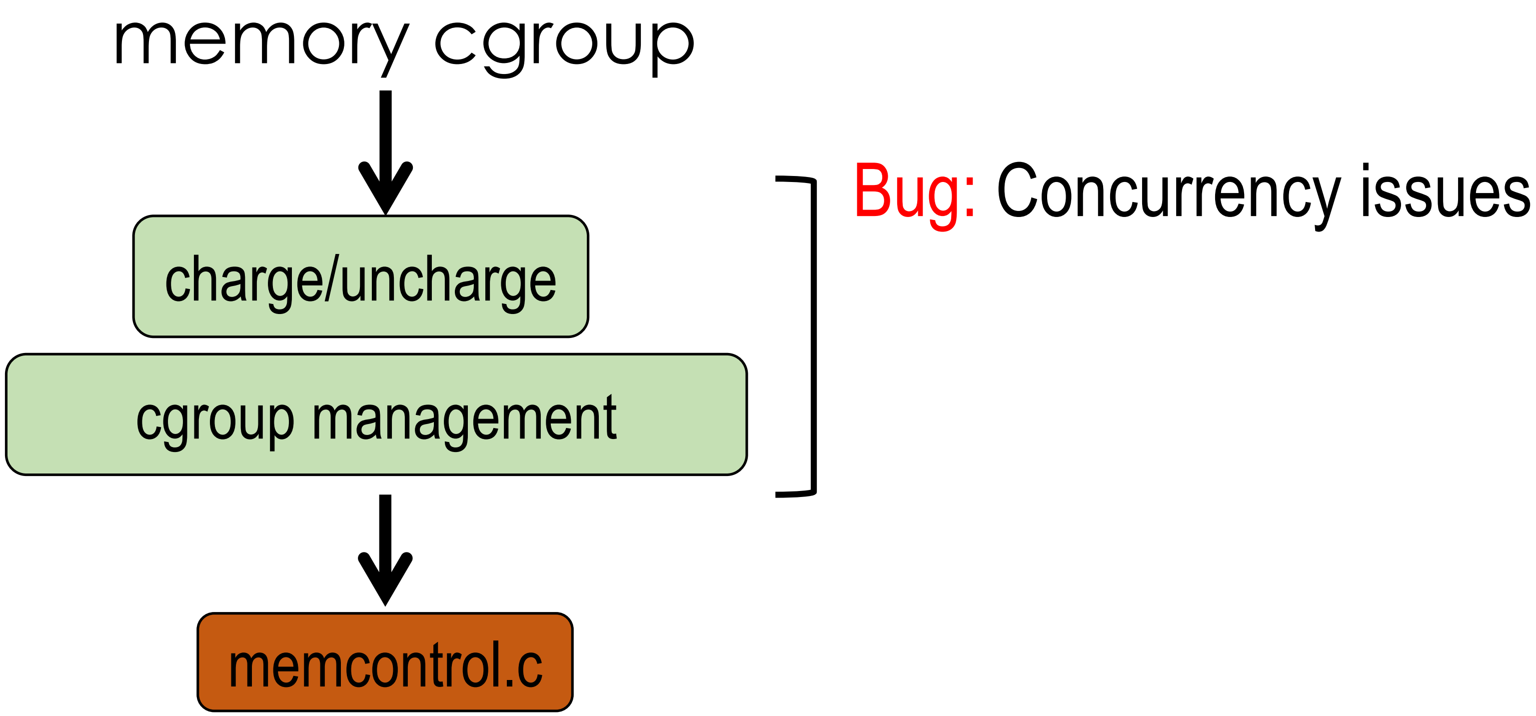
Memory Semantics

Memory Resource Controller



Memory Semantics

Memory Resource Controller



Memory Semantics

Memory Resource Controller

memory cgroup

charge/uncharge

cgroup management

memcontrol.c

Bug: Concurrency issues

↓

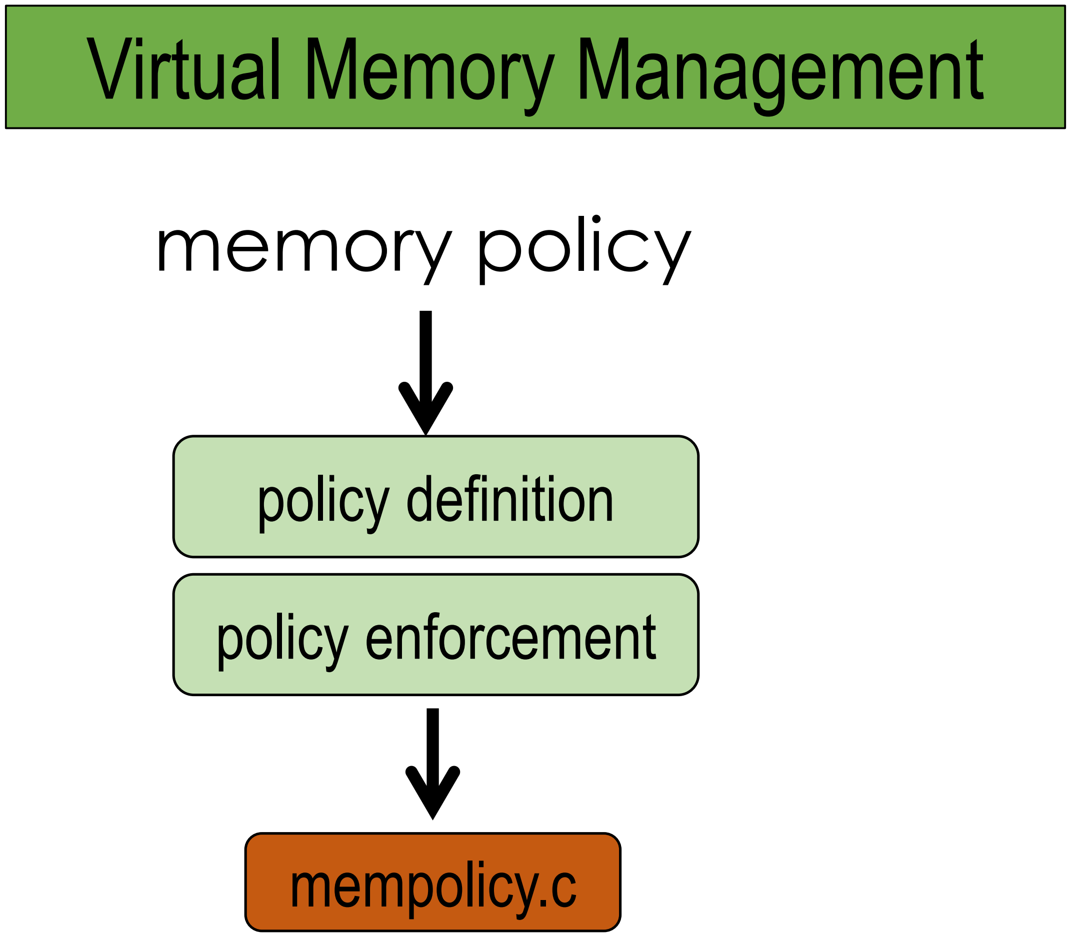
Cause: missing locks in charging & uncharging pages (truncation, reclaim, swapout and migration)

Memory Semantics

Virtual Memory Management

memory policy

Memory Semantics



Memory Semantics

Virtual Memory Management

memory policy

↓

policy definition

policy enforcement

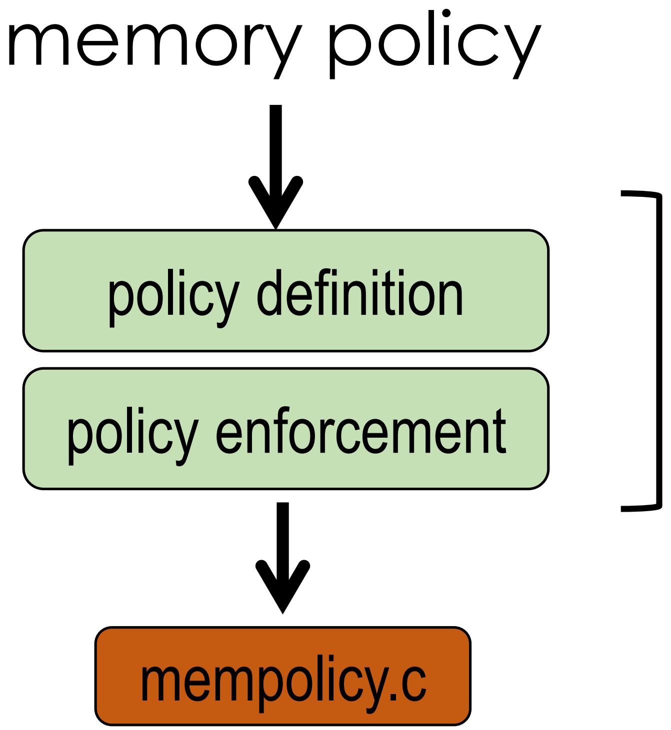
↓

mempolicy.c

Bug: policy enforcement failure

Memory Semantics

Virtual Memory Management



Bug: policy enforcement failure

↓

Cause: missing check on page states & statistics, e.g., whether a page is dirty, cache hit/miss rate

Conclusion

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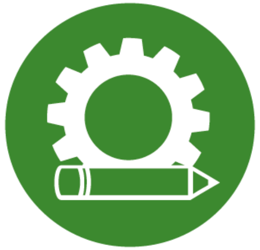
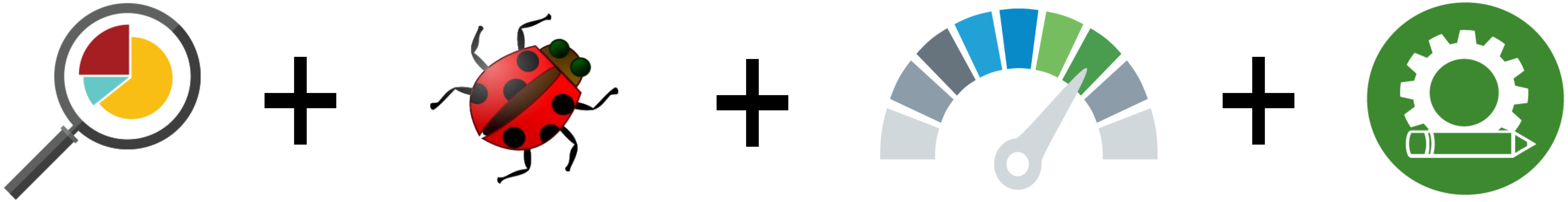


Pattern + Memory Bug + Optimization + Semantic

Conclusion



Pattern + Memory Bug + Optimization + Semantic

- Complex page states → Concurrency bugs → Simplified page management
- Fast path → Introduce new errors → Fast path verification
- Bugs in checking → Model checking for memory manager
- ……

Thanks!

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Q&A