Leveraging ARM TBI for Next-Generation Kernel Memory Sanitization

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What is TBI

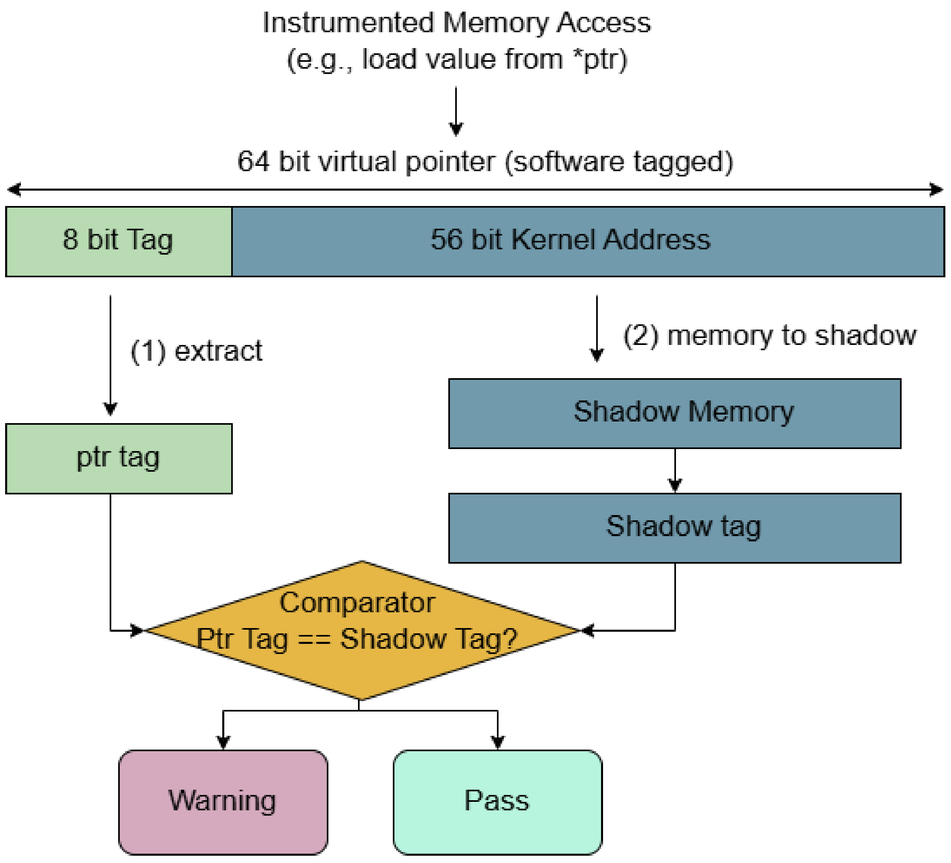
- Top Byte Ignore (TBI) is an ARM64 feature that allows the processor to ignore the top byte of a virtual address during memory access.

Motivation

- **Limitation in KMSAN**: KMSAN incurs significant memory overhead, which can be problematic in large-scale systems. To prevent memory exhaustion, the detection scope often has to be reduced, limiting its ability to identify uninitialized memory.
- **Potential of TBI**: TBI introduces a dedicated byte in memory addresses for tagging, enabling tags to represent states, metadata, or ownership information.

TBI current usage in Sanitizer

- **Software tag-based KASAN**: stores a tag in shadow memory and embeds the same tag into the pointer's top byte. On every memory access, instrumented code compares the pointer's tag with the shadow memory's tag.
- **MTSan:** utilizes Memory Tagging Extension to provide tag-based memory safety sanitizer with minimal runtime cost.



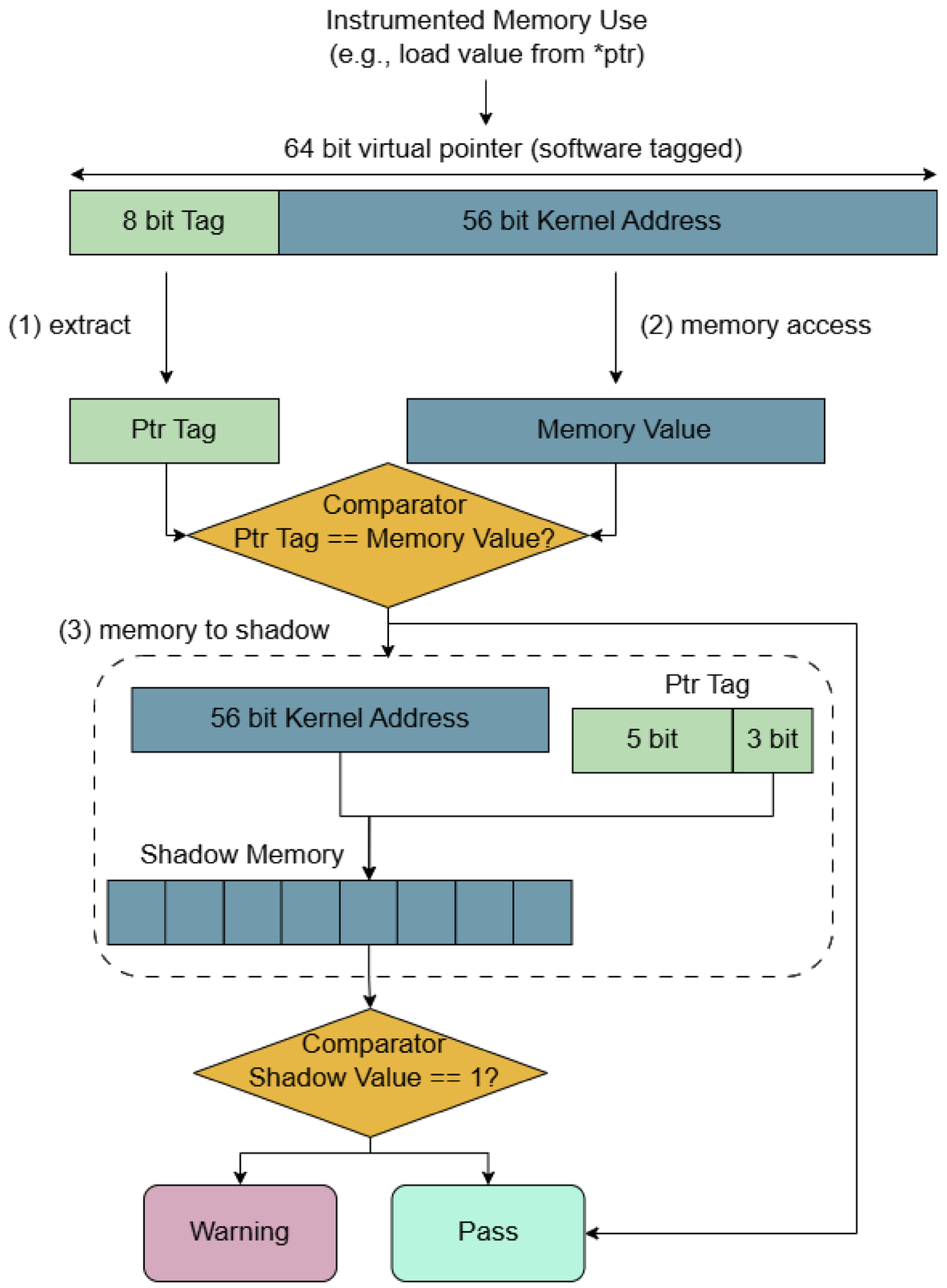
1. TBI implementation in address sanitizer

Lessons from Software tag-based KASAN

- **Tag as Metadata**: A tag acts as metadata denoting memory ownership, decoupling safety checks from the primary data.
- **Shadow Memory Principle**: Safety is verified by mapping the target address to a shadow that stores the expected tag.
- **Performance Benefit**: This architectural separation enables precise bug detection with significantly lower memory overhead compared to full redundancy.

Proposed TBI-enhanced KMSAN

- **Tag-as-Offset for Compact Shadow Memory**: We encode initialization state (1 bit per byte) in shadow memory, using the pointer tag's low 3 bits as an offset for lookup.
- **Tag Pre-Check for Selective Validation**: Before shadow memory access, we compare the pointer's tag against the value in the target memory. A tag mismatch serves as a fast path, confirming initialization and avoiding the slower shadow check for most memory accesses.



2. TBI-optimized KMSAN

Contribution

- **Expanded Tag Usage**: (1) as an indicator of initialization state, and (2) as a helper to encode shadow memory bit offsets
- This dual-purpose approach can serve as a starting point for exploring further methods to enhance other sanitizers.

Related Work

- **CombiSan**: CombiSan detects multiple classes of memory and undefined behavior errors simultaneously.
- **QMSan**: By leveraging QEMU's dynamic binary translation, QMSan efficiently detects Uninitialized Use of Memory (UUM) errors without requiring source-based recompilation.

Future Work

1. **KCSAN: Optimizing Detection.** Use memory tags as access locks to indicate if a memory location is being written by another thread.
2. **KUBSAN: Accelerating Checking.** Leverage tags to encode type information or bounds metadata, enabling faster verification of type confusion and array bounds violations.

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