Cage

Hardware-Accelerated Safe WebAssembly

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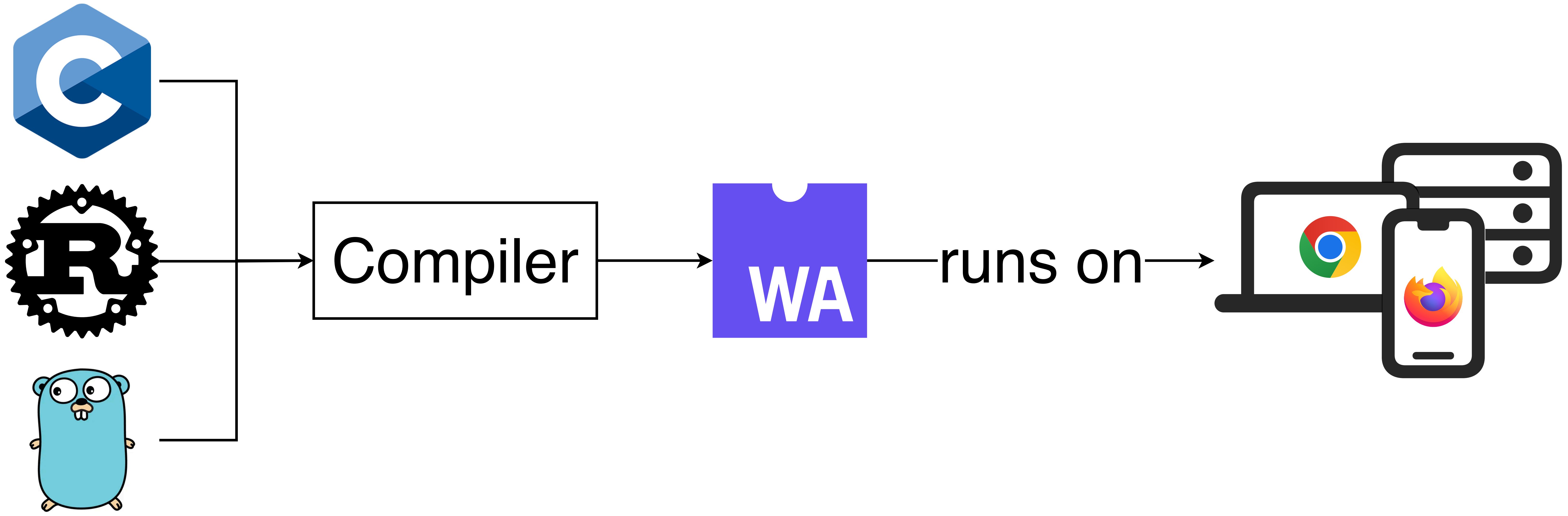
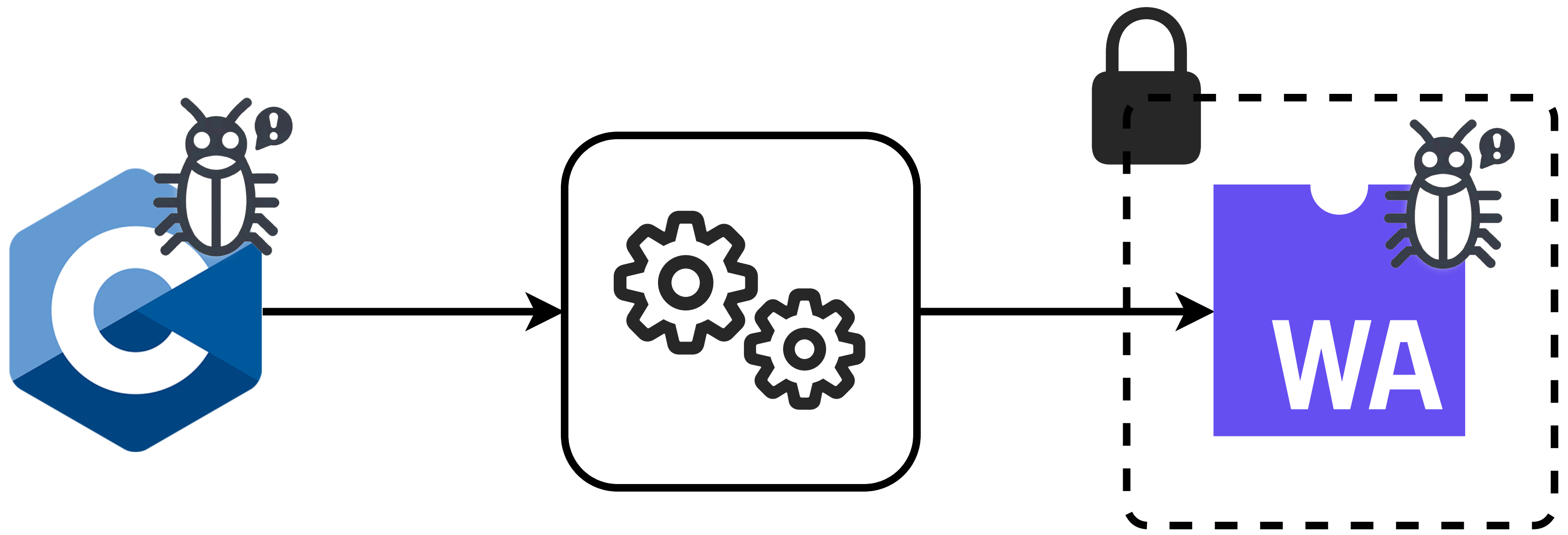
Technical University of Munich | Systems Research Group

WebAssembly



- Versatile compilation target
- Portable and near-native performance
- No direct access to host resources

Security Guarantees of WebAssembly



- Provides a sandboxed execution environment

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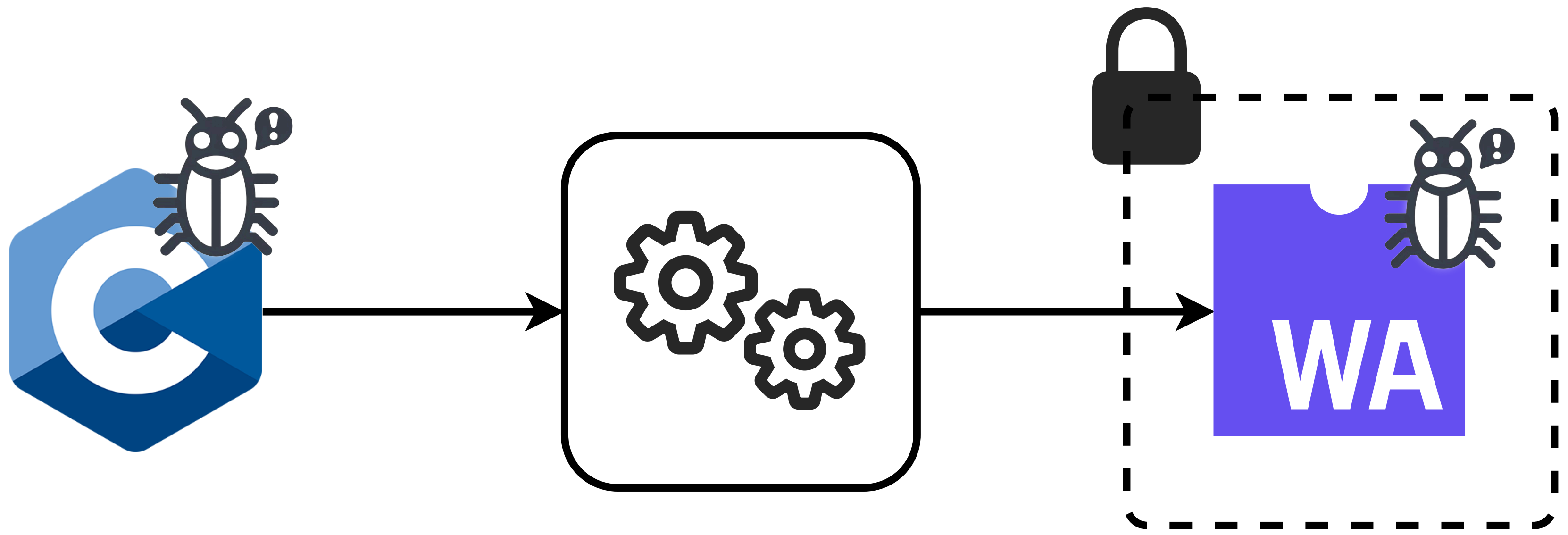
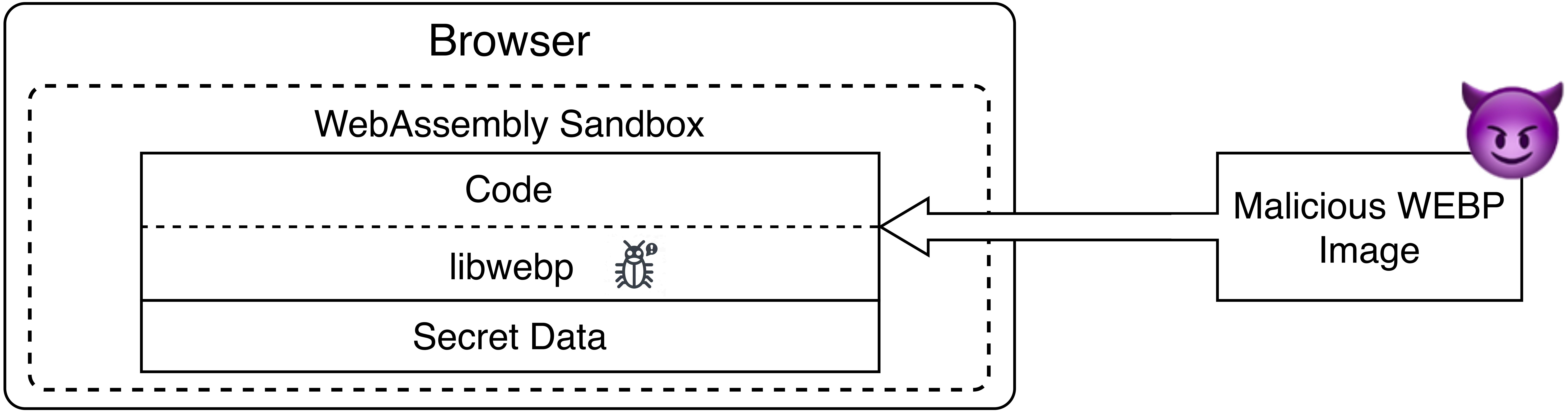


- Provides a sandboxed execution environment
- **No memory safety** guarantees for programs in memory-unsafe languages

Example: A Real-World Vulnerability



- CVE-2023-4863: Heap buffer overflow in libwebp
- Buggy library can be exploited
- WebAssembly does **not** protect against such exploits!

Memory Safety Issues

Google Project Zero

- **72%** of “in the wild” 0-days are memory safety bugs [1]

Microsoft

- **70%** of vulnerabilities in security patches are memory safety violations [2]

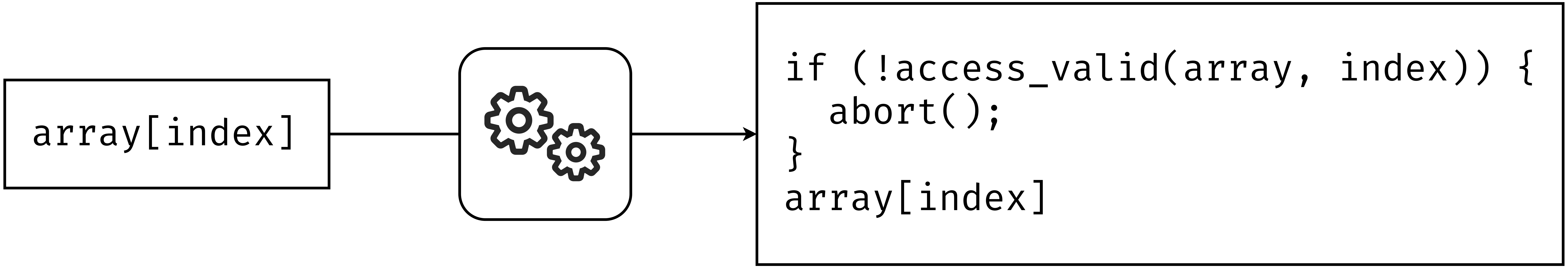
Android

- **24%** of vulnerabilities are memory safety issues (down from 70% in 2019) [3]

[1] Google Project Zero: https://docs.google.com/spreadsheets/d/1lkNJ0uQwbeC1ZTRrxdtuPLCIl7mlUreoKfSIgajnSyY/view
[2] Microsoft: https://msrc-blog.microsoft.com/2019/07/16/a-proactive-approach-to-more-secure-code/
[3] Android: https://security.googleblog.com/2024/09/eliminating-memory-safety-vulnerabilities-Android.html

Software-Based Approach

Deterministic Bounds Checking



- **Address Sanitizer**: Average slowdown of **73%** [4]

[4] Serebryany, Konstantin, et al. "AddressSanitizer: A fast address sanity checker." 2012 USENIX annual technical conference (USENIX ATC 12). 2012

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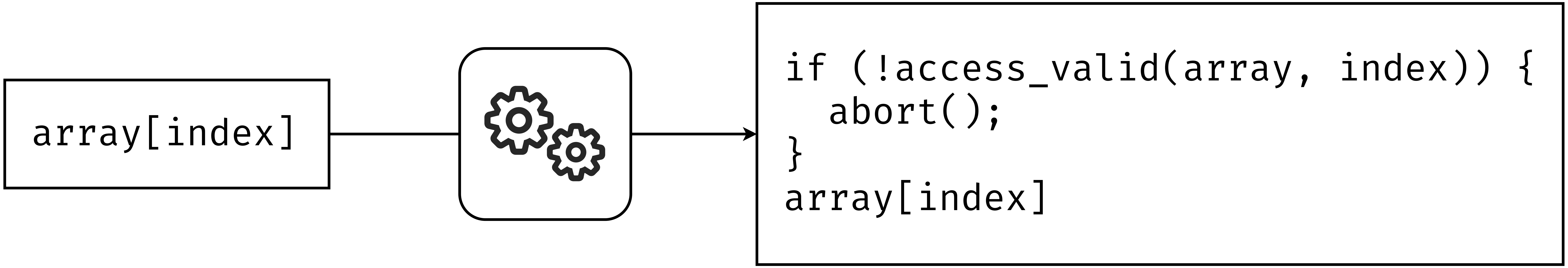

- **Address Sanitizer**: Average slowdown of **73%** [4]

Not suitable for production deployment!

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Problem Statement

How can we provide **memory safety** for **WebAssembly** with **low performance** and **memory overheads**?

Design Goals

- **Memory Safety**: spatial and temporal
- **Transparency**: no modification to existing code
- **Portability**: hardware-independent abstraction
- **Security**: WebAssembly modules might be adversarial

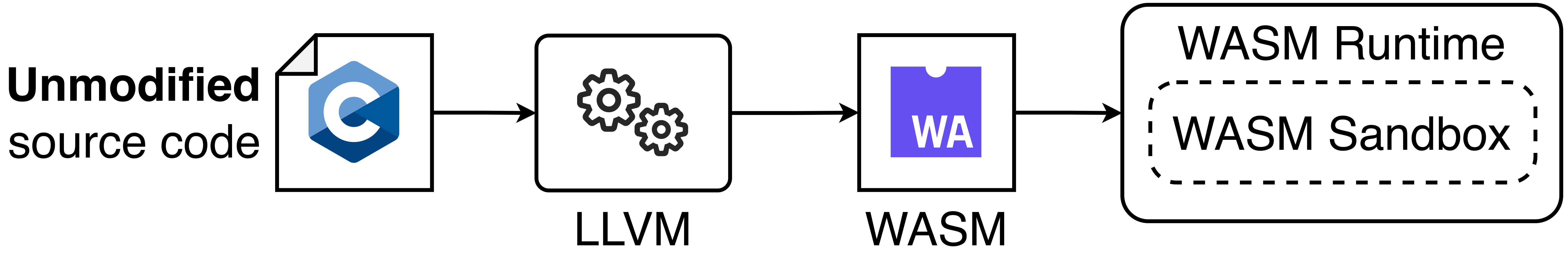
Low Overheads:

- Performance
- Memory Usage
- Sandboxing

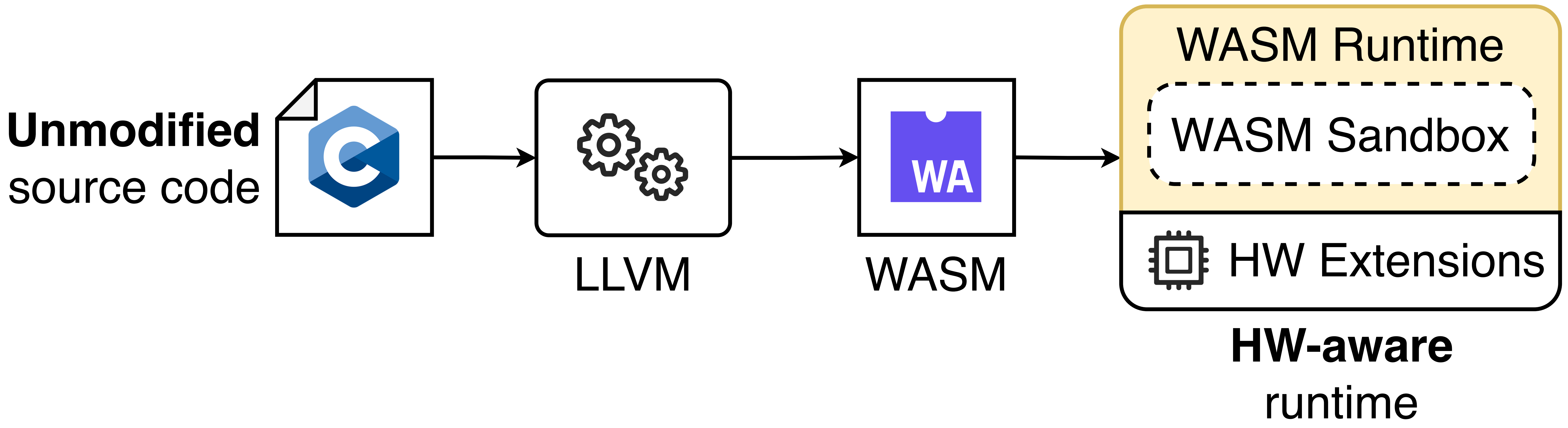
Outline

- Background and Motivation
- **Design**
  - Internal Memory Safety
  - External Memory Safety (Sandboxing)
  - Combining Internal and External Memory Safety
- Implementation
- Evaluation

Key Ideas


Unmodified
source code
LLVM
WA
WASM
WASM Runtime
WASM Sandbox

Key Ideas



- Hardware-acceleration in CPUs (e.g., Arm MTE)

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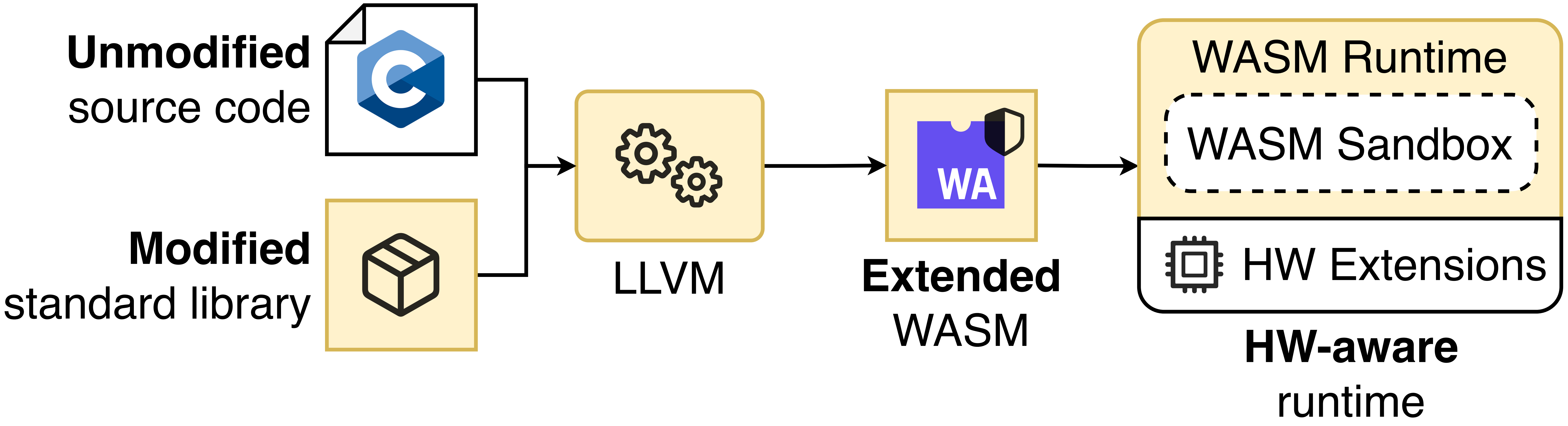

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- Generic abstraction in WebAssembly: tagged pointers and segments

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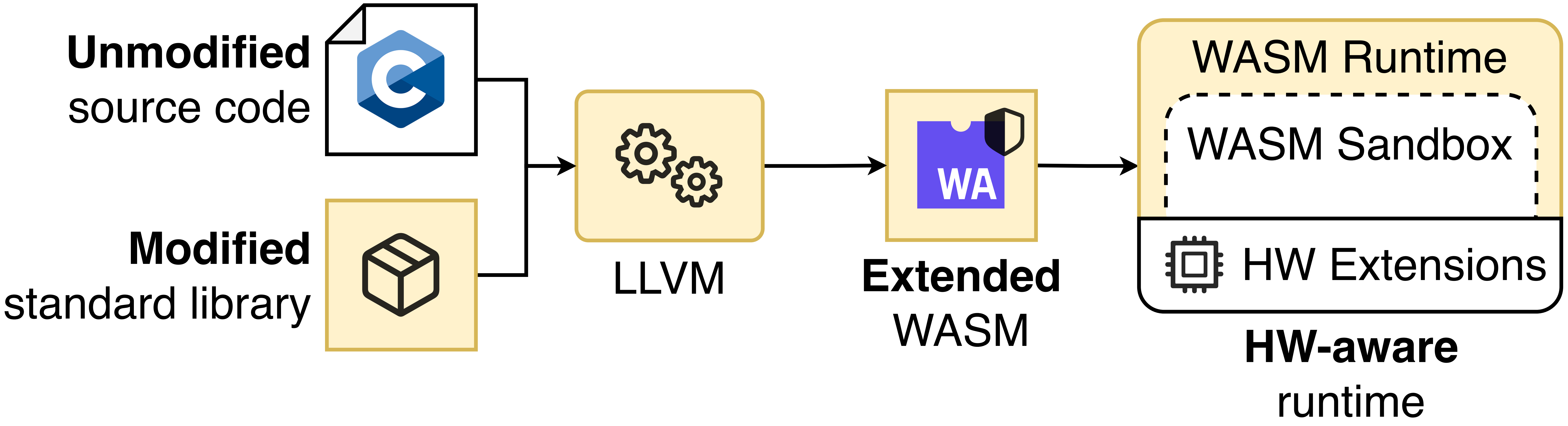

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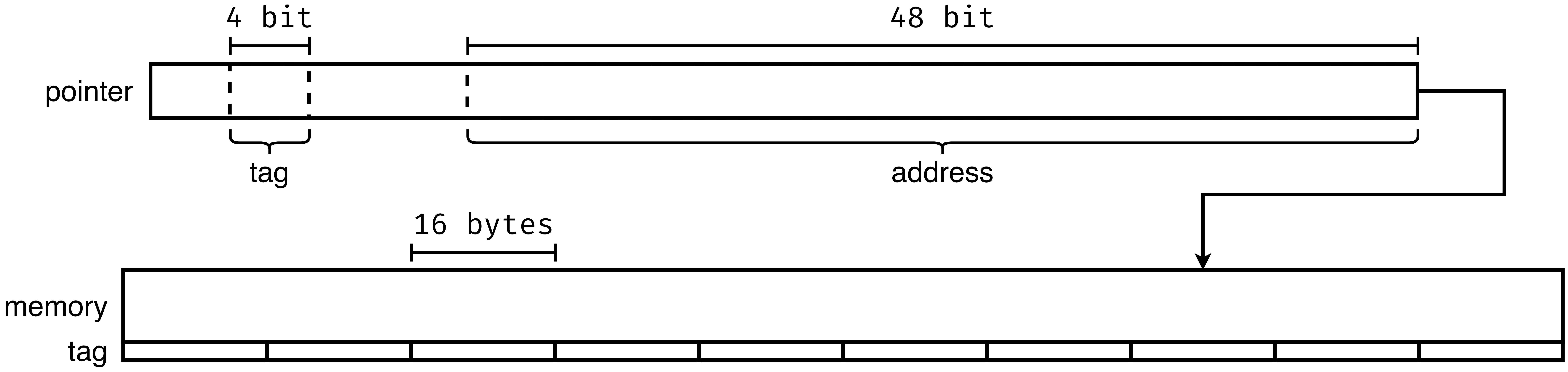
- Generic abstraction in WebAssembly: tagged pointers and segments

ARM Memory Tagging Extension (MTE)



- **4 bit tag** in unused address bits
- **16 byte granularity**
- Tag mismatch is caught by hardware

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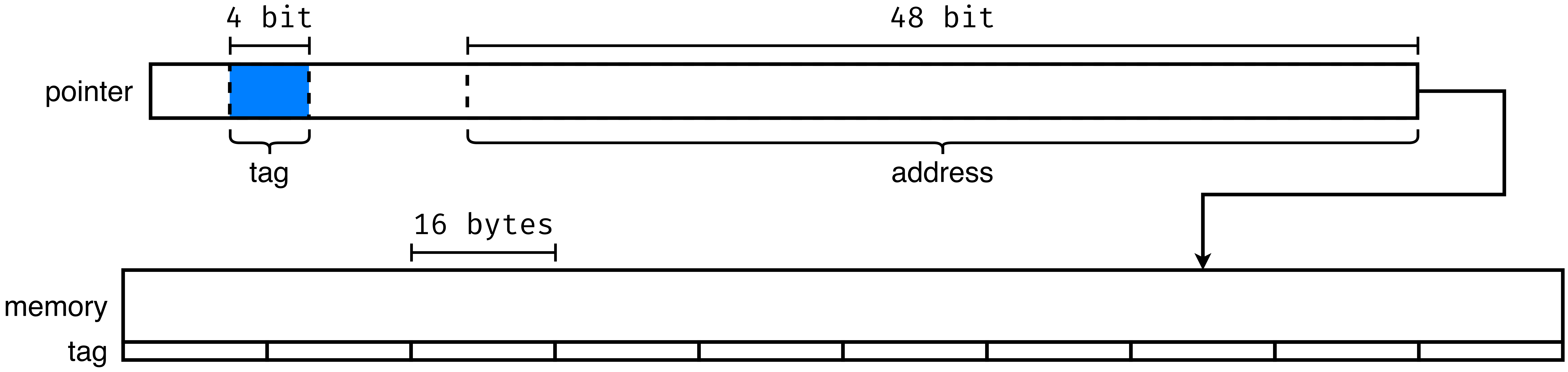

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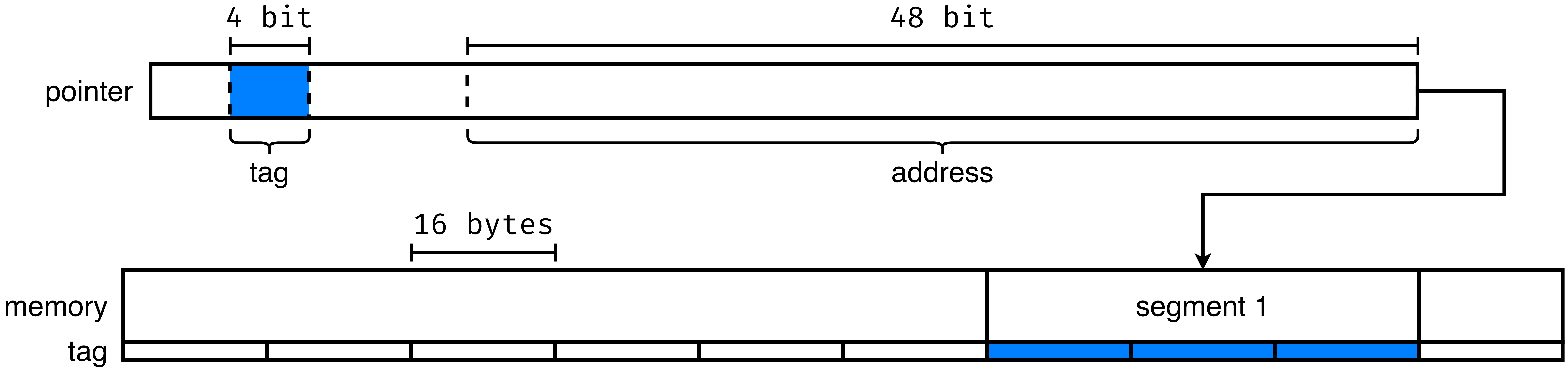

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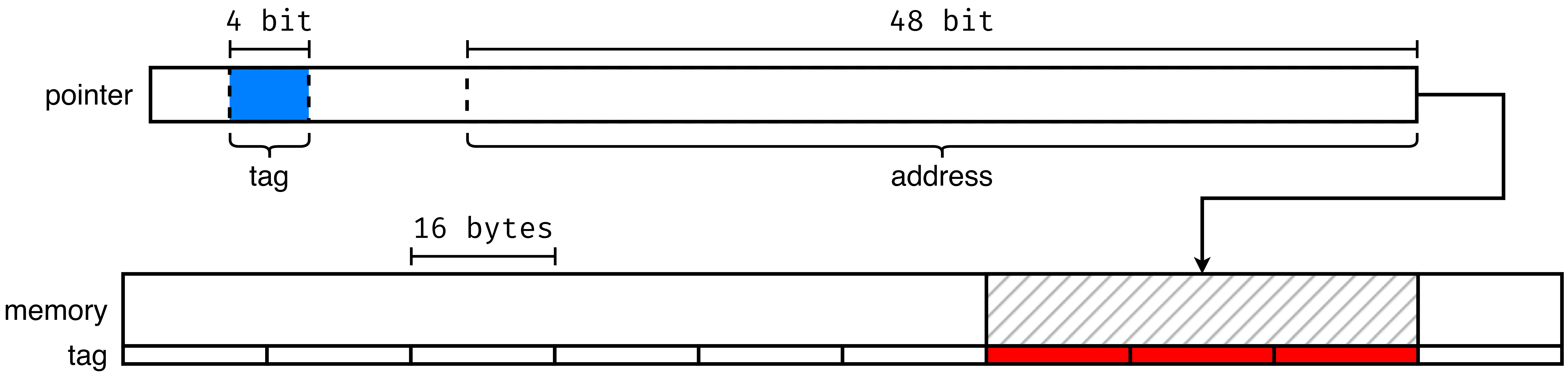

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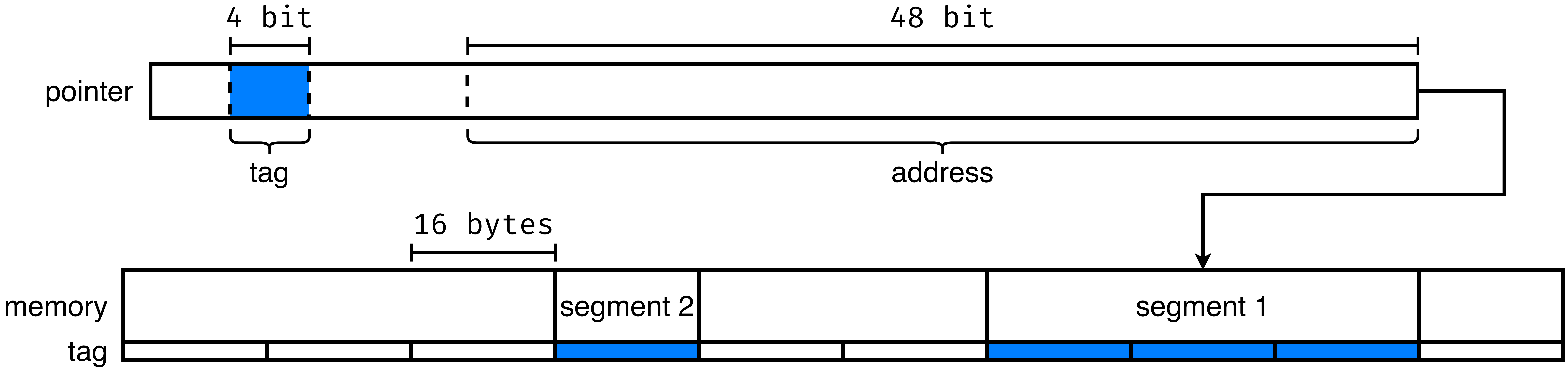
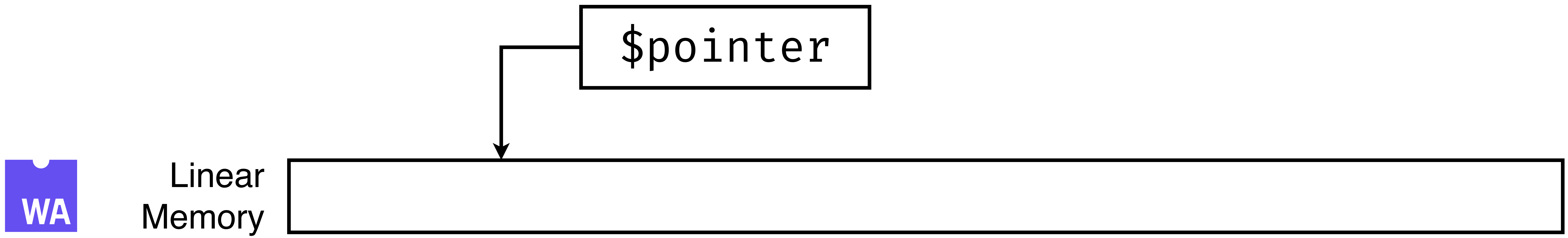


- Probabilistic Memory Safety
- 16 distinct tags → **tag collisions**

Memory Segments

```
char *pointer = malloc(32);
```

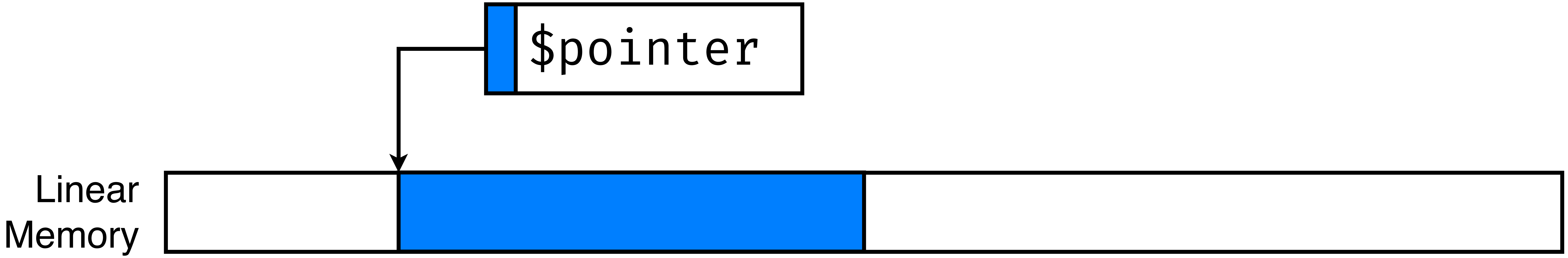


Memory Segments

Memory Segments and Tagged Pointers

```
char *pointer = malloc(32);
```

```
segment.new $ptr $len
```

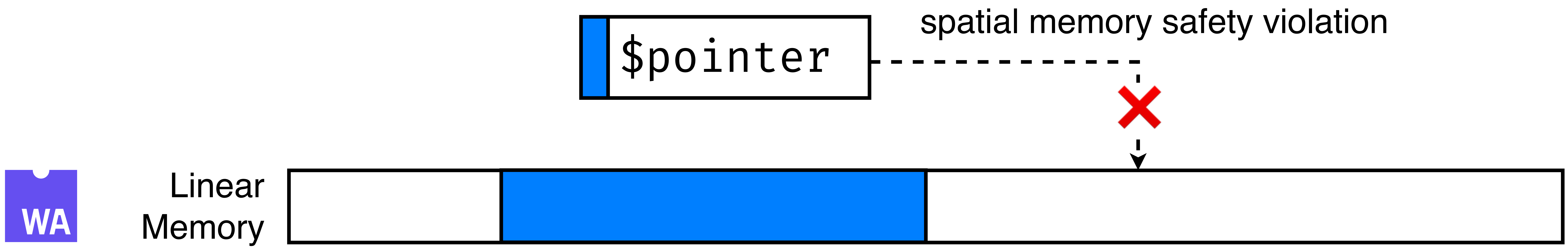


Memory Segments

Spatial Memory Safety Violations

```
char *pointer = malloc(32);
pointer[40];
```

```
segment.new $ptr $len
```

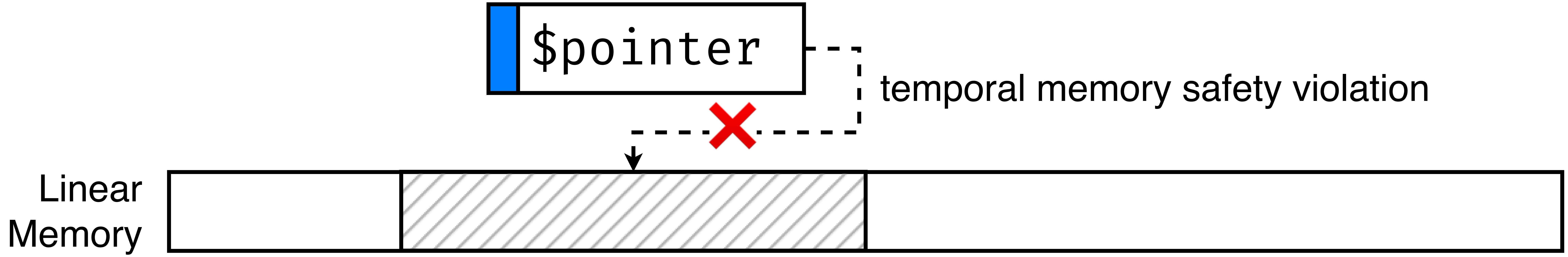


Memory Segments

Temporal Memory Safety Violations

```
char *pointer = malloc(32);
free(pointer);
pointer[24];
```

```
segment.free $ptr $len
segment.set_tag $ptr $tag $len
```



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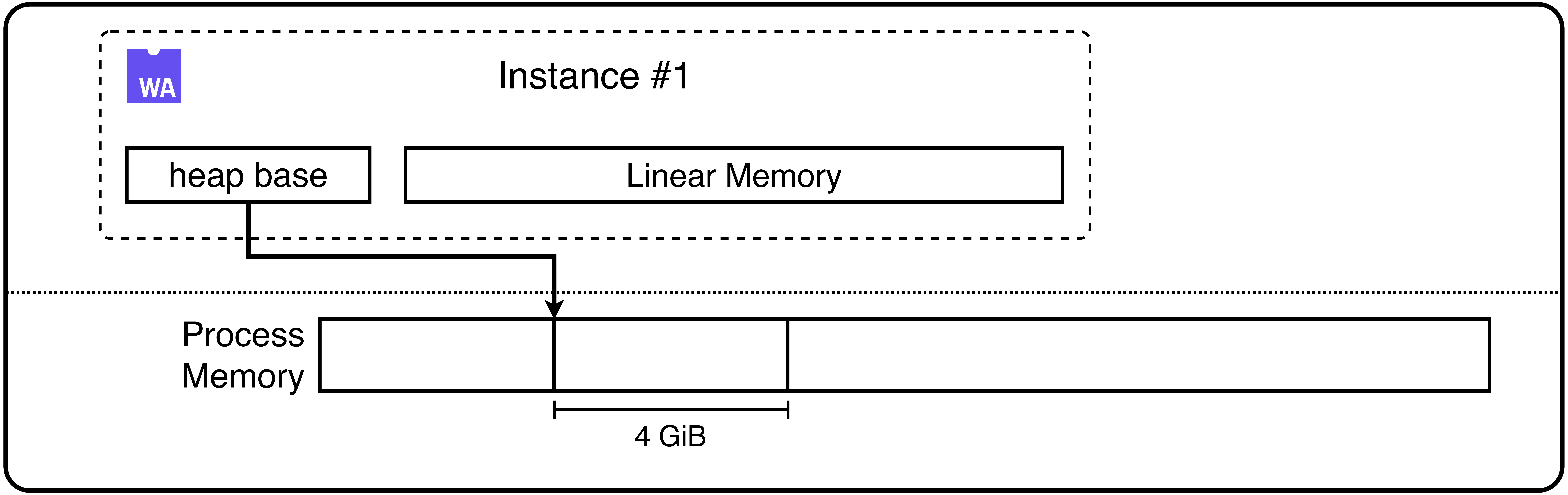

- Sandboxing using **guard pages**
- Allocate 2^{32} = 4 GiB of virtual memory per sandbox
- Only possible for 32-bit WebAssembly

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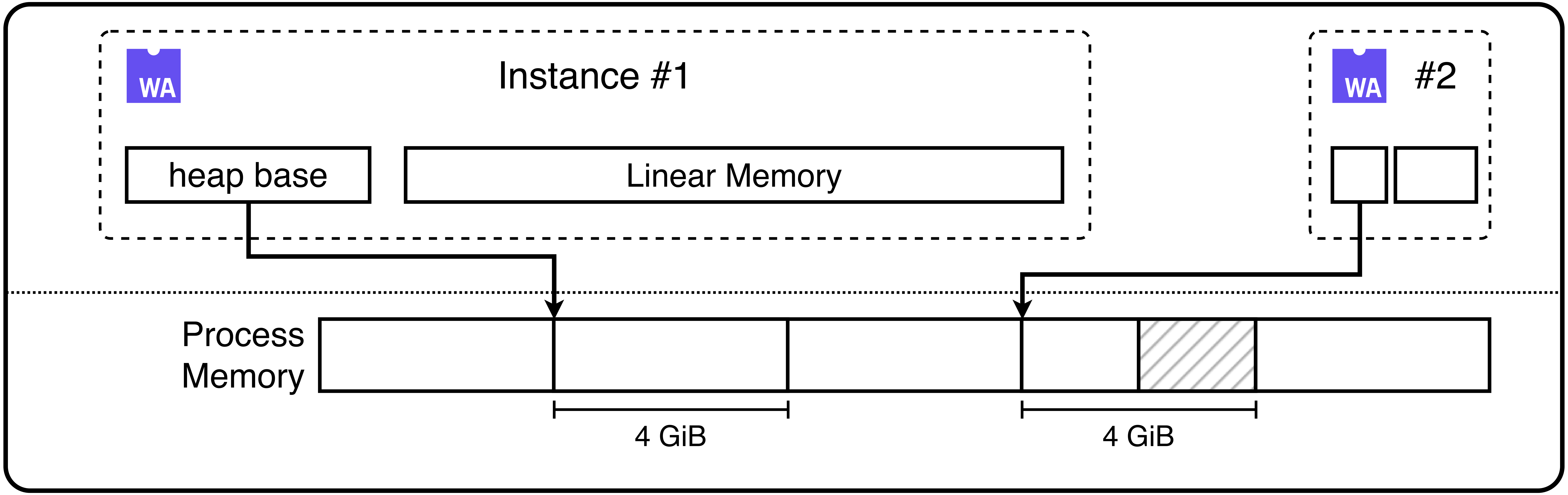

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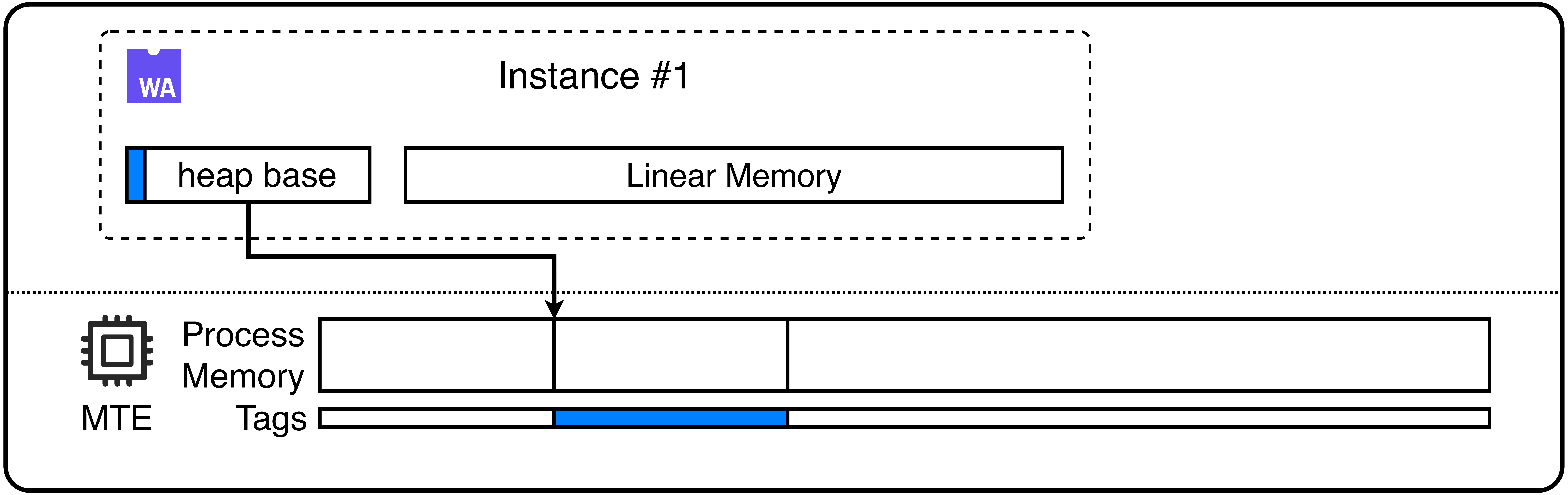

- Assign distinct tag for each sandbox
- Perform access relative to tagged base pointer

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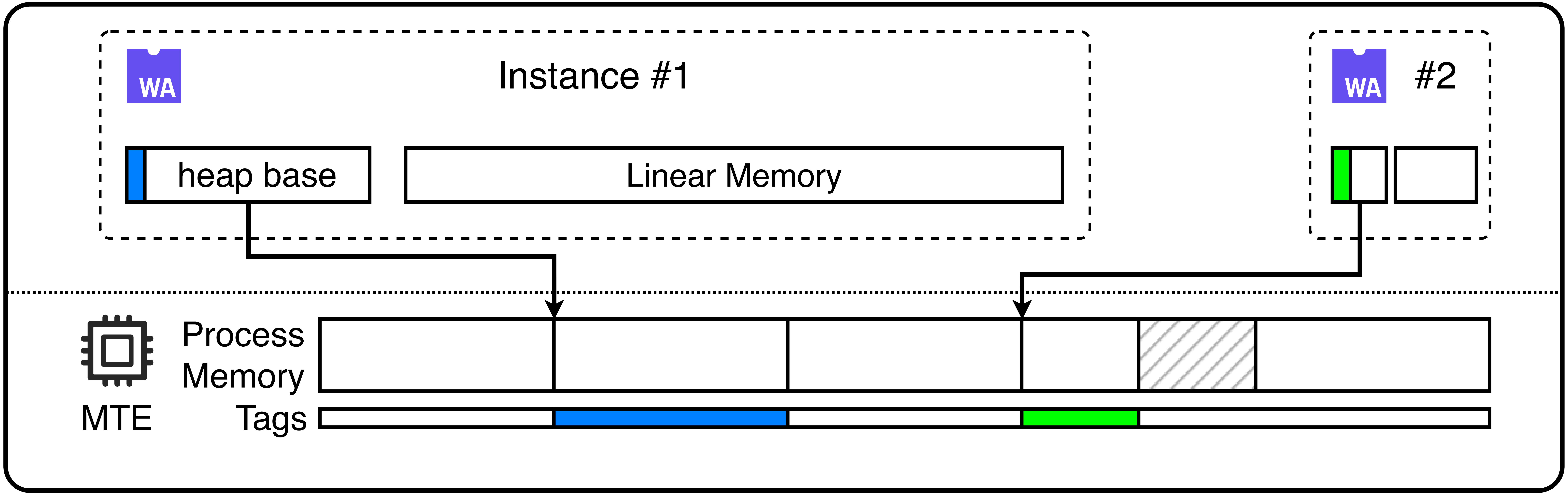

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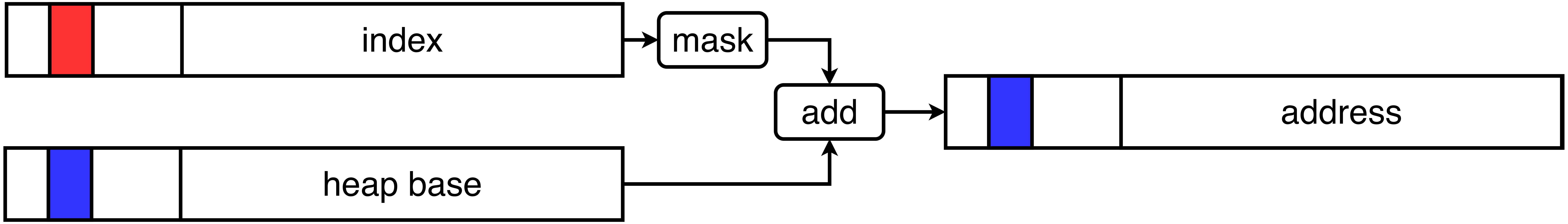
Combining Memory Safety and Sandboxing



- Split tag bits
  - Up to four bits for sandboxing
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- On address translation, mask out runtime-reserved bits

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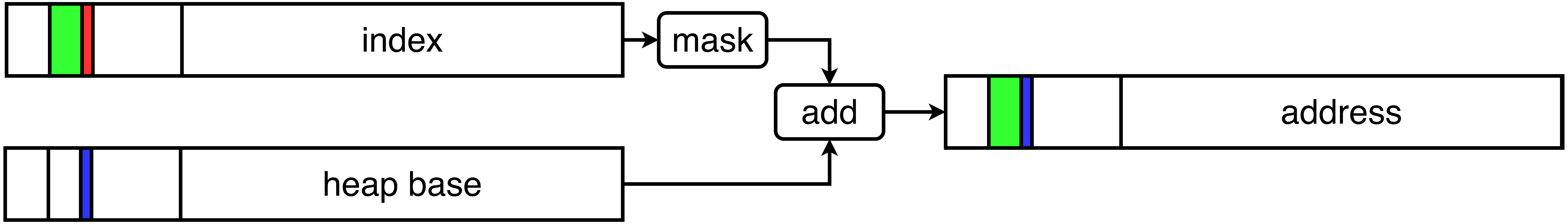

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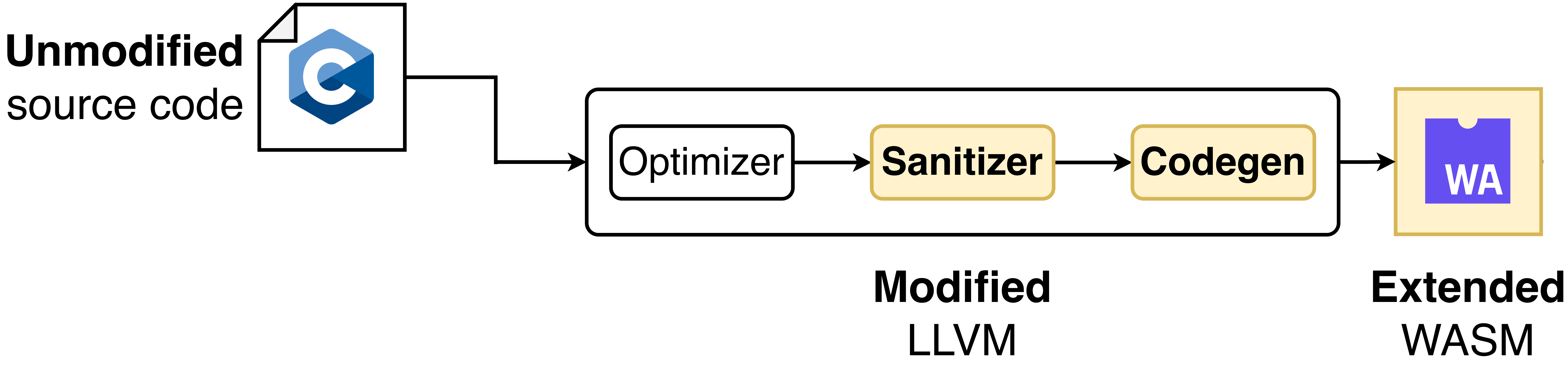
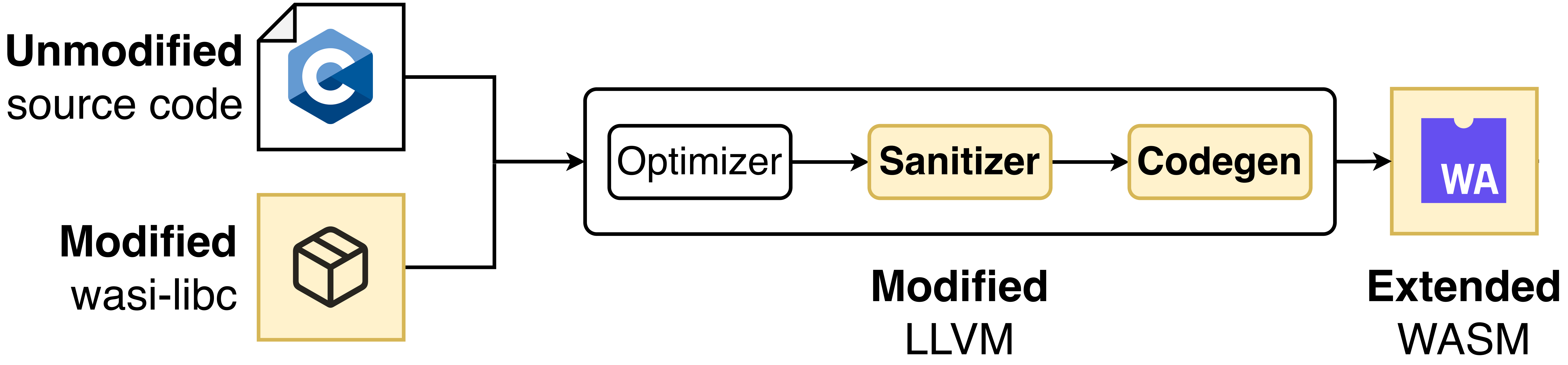


Compiler Toolchain

- LLVM 17
- Sanitizer passes

Implementation



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Libc

- wasi-libc
- 64-bit WASM
- Memory-safe allocator

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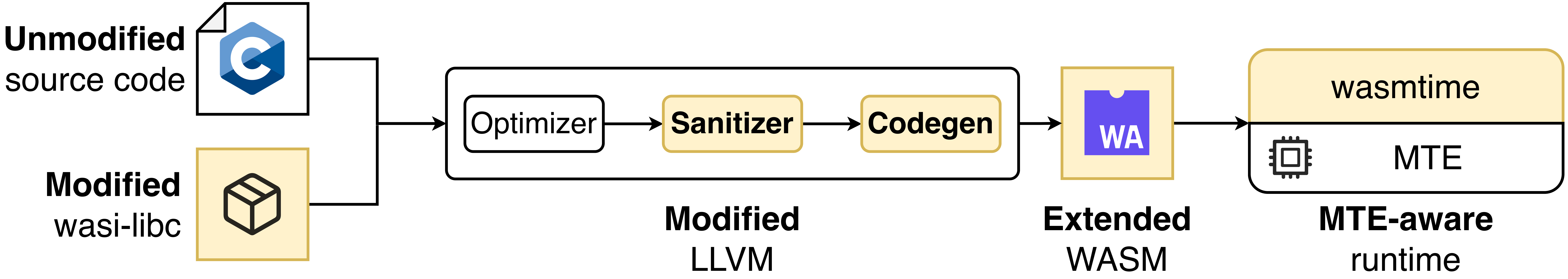

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WASM Runtime

- wasmtime 16
- MTE-based memory safety
- MTE-based sandboxing

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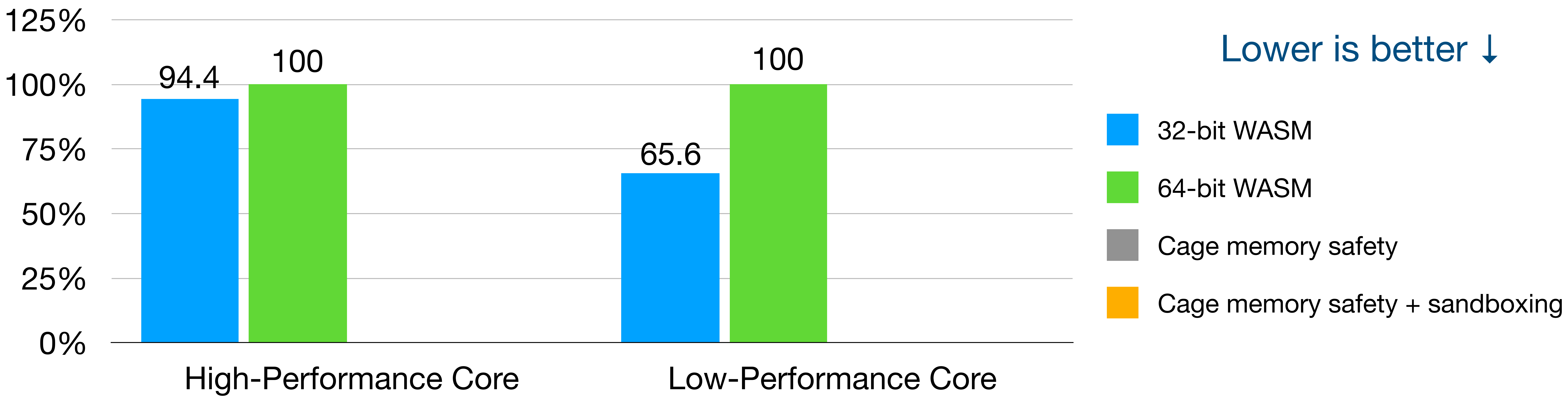
- Implementation
- **Evaluation**

Runtime Overheads

PolyBench/C on Google Pixel 8



Baselines: 32-bit WASM **34.5—5.6% faster** than 64-bit WASM

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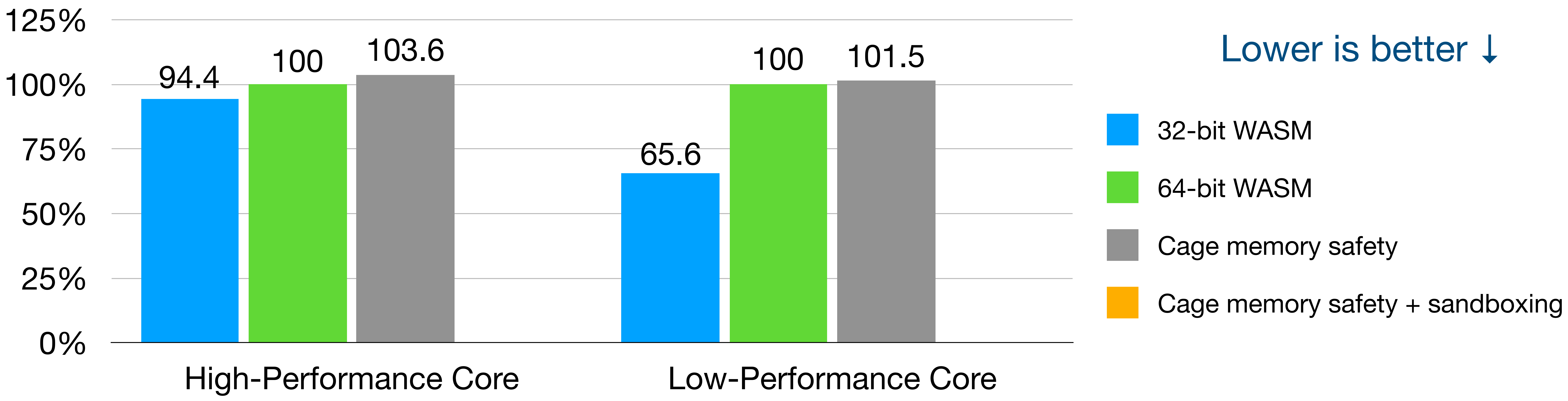

Memory Safety: **1.5—3.6%** overhead
Address Sanitizer: Runtime overheads of **> 70%**

Runtime Overheads

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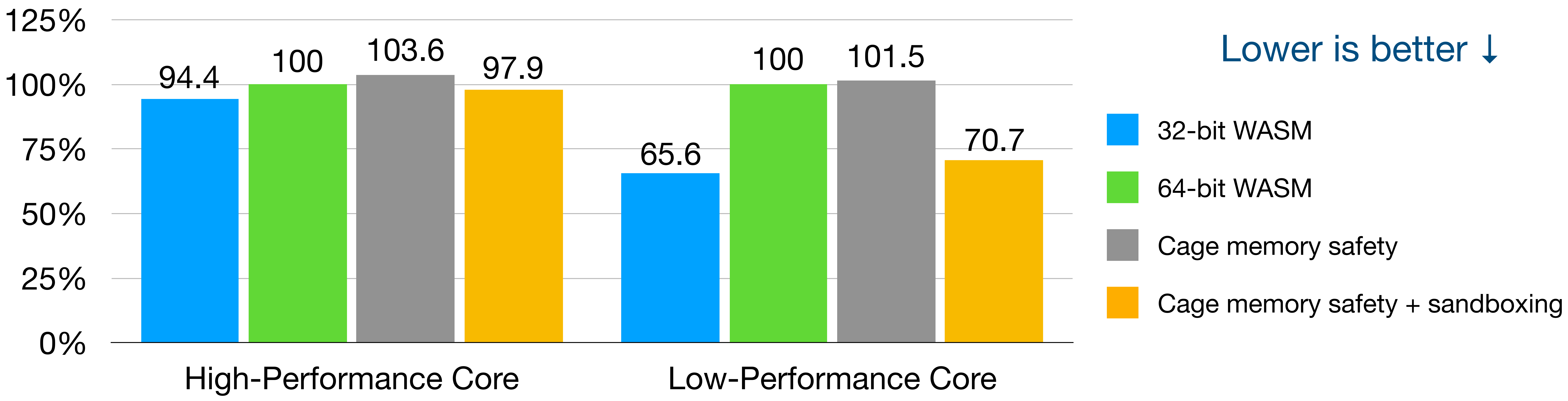

Combined with MTE-based sandboxing: 2.1—29.3% speedup

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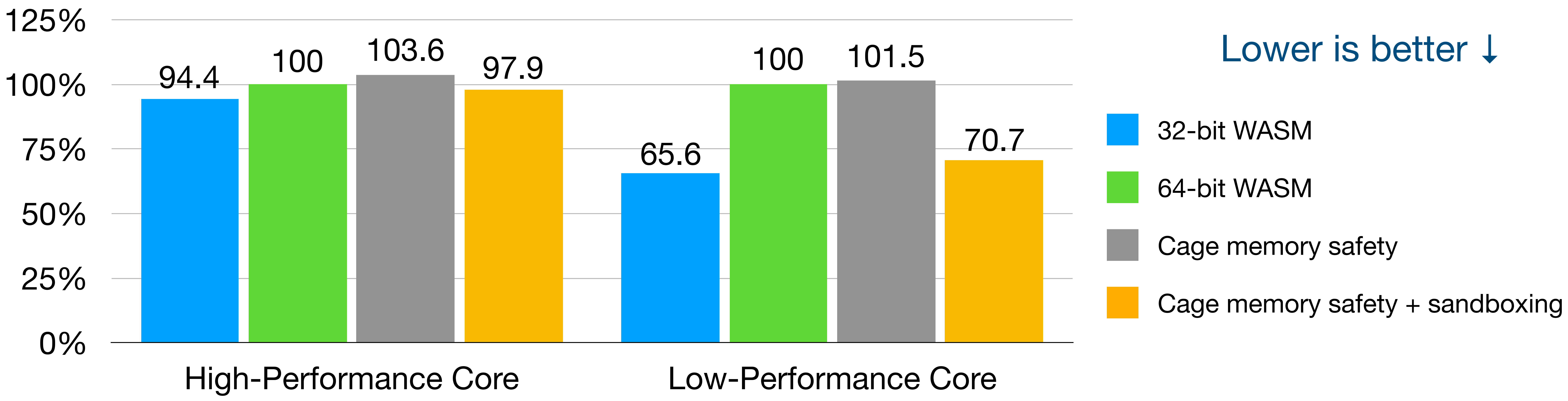

Minimal overheads for production deployments, speedups compared to 64-bit WASM!

Memory Overheads

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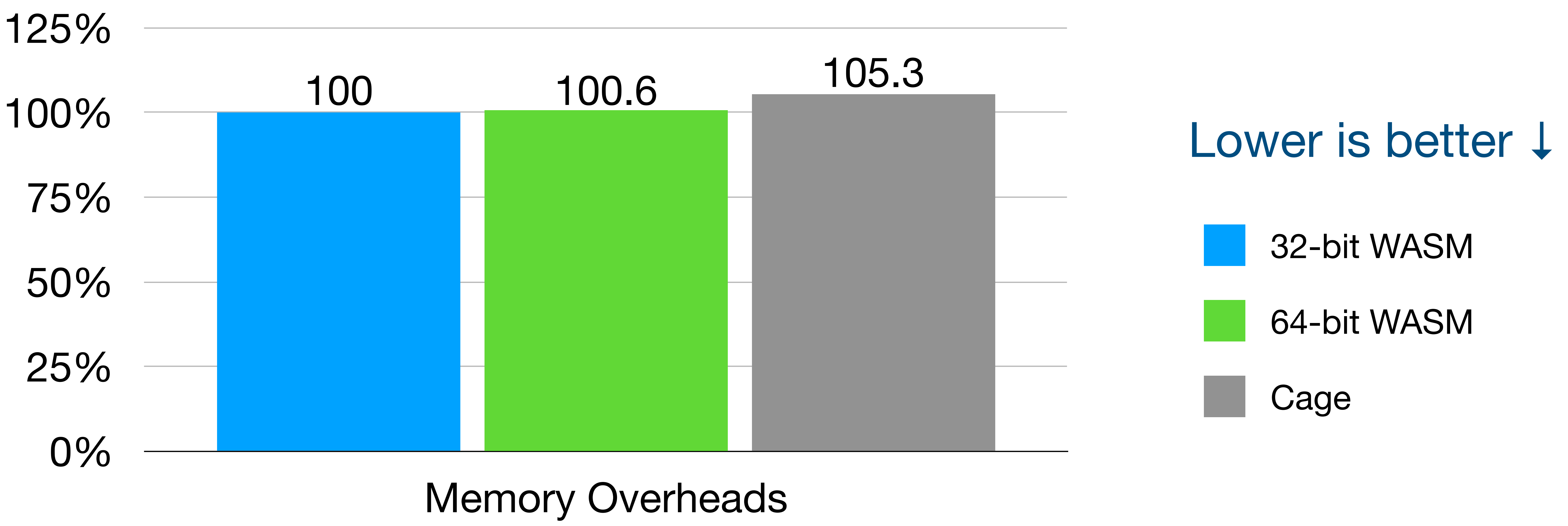

Memory Overheads

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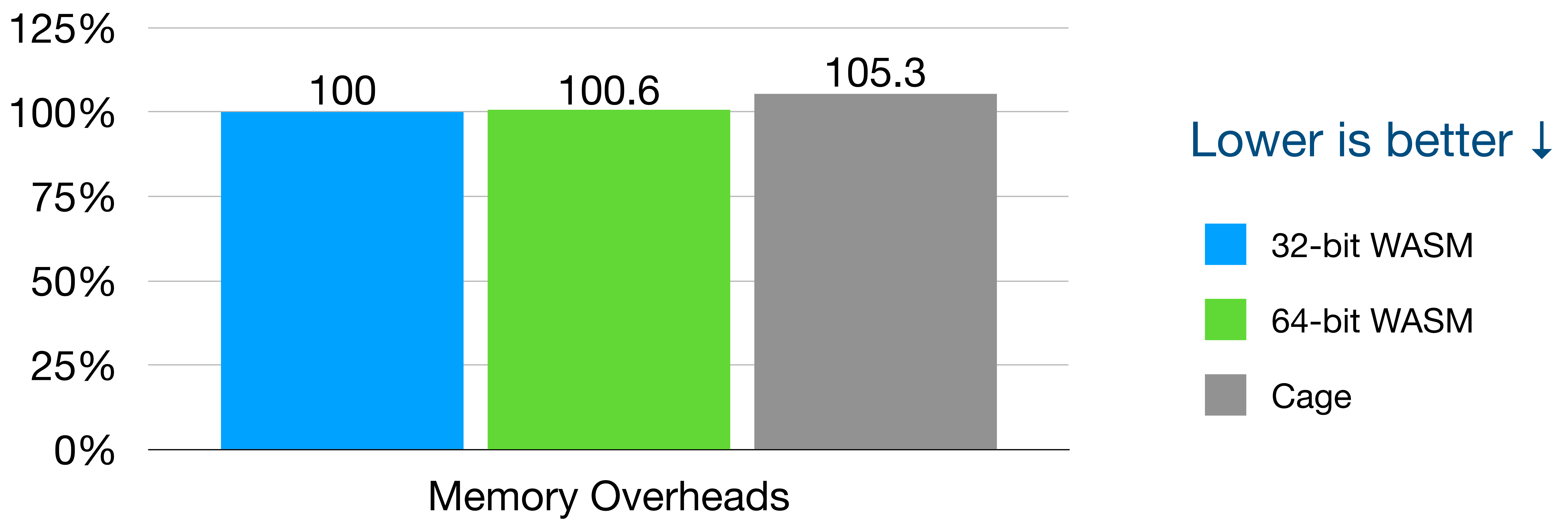

Cage introduces minimal memory overheads (~5.3%)
Address sanitizer incurs much larger overheads (2-3x)

Outlook

Growing Importance of Memory Safety

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- Sensitive data is located on mobile devices and in the cloud

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Hardware-Assisted Memory Safety

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Growing Adoption of Memory Safety Extensions

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  - Arm MTE, Arm PAC, CHERI, Intel MPK, …

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Growing Adoption of Memory Safety Extensions

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- Widespread deployment in production environments
  - MTE: Google Pixel, Ampere One
- Differing tradeoffs
  - Capabilities vs. tagged memory, …

Summary

- **Memory Safety Extension** for 64-bit WebAssembly
- Implementation using **Arm MTE**
- Overheads **<5.6%**, **speedups** when using MTE for sandboxing
- More details, such as formalization, evaluation, and pointer authentication in the paper!

Paper

Source Code