PICASSO: Scaling CHERI Use-After-Free Protection to Millions of Allocations using Colored Capabilities

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ARTIFACT EVALUATED USENIX AVAILABLE

ARTIFACT EVALUATED USENIX FUNCTIONAL

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https://github.com/coloredcapabilities

https://www.usenix.org/conference/usenixsecurity26/presentation/guelmez

Colored Capabilities introduce a limited form of indirection to CHERI which allows tracking allocation provenance (whether a capability corresponds to valid allocation)

Hardware support for **memory safety**, such as **CHERI**, is attractive for securing existing codebases in unsafe languages, e.g., C and C++

- CHERI replaces conventional pointers with **capabilities**

An ordinary "pointer" (reference to memory)

`0x7ffe204`

Just a number. Nothing records where it's allowed to point or what it's allowed to do – a bug can send it anywhere!

A CHERI capability consists of:

- **Address** – where it points to
- **Bounds** – the range it may touch
- **Permissions** – read / write / execute
- **Validity tag** – proof it hasn't been forged

On CHERI processors memory accesses checked by hardware to ensure they:

Stay within bounds (spatial safety)
A capability can only reach memory range it is valid for; out-of-bound accesses are refused

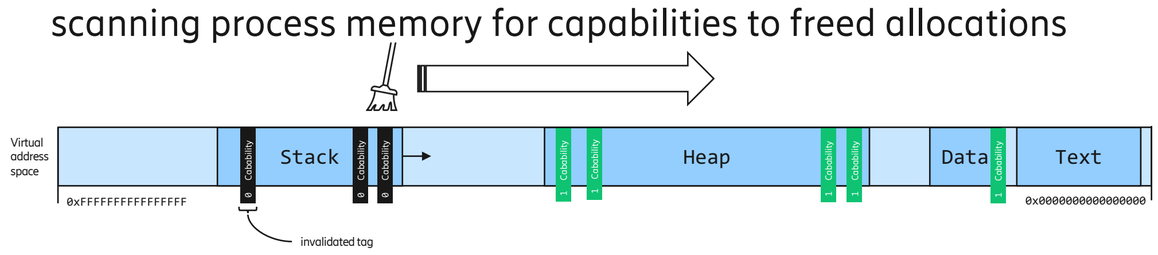
Can't be forged
Every capability is associated with a hardware tag; attempts to tamper with a fabricate a capability instantly invalidates it

Has the correct rights
Capabilities embody the principle of least privilege; can only be used in permitted operations

Any violation of these rules makes the hardware immediately block attempted memory access; buffer overflows, forged capabilities or out-of-bounds reads never succeed

To ensure **temporal safety** (memory not accessed outside lifespan) CHERI capabilities must be **revoked** when a heap allocation is freed

- Revocation requires knowing a capability's (and its validity tag's) location in memory and invalidating its tag
- CHERI temporal safety relies on **sweeping-based revocation:** scanning process memory for capabilities to freed allocations



The revocation sweep is **CHERI's Achilles' heel**; temporal-safety solutions for CHERI postpone revocation by quarantining freed memory


Image generated using AI

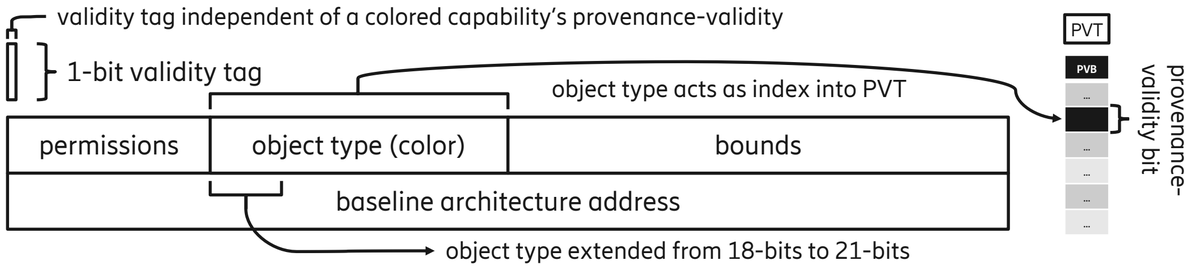
Cornucopia & Cornucopia Reloaded:

- Only address use-after-reallocation bugs: **use-after-free / use-after-reallocation gap**
- Quarantined allocations only reuseable after revocation: **add to memory overhead**
- Revocation frequency **scales** inversely with memory overhead

Filardo, N. W. et al. 2020. Cornucopia: Temporal Safety for CHERI Heaps. IEEE S&P '20.
Filardo, N. W. et al. 2024. Cornucopia Reloaded: Load Barriers for CHERI Heap Temporal Safety. ASPLOS '24

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

- Track **allocation provenance** of capabilities: *whether* a capability corresponds to valid allocation (but not *which* allocation)
- Capabilities sharing provenance also share **provenance ID** ("color") stored in a capability's object type (otype) field
- Validity of ID's provenance tracked by 1-bit entry (PVB) in **provenance-validity table** (PVT)
- Capabilities with provenance IDs, but invalid provenance are **temporarily retracted** (rendered unusable, but not fully revoked)



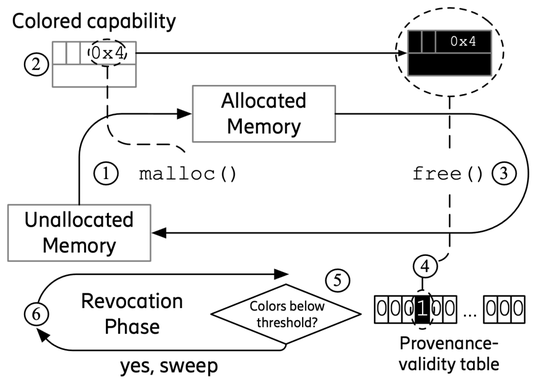
Colored Capabilities improve precision of CHERI's temporal safety:

Use After Reallocation (UAR)
Dereferencing dangling pointer after memory has been reallocated and used for another object

Use After Free (UAF)
Accessing memory through a dangling pointer after original allocation has been freed

Colored Capabilities:

+ Address the **UAF/UAR gap**
+ Allow **immediate reuse** of freed memory
+ Revocation frequency **scales with number of supported colors**



①, ② **Allocation**: assign unique provenance ID from unassigned color values to capability

③, ④ **Free**: Invalidate provenance ID's PVB in PVT

⑤, ⑥ **Unassigned colors below threshold**: Sweep memory and revoke capabilities with invalid PVB

We implement Colored Capabilities in PICASSO extension to CHERI ISA

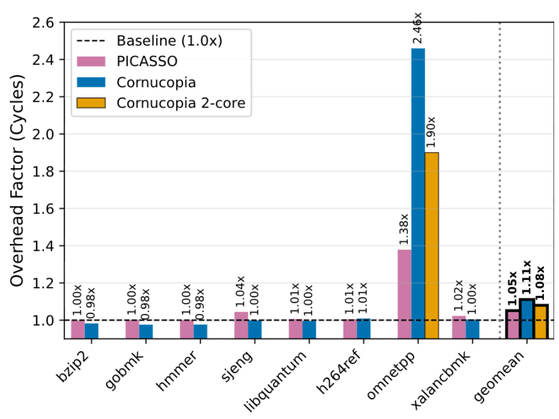
Hardware: Two versions of PICASSO provided in artifact
1. QEMU-system-CHERI128 full-system emulator, and
2. CHERI-Toooba processor with colored capability support

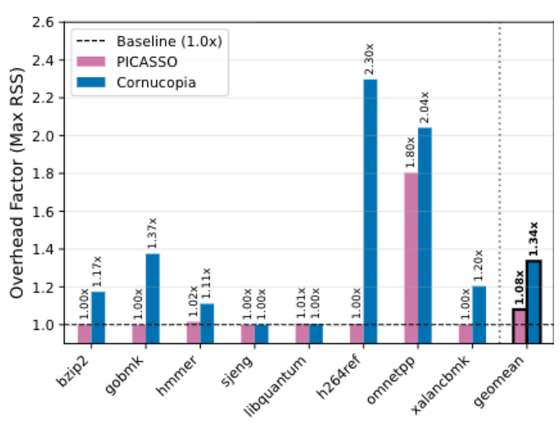
Software: Colored Capability support in CheriBSD 25.03
- Drop-in userspace support through CheriBSD malloc revocation shim (MRS)
- Userspace provenance-identifier management (unr allocator)
- Integration with CheriBSD in-kernel revocation service

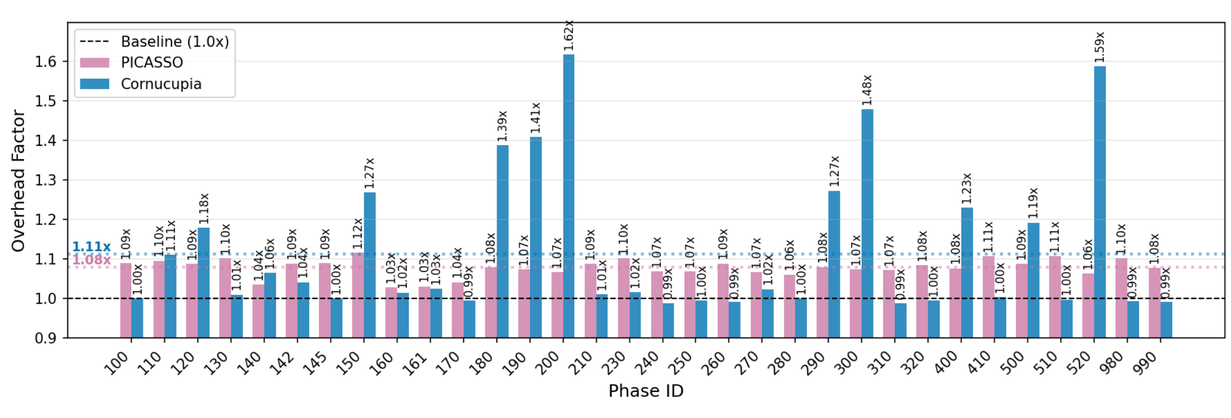
We evaluate PICASSO using Juliet Test Suite:
- All CWE-416 (Use After Free) test cases
- All CWE-415 (Double Free) test cases
- In total: 1385 "bad" test cases
- Equal number of "good" (patched) test cases

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

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 unpractical overhead
- Both configurations detect all CWE-415 bad cases







Evaluation: SPEC CPU 2006
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.)

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

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