CrypTag: Thwarting Physical and Logical Memory Vulnerabilities using Cryptographically Colored Memory

Pascal Nasahl, Robert Schilling, Mario Werner, Jan Hoogerbrugge, Marcel Medwed, Stefan Mangard

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Motivation

Memory Safety Vulnerabilities

- MITRE: 3 out of 10 are memory vulnerabilities [MIT19]
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- Entry point for various attacks

Memory Safety Vulnerabilities

- Logical Memory Safety Vulnerabilities
- Physical Memory Safety Vulnerabilities

Phyiscal Memory Safety Vulnerabilities

- Exposed external memory
- Cold-boot [Hal+08], Bus sniffing [Nur20]
- Software-based attacks
- Cloud and IoT

Thwarting Phyiscal Memory Safety Vulnerabilities

- Confidentiality & Integrity
- Memory Encryption
- Average runtime overheads between 5 % and 109.8 %
- Broadly available in Intel and AMD processors

Logical Memory Safety Vulnerabilities

- Memory vulnerabilities exploit a memory bug
- Classified in spatial and temporal memory bugs
- Temporal error: dereferencing a dangling pointer
- Spatial error: out-of-bounds access

Logical Memory Safety Vulnerabilities

- Use the pointer: [Sze+13]
  - Modify a data pointer
  - Modify code and data
  - Modify a code pointer
  - Output data

Thwarting Logical Memory Safety Vulnerabilities

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- Data-flow integrity
  - DFI, HDFI: Enforcing data-flow graph
- Code-pointer integrity
  - CPI: Store in safe region
- Code- and data-pointer integrity
  - PARTS: Integrity of all code- and data-pointers

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  - Softbound, Hardbound: Bounds for each object
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- **Large** performance overhead
- **Hardware support is needed!**

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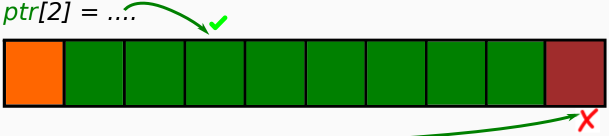
*char *ptr = new char[8];*
ptr[2] = ...



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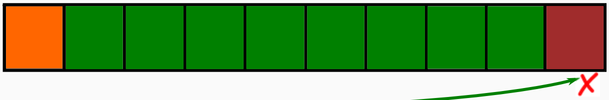

ptr[8] = ...

- Memory Allocation: lock object with a distinct color
- Memory Access: access object with the correct color

Tagged Memory

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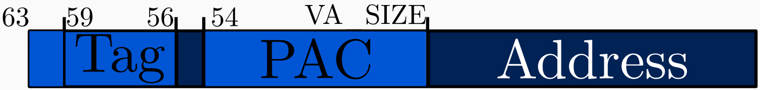

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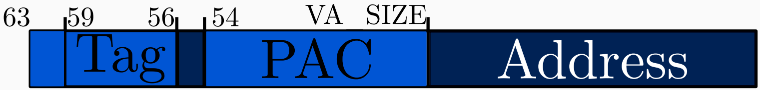

- Google's MemTagSanitizer utilizes MTE for memory coloring

Tagged Memory Overhead

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- High detection probability for tag sizes of 16-bits
- Increases memory overhead to 12%
- Security $\leftrightarrow$ Memory Overhead
- Mainly used for debugging

CrypTag

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- Maximize security guarantees and keep overhead at a minimum

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- Goal: Enforcing **physical** and **logical** memory safety
- Maximize security guarantees and keep overhead at a minimum
- Combining transparent memory encryption and memory coloring

Concept

- Each memory object is tagged with a color
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- Each memory object is tagged with a color
- Color is transported in upper bits of the pointer
- Color tweaks the encryption of the memory object
- Each memory object is encrypted with a distinct color
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  → No color storage overhead

  → No memory traffic overhead

  → Increase color size

Color Mismatch

- Memory encryption
  - Color mismatch decrypts with wrong tweak
  - Security policy **S1**

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- Memory encryption and authentication
  - Color mismatch triggers an authentication error
  - Security policy **S2**

Implementation

Hardware Support

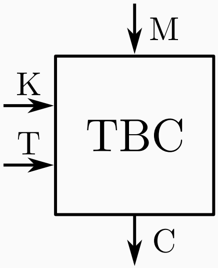
- Minimal hardware changes

Hardware Support

- Minimal hardware changes
- Instruction to set color in unused upper bits of a pointer
- MMU ignores theses bits in address translation
- Cache is extended to store the color
- CrypTag allows sub-cache line granularity

Memory Encryption

- Based on a system with transparent memory encryption
- Encryption or encryption and authentication
- Tweakable block cipher
- MEMSEC [Wer+17]
  - **S1**: QARMA
  - **S2**: ASCON



Software Support

- Protection of heap, local, and global data

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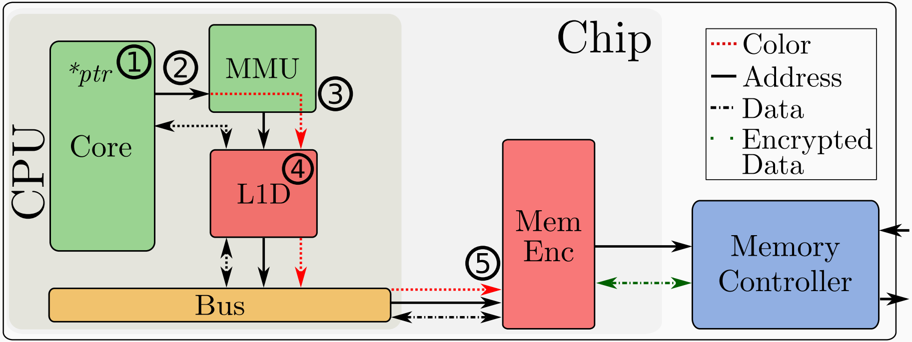
- Protection of heap, local, and global data
- Automatic instrumentation:
  - LLVM toolchain for local and global data
  - Tiny runtime library for heap allocations

```c
void* __wrap_malloc(size_t size) {
  size = roundup(size);
  void *ptr = __real_malloc(size);
  if (ptr == NULL) return NULL;
  return mstp(ptr);
}
```

CrypTag


Chip
CPU
*ptr
1
2
3
4
5
Core
MMU
L1D
Bus
Mem
Enc
Memory
Controller
Color
Address
Data
Encrypted
Data

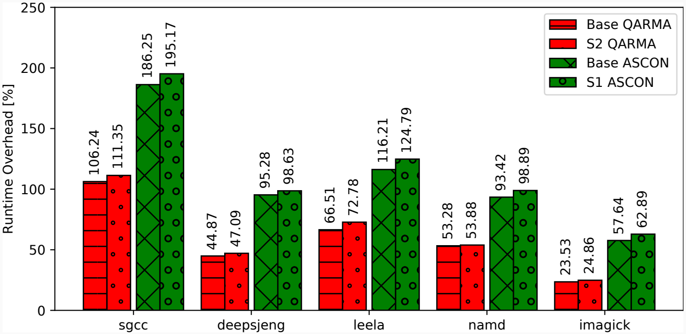
Evaluation

Hardware Overhead

- Hardware overhead of less than 93%
- Tag generation and transportation
- Cache overhead
  - Between 1.56% and 19.53%

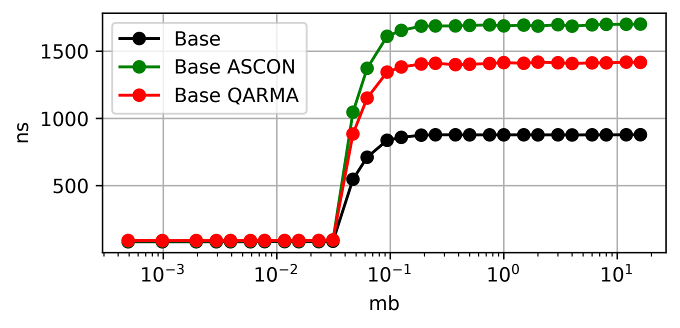
Runtime Overhead

- SPEC2017: 5.2% and 6.1%
- SciMark2: 3.9% and 4.79%
- MiBench: 1.5% and 4.9%



Prototype Limitations

- On top of the memory encryption overhead
- MEMSEC: up to 110%
- Commercial solutions [Rob20]: 5% to 26%



Security Discussion

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- CrypTag is a probabilistic scheme
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- Temporal memory safety:
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  - **S2**: Authentication error
- Physical memory safety

Conclusion

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- Extension to systems already featuring a transparent memory encryption
- Memory coloring scheme utilizing transparent memory encryption
- Low performance ($< 6.2\%$) and hardware overhead ($< 1\%$)
- Larger tag sizes (e.g., 25-bits)
- Suitable as a security countermeasure
- RISC-V implementation and custom LLVM-based toolchain

Thank you!

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