METASAFE: Compiling for Protecting Smart Pointer Metadata To Ensure Safe Rust Integrity

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Rust: A Memory Safe System Programming Language

- Rust is gaining popularity as a memory safe programming language
  - Replacing C/C++ in some production software (Linux, Microsoft, Android)
  - Reportedly resulted memory bug reduction (Android: 76% ➔ 25%)

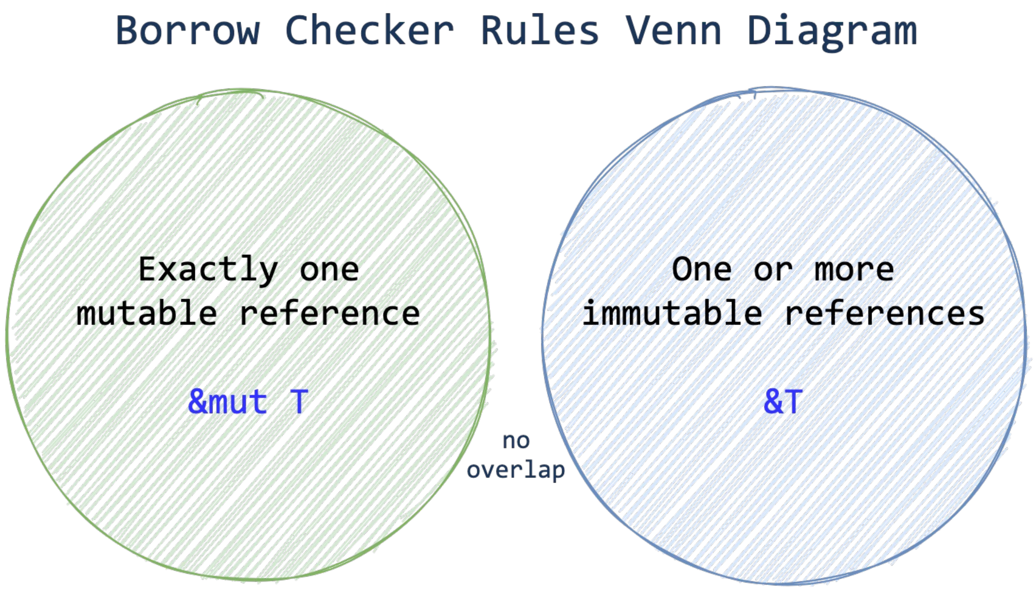
- Aspires to maintain runtime performance
  - In some cases faster than C/C++

- Currently gradually replacing C/C++, Python, Java

CLOUDFLARE

Memory Safety in Rust: Policy

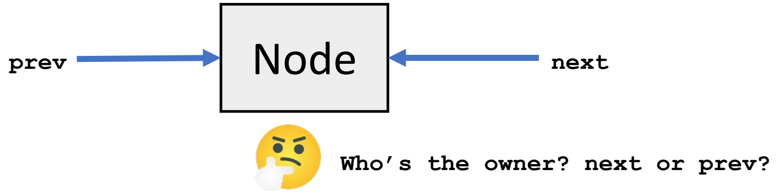
- Memory Access Policy:
  - Ownership: A memory object shall have one owner at any point in time.
  - Borrowing: A memory object may be borrowed:
    - Immutably by one or more entities
    - Mutably by a single entity
  - Lifetimes: A memory object can only be accessed when it is live
- Policy Enforcement:
  - Compiler-based (borrow checker, lifetime analyzer)



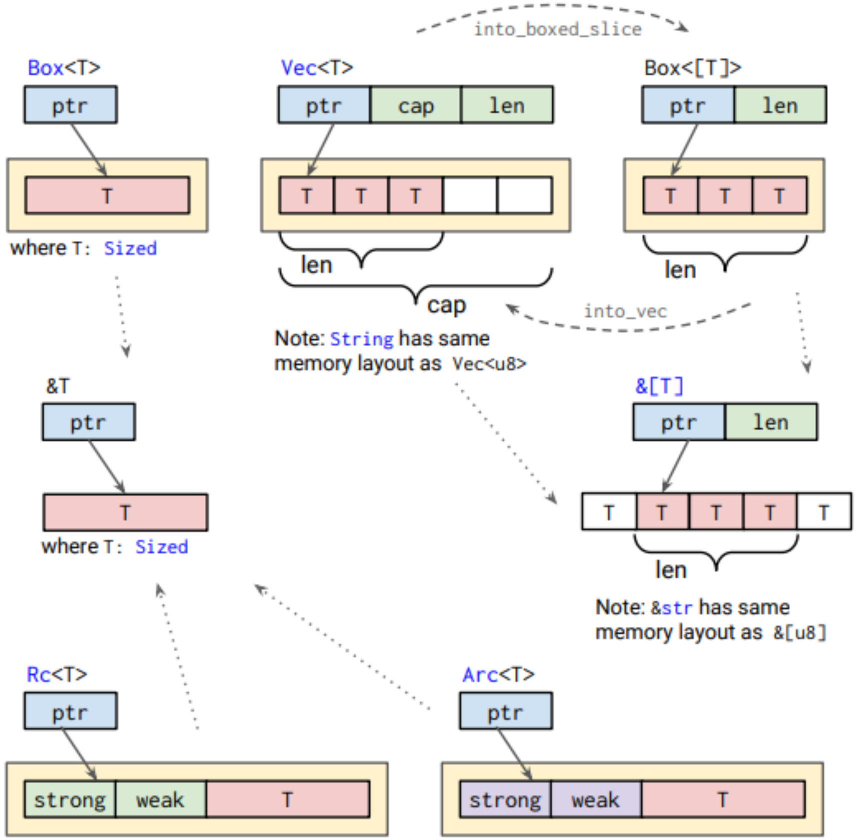
https://livebook.manning.com/book/code-like-a-pro-in-rust/chapter-1/v-2/

Smart Pointers and Their Metadata in Rust

- Rust Memory Rules are too strict
  - Limit expressive power
  - Impossible to implement some widely-used DS.
    - How to design a Doubly Linked List?



- Smart Pointers to the **SAFE** rescue
- A way to enforce memory safety rules at **runtime**
  - Buffer Pointers with buffer length metadata
    - Vec<T>, Slice<T>
  - Shared Pointers with reference counters
    - Rc<T>, Arc<T>
  - Interior Mutability with special metadata
    - RefCell<T> with mutable borrower counters
    - Mutex<T>, RwLock with lock metadata

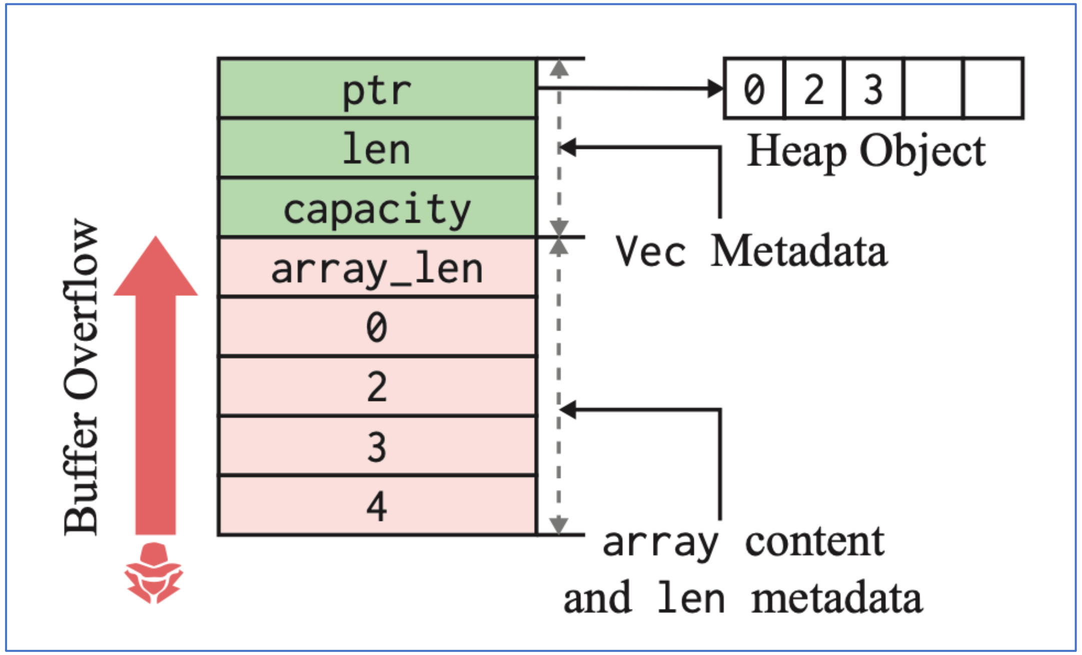


https://tc.gts3.org/cs3210/2020/spring/l/lec09/lec09.html

Smart Pointer Metadata Storage

```
use std::rc::Rc;
fn main {
    let mut xvec = vec![0,2,3];
    let mut array = [0,2,3,4];

    unsafe {
        let mut ptr = array.as_mut_ptr()
                      .offset(10);
        *ptr = 10;
    }
    //...
    //...
```



Several existing CVEs on unsafe Rust and unchecked length-related buffer overflows.

Smart Pointer APIs and Metadata Access

```rust
use std::ptr;
use std::alloc::{dealloc, Layout};
fn test(input: *mut String){
    unsafe{
        //destructor of the pointed-to value
        ptr::drop_in_place(input);
        dealloc(input);
    }
}
fn main(){
    let x = Box::new(String::from("hello"));
    let p = Box::into_raw(x);
    test(p);
    println!("{:?}",p);
    let tmp1 = unsafe{ Box::from_raw(p)}
    println!("{:?}",tmp1)
}
```

User drops the string pointer

User creates Box pointer using *from_raw*
Box doesn't check received pointer
println! reads from new pointer ➔ UAF

CVE-2021-25900

```rust
fn main() {
    let mut buffer = vec![0,2,3];
    unsafe {
        buffer.set_len(10);
    }
    println!("Element at 9: {}", buffer[9]);
}
```

User overwrites Vec metadata using *set_len*
Vec doesn't validate new length

buffer[9] makes OOB read due to new invalid length metadata

Related Works: Enhancing Rust Safety

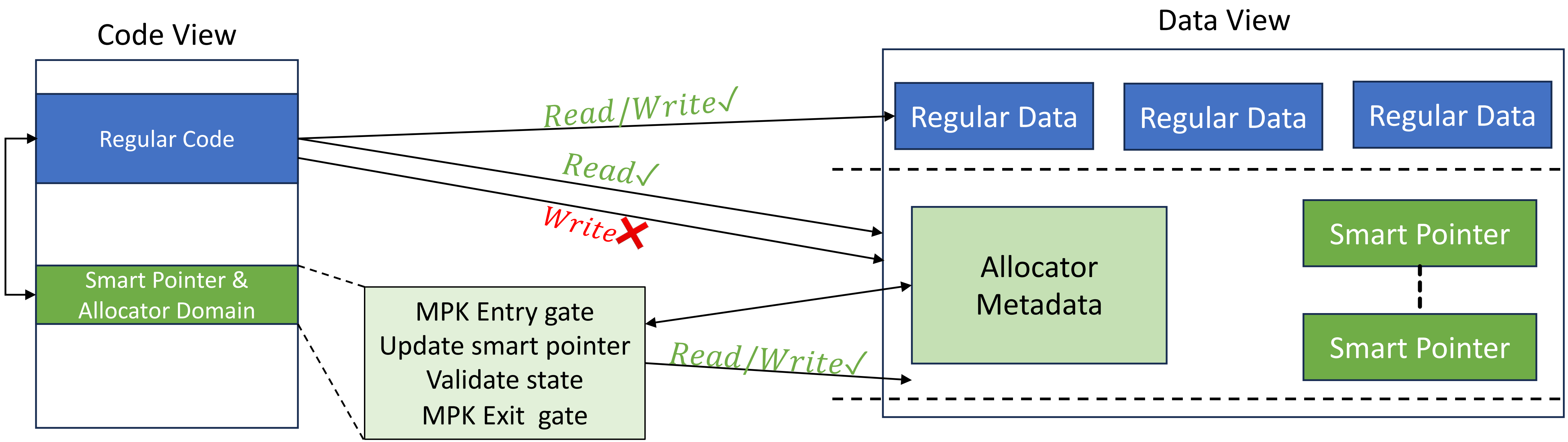
- Most works focus on Unsafe Vs Safe Rust memory Isolation.
- TRust: USENIX Security 2023
  - Protects Safe Rust by isolating memory used by Safe Rust and Unsafe/FFI
  - Uses static analysis, Intel MPK + SFI to achieve runtime performance
- PKRU-Safe: CCS 2022
  - Similar to TRust, isolates safe Rust and FFI with Intel MPK
  - Relies on dynamic profiling instead of static analysis
- Galeed: ACSAC 2021
  - Similar to TRust, isolates safe Rust and FFI with Intel MPK
  - Uses pseudo-pointers to provide strict Temporal access to shared Rust objects by FFI
- XRust: ICSE 2020
  - Provides isolation between safe and unsafe Rust memory
  - Does not specifically consider FFI

- None of Existing works give special care to smart pointers, eg. Validating metadata updates
- METASAFE aims NOT to REPLACE unsafe Rust Isolation works, rather to COMPLEMENT them

Protecting Smart Pointer Metadata

- METASAFE:
  - Protects smart pointer metadata & validates updates
- Requirements:
  - Identification of Smart Pointers
    - The Rust Compiler treats smart pointers similarly to other data structures (except Box)
  - Separate isolated storage
    - Need for storing smart pointers in a gated region.
  - Controlled write access to metadata
    - Preventing illegal access to smart pointer metadata
  - Authentication of metadata updates through unsafe APIs
    - Ensure unsafe APIs write valid smart pointer metadata

METASAFE Overview



- Categorize code between regular and smart pointer domain
- Categorize data into regular, allocator and smart pointer metadata
- Enforce access control on allocator and smart pointer metadata
- Metadata updates validated by comparison with ground truth

Identifying Smart Pointers

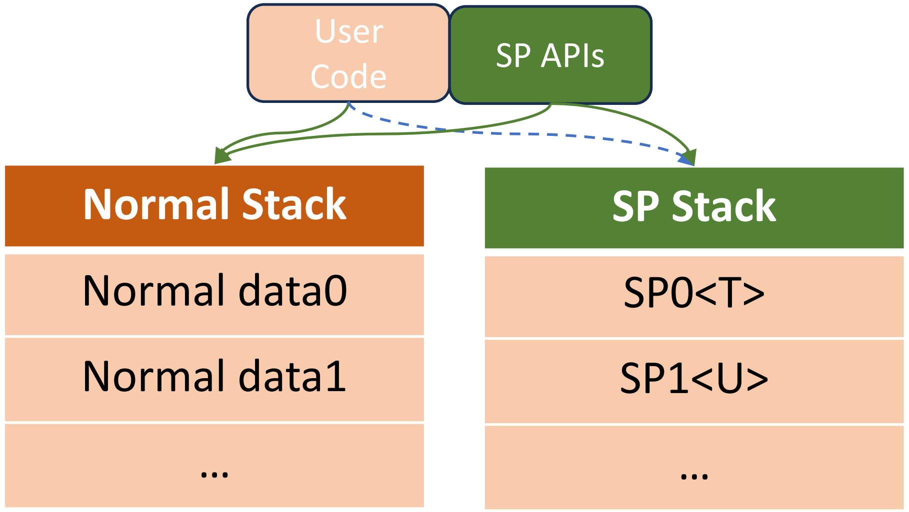
- Identifying Smart Pointers at Compile time
  - Require Smart Pointer Developers to implement a special trait (MetaUpdate)
- Diversity of Smart Pointer types & uses
  - Challenge for authenticating metadata updates
  - The MetaUpdate trait requires implementation of a *validate* function
- Insert calls to validate function after API call that takes mutable sp.

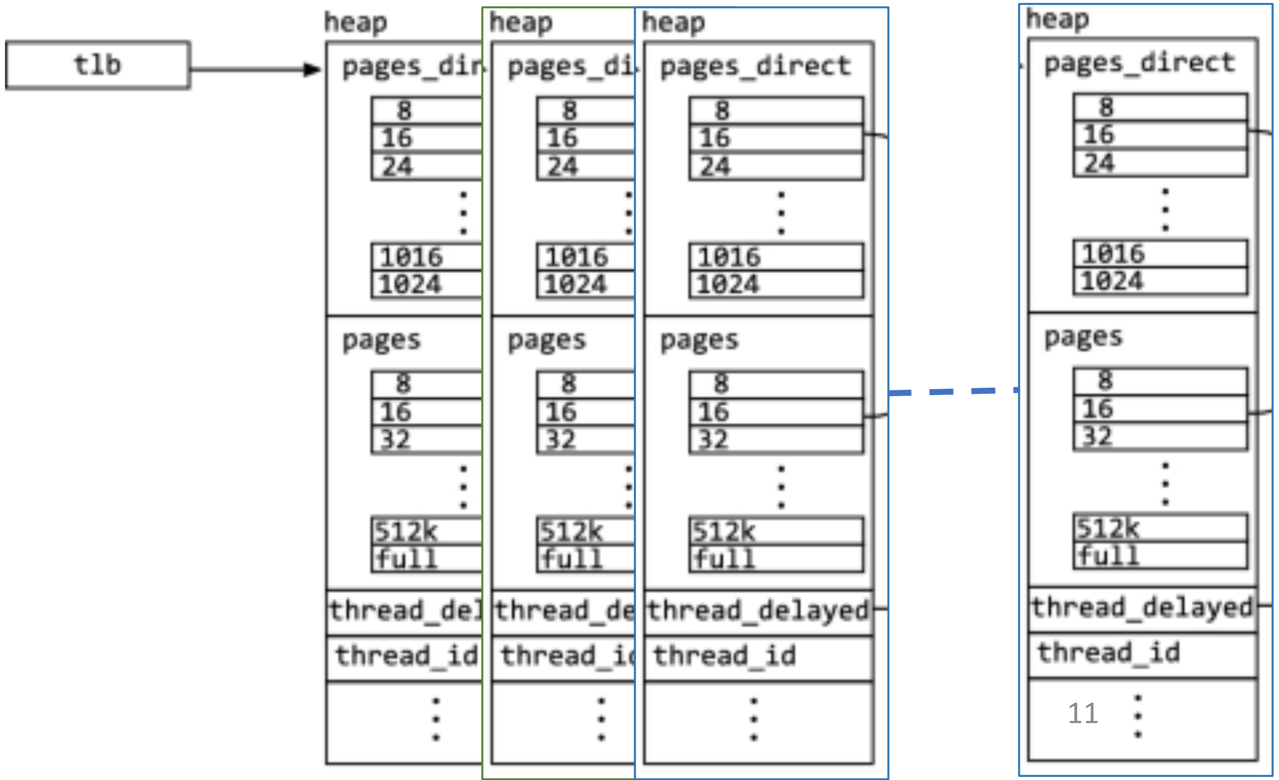
```
impl<T, A> MetaUpdate for Vec<T, A> {
    fn validate(&self) -> bool {
        metasafe::isLive(self.ptr) &&
        metasafe::getSize(self.ptr) >=
        self.capacity()*sizeof(T) &&
        self.capacity() >= self.len()
    }
}
```

```
fn main() {
    let mut buffer = vec![0,2,3]
    unsafe {
        mpk_enable_sp_write();
        buffer.special_set_len(10);
        if !(<Vec<i32> as MetaUpdate>::validate(&buffer)) {
            panic!("METASAFE: Failed to validate Vec<i32>");
        }
    }
}
```

Isolated Storage for Smart Pointers & Metadata

- Separate Compartmentalized Storage for Metadata
  - Stack ➔ Allocate a separate stack for smart pointers (similar to safestack)
  - Heap ➔ Use Allocator with grouping property (Arenas) (tcmalloc, **mimalloc**)
    - Heap[0] for FFI
    - Heap[1] for Smart Pointers
    - Heap[2…TypeN] for user data

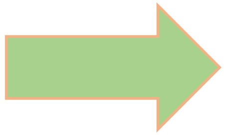




Protecting Smart Pointer Metadata

- Enforcing In-process Isolation.
  - Use Intel-MPK to enforce different access permissions on gated region
- Deciding the boundary of gated region access.
  - Find call sites to smart pointer APIs in application context.
  - Insert WPKRU instructions to enable write before API call.
  - Insert WPKRU instructions to disable write before return inside API function

```
fn main() {
    let mut buffer = vec![0,2,3];
    unsafe {
        buffer.set_len(10);
    }
    println!("Element at 9: {}", buffer[9]);
}
```

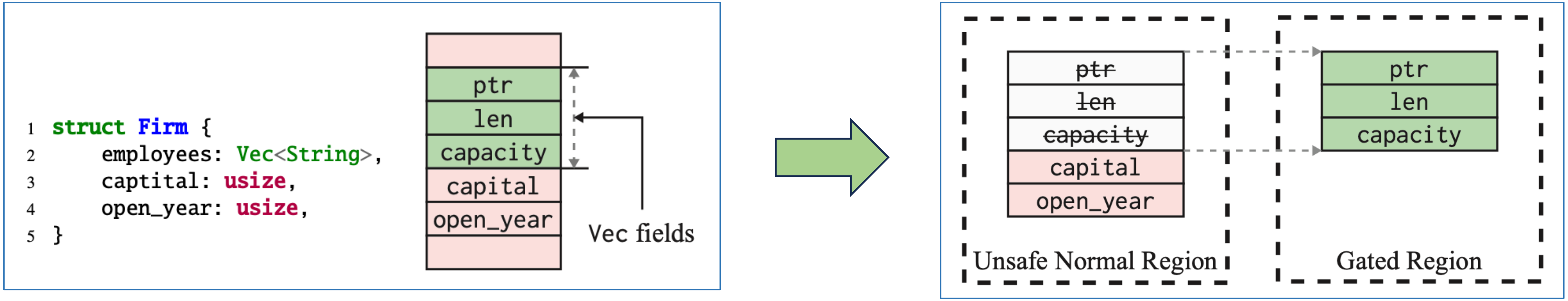


```
fn main() {
    let mut buffer = vec![0,2,3]
    unsafe {
        mpk_enable_sp_write();
        buffer.special_set_len(10);
    }
}

impl<A,T> Vec<A,T> {
    fn special_set_len(&mut self, len: usize) {
        ...
        mpk_disable_sp_write();
    }
}
```

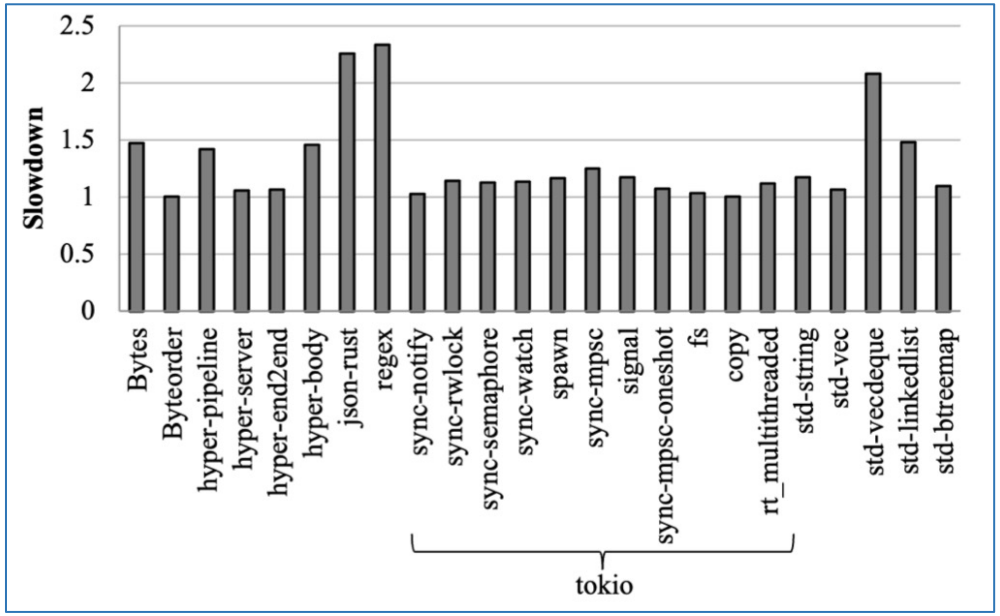
Struct-Inlined Smart Pointers

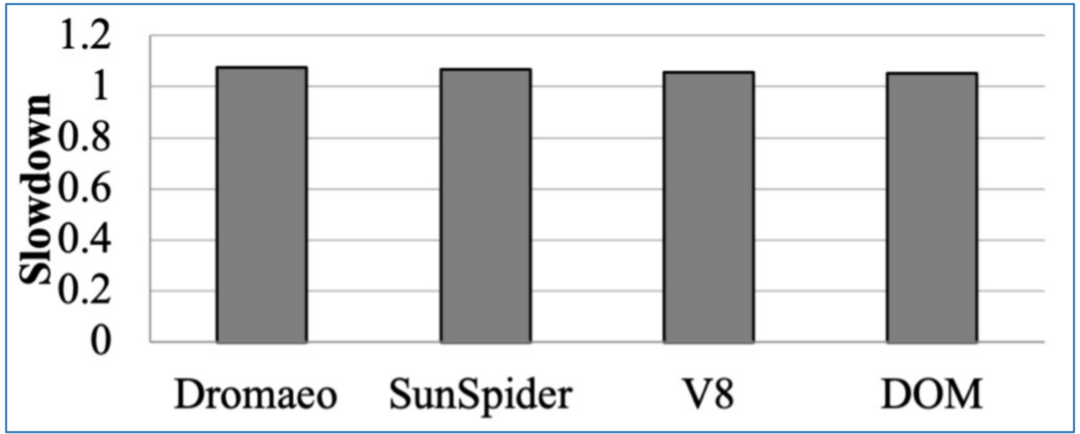
- Protecting In-struct Embedded Smart Pointers
  - How to control access to in-struct embedded smart pointer
    - Treat whole struct as smart pointer ➔ Not safe
    - Treat smart pointer as user-data ➔ Defeats METASAFE
    - Use shadow memory for inlined smart pointers.



Evaluation: Performance

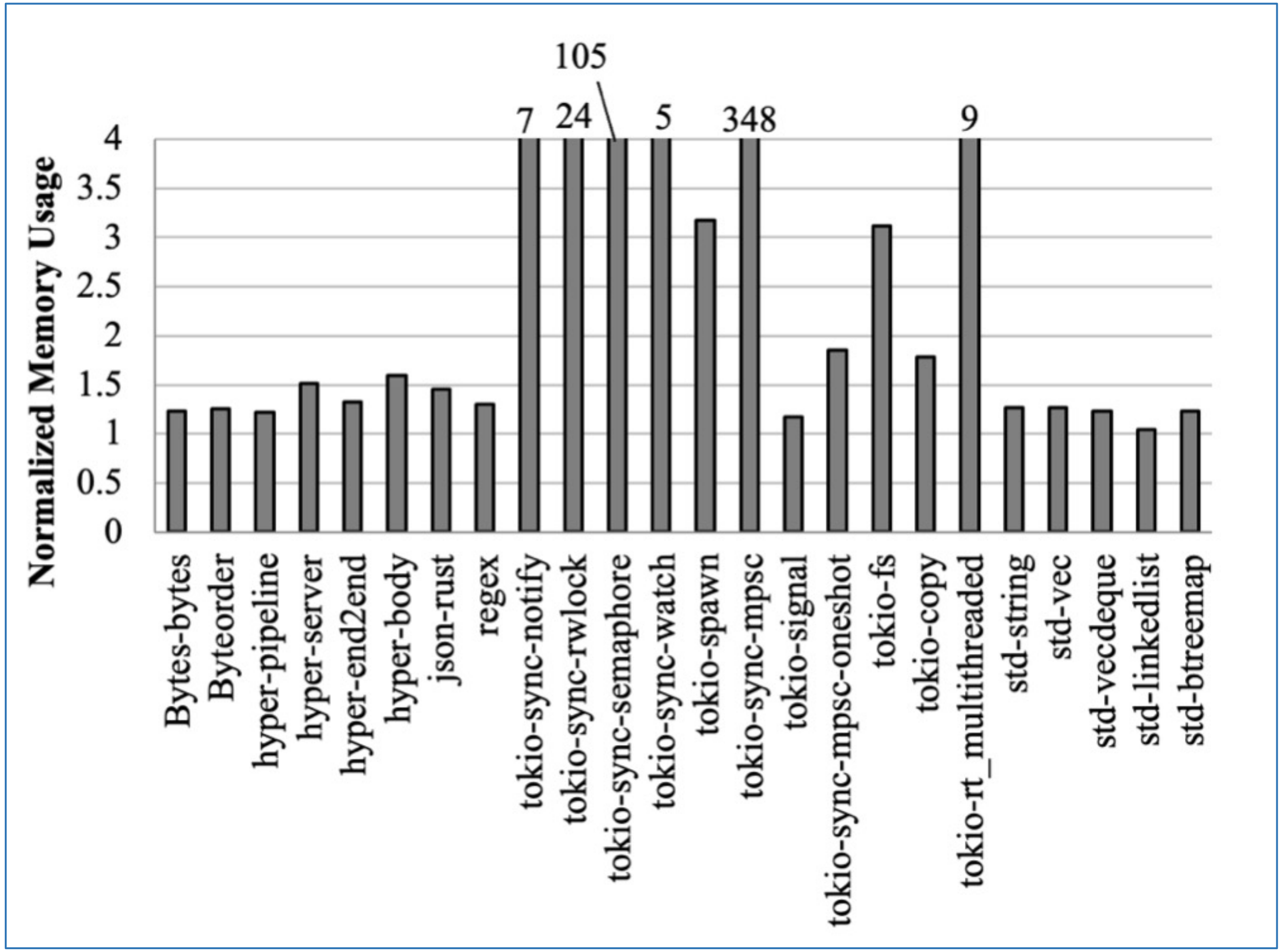
- METASAFE Alone:
  - 25.5% performance overhead on micro benchmarks
  - 3.5% performance overhead on servo browser





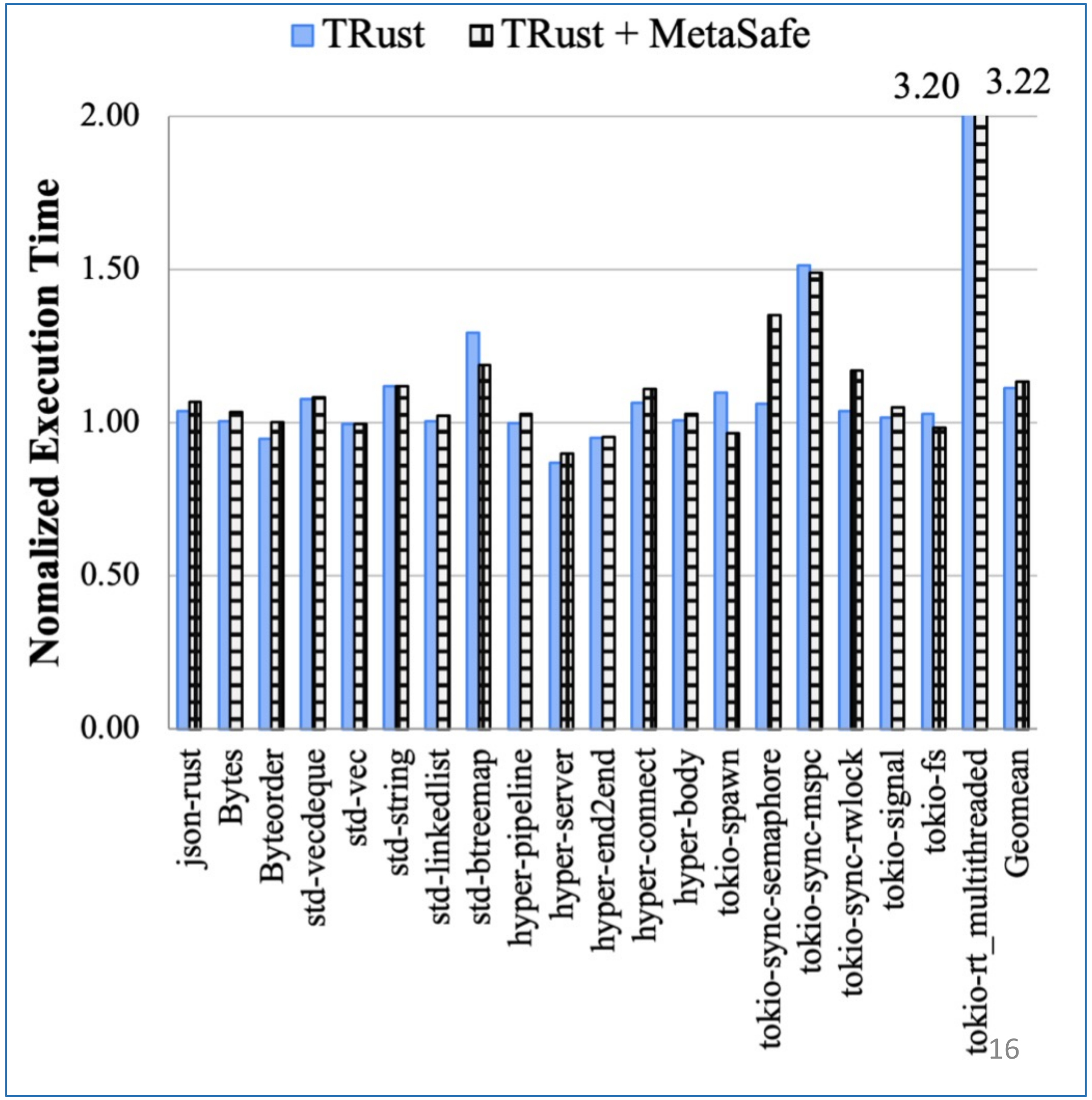
Evaluation: Memory Usage

- METASAFE Alone:
  - 27% Memory usage overhead on single-threaded micro-benchmarks
  - Upto 8x more memory usage for heavily multithreaded micro-benchmarks
    - 31% memory overhead if separate stacks are disabled



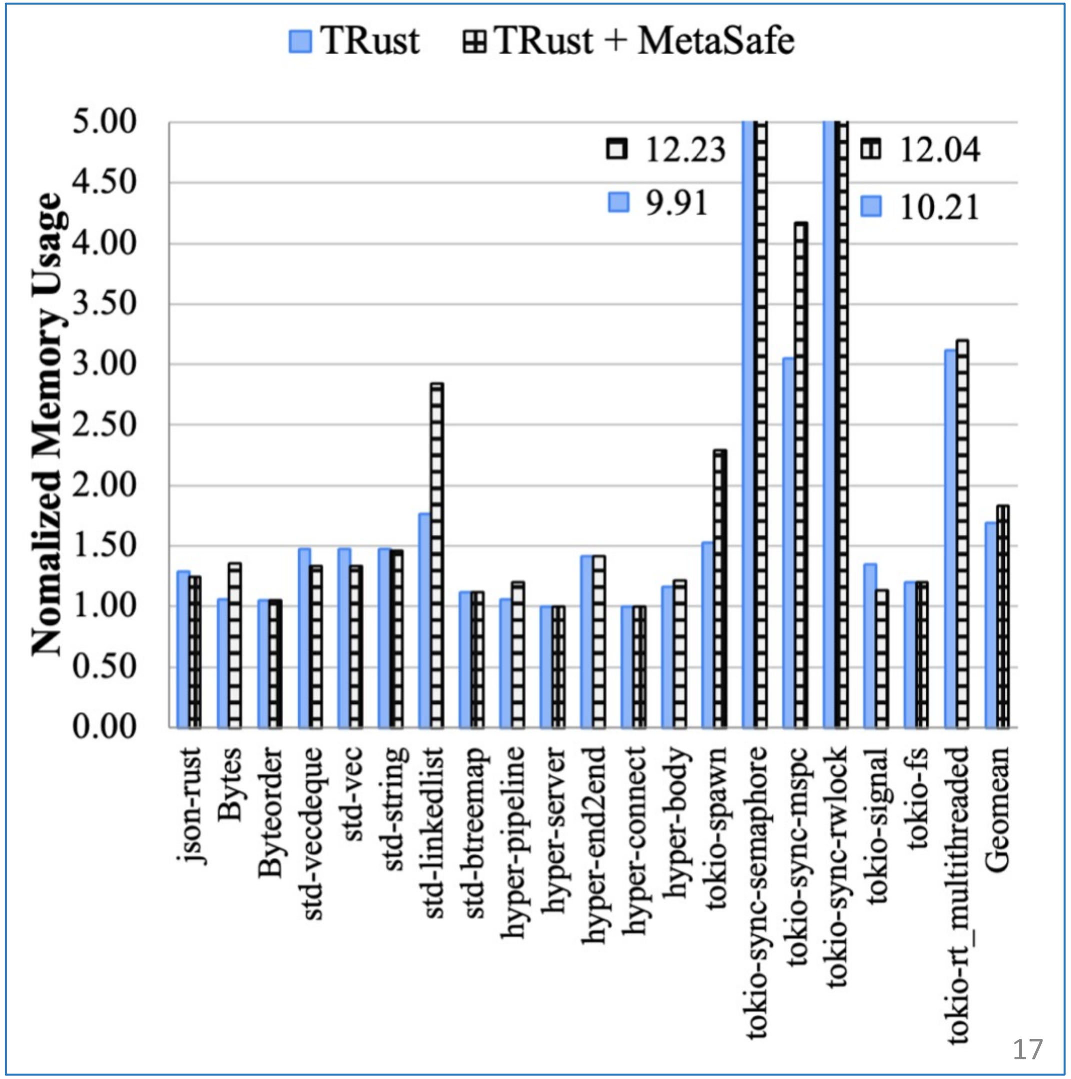
Evaluation: Performance

- METASAFE + TRust
  - TRust: A mechanism for isolating unsafe Rust to protect Safe Rust
  - METASAFE + TRust incurs 13% performance overhead on micro-benchmarks.
  - TRust Alone incurs 11% performance overhead



Evaluation: Memory Usage

- METASAFE + TRust
  - METASAFE + TRust incurs 89% memory overhead
  - TRust alone incurs 69% memory overhead
  - More memory for separating smart pointers



Conclusion

- METASAFE presents a mechanism to recognize and protect smart pointer metadata, thus enhancing Rust memory safety.
- It allows developers to mark smart pointers and provide means of validating metadata updates.
- Relying on Intel-MPK and Compiler instrumentation, METASAFE incurs acceptable runtime overhead for realworld programs such as servo.
- Artifact Open Sourced at:
  https://github.com/seccompgeek/trust23-metsafe24.git
  kayondo/metasafe for built image

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