Rex: Closing the language-verifier gap with safe and usable kernel extensions

Jinghao Jia, Ruowen Qin, Milo Craun, Egor Lukiyanov,
Ayush Bansal, Minh Phan, Michael V. Le, Hubertus Franke,
Hani Jamjoom, Tianyin Xu, Dan Williams

Safe extensions are taking over the OS kernel

cilium

bpftrace

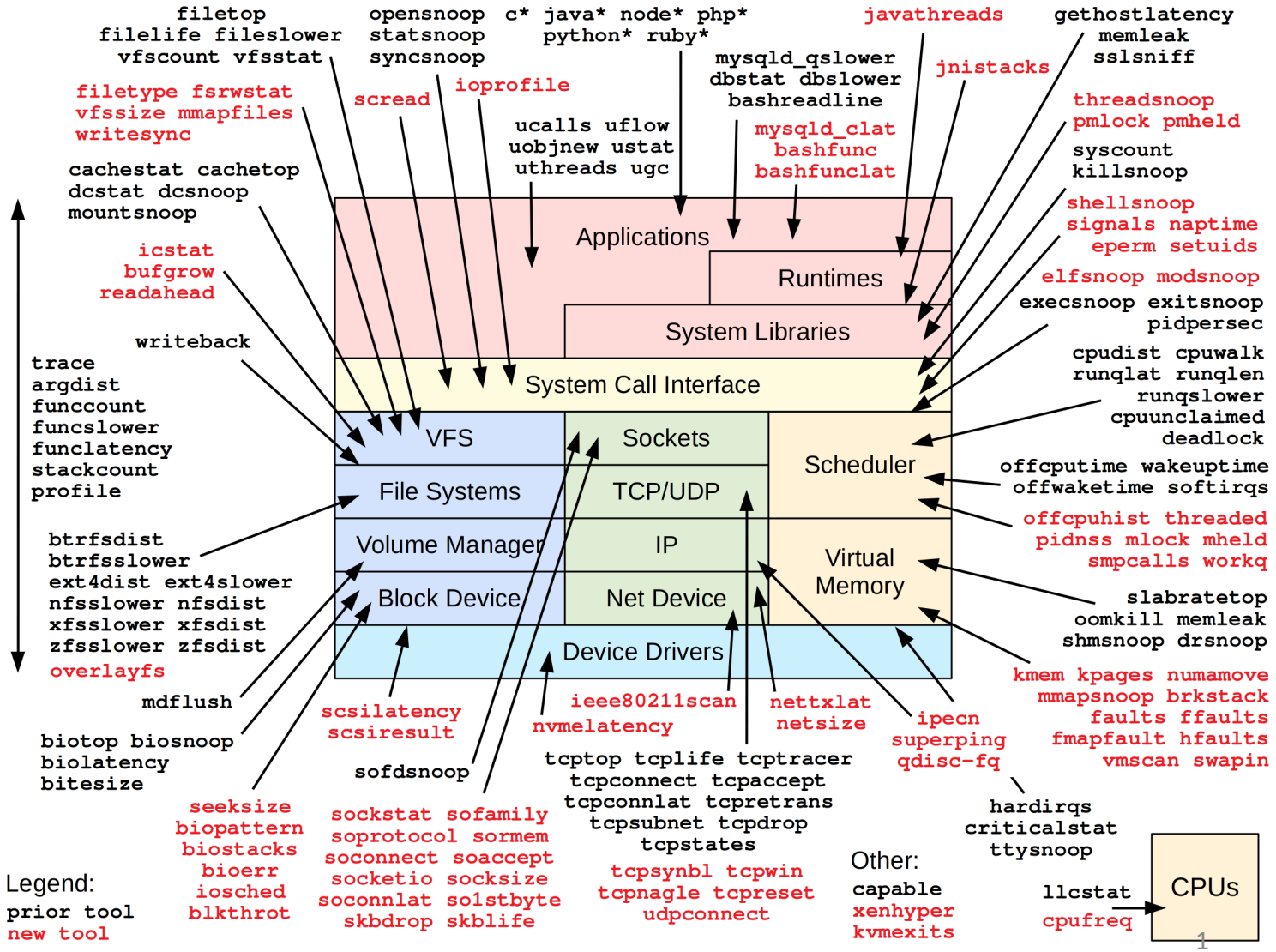

Figure credit: Brendan Gregg

Safe extensions are taking over the OS kernel

BMC: Accelerating Memcached using Safe In-kernel Caching and Pre-stack Processing

Yoann Ghigoff, *Orange Labs, Sorbonne Université, Inria, LIP6;* Julien Sopena, *Sorbonne Université, LIP6;* Kahina Lazri, *Orange Labs;* Antoine Blin, *Gandi;* Gilles Muller, *Inria*

XRP: In-Kernel Storage Functions with eBPF

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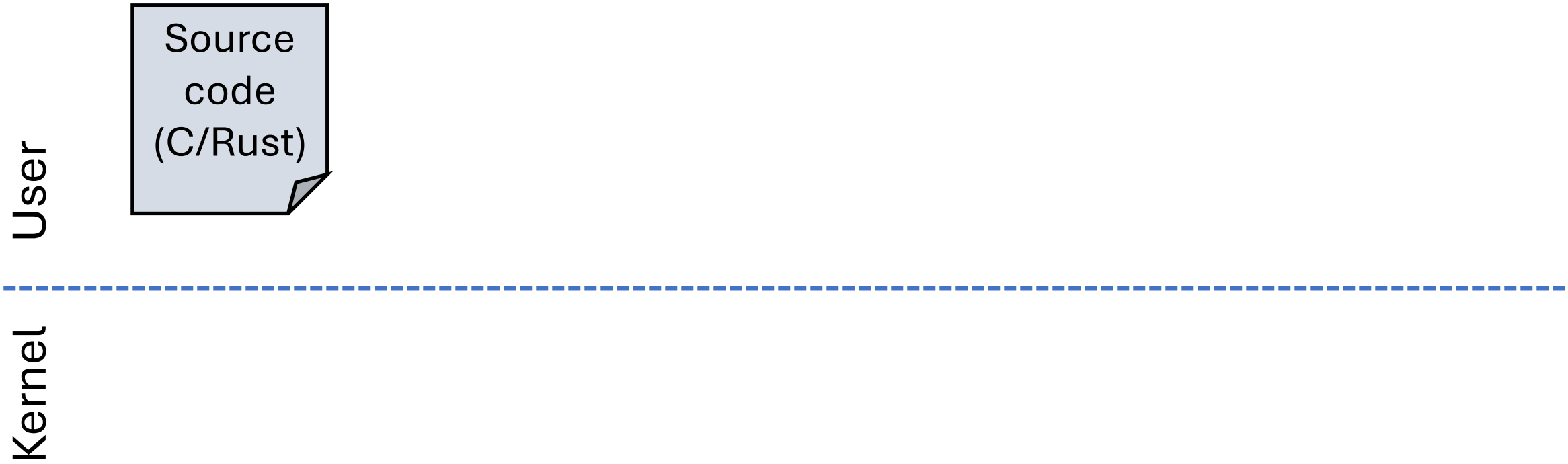
eBPF in CPU Scheduler

Hao Luo <haoluo@google.com>
Barret Rhoden <brho@google.com>

Towards Programmable Memory Management with eBPF

Presented by Kaiyang Zhao <kaiyang2@cs.cmu.edu>

Basic principle of eBPF: Safety verification



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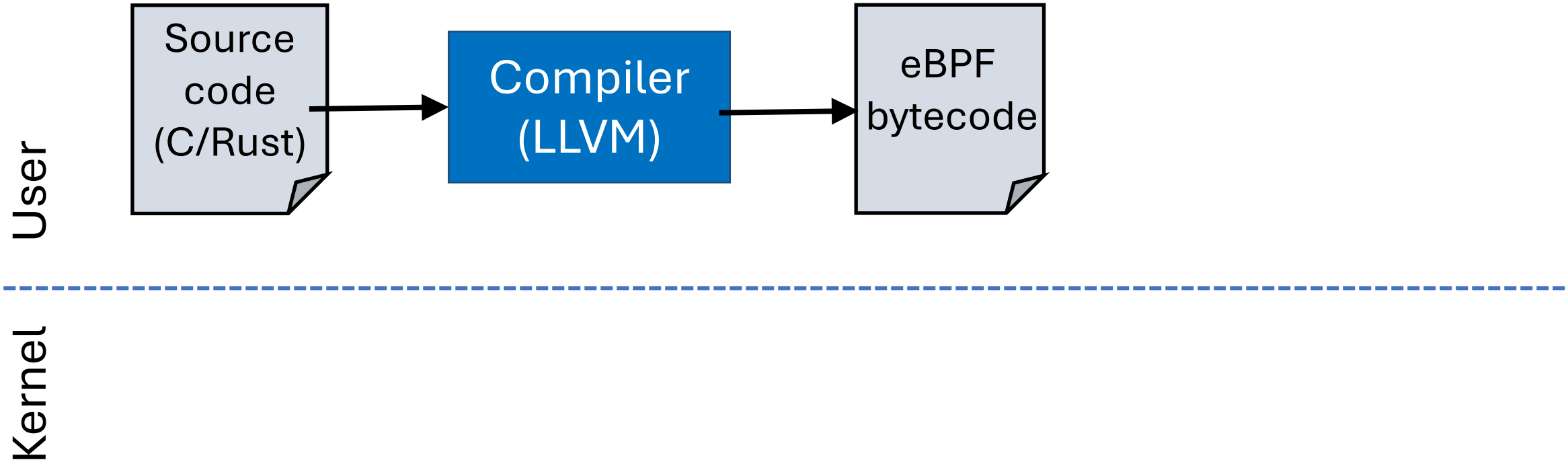

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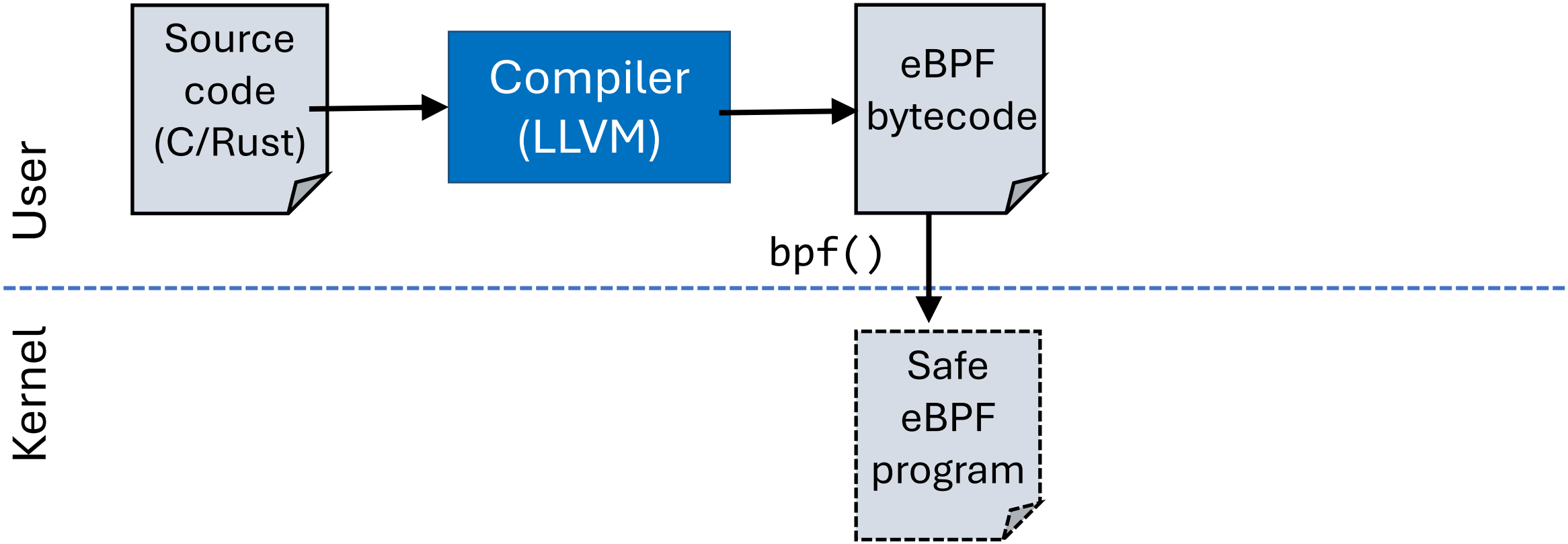

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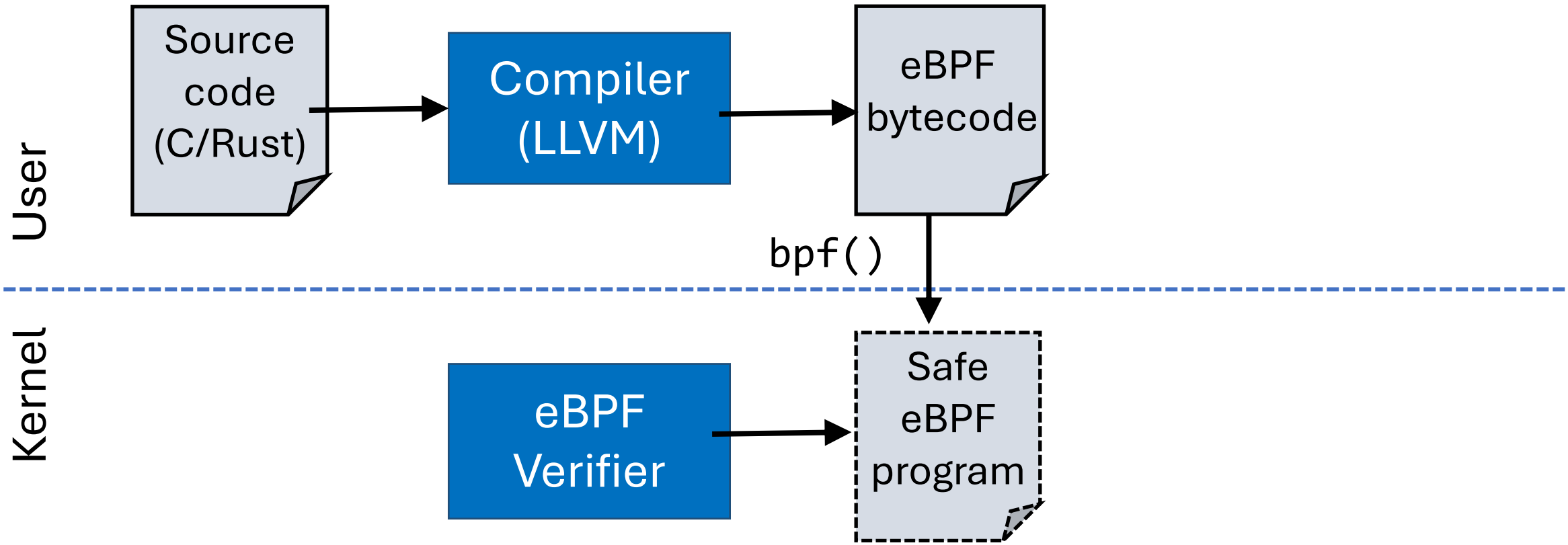
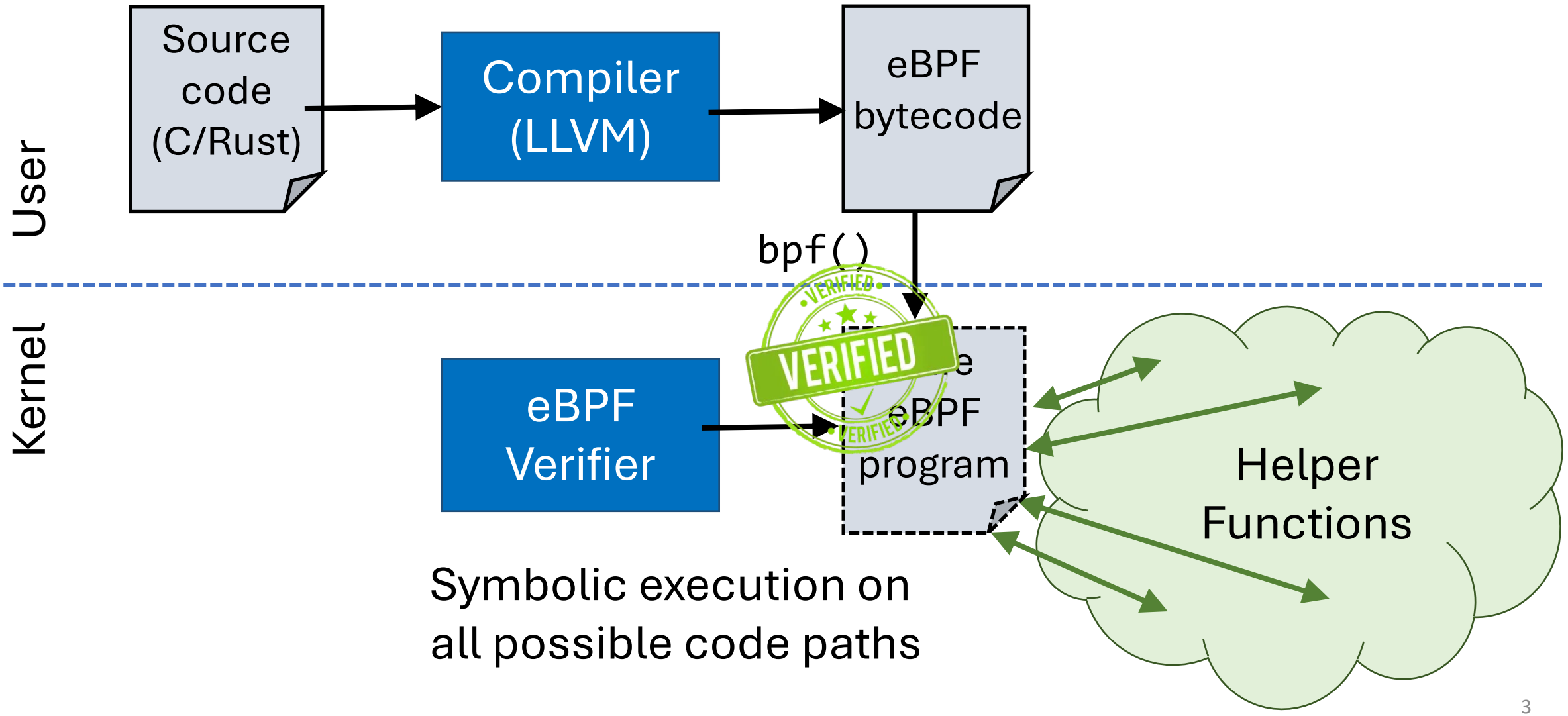


Symbolic execution on all possible code paths

Basic principle of eBPF: Safety verification



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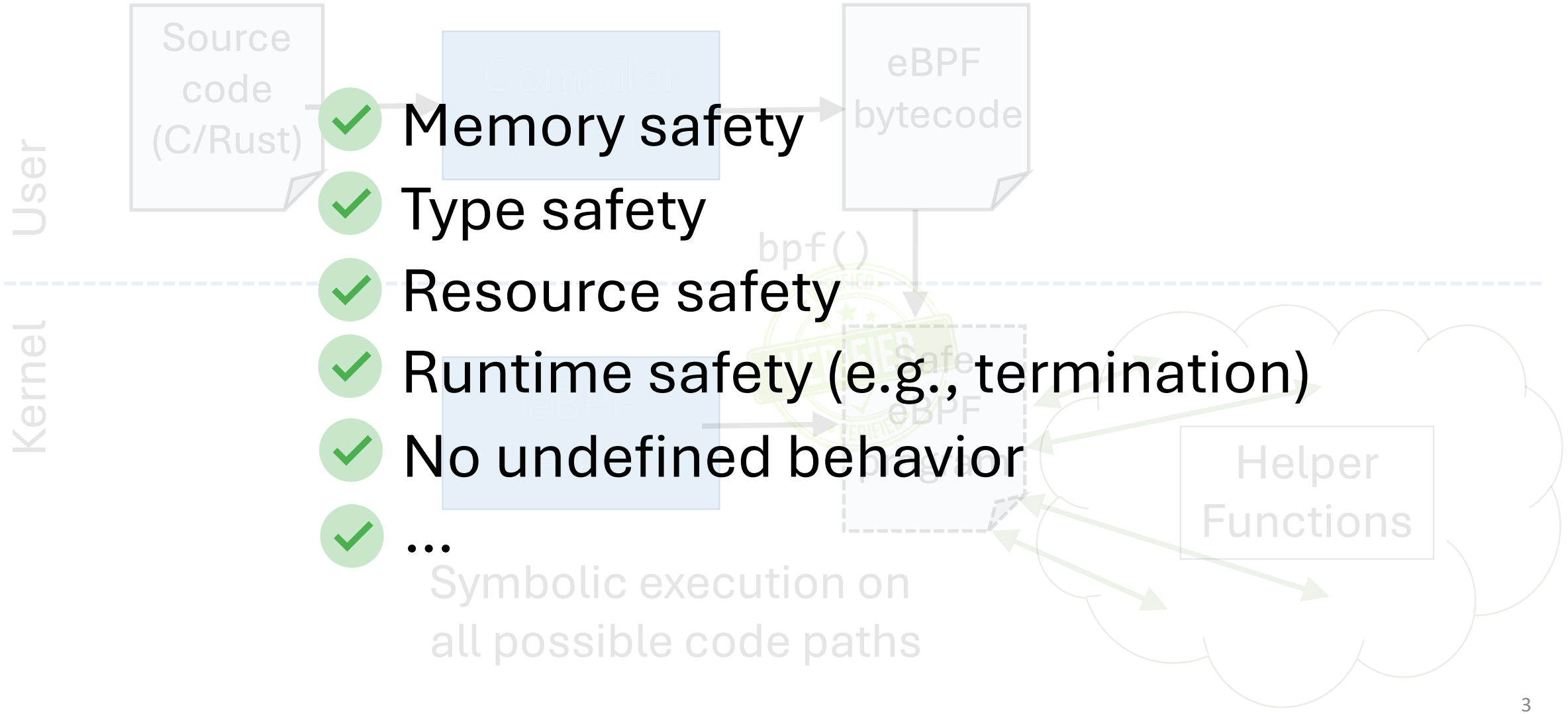
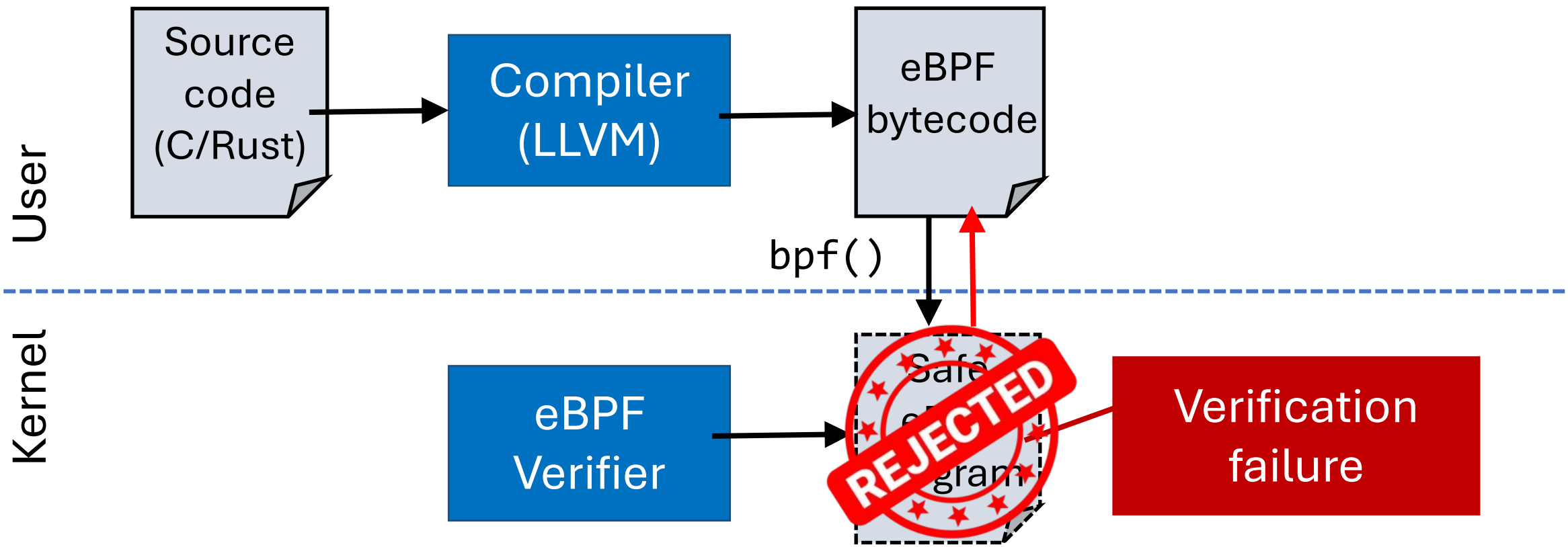


- Memory safety
- Type safety
- Resource safety
- Runtime safety (e.g., termination)
- No undefined behavior
- …

Basic principle of eBPF: Safety verification



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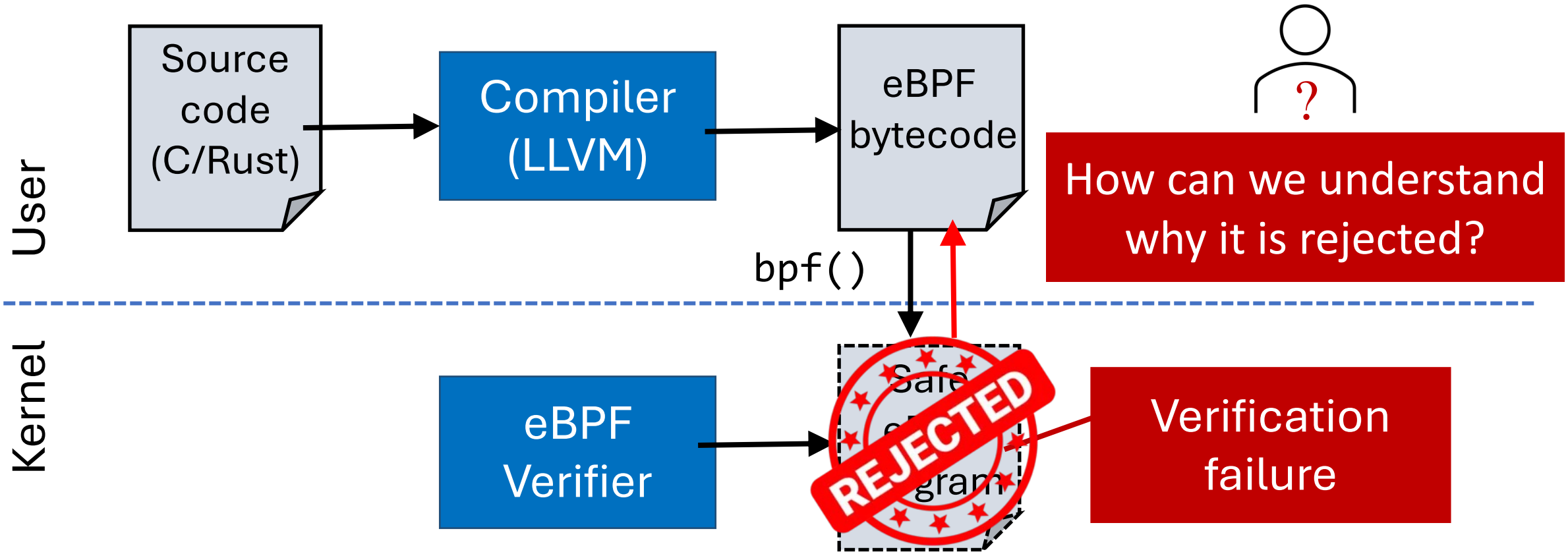

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Roadmap

- Usability problem: the language-verifier gap in extensions
- Rex: Closing the language-verifier gap
- Usability and performance evaluation

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Safety at the cost of usability


```c
/* cilium/bpf/bpf_sock.c */
int __sock4_post_bind(struct bpf_sock *ctx)
{
  struct lb4_service *svc;
  struct lb4_key key = ...;
  ...
  svc = __lb4_lookup_service(&key);
  if (!svc) {
    key.dport = bpf_htons(ctx->src_port);
    svc = sock4_nodeport_wildcard_lookup(&key, ...);
  }
  ...
}
```

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Look up the service from a map using key

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  }
  ...
}
```

Look up the service from a map using key

Redo a wildcard lookup if not found in the last round

Safety at the cost of usability

cilium


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  }
  ...
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```

This simple code does not pass the eBPF verifier!

Safety at the cost of usability


```
32: (85) call bpf_map_lookup_elem#1
33: (15) if r0 == 0x0 goto pc+2"
; R0=map_value(id=0,off=0,ks=12,vs=12,imm=0)
; R6=ctx(id=0,off=0,imm=0)
34: (69) r1 = *(u16 *)(r0 +4)"
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35: (55) if r1 != 0x0 goto pc+51
; R0=map_value(id=0,off=0,ks=12,vs=12,imm=0) R1=inv0
; R6=ctx(id=0,off=0,imm=0)
36: (69) r2 = *(u16 *)(r6 +44)
invalid bpf_context access off=44 size=2
```

Verifier log

Safety at the cost of usability

cilium

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Which source-code line do these instructions map to?

Why is it an invalid access?

Verifier log

Root cause: verifier does not understand compiler

- The program uses `bpf_htons()` to convert the endianness of the `src_port` field in the context.
  - `src_port` is defined as a 32-bit int, while `bpf_htons()` only performs operations on the upper 16 bits
- The compiler optimizes the code to only load the upper 16 bits
- The verifier checks context field accesses based on its size
  - Expect a 32-bit load on `src_port`, but only sees a 16-bit load
  - Reject the extension program with size mismatch error

Workarounds

```
+static __always_inline __maybe_unused __be16
+ctx_src_port(struct bpf_sock *ctx)
+{
+. volatile __u32 sport = ctx->src_port;
+  return (__be16)bpf_htons(sport);
+}
+
...
   if (!svc) {
-    key.dport = bpf_htons(ctx->src_port);
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}
```
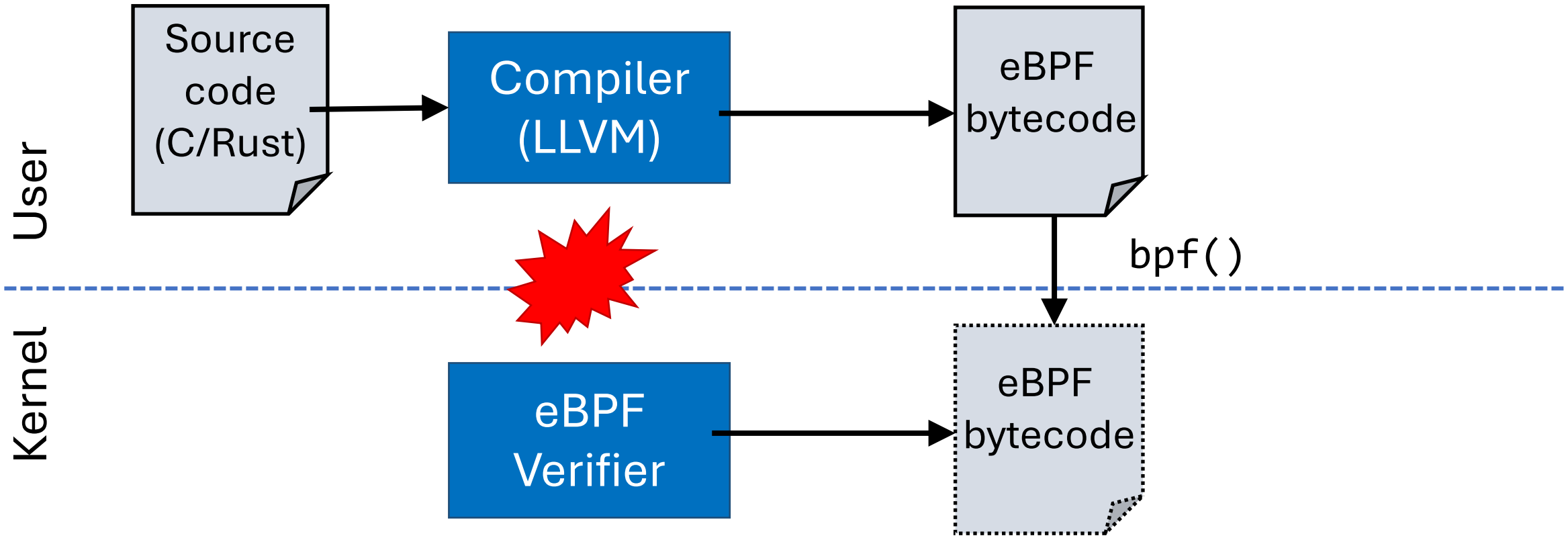

Used `volatile` to force a 32-bit load from the compiler

The language-verifier gap



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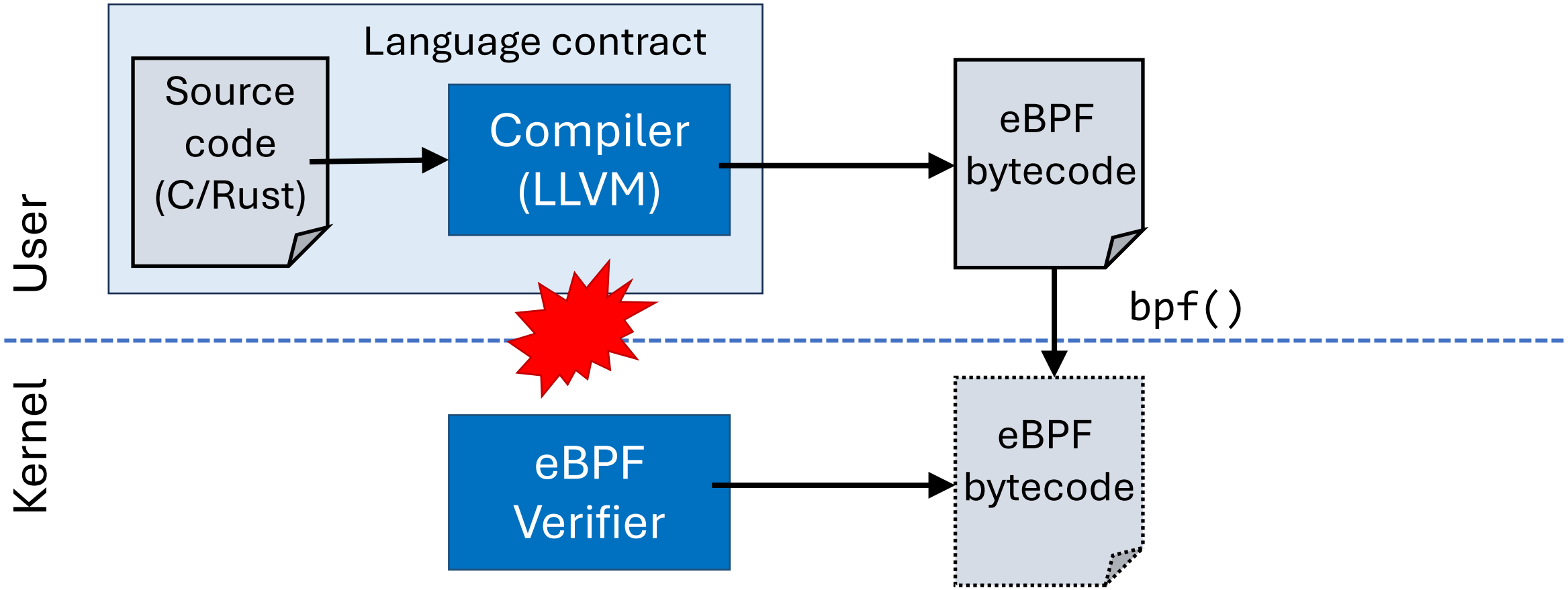

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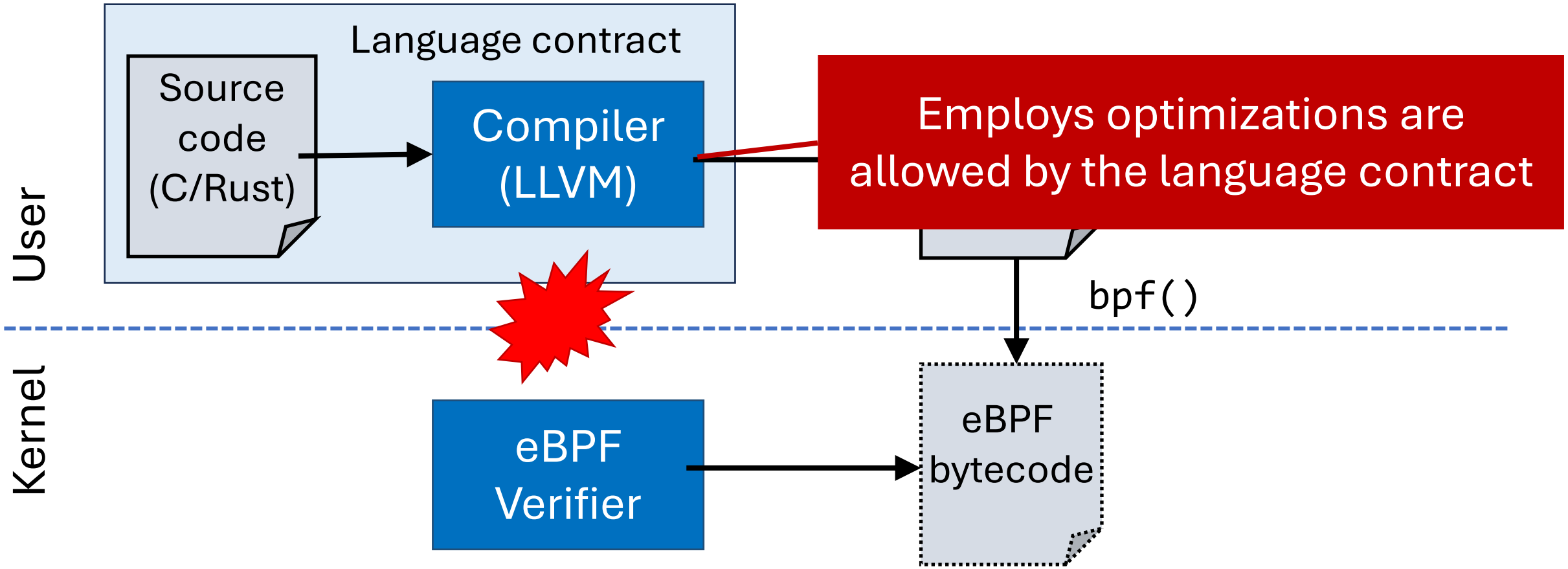

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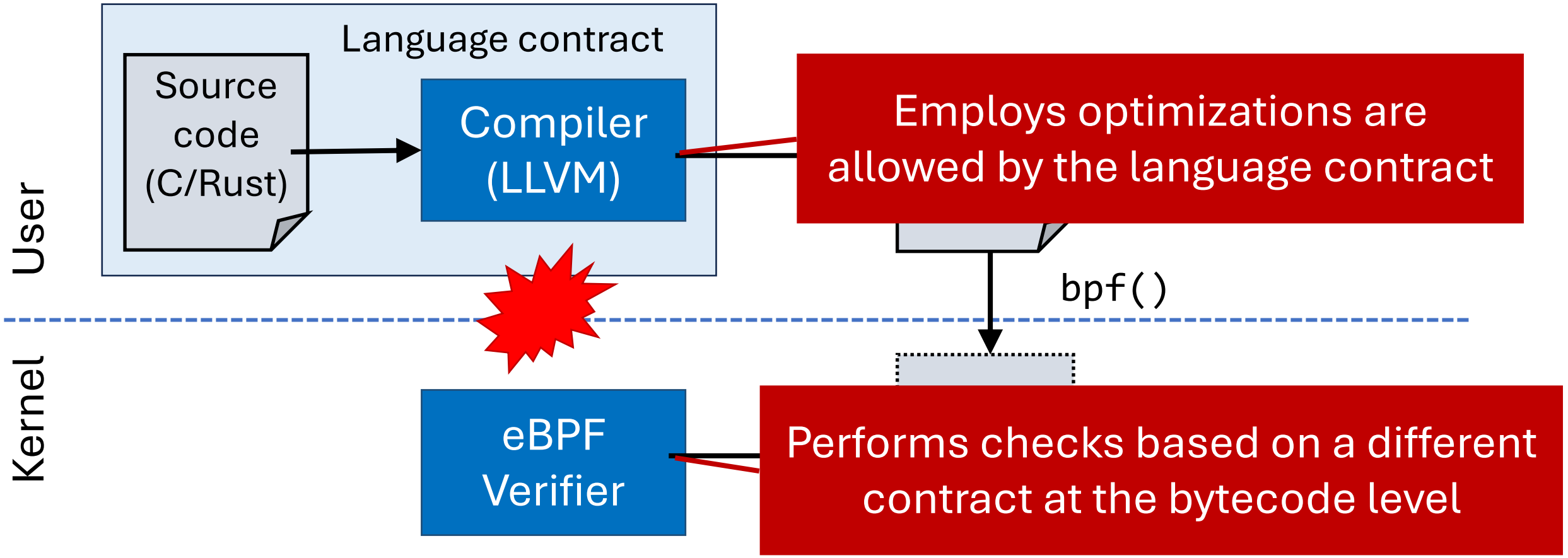

Symbolic execution on all possible code paths

The language-verifier gap causes many problems

Workaround	Count
Refactoring extension code into smaller ones	27
Hinting compilers to generate verifier-friendly code	22
Tweaking code to assist verification	15
Dealing with verifier bugs	9
Reinventing the wheels	1

cilium

AYA

katran

Closing the language-verifier gap

- Running kernel extensions *safely* without a verifier
  - Key challenge: how to ensure safety?

Closing the language-verifier gap

- Running kernel extensions *safely* without a verifier
  - Key challenge: how to ensure safety?

- Insight: Language-based safety + runtime mechanism
  - Rust as the safe language (safe Rust only)
  - Runtime safety checks for other safety properties
    - e.g., termination and stack safety

Roadmap

- Usability problem: the language verifier gap in extensions
- Rex: Closing the language-verifier gap
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Rex: Safe, usable Rust kernel extensions

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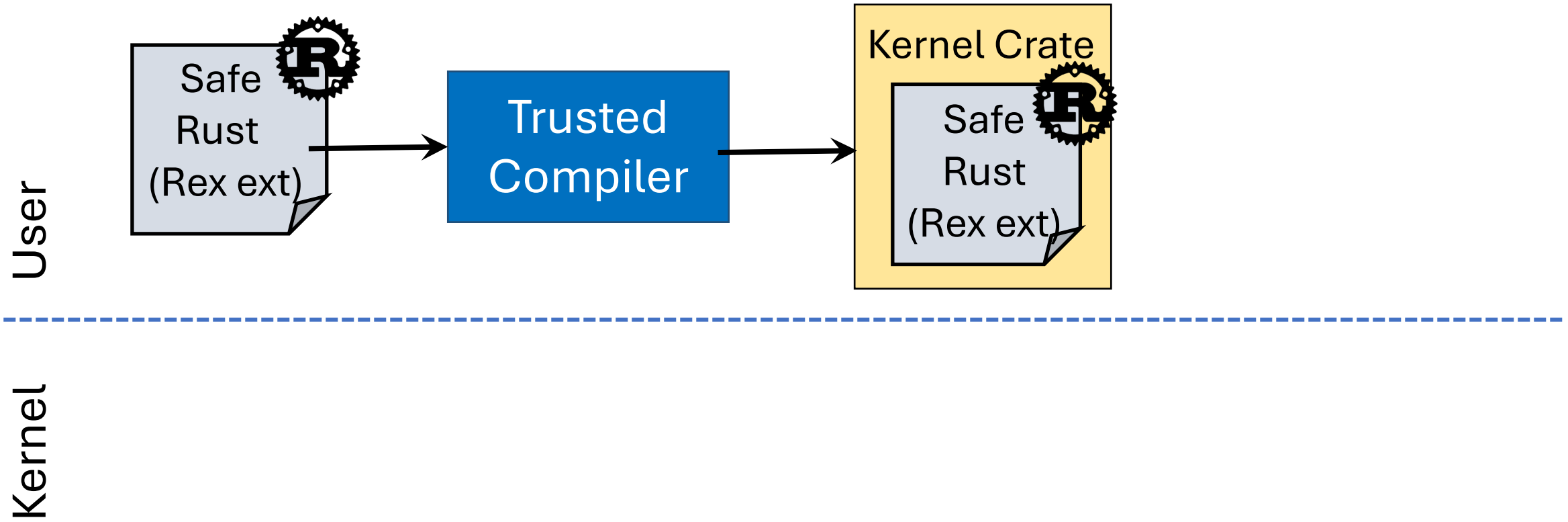
User

Kernel

Rex: Safe, usable Rust kernel extensions



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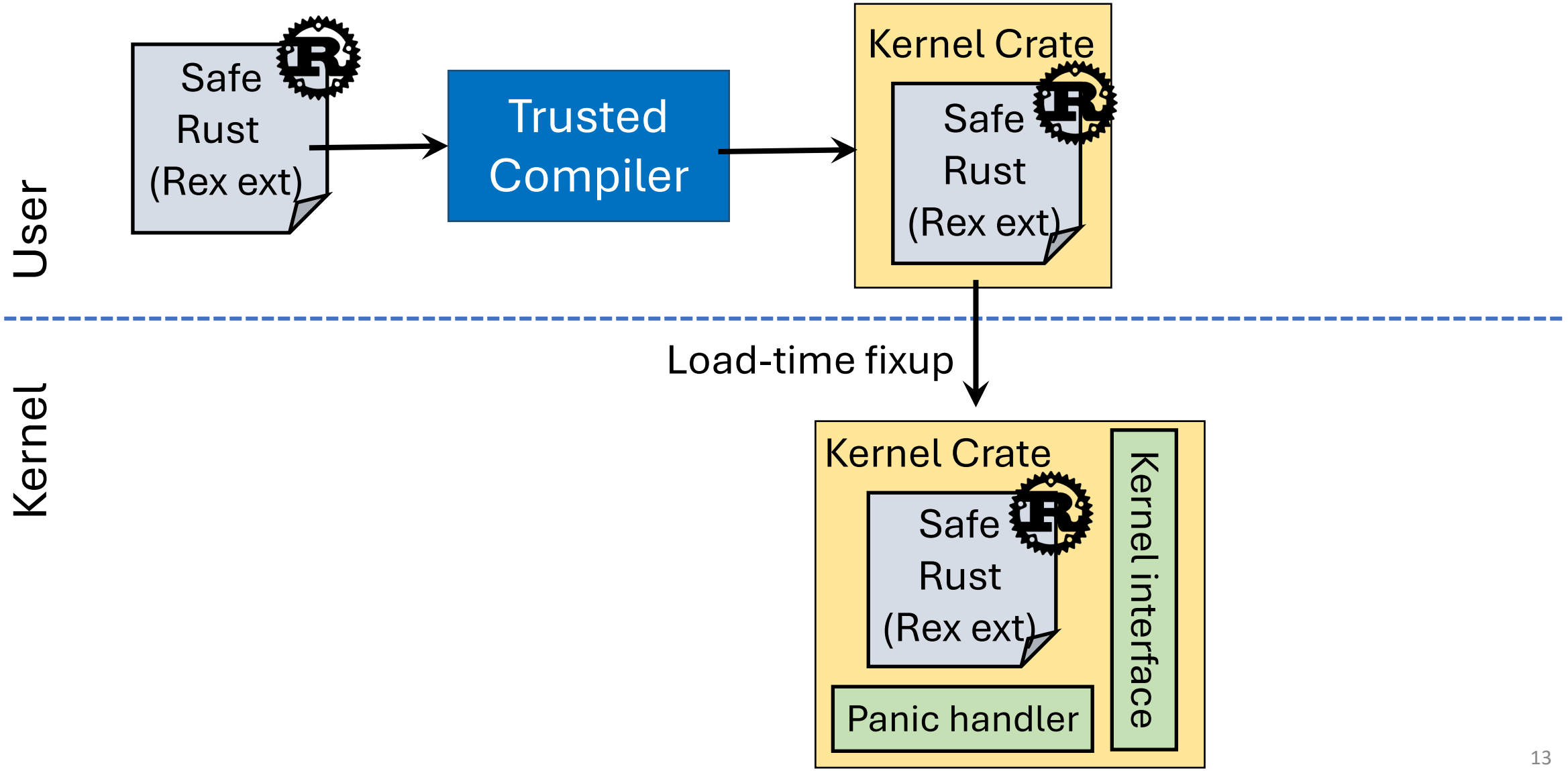

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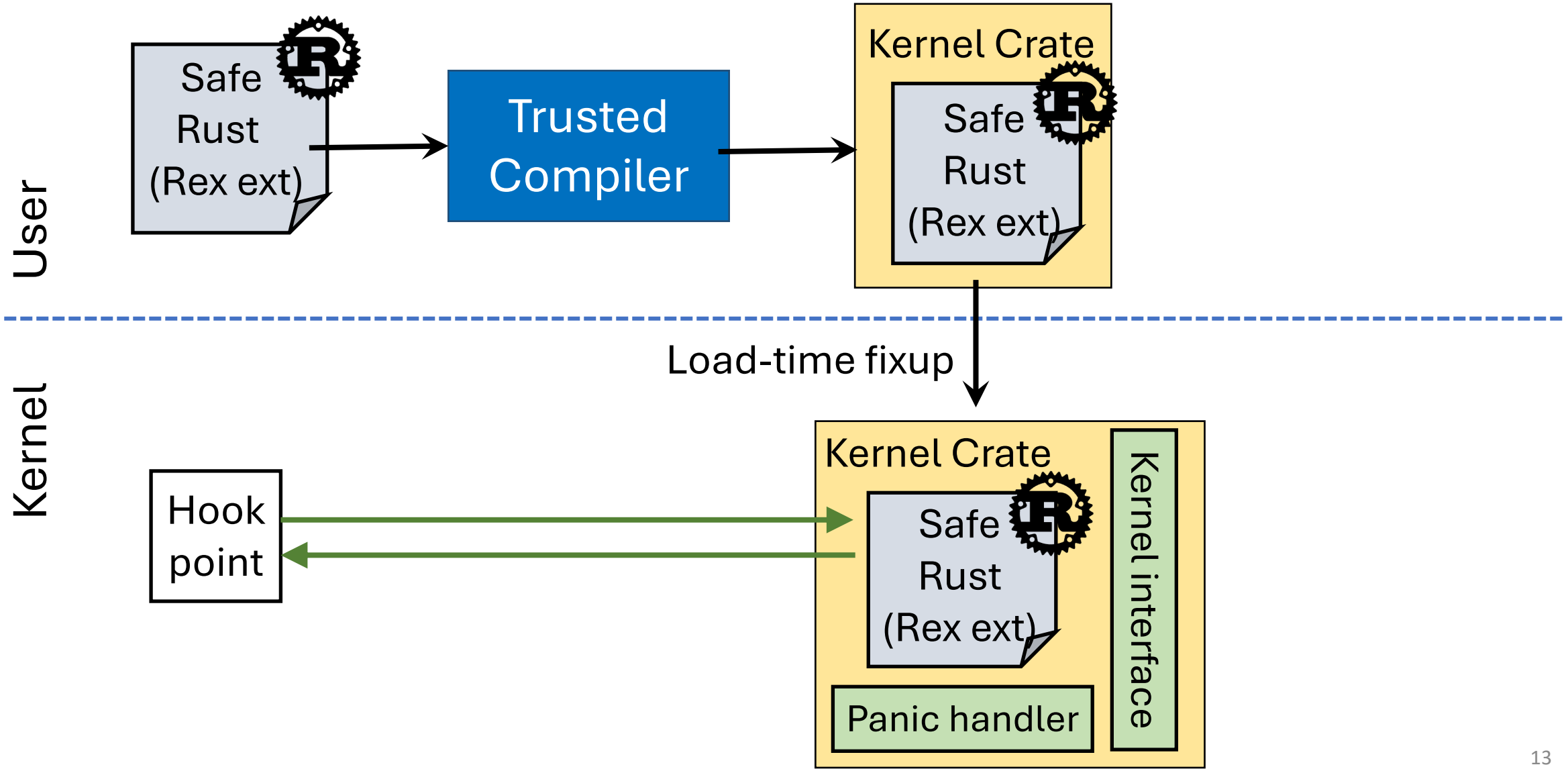

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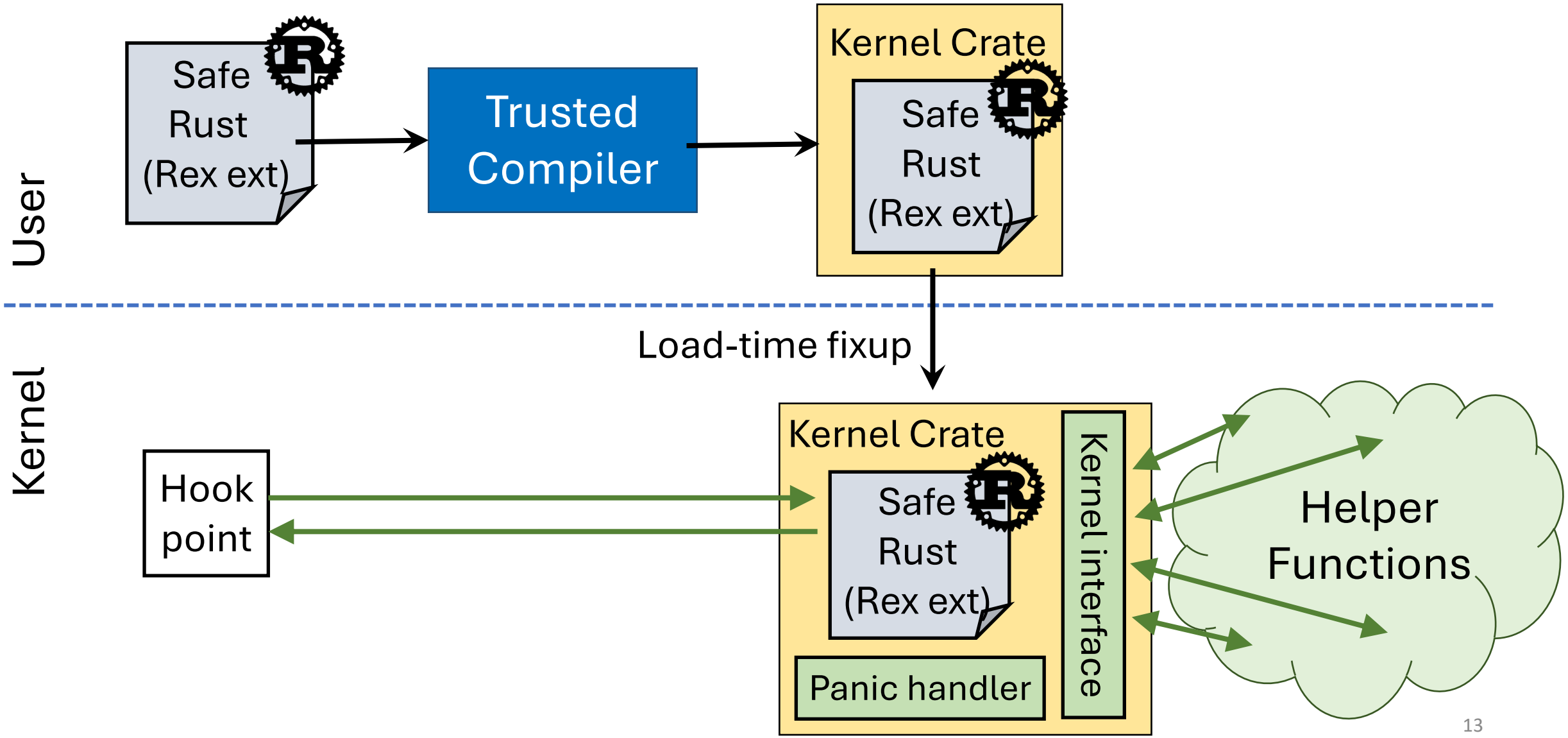

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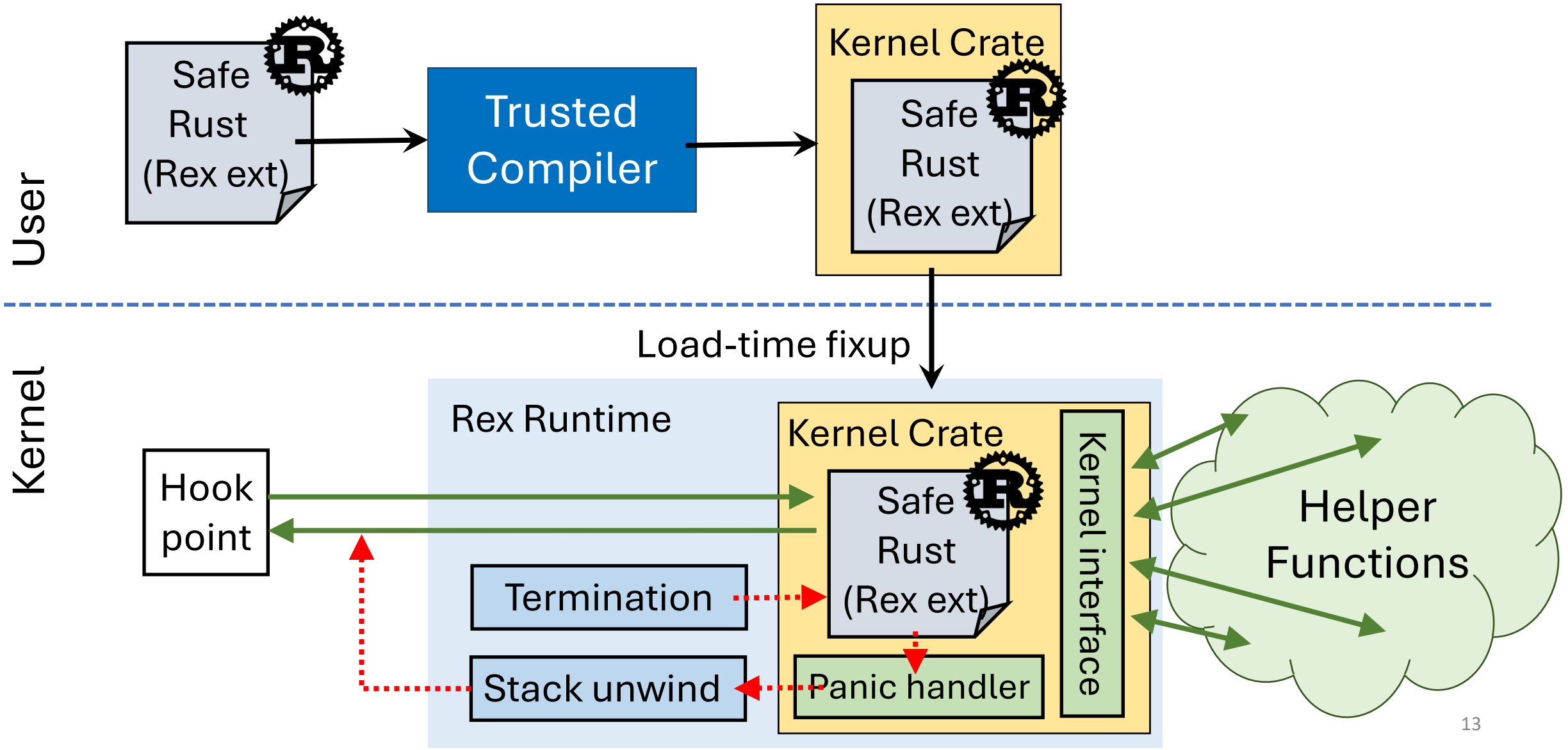

Safety in Rex

- Rex kernel crate: Compile-time safety
  - Memory safety
  - Extended type safety
  - Safe resource management
- Rex Runtime safety
  - Safe exception handling
  - Kernel stack safety
  - Program Termination

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Extended type safety

- There is the desire of transforming a byte stream to typed data
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```
void *payload = ctx->data;
/* extract ip header */
struct iphdr *ip = payload;
__u8 protocol = ip->protocol;
```

Extended type safety

- There is the desire of transforming a byte stream to typed data
  - Common in networking use cases
  - **Inevitably requires unsafe code** under the Rust type system

```
let payload: &[u8] = ctx.data;
// extract ip header
let ip = unsafe { &*(payload.as_ptr() as *const iphdr) };
let protocol = ip.protocol;
```

Extended type safety

- There is the desire of transforming a byte stream to typed data
  - Common in networking use cases
  - **Inevitably requires unsafe code** under the Rust type system

- eBPF considers the cast safe under two rules
  - #1 Not making a pointer by casting a scalar value
  - #2 New value fitting in the memory boundary
- Rex follows the same rules and extends the Rust type safety

Extended type safety

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Extended type safety

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- Create an **auto trait**: `rex::NoRef`
  - Default implemented on a type if all fields are `rex::NoRef`
  - Negative implementation on reference and pointer types

```
pub unsafe auto trait NoRef {}
impl<T: ?Sized> !NoRef for &T {}
impl<T: ?Sized> !NoRef for &mut T {}
impl<T: ?Sized> !NoRef for *const T {}
impl<T: ?Sized> !NoRef for *mut T {}
```

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```
pub struct my_hdr {
  request_id: u16,
  seq_num: u16,
  num_dgram: u16,
  other: NonNull<u64>,
}
```

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```rust
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`NonNull` contains a `*const u64`

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`Rex::NoRef` is not implemented for `NonNull` and `my_hdr`

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- Require type to be `rex::NoRef` to convert from bytes (#1)
- Check memory bounds at runtime (#2)

```
fn from_bytes<T: NoRef>(bytes: &[u8]) -> &T {
  assert!(data.len() >= mem::size_of::<T>());
  ...
}
```

Safe exception handling

- Certain safety properties of Rust are checked at runtime
  - Violations (e.g., out-of-bound access) trigger Rust panics
- Rust performs Itanium-ABI exception handling in user space
  - Unwind each stack frame and executes cleanup code
  - Not suitable in context of safe kernel extensions
    - Stack unwinding **cannot** fail (causing kernel crash or resource leaks)
    - Executing user-defined destructors is **not safe**
- Rex supports safe exception handling with two components
  - Graceful exit
  - Resource cleanup

Safe exception handling (graceful exit)

```
// In-kernel dispatcher function
rex_dispatcher_func:
// save old stack pointer
mov %rsp, PER_CPU_VAR(rex_old_sp)
...

// invoke the REX program
call *%rdx

rex_exit:
// reset to old stack pointer
mov PER_CPU_VAR(rex_old_sp), %rsp
...
ret
```

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Save the old stack pointer before program invocation

Safe exception handling (graceful exit)

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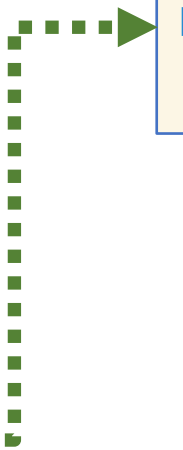
```
// Rex program
rex_prog1:
...
```



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mov PER_CPU_VAR(rex_old_sp), %rsp
...
ret
```

```
// Rex program
rex_prog1:
...
```

Panic

```
// Rex panic handler
rust_begin_unwind:
// Cleanup resources
...
call rex_landingpad
```

Safe exception handling (graceful exit)

```
// In-kernel dispatcher function
rex_dispatcher_func:
// save old stack pointer
mov %rsp, PER_CPU_VAR(rex_old_sp)
...

// invoke the REX program
call *%rdx

rex_exit:
// reset to old stack pointer
mov PER_CPU_VAR(rex_old_sp), %rsp
...
ret
```

```
// Rex program
rex_prog1:
...
```

Panic

```
// Rex panic handler
rust_begin_unwind:
// Cleanup resources
...
call rex_landingpad
```

```
// In-kernel landingpad
rex_landingpad:
// Report error
...
jmp rex_exit
```

Safe exception handling (graceful exit)

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Panic

```
// Rex panic handler
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// Cleanup resources
...
call rex_landingpad
```

```
// In-kernel landingpad
...
jmp rex_exit
```

Restore the old stack pointer to unwind stack

Safe exception handling (resource cleanup)

- Safe exception handling **must clean up** acquired resources
  - Itanium EH uses DWARF to identify acquired resources

- Insight: extensions can only acquire resources via helpers
  - Only these resources need to be released
  - Record resources allocated via helper functions in a per-CPU buffer
  - Upon panic, iterate the resources and perform cleanup

Implementation

- We implement Rex on top of Linux v6.15
  - Kernel crate
    - Helper function interface
    - Kernel data-type bindings
    - Program-type-specific code
  - Kernel support
    - Program loading and symbol resolution
    - In-kernel Rex runtime
  - Compiler support
    - LLVM pass to perform Rex-specific instrumentations

Roadmap

- Usability problem: the language verifier gap in extensions
- Rex: Closing the language-verifier gap
- Usability and performance evaluation

Usability evaluation

- Heuristic evaluation
  - **No language-verifier gap anymore**
- Dogfooding
  - Used Rex to implement the BPF Memcached Cache (BMC)
  - **Much cleaner, simpler code**
    - 326 lines of Rust code vs. 513 lines of C code
- Classroom experience
  - Designed 3 assignments on kernel tracing and networking
  - Our undergraduate students can write correct Rex extensions!

Case study: BMC cache invalidation

Original eBPF-BMC

```
// Searches for SET command in payload
for (unsigned int off = 0;
     off < BMC_MAX_PACKET_LENGTH &&
     payload + off + 1 <= data_end;
     off++) {
    if (set_found == 0 &&
        payload[off] == 's' &&
        payload + off + 3 <= data_end &&
        payload[off + 1] == 'e' &&
        payload[off + 2] == 't') {
            off += 3;
            set_found = 1;
    }
    ...
}
```

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     off < BMC_MAX_PACKET_LENGTH &&
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    }
    ...
}
```

Additional limit to fit in verifier's complexity limit

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Additional limit to fit in verifier's complexity limit

Boilerplate to explicitly check end of payload

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}
```

Additional limit to fit in verifier's complexity limit

Boilerplate to explicitly check end of payload

Verbose logic to match SET command in payload

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        payload[off + 1] == 'e' &&
        payload[off + 2] == 't') {
            off += 3;
            set_found = 1;
    }
    ...
}
```

Rex-BMC

```
// Searches for SET command in payload
let set_iter = payload
    .windows(4)
    .enumerate()
    .filter_map(|(i, v)|
        if v == b"set " {
            Some(i)
        } else {
            None
        }
);
...
```

Case study: BMC cache invalidation

Original eBPF-BMC

No extra code to handle complexity limit from verifier

```
// S                                          d
for
     payload + off + 1 <= data_end;
     off++) {
    if (set_found == 0 &&
        payload[off] == 's' &&
        payload + off + 3 <= data_end &&
        payload[off + 1] == 'e' &&
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            off += 3;
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}
```

Rex-BMC

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        }
);
...
```

Case study: BMC cache invalidation

Original eBPF-BMC

```
// S                                                    d
for                                                     (
    payload + off + 1 <= data_end;
    off++) {
                                                        &&
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    payload[off + 2] == 't') {
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    }
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```

No extra code to handle complexity limit from verifier

Rust slices already provides bound checks in its methods

Rex-BMC

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Case study: BMC cache invalidation

Original eBPF-BMC

```
// S                                                    d
for                                                     (
    payload + off + 1 <= data_end;
    off++) {
    payload[off] == 's' &&                                  &&
    payload[off + 1] == 'e' &&
    ...
}
```

No extra code to handle complexity limit from verifier

Rust slices already provides bound checks in its methods

Easy match of SET command using Rust byte slice

Rex-BMC

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Case study: BMC cache invalidation

Original eBPF-BMC

```
// S                                                    d
for                                                     (
    payload + off + 1 <= data_end;
    off++) {
                                                        &&
    payload[off + 1] == 'e' &&
}
...
}
```

No extra code to handle complexity limit from verifier

Rust slices already provides bound checks in its methods

Easy match of SET command using Rust byte slice

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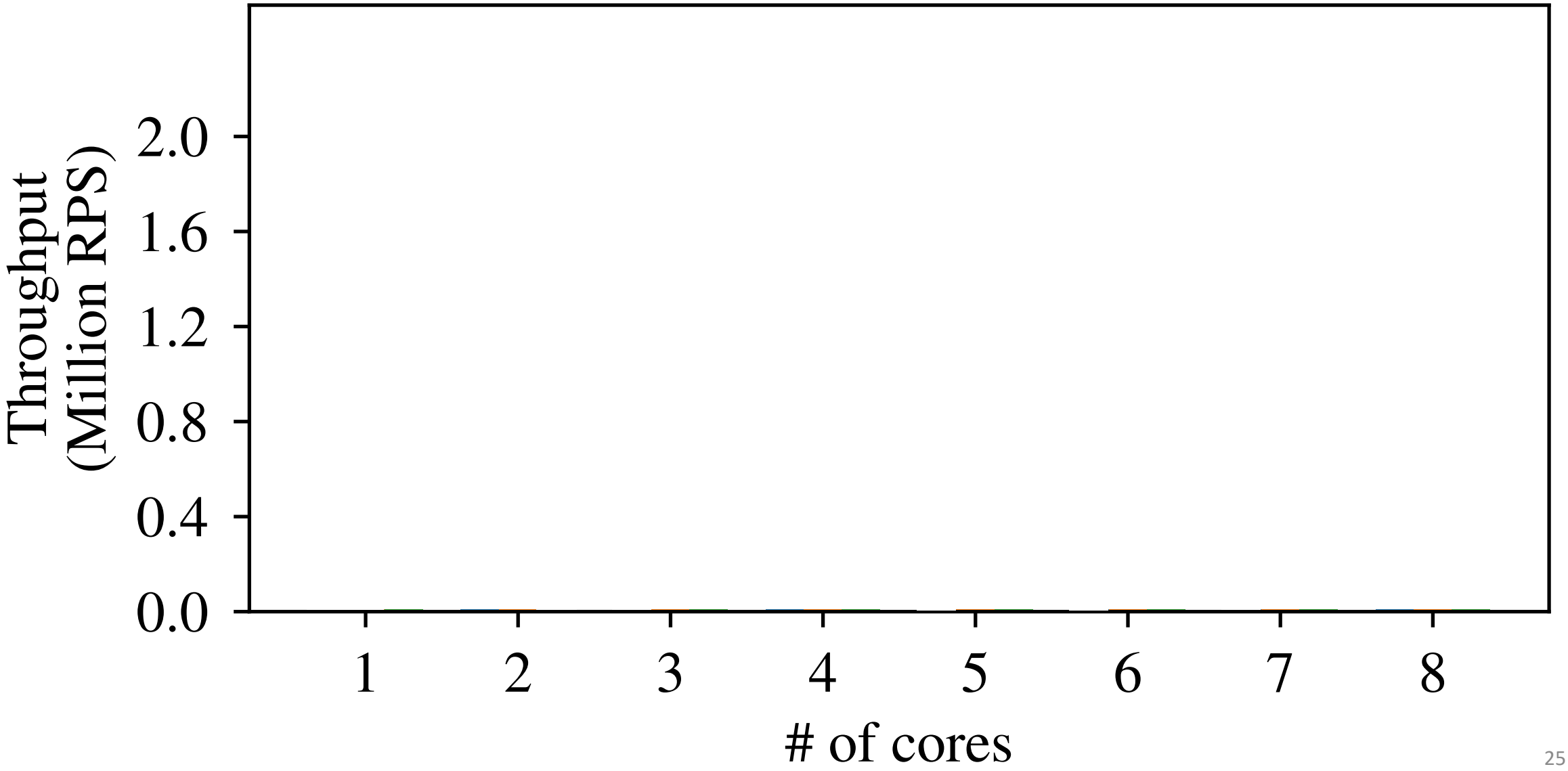
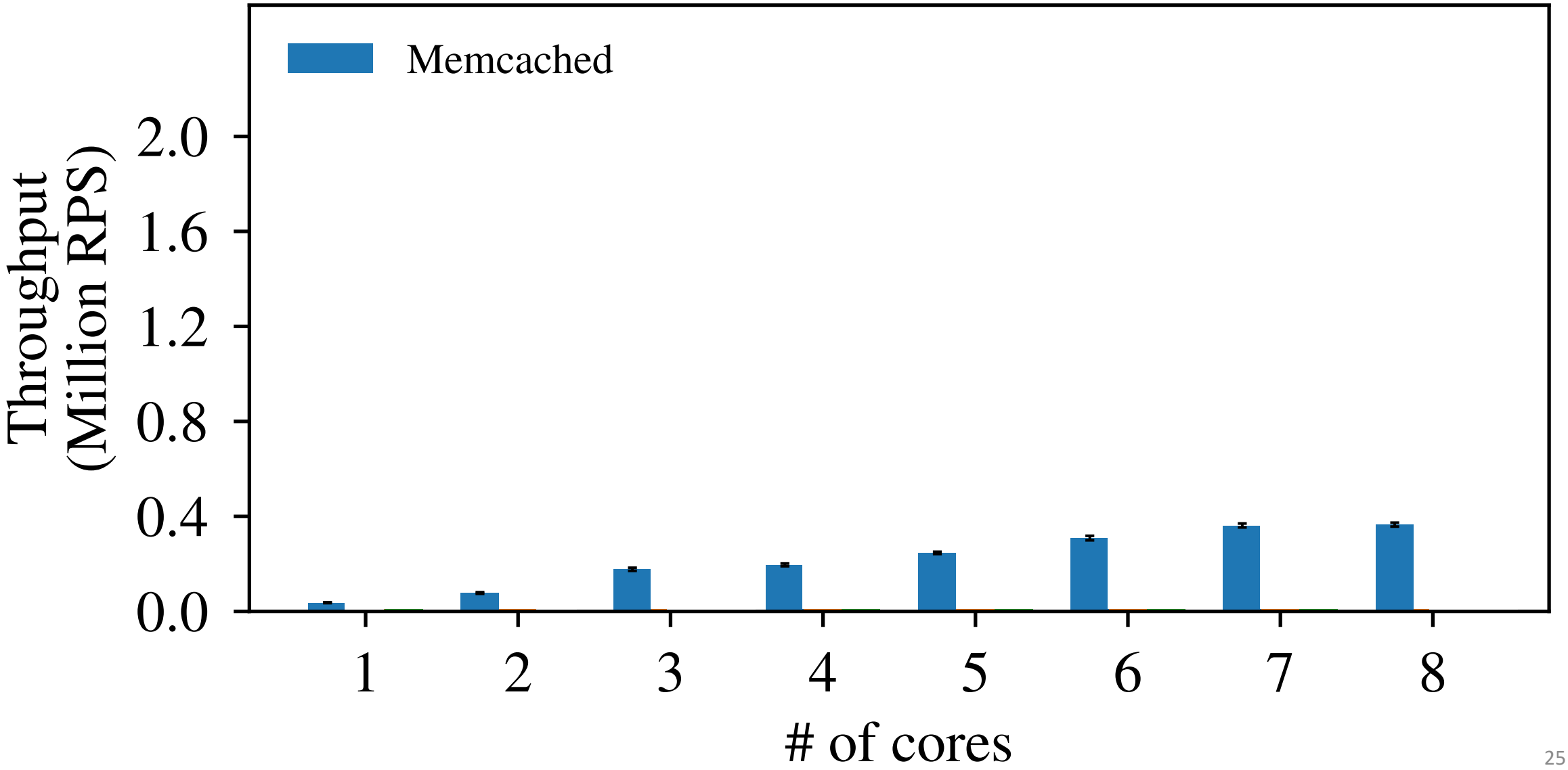
        if v == b"set " {
            Some(i)
        } else {
            None
        }
);
...
```

Rex-BMC is much *cleaner* and *simpler*

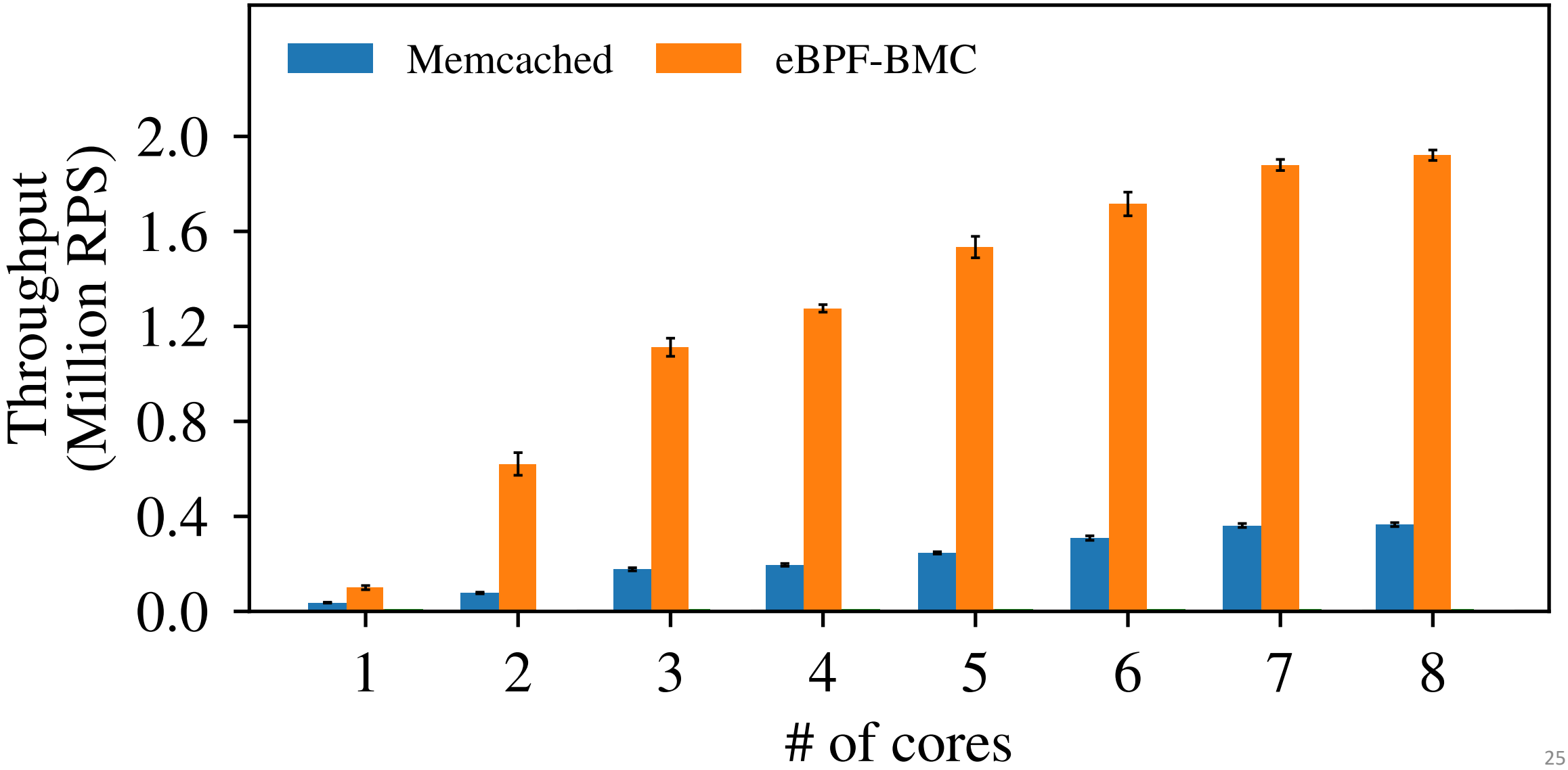
Performance evaluation



Performance evaluation



Performance evaluation



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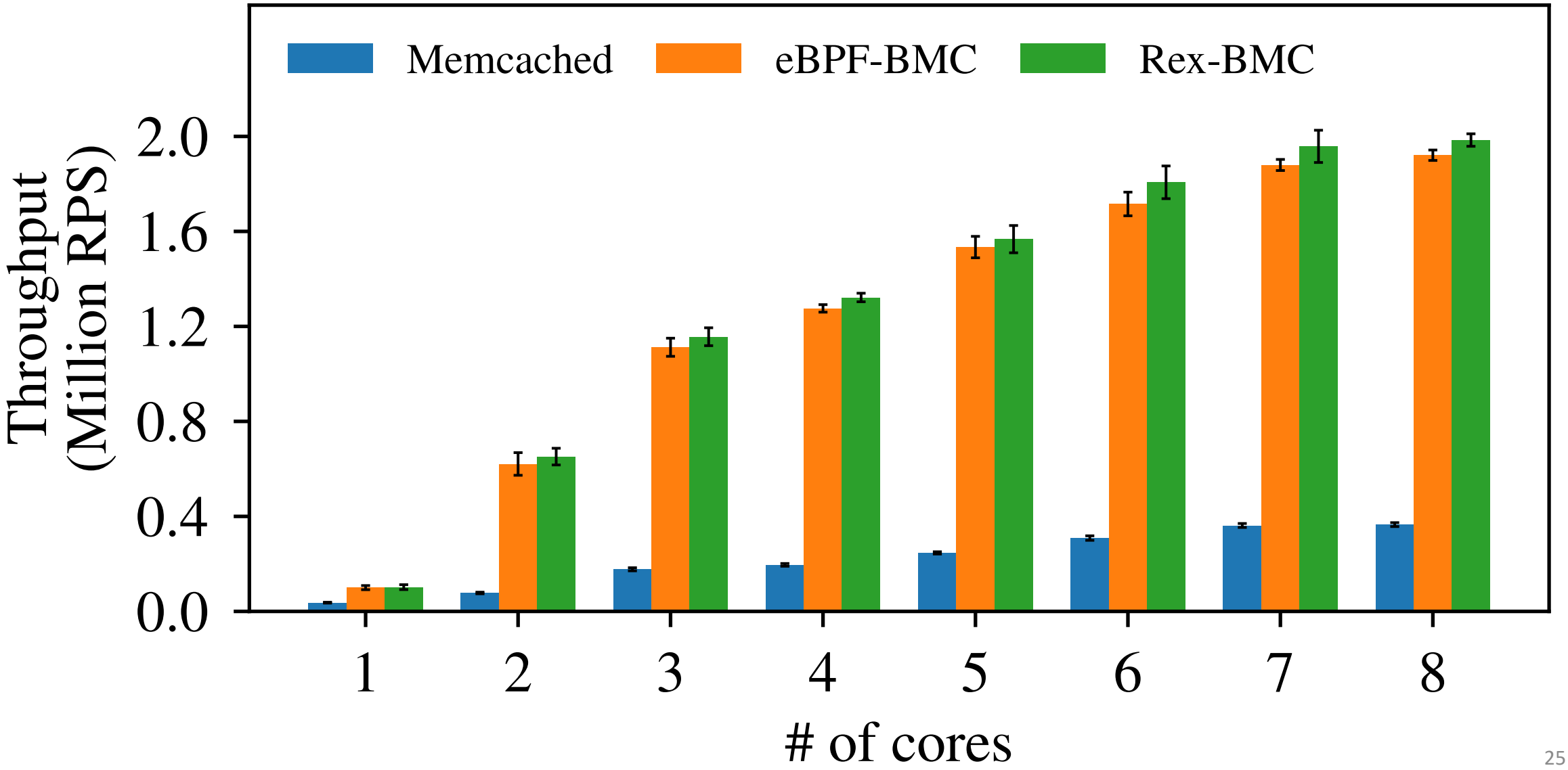

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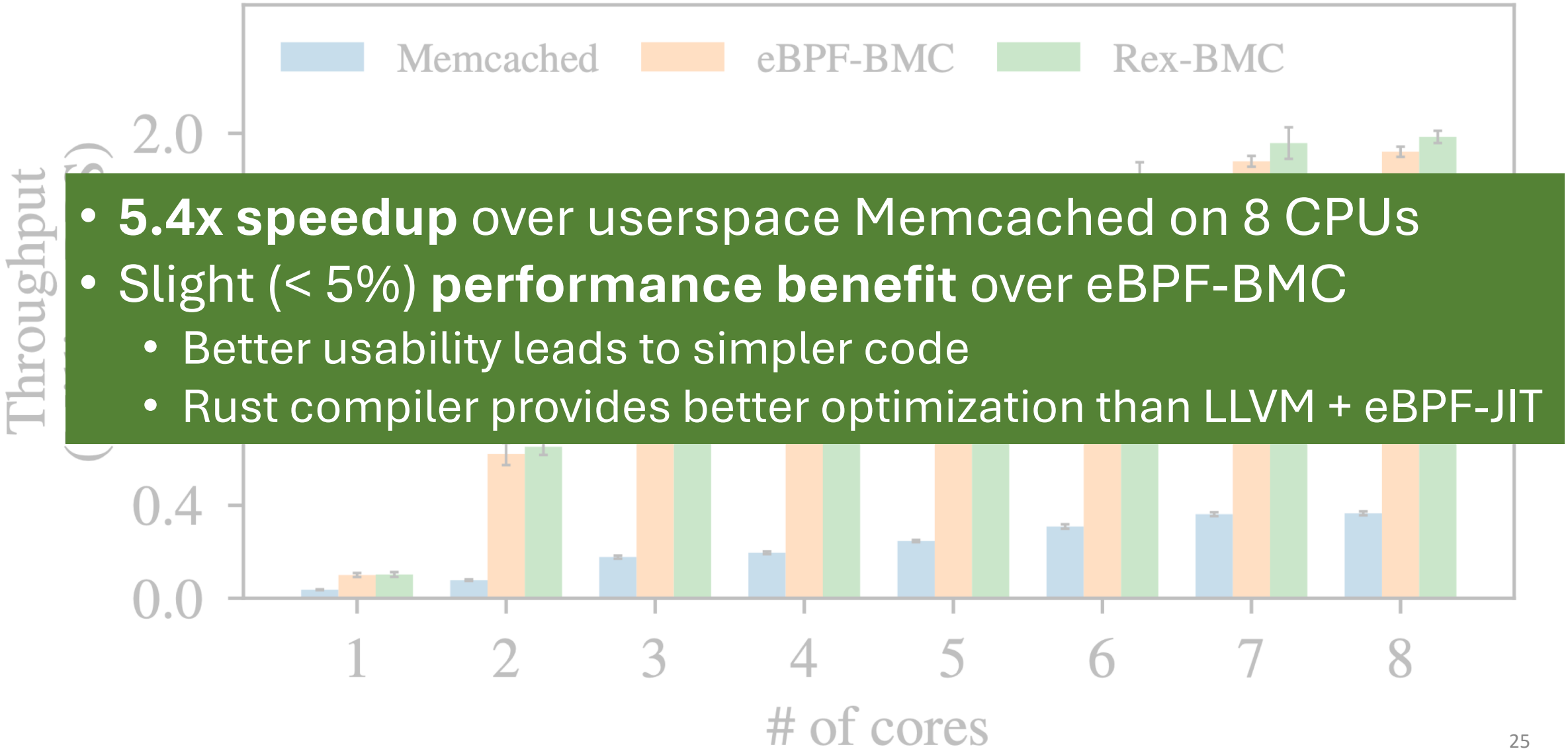

- **5.4x speedup** over userspace Memcached on 8 CPUs
- Slight (< 5%) **performance benefit** over eBPF-BMC
  - Better usability leads to simpler code
  - Rust compiler provides better optimization than LLVM + eBPF-JIT

Conclusion

- Static verification in kernel extensions leads to poor usability
- Insight of Rex: Language-based safety + runtime mechanism
- Rex delivers usability without losing safety and performance
- Code repo: https://github.com/rex-rs/rex