Scaling CHERI Use-After-Free Protection to Millions of Allocations

CHERI Blossoms Conference, 26 – 27 March 2026

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CHERI avoids indirection

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Capability #3

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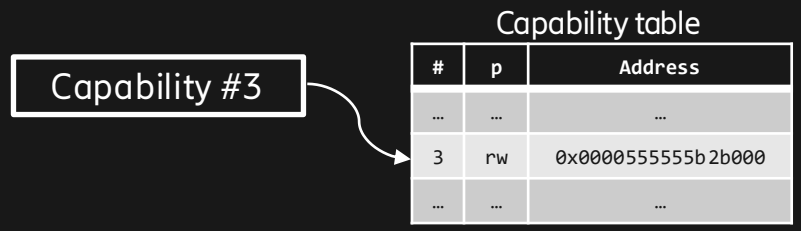

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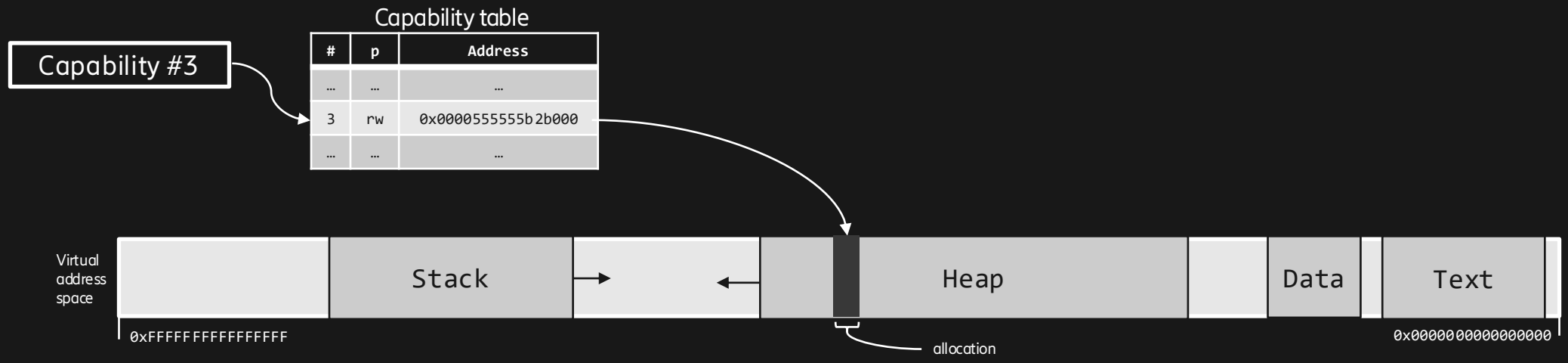

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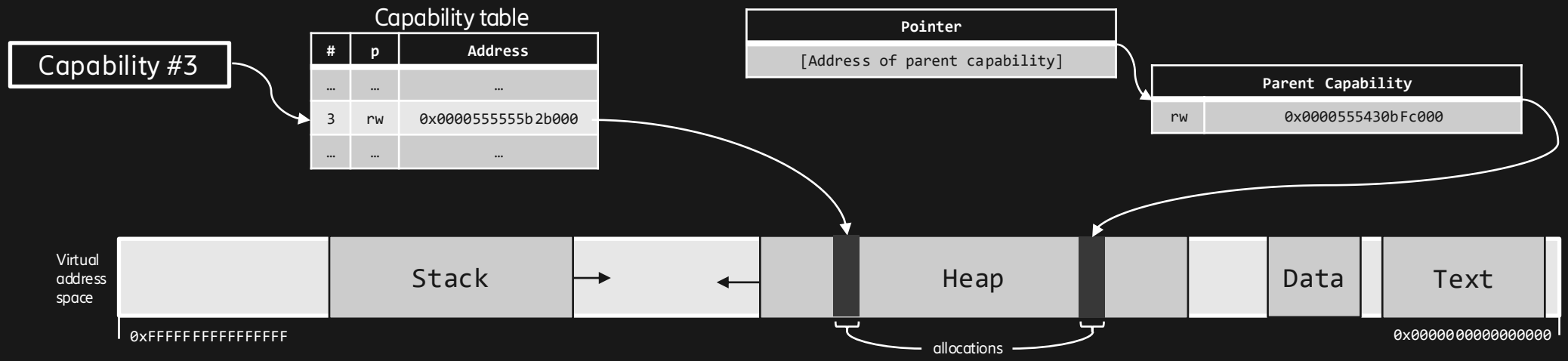
CHERI, *by design*, avoids **table-based lookups** and **indirection on pointer operations**



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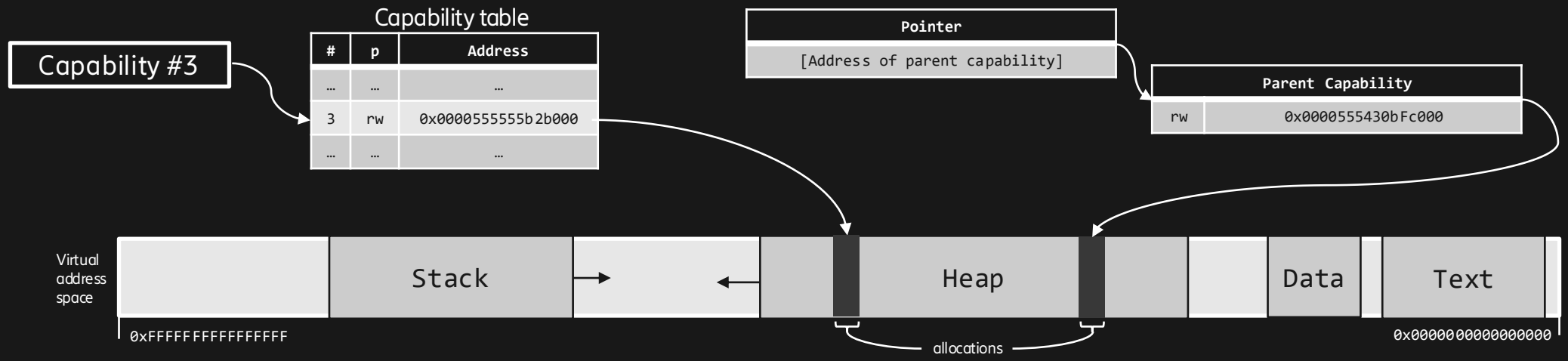

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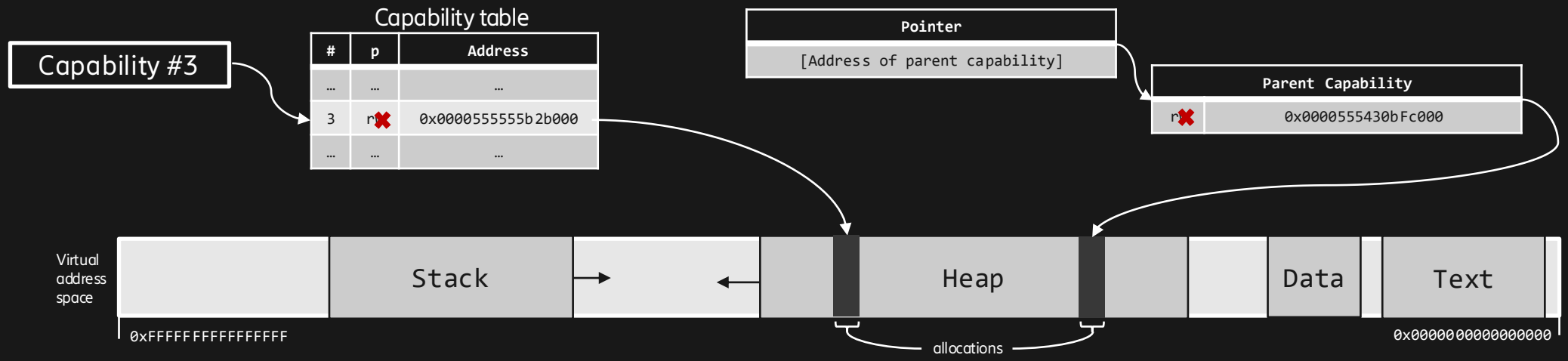

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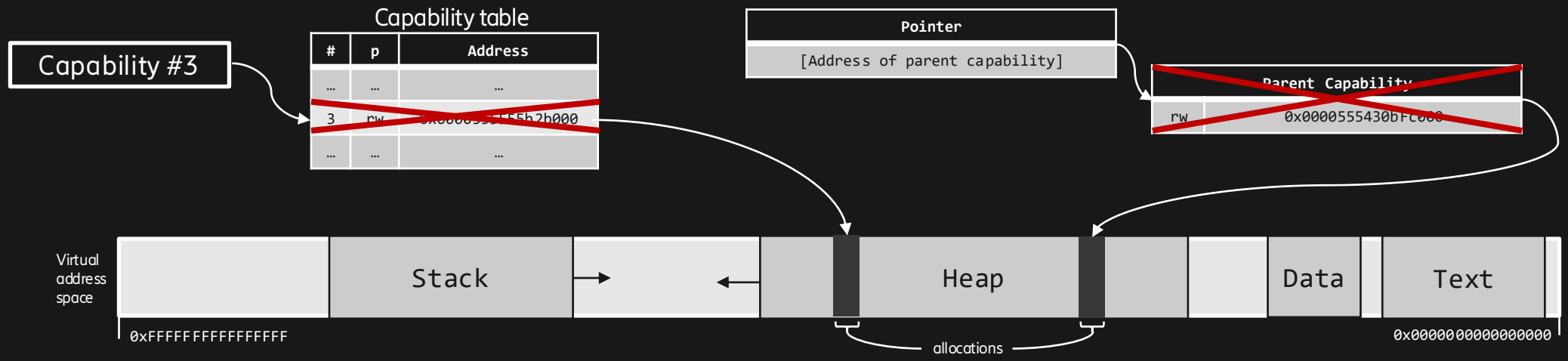

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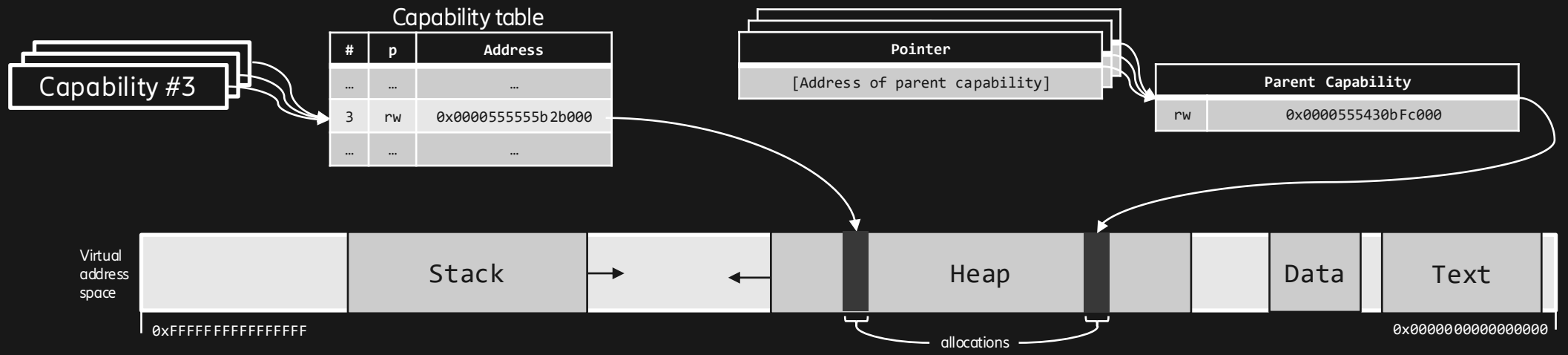

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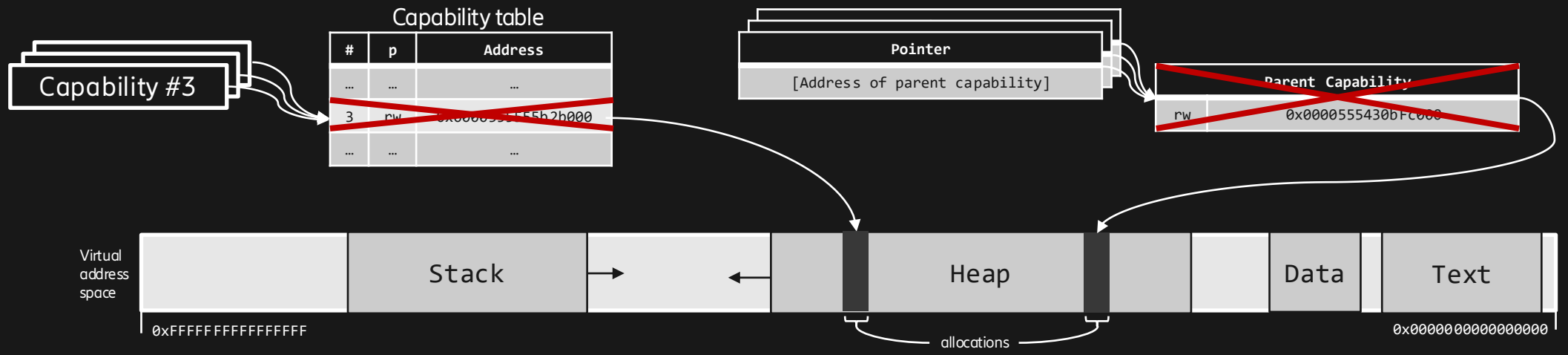

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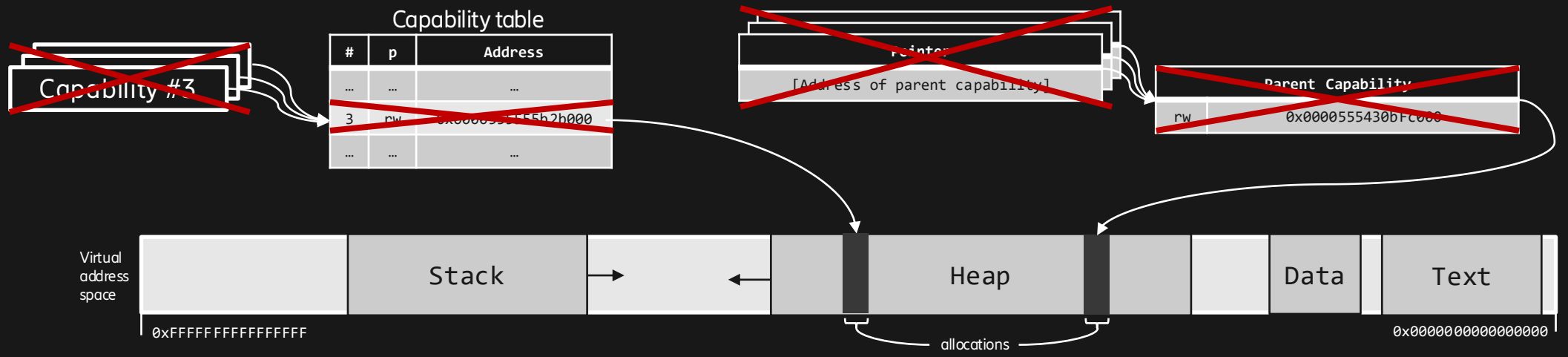
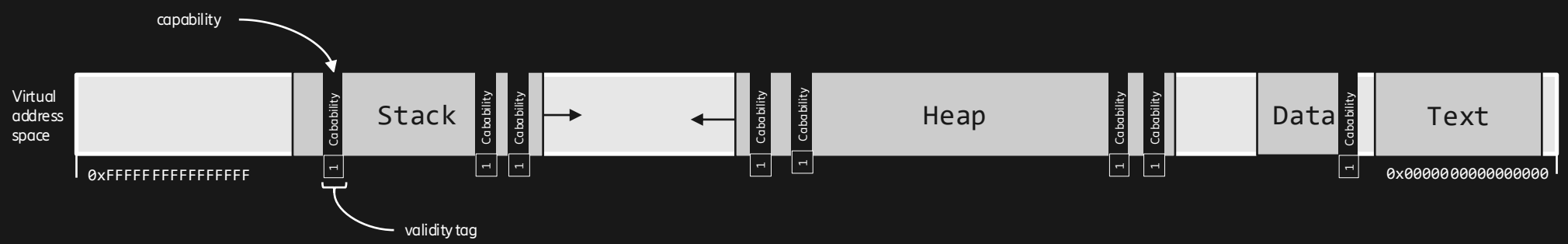


Tradeoffs of avoiding indirection: revocation sweep

In CHERI, revocation requires knowing a capability's (and its validity tag's) location in memory



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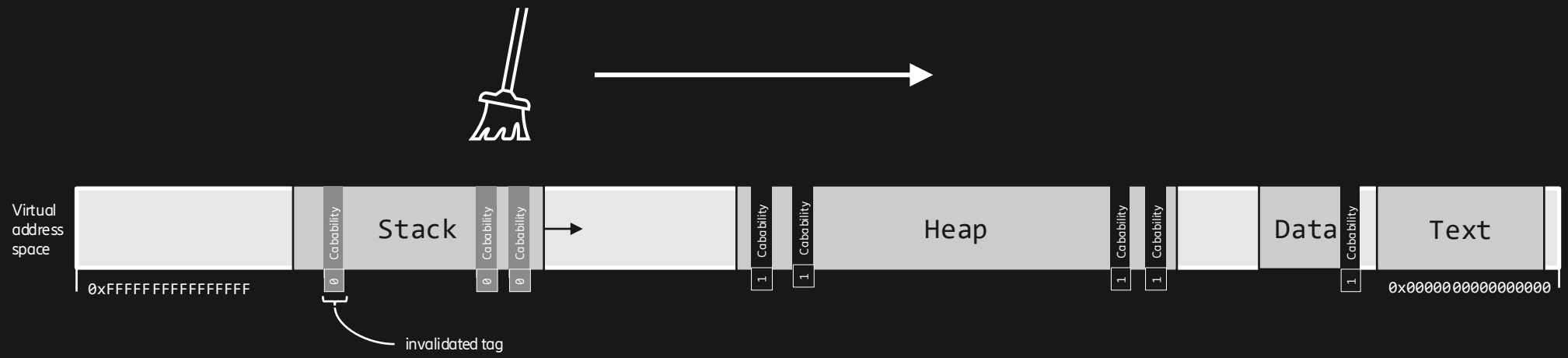

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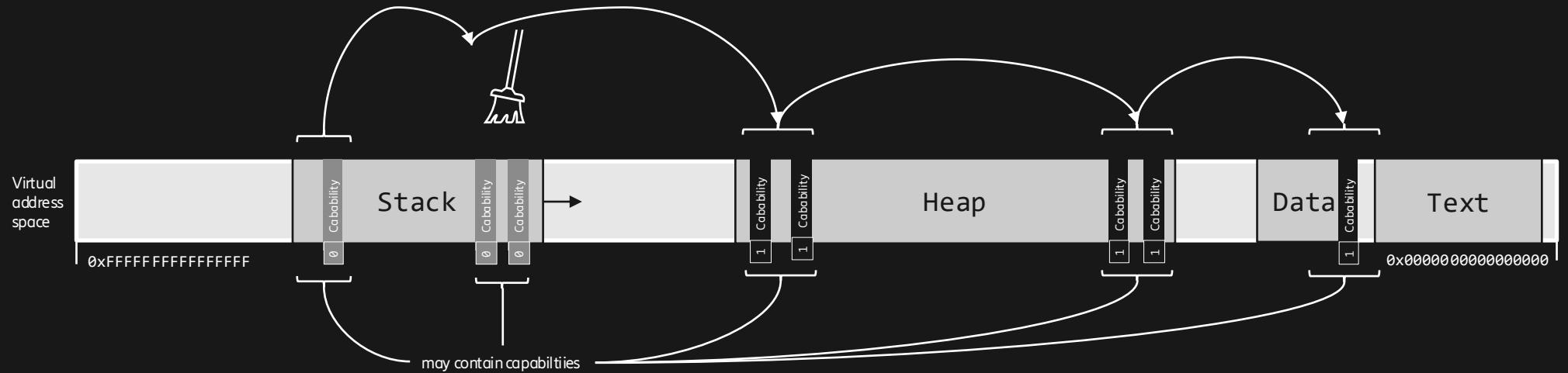

Filardo, N. W. et al. 2024. Cornucopia Reloaded: Load Barriers for CHERI Heap Temporal Safety. ASPLOS '24
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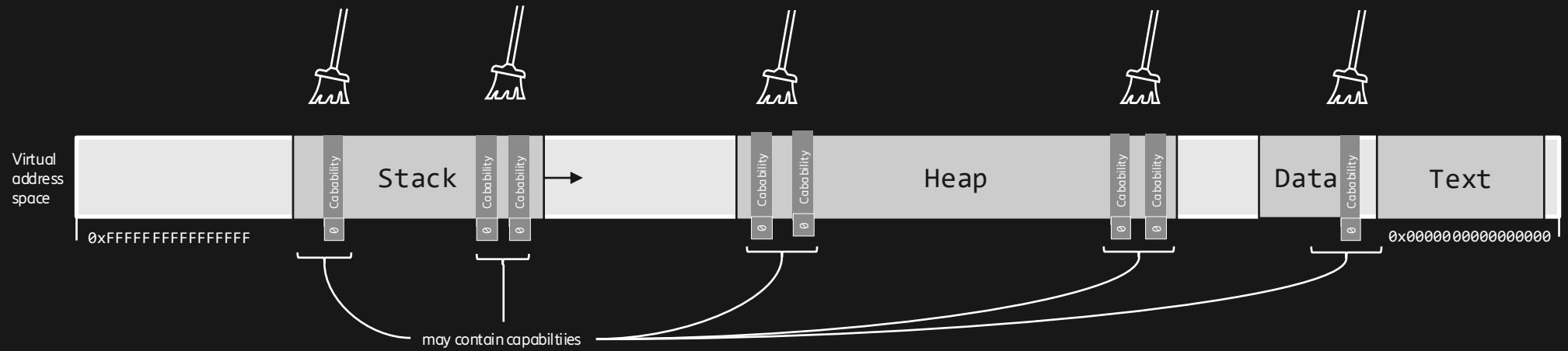

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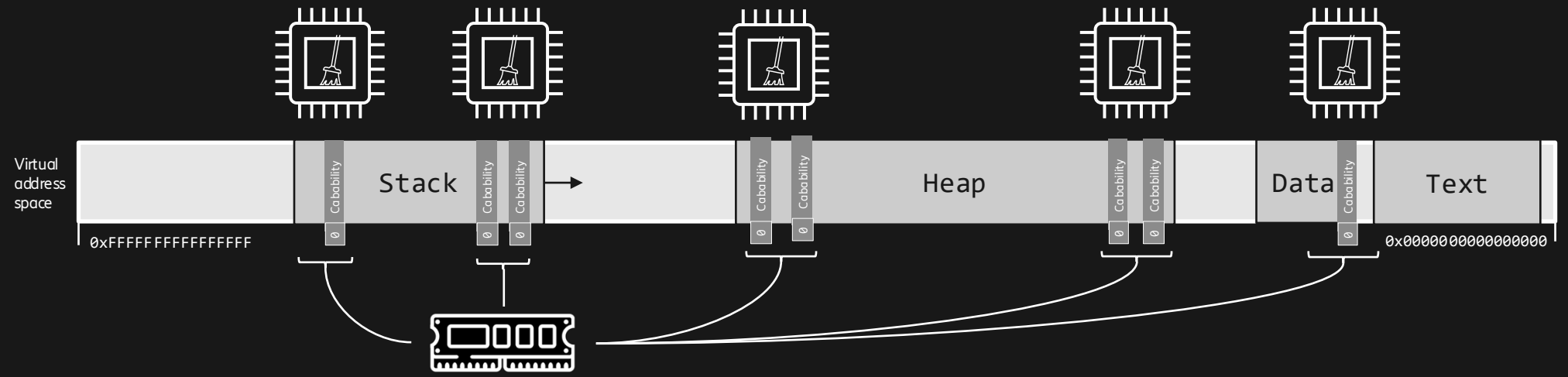
- Invalidating *sets of capabilities* relies on *sweeping revocation*, e.g., for enforcing temporal safety
- Can be sped up by limiting sweeps to pages with capabilities and parallelizing sweeps…
- …but sweeps still consume **overall** system resources: CPU, memory bandwidth..



Rethinking indirection?

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ERICSSON

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In practice, all CHERI temporal-safety schemes have **indirect ways** of keeping track of invalid capabilities

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In practice, all CHERI temporal-safety schemes have **indirect ways** of keeping track of invalid capabilities

- Shadow bitmap in Cornucopia / Cornucopia Reloaded
- Revocation bitmap and load filter in CHERIoT

Filardo, N. W. et al. 2024. Cornucopia Reloaded: Load Barriers for CHERI Heap Temporal Safety. ASPLOS '24
Amar S. et al. 2023. CHERIoT: Complete Memory Safety for Embedded Devices. MICRO '23

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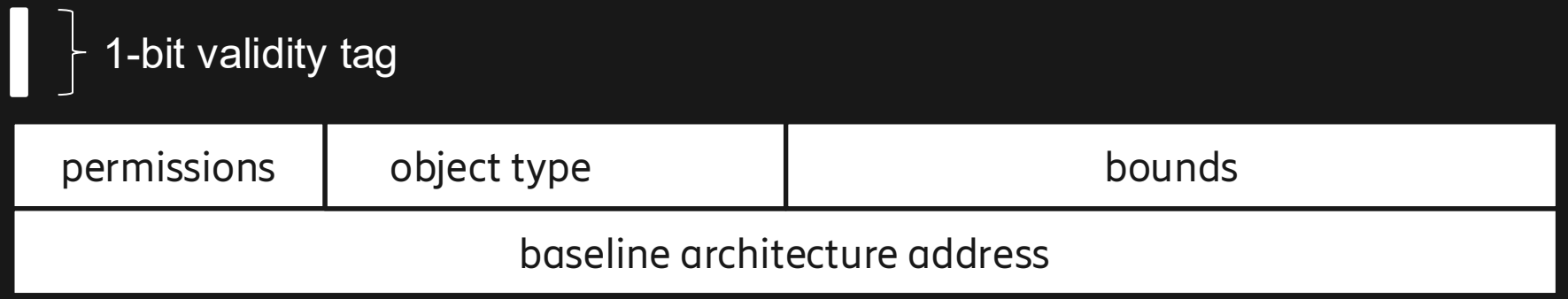
Can we apply **indirection selectively** to only certain capabilities?

Colored Capabilities: High-Level Idea

Colored Capabilities introduce a **limited form of indirection** to CHERI



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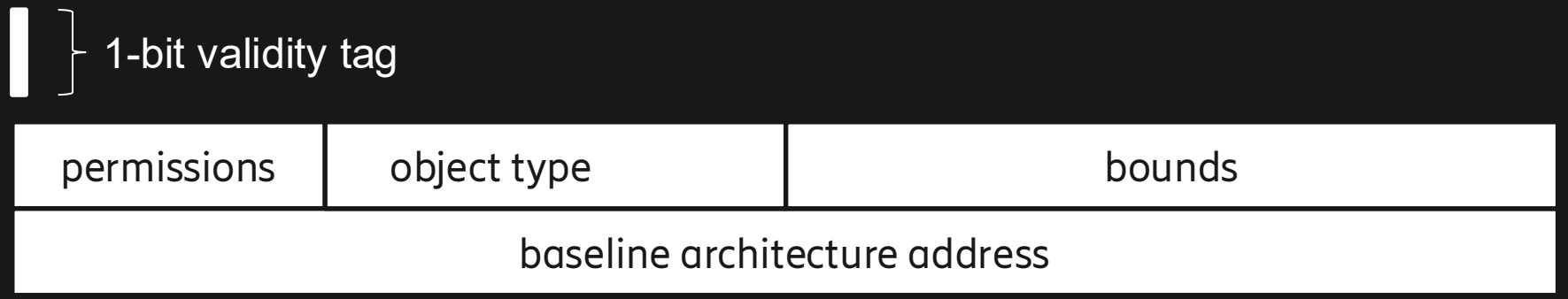

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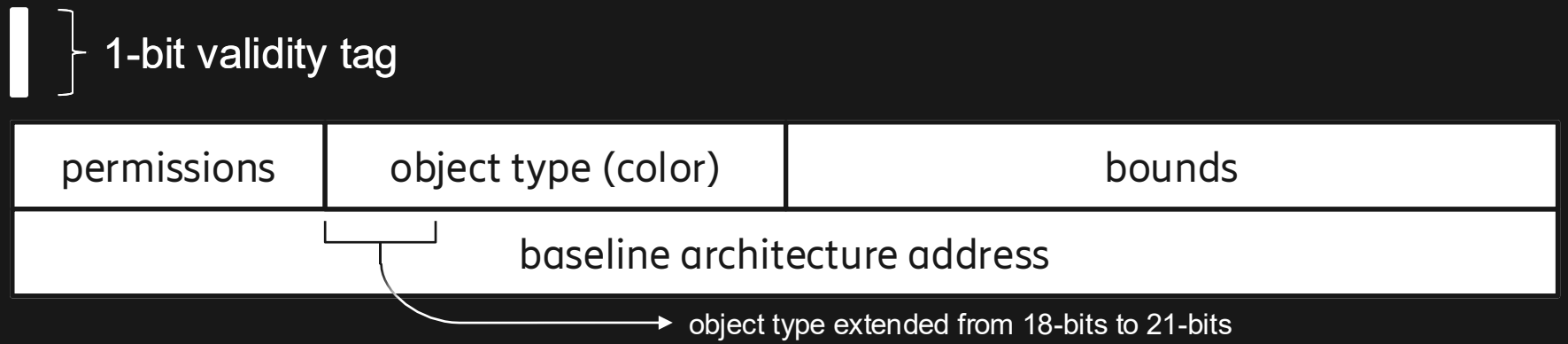

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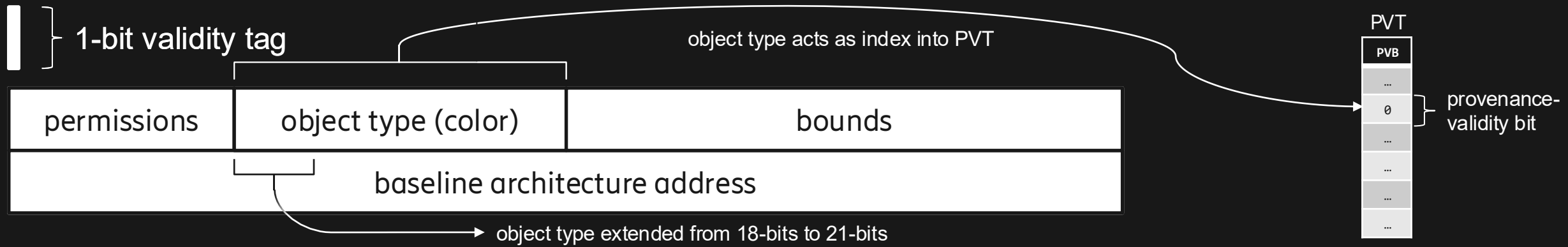

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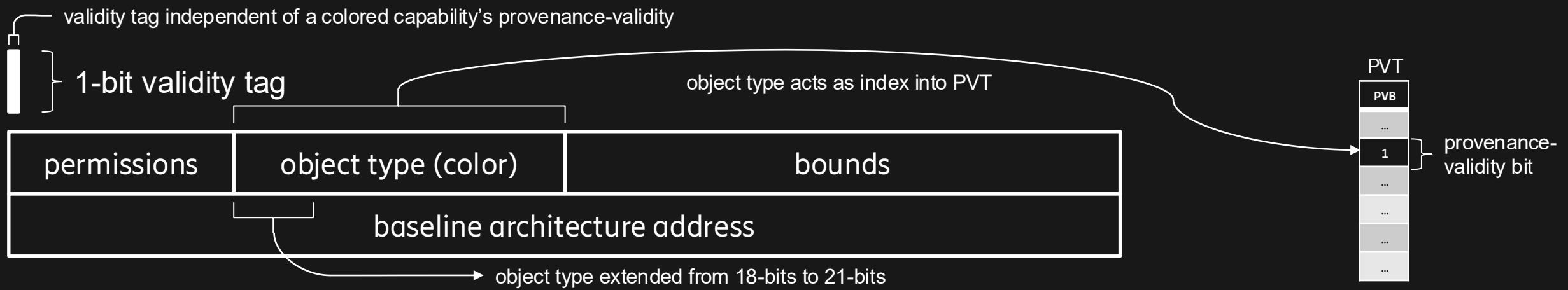
- Capabilities with provenance ID, but no provenance are **temporarily retracted** (not fully revoked)



Temporal Safety using Colored Capabilities

Use After Free / Use After Reallocation

Temporal safety relates to memory locations containing different objects at different points in time

Use After Free (UAF)

Accessing memory through a dangling pointer after original allocation has been freed

Use After Reallocation (UAR)

Dereferencing a dangling pointer after original memory has been reallocated and used for another object

```c
int main(void) {
    int *p = malloc(sizeof(int));
    //..
    free(p);  // p becomes a dangling pointer
    p[0] = 1; // use-after-free violation
    //...  p memory is allocated to p2
    p[0] = 1; // use-after-reallocation
}
```

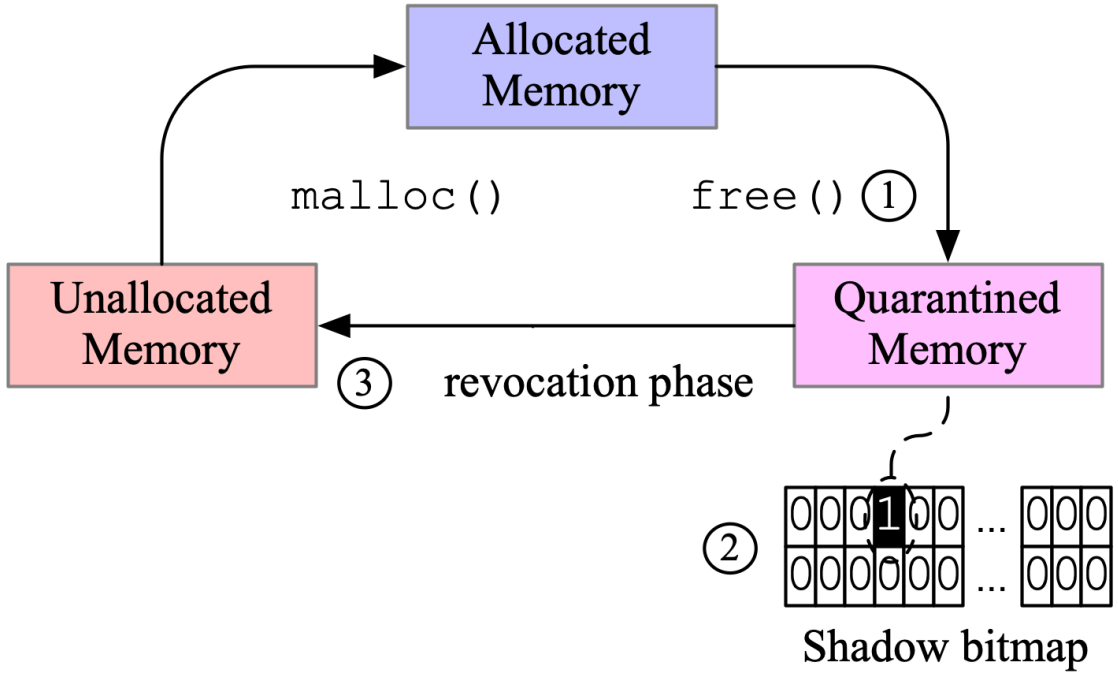
Prior work: Cornucopia

Cornucopia is capability revocation system for CHERI that implements deterministic temporal safety for standard heap allocations

① **Free → Quarantine**: Freed blocks are kept in a quarantine buffer until all capabilities referencing original allocation have been revoked (③)

② **Shadow bitmap**: Freed regions marked at word granularity in shadow bitmap

③ **Periodic sweeping**: Revocation service scans memory for stale (freed) capabilities, clears their tags and frees quarantined memory for reuse



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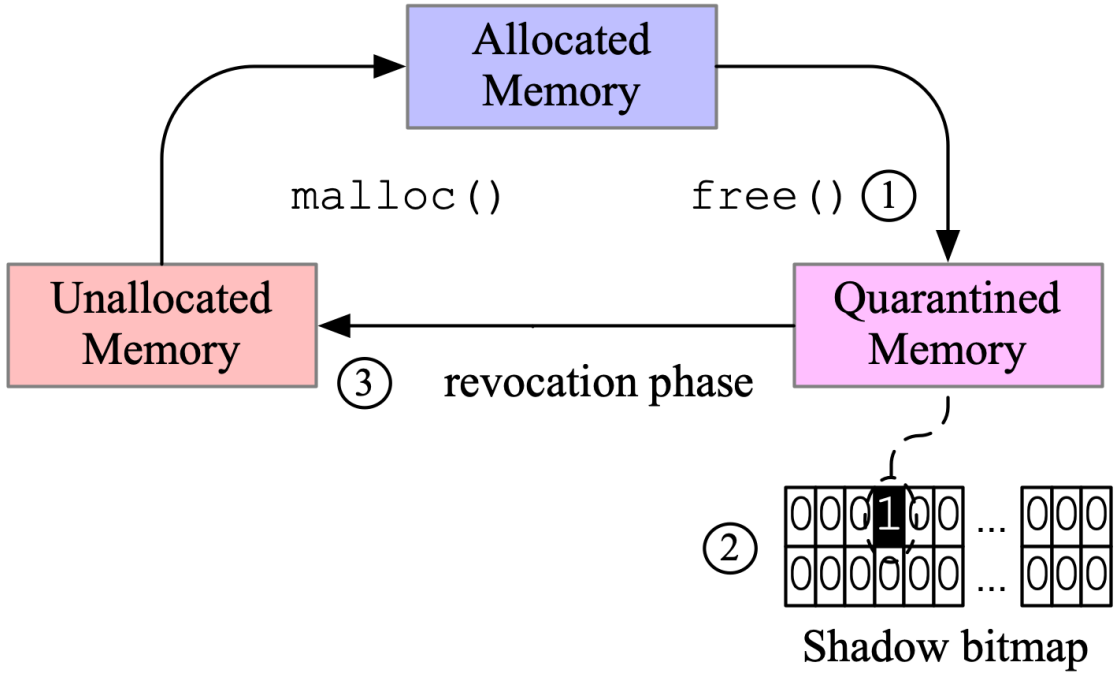

- Only address the use-after-reallocation bugs
- The use of a quarantine buffer increases memory usage
- Revocation frequency scales conversely with memory overhead

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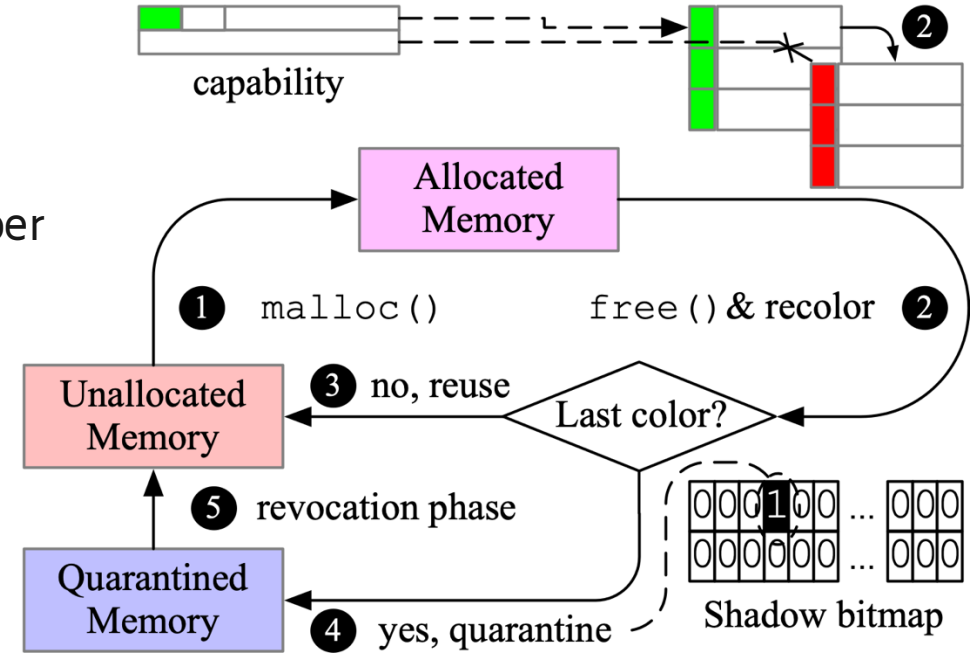
Prior work: Cornucopia + Memory Coloring

Combining CHERI with memory tagging to close the UAR/UAF mitigation gap

1. **Allocation:** capability + memory tag assigned same color ID
2. **Free:** memory is coloring to invalidate stale pointers
3. **Reuse:** freed colors recycled. Detects dangling pointers, but number of colors is limited

When colors IDs (e.g., 16 for MTE) exhausted:

4. Quarantine freed memory
5. Fall back to Cornucopia's capability sweeping



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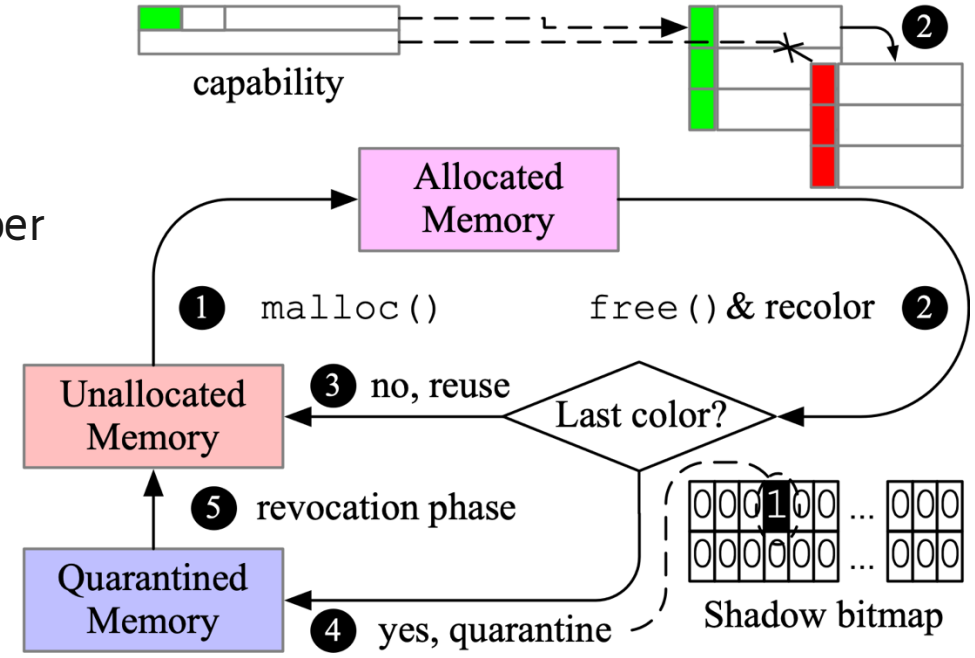

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Colored Capability Goals

Deterministically close the UAF/UAR gap

Immediately reuse free memory (no quarantine buffer)

Reduce the frequency of revocation sweeps

Temporal Safety using Colored Capabilities

2 million color

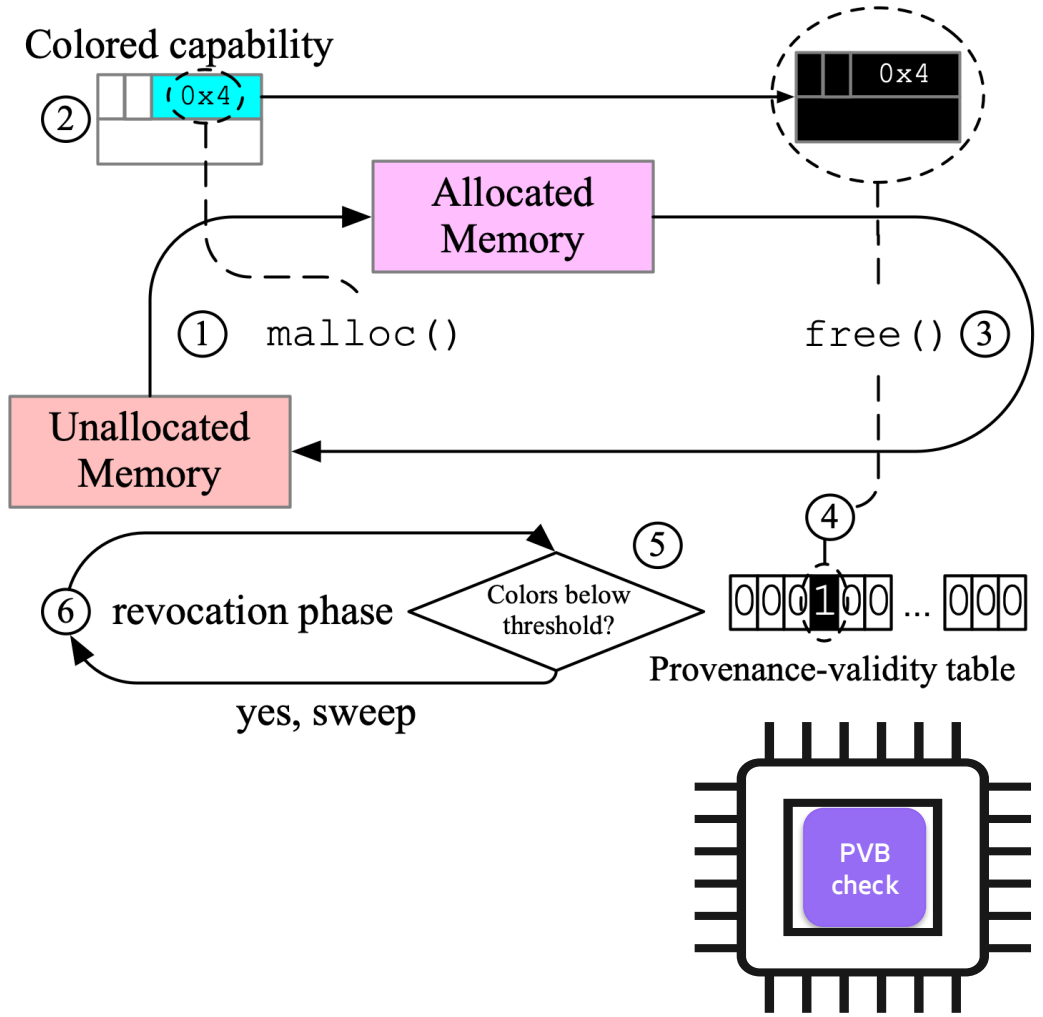
①, ② **On allocation**: Assign a unique provenance ID from available (unassigned) otype (color) values to capability

- Becomes colored capability by setting otype to assigned value

③, ④ **On free**: Mark provenance ID's PVB as invalid in PVT

- CPU prevents dereferences through colored capabilities whose provenance-validity bit (PVB) is invalid

⑤, ⑥ **When available colors below pre-set threshold**: Sweep memory and revoke capabilities marked invalid in PVT



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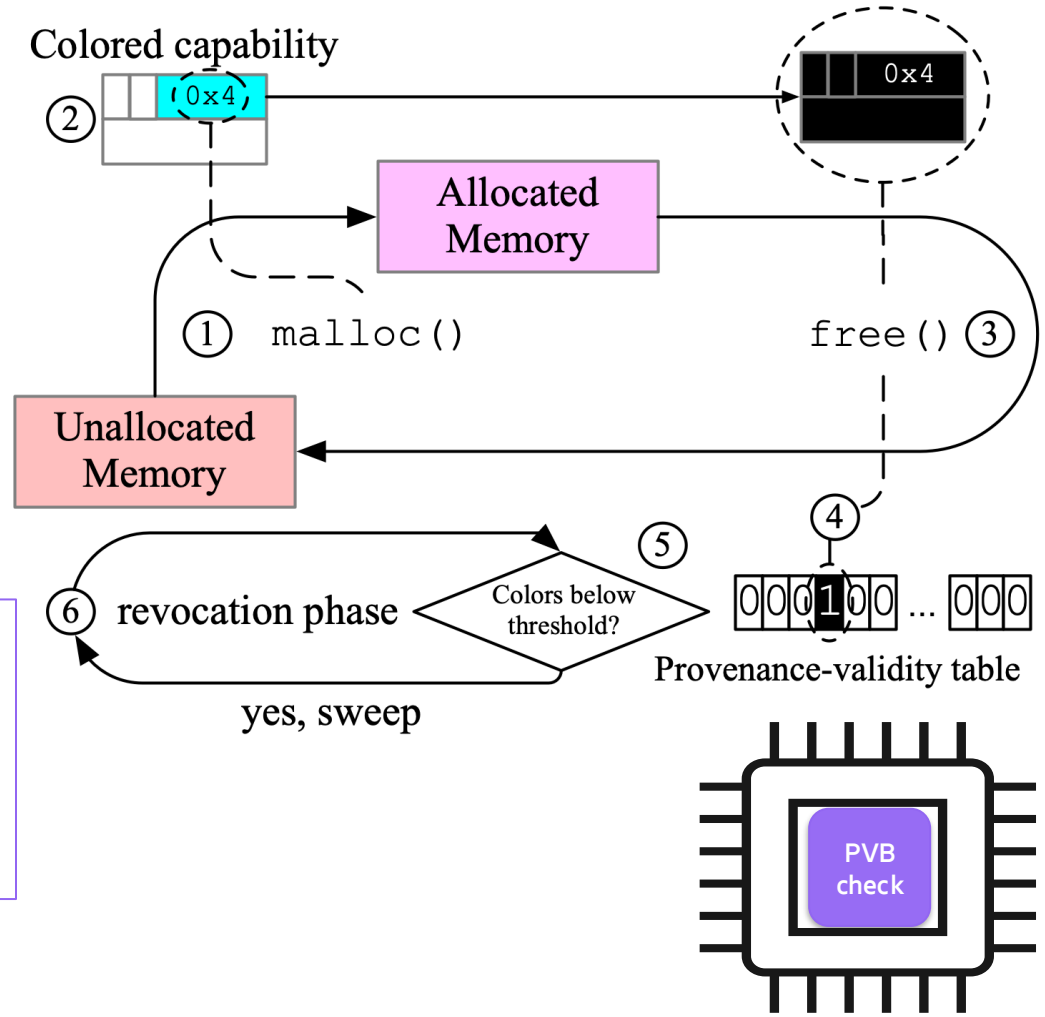


+ Addresses the UAF/UAR gap
+ Immediately reuse freed memory
+ Revocation frequency scales with number of supported colors

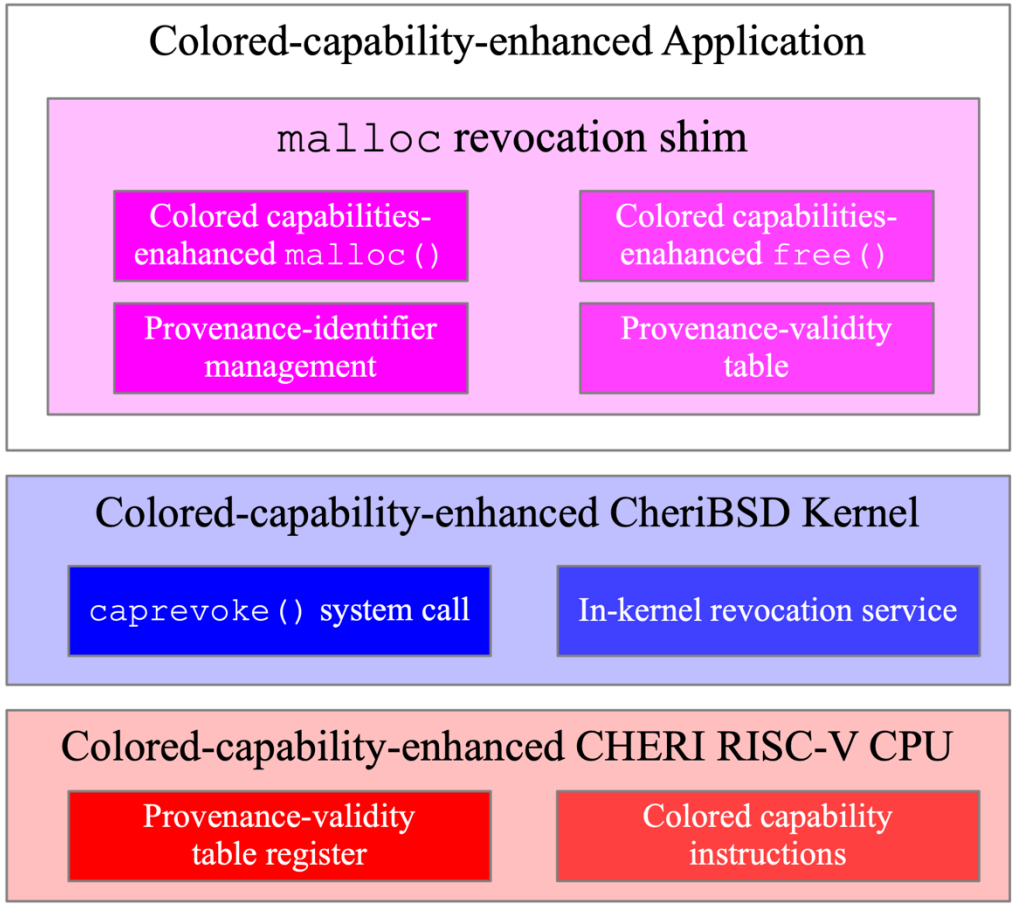
PICASSO: Colored Capability System Architecture

Hardware: We implemented two versions of PICASSO:

1. QEMU-system-CHERI128 full-system emulator, and
2. CHERI-Toooba processor with colored capability support
   - Supporting ~2 million of allocations using 21-bit otype
   - PVB checks on loads and stores using colored capabilities
   - PVB buffer caching PVT fetches, reducing cycle overhead
   - Compatible with CHERI sealing by reserving subset of otypes

Software: We integrated colored capabilities into CheriBSD 25.03.

- Memory allocator support by integrating colored capabilities into CheriBSD malloc revocation shim (MRS)
- Userspace provenance-identifier management (unr allocator)
- Colored Capability-enhanced revocation integrated into CherBSD in-kernel revocation service



Evaluation

RQ1: Can PICASSO reliably detect UAF conditions?

RQ2: What is the performance and memory overhead of enforcing temporal-safety with PICASSO?

RQ3: To what extent does PICASSO reduce the frequency of CHERI revocation sweeps?

RQ1: Can PICASSO reliably detect UAF conditions?

We evaluate PICASSO using Juliet Test Suite:

- All CWE-416 (Use After Free) test cases
- All CWE-415 (Double Free) test cases
- In total: 1385 "bad" test cases
- Equal number of "good" (patched) test cases

PICASSO detects **all bad cases** and **no false positives**

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We compare our results against CheriBSD Cornucopia in two-different configurations:

- Default configuration fails to detect any bad CWE-416 cases (since test cases do not reallocate)
- In **revoke-on-free** configuration Cornucopia detects all CWE-416 cases but at increased perf overhead
- Both configurations detect all CWE-415 bad cases

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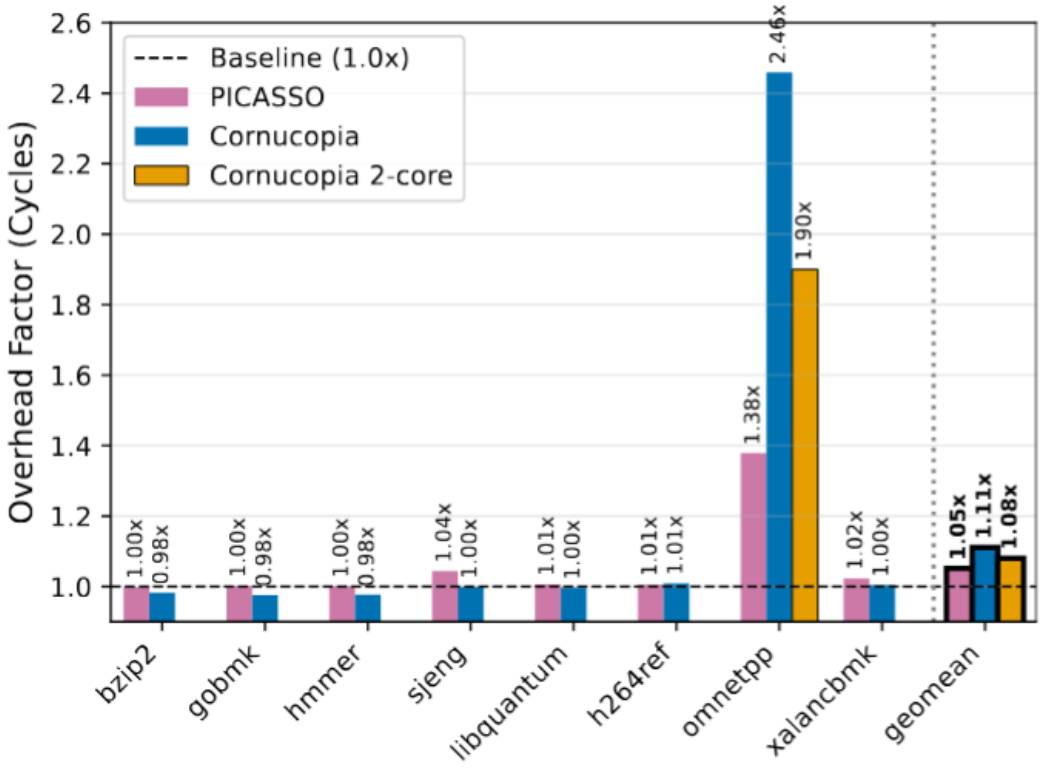
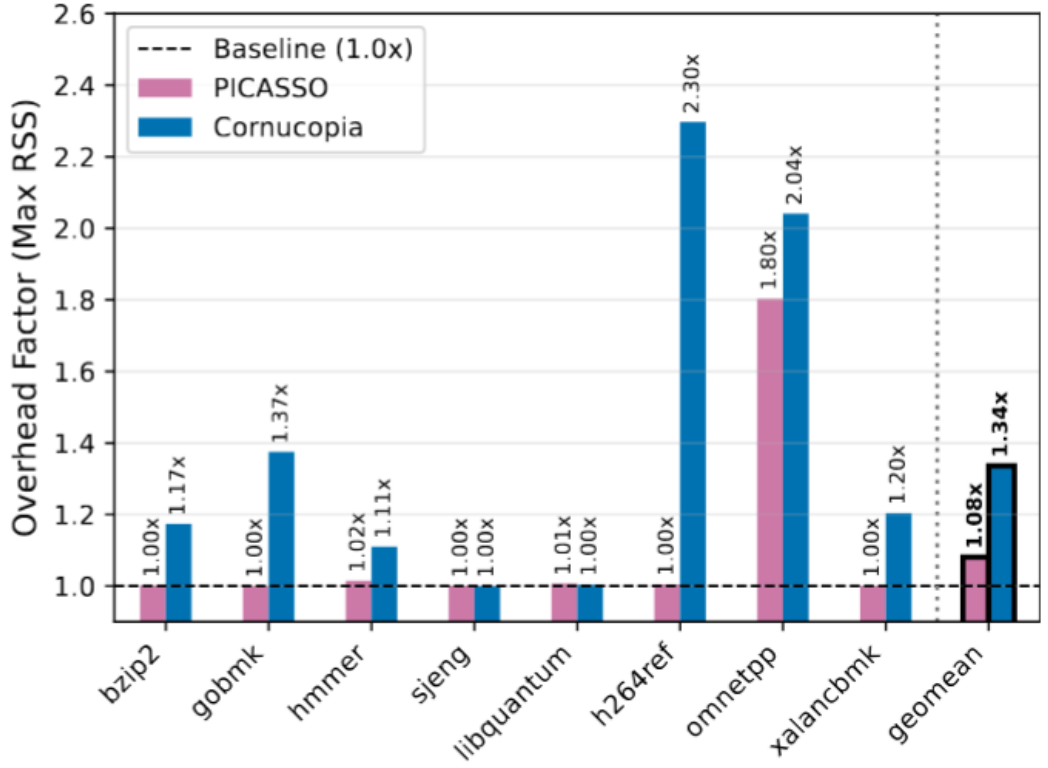
PICASSO achieves perfect, deterministic accuracy in detecting use-after-free conditions
PICASSO successfully closes the UAF / UAR gap

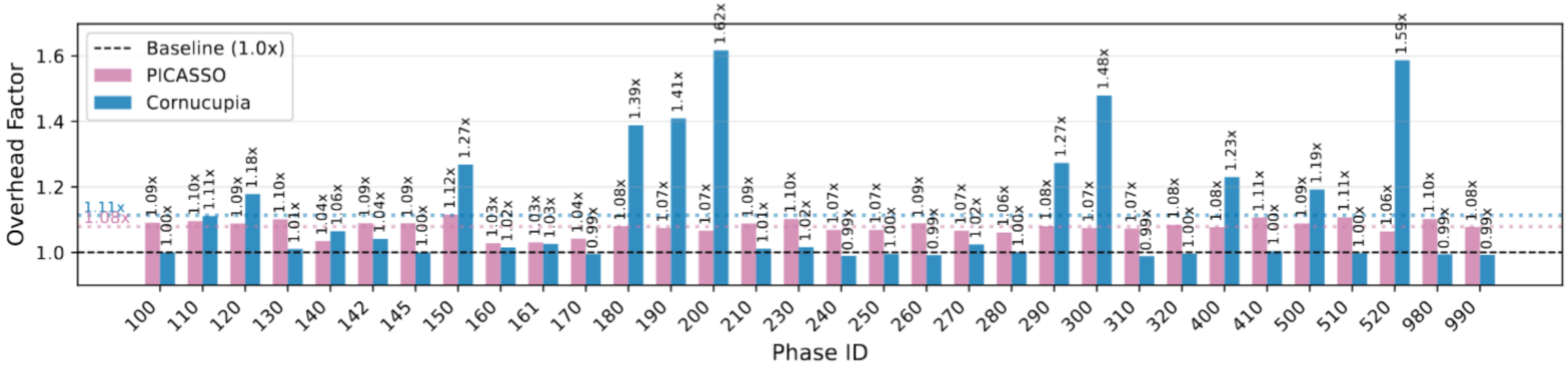
RQ2: SPEC 2006 benchmark Results





- **Performance overhead**: PICASSO (5% g.m.) and CheriBSD 25.03 Cornucopia (11% g.m. single-core, 8% g.m. 2-core)
- **Memory overhead** (measured as maximum resident set size): PICASSO (8% g.m.) and Cornucopia (34% g.m.)

RQ2: SQLite speedtest1



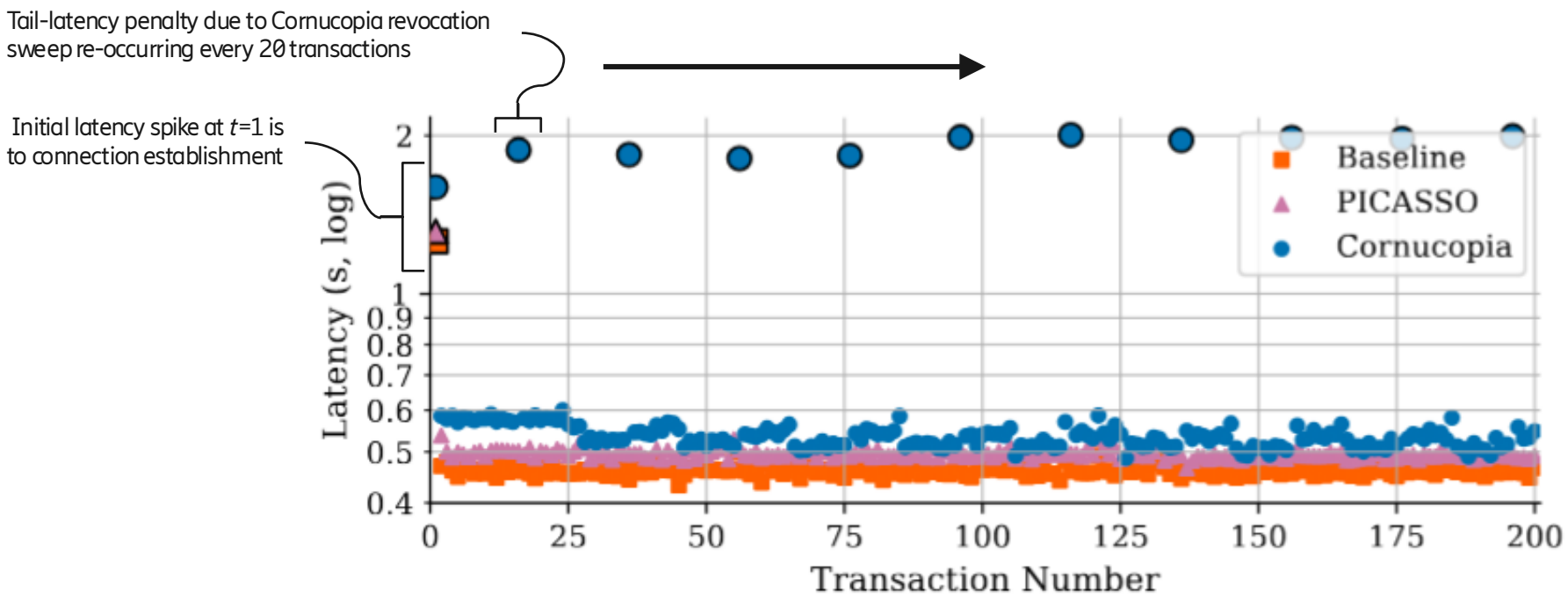
Performance overhead

- PICASSO: 8% avg., 12% max.
- Cornucopia: %12 avg., 62% max.

Memory overhead

- PICASSO: no memory overhead
- Cornucopia: 99% memory overhead across whole benchmark

RQ2: PostgreSQL pgbench



Latency graph for 200 sample pgbench transactions with markers denoting individual response times

Throughput degradation (transactions per second)

- PICASSO: 6.2%
- Cornucopia: 23.1%

RQ3: Reduction in frequency of revocation sweeps?

		# Revocations	
Benchmark	**# Allocations**	**Cornucopia**	**PICASSO**
bzip2	87	3	0
gobmk	121361	17	0
hmmer	170126	16	0
sjeng	5	0	0
libquantum	108	1	0
h264ref	38270	12	0
omnetpp	129620400	2792	76
xalancbmk	1057345	2	0
SQLite	224917	272	0
Benchmark	**# Transactions**	**Cornucopia**	**PICASSO**
PostgreSQL	≈66000	≈ 3300	1
gRPC	≈100000	≈ 400	1

No revocation with PICASSO in majority of benchmarks

- Further experiments with long-running PostgreSQL and gRPC benchmarks show that PICASSO significantly reduces revocation time without increasing the latency percentile even with p999

Conclusion

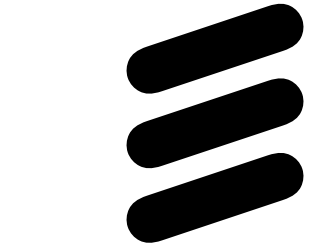
Colored Capabilities enhance CHERI's temporal memory safety through efficient support for **bulk retraction** of capabilities

Colored Capabilities add **limited indirection** to CHERI's capability model and

- Address the **UAR/UAF gap**
- Reduces memory overhead by **eliminating quarantine buffers**
- Significantly **reduce the frequency of needed revocation sweeps**

https://arxiv.org/abs/2602.09131

- Evaluation on **thousands of NIST Juliet test cases**, **SPEC CPU benchmarks**, and **latency-sensitive real-world benchmarks** confirm that **colored capabilities improve temporal safety** with **reasonable performance overhead** (3% – 8% overhead on average compared to CHERI purecap baseline)



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