Fast, Flexible, and Practical Kernel Extensions

Kumar Kartikeya Dwivedi, Rishabh Iyer, Sanidhya Kashyap

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- Mechanism to safely modify the kernel at runtime

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- Mechanism to safely modify the kernel at runtime
- Used for observability, security, networking
- Emerging use cases: Application offloads, CPU scheduling
- eBPF is 1% of all CPU cycles globally on Meta's fleet

Ideal extensibility goals

Safety: Cannot crash or stall the kernel

Flexibility: Allow diverse behavior in extension code

Performance: Low overhead on execution

Practicality: Language-independence

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Ideal extensibility goals

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Performance: Low overhead on execution

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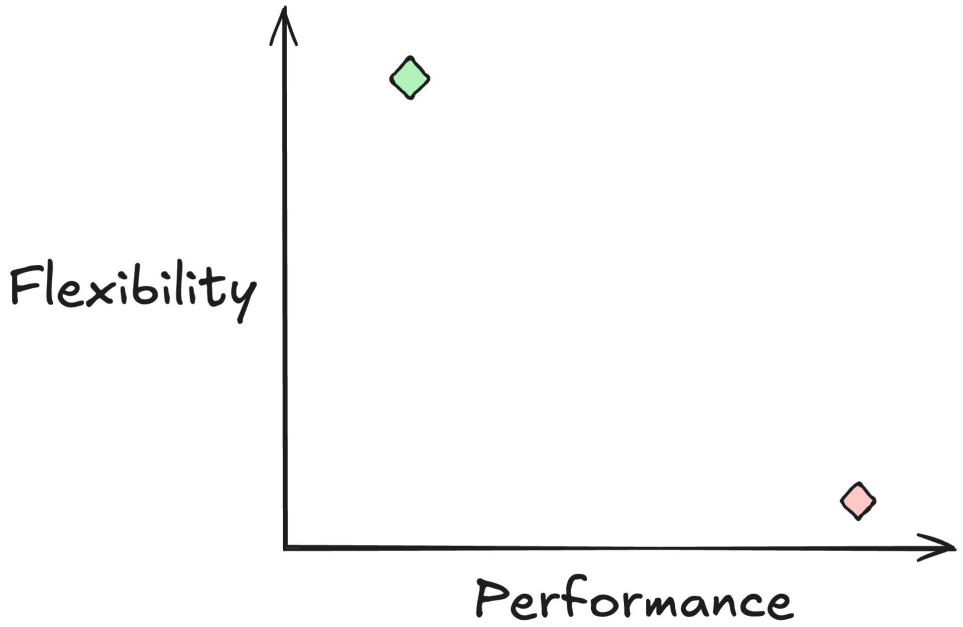
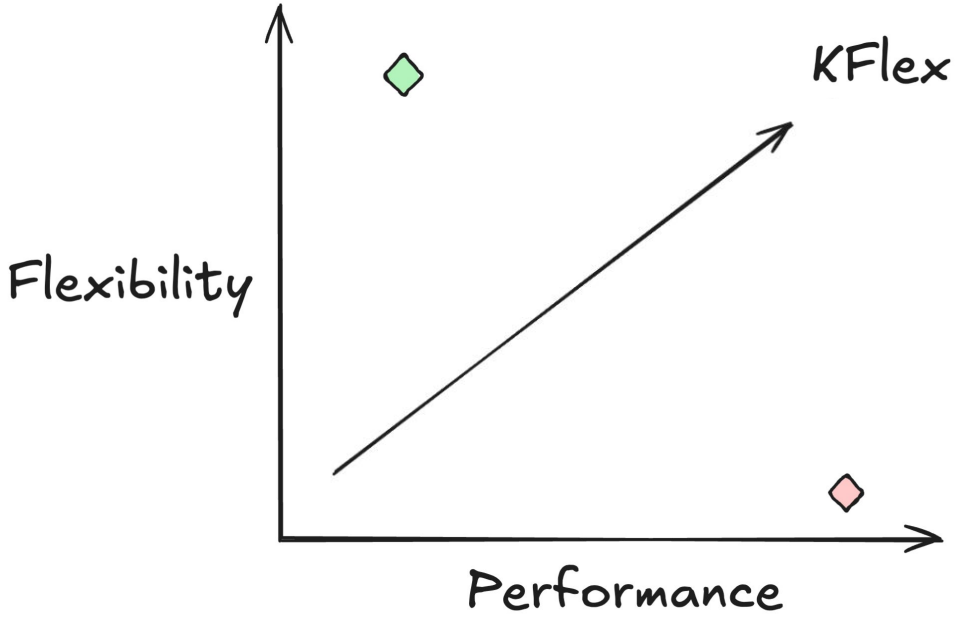
Safety is fundamental for kernel extensions

Problem Statement

Kernel extensibility today is either flexible or performant — not both

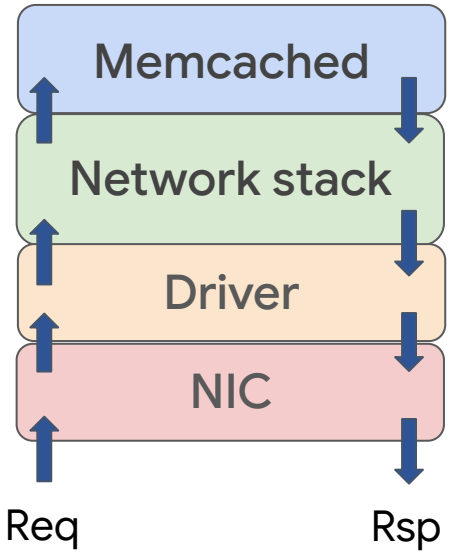


KFlex: fast, flexible, and practical extension framework



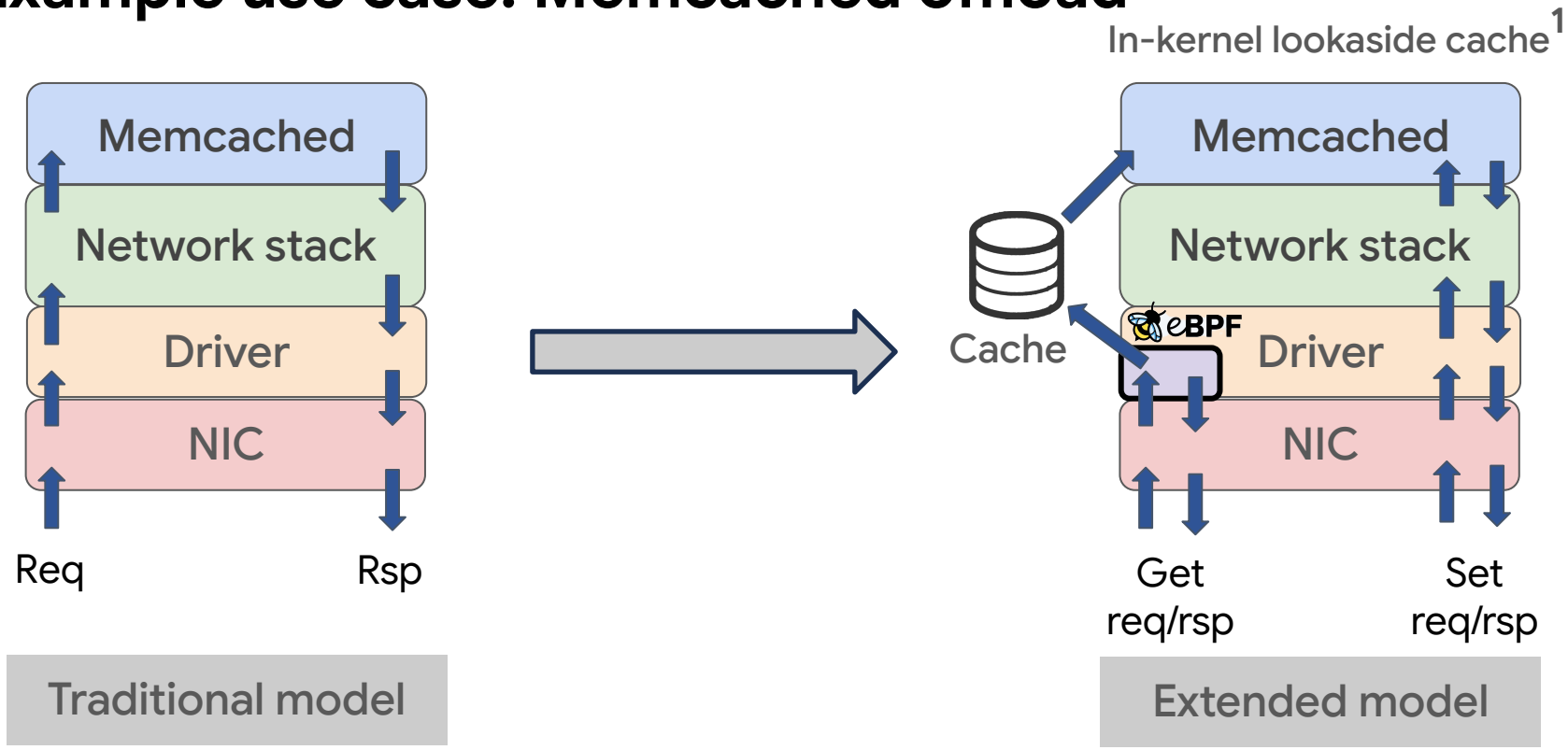
Upstreamed into the Linux kernel mainline

Example use case: Memcached offload



Traditional model

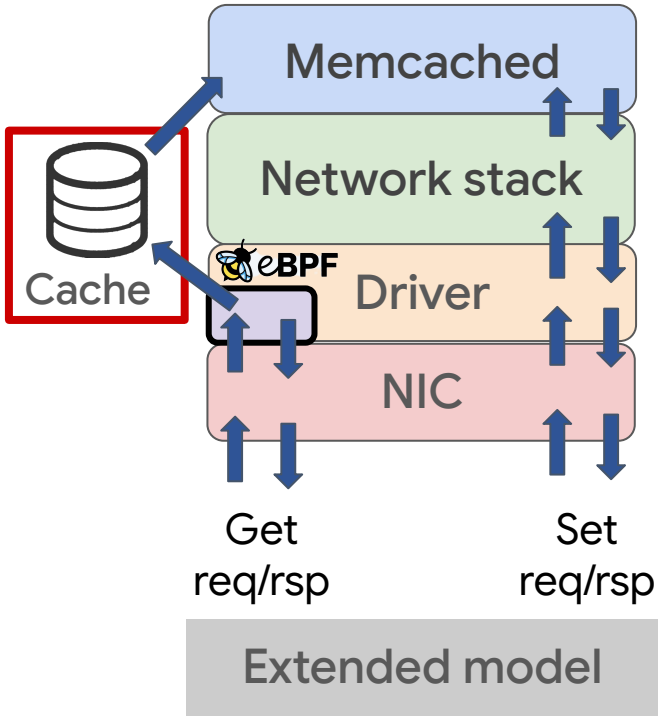
Example use case: Memcached offload



[1] BMC: Accelerating Memcached using Safe In-kernel Caching and Pre-stack Processing, NSDI'21

Lack of flexibility with eBPF

- Data structures cannot be shared
  - Wasted memory



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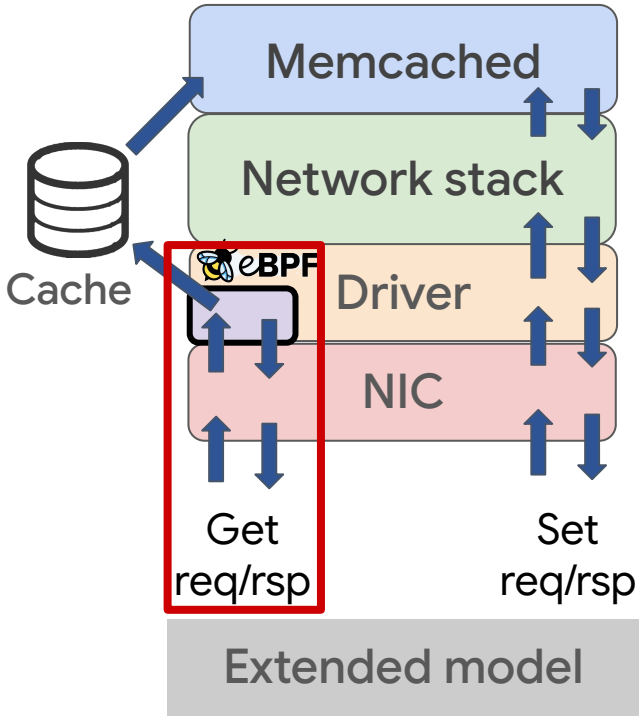

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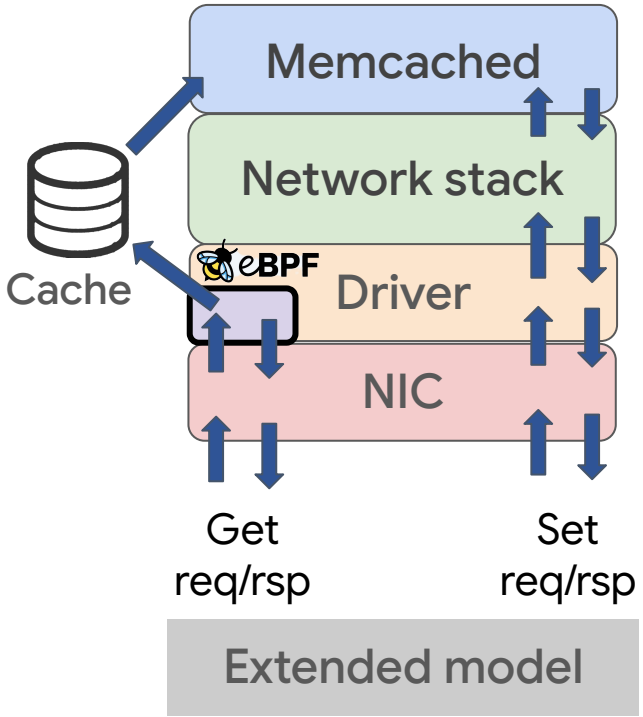

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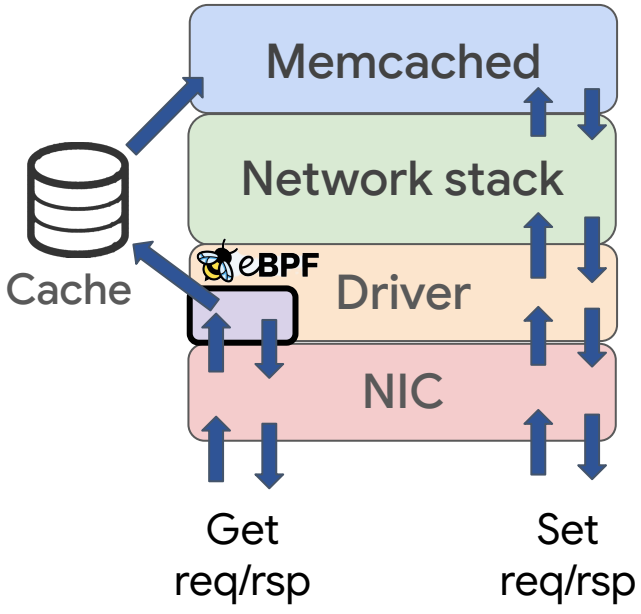

Current extensibility approach to safety hurts flexibility

eBPF overview: linked list iteration

```
struct list_head *head;
int prog(struct xdp_md *ctx) {
    while (head != NULL) {
        head = head->next;
    }
    return bpf_redirect(...);
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```

Linked list head

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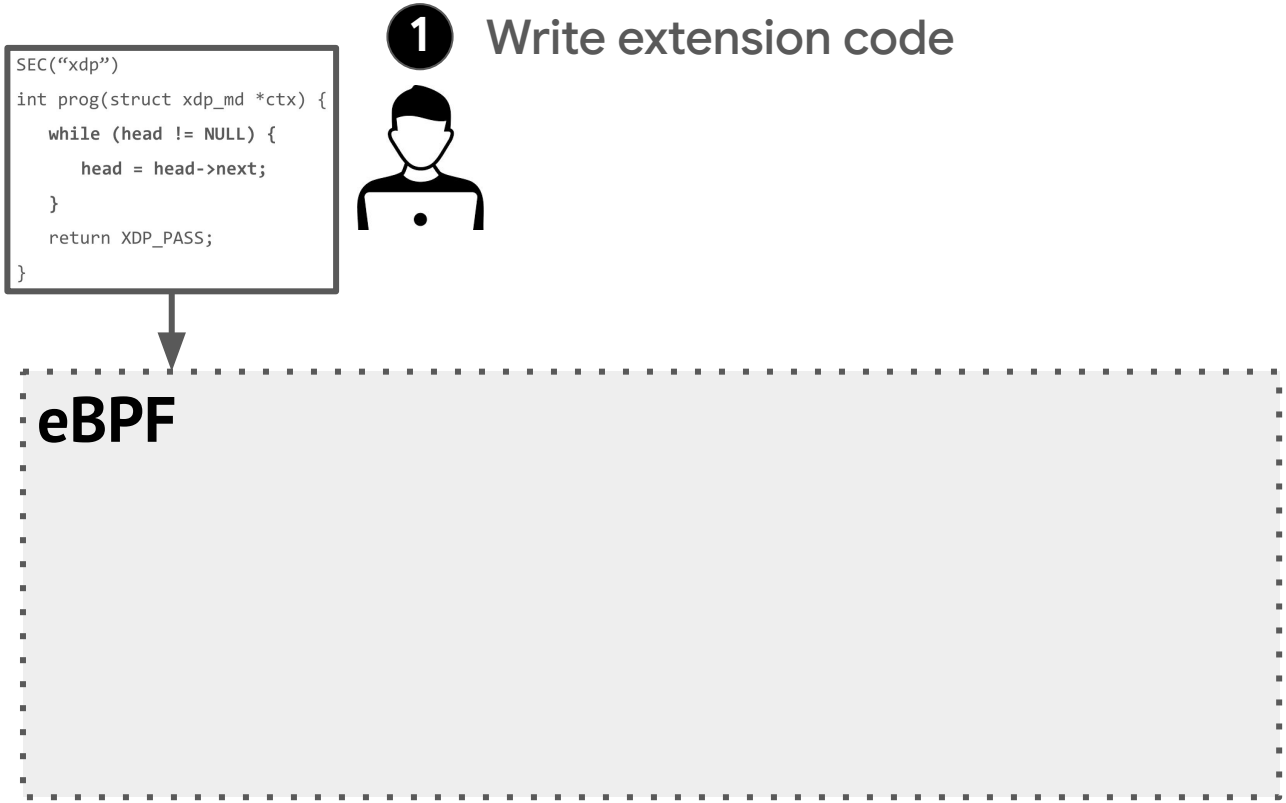

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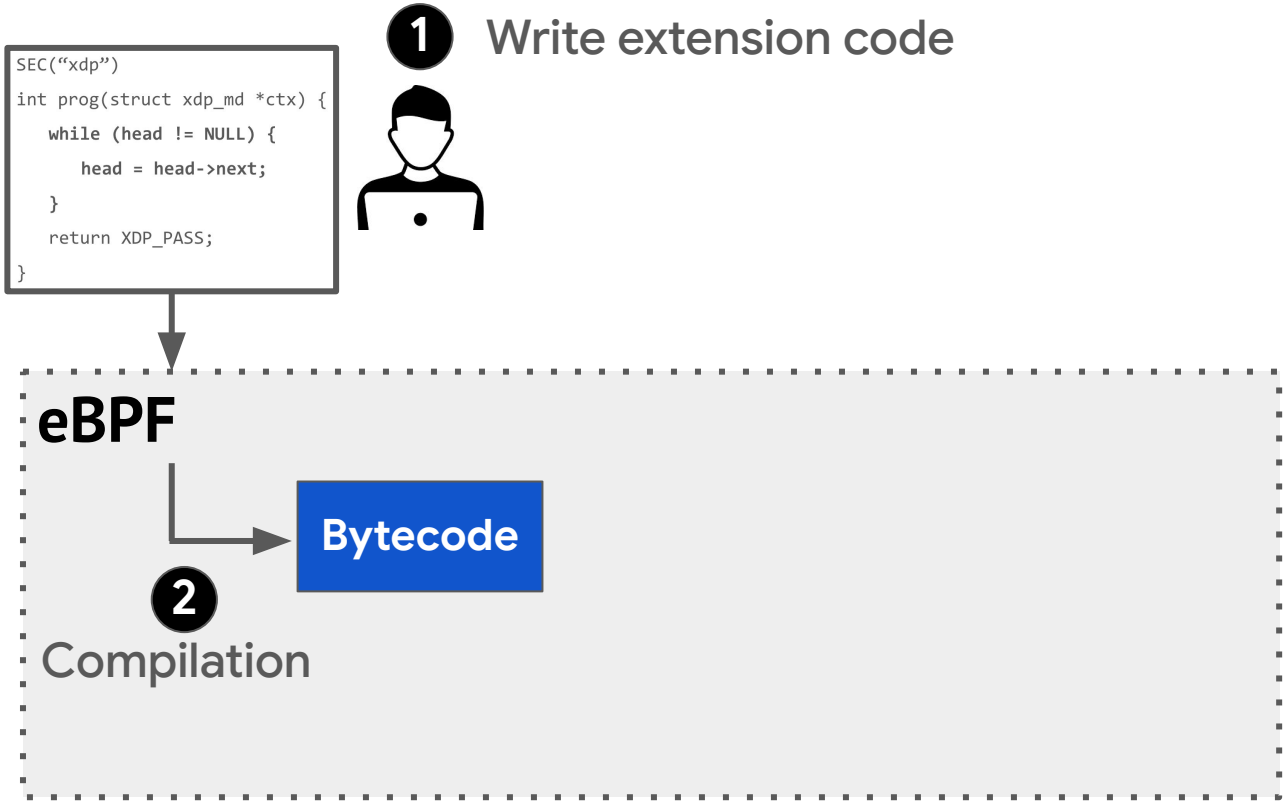

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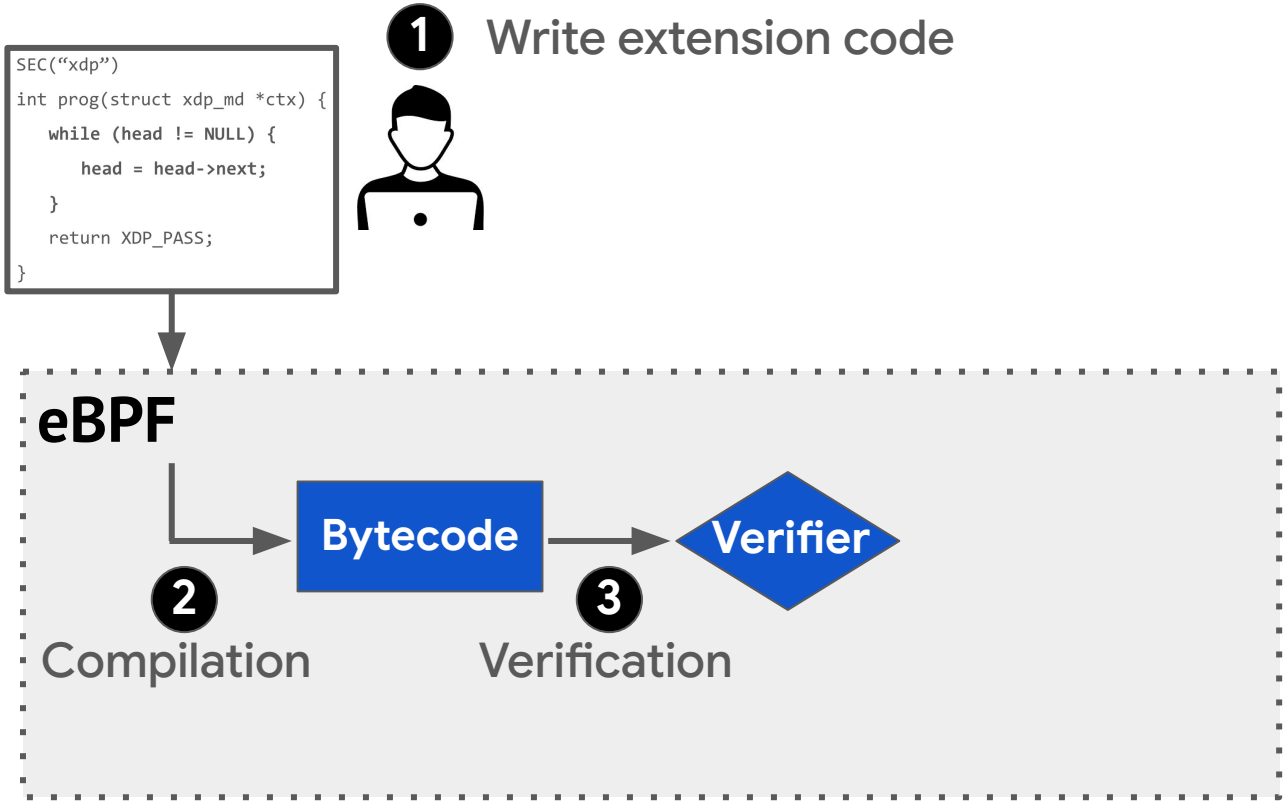

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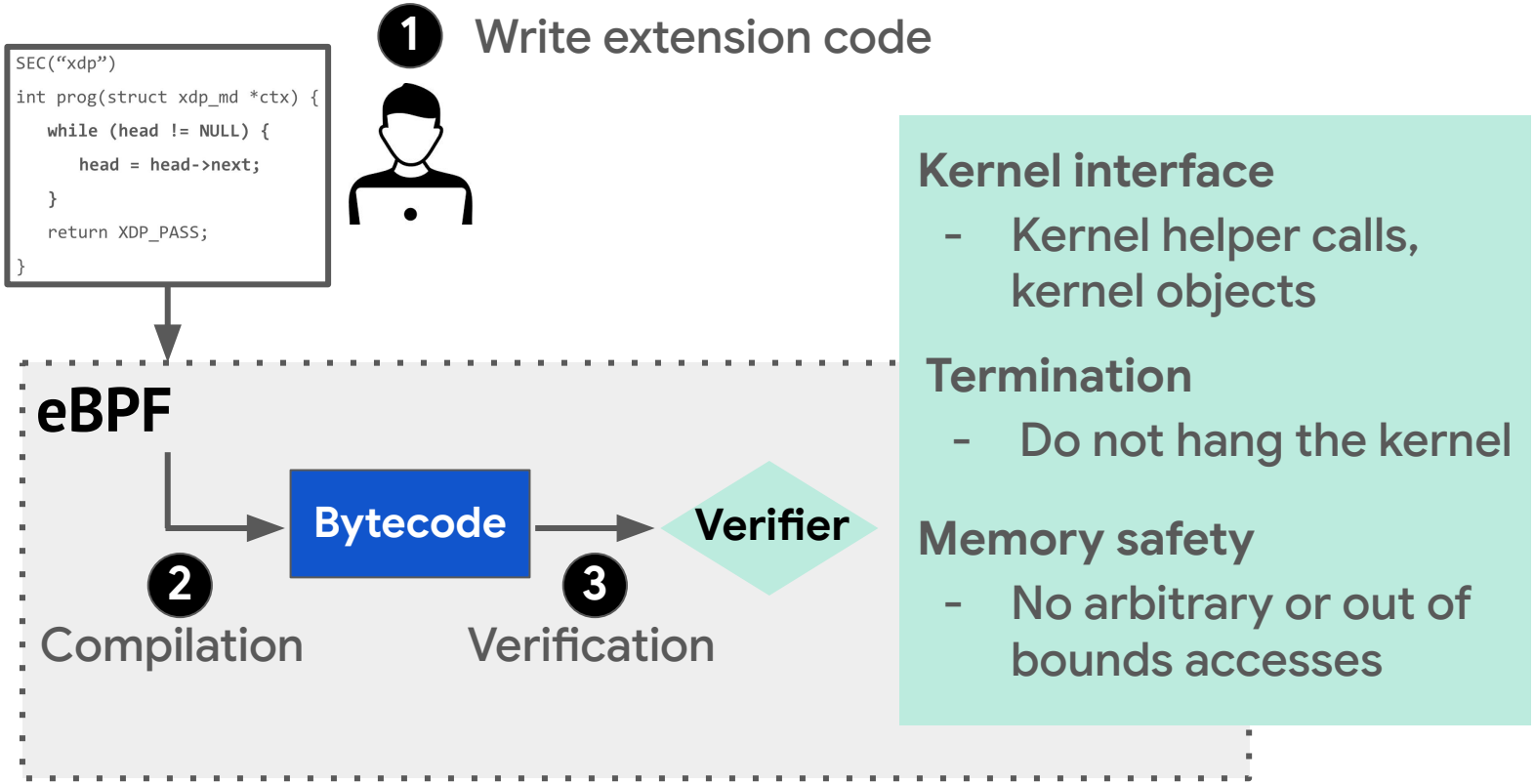

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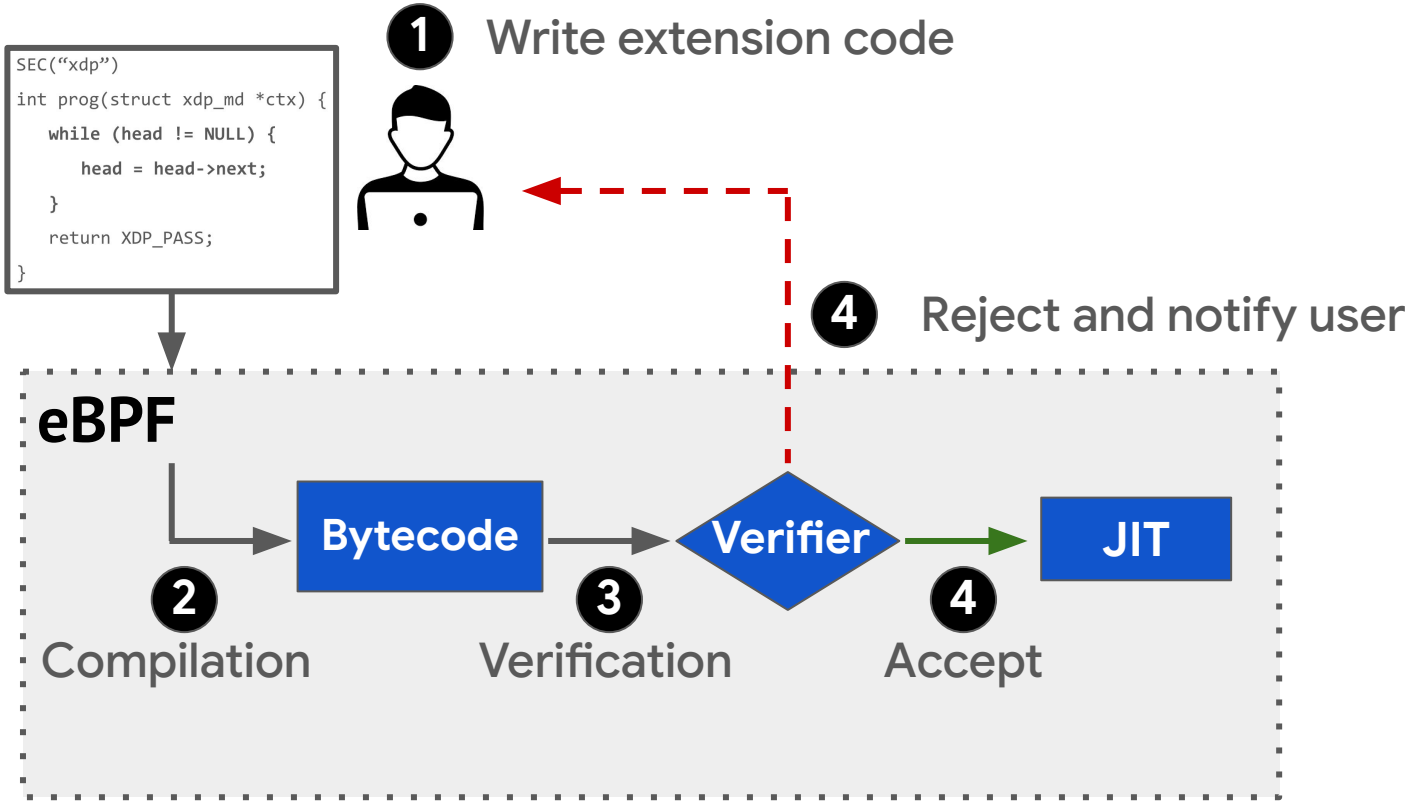

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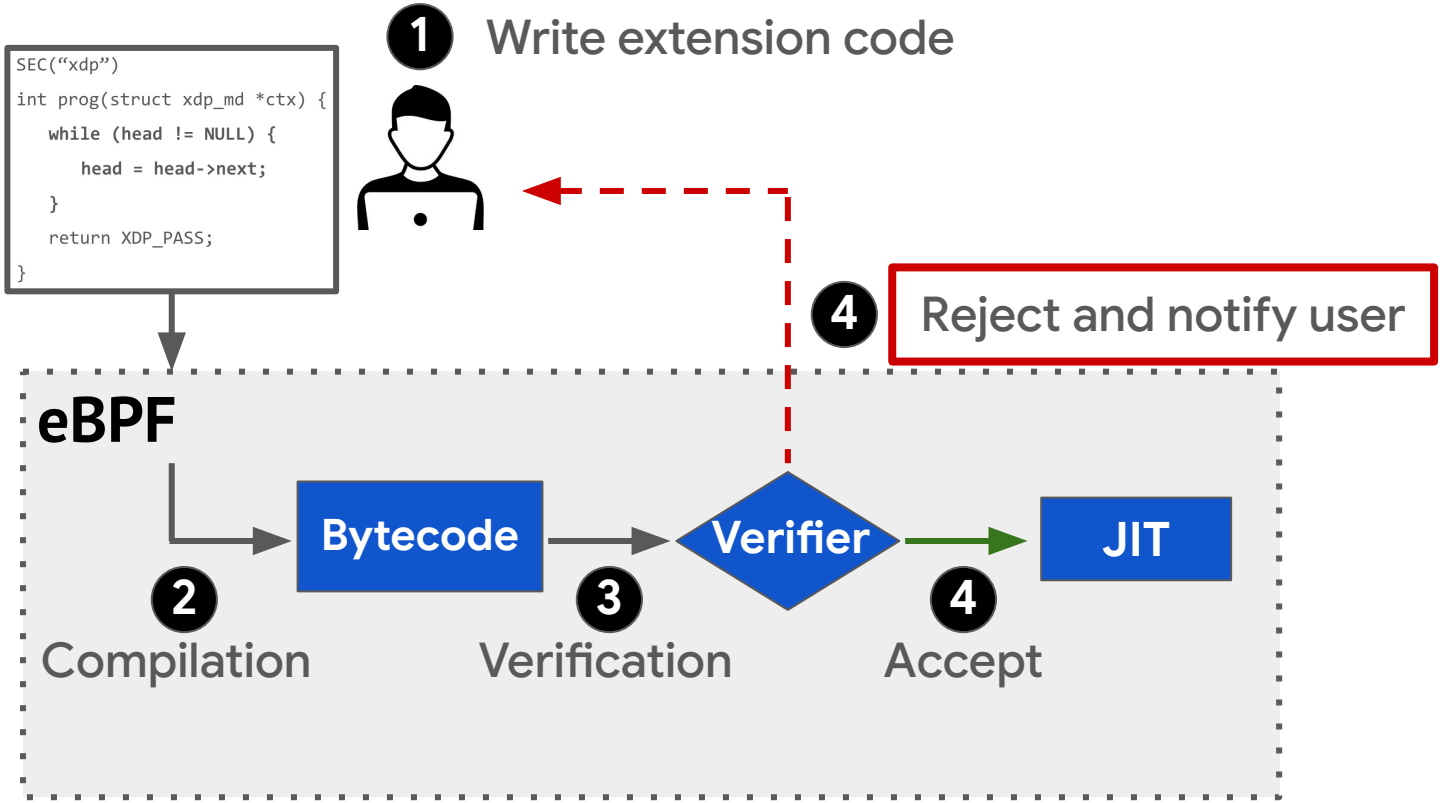

eBPF: issues with current design

```
int prog(struct xdp_md *ctx) {
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```

Verifier

Kernel interface
- Kernel helper calls, kernel objects

Termination
- Do not hang the kernel

Memory safety
- No arbitrary or out of bounds accesses

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eBPF: safety of kernel interfaces

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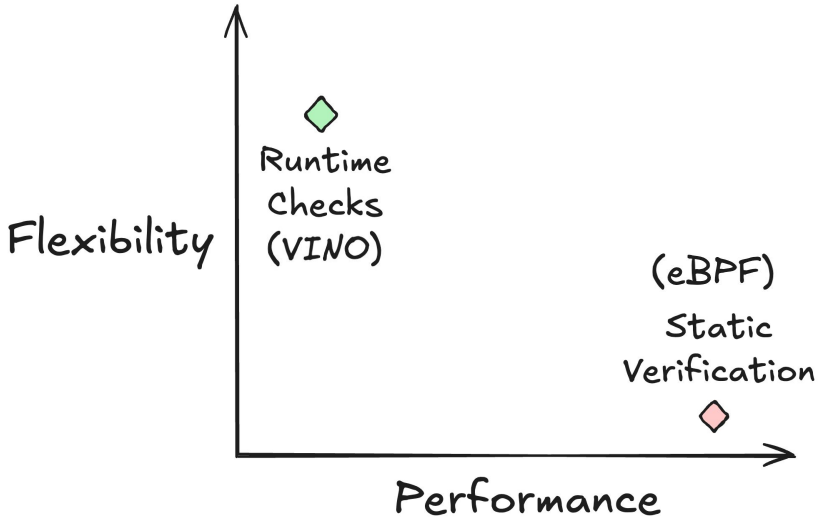
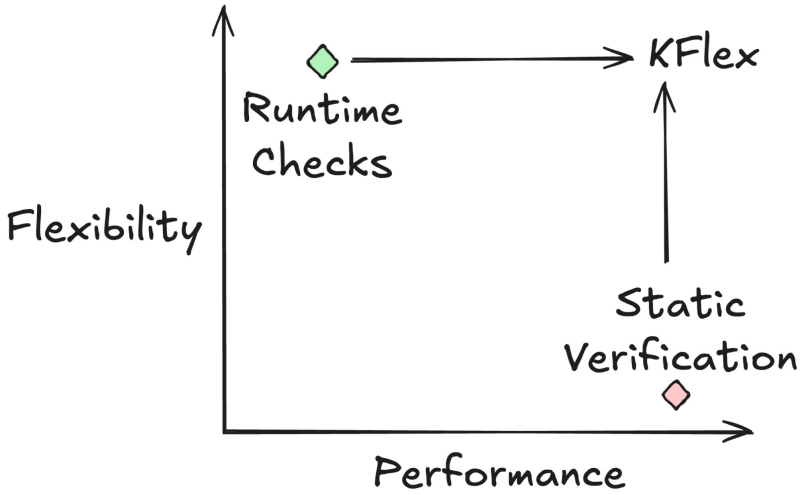


KFlex



An extension framework for arbitrary code extensibility

Insight: separate safety properties

Kernel helper calls, kernel-owned memory

Kernel interface compliance

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- Kernel helper calls, kernel objects

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Insight: separate safety properties

Kernel helper calls, kernel-owned memory

Kernel interface compliance

Flexibility is w.r.t extension memory & time

Extension correctness

Kernel interface
- Kernel helper calls, kernel objects

Termination
- Do not hang the kernel

Memory safety
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KFlex: use dedicated mechanisms

- Kernel interface compliance: Narrow, well-defined

Static verification

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Static verification

- Extension correctness: Diverse and arbitrary behavior

Runtime checks

KFlex: use dedicated mechanisms

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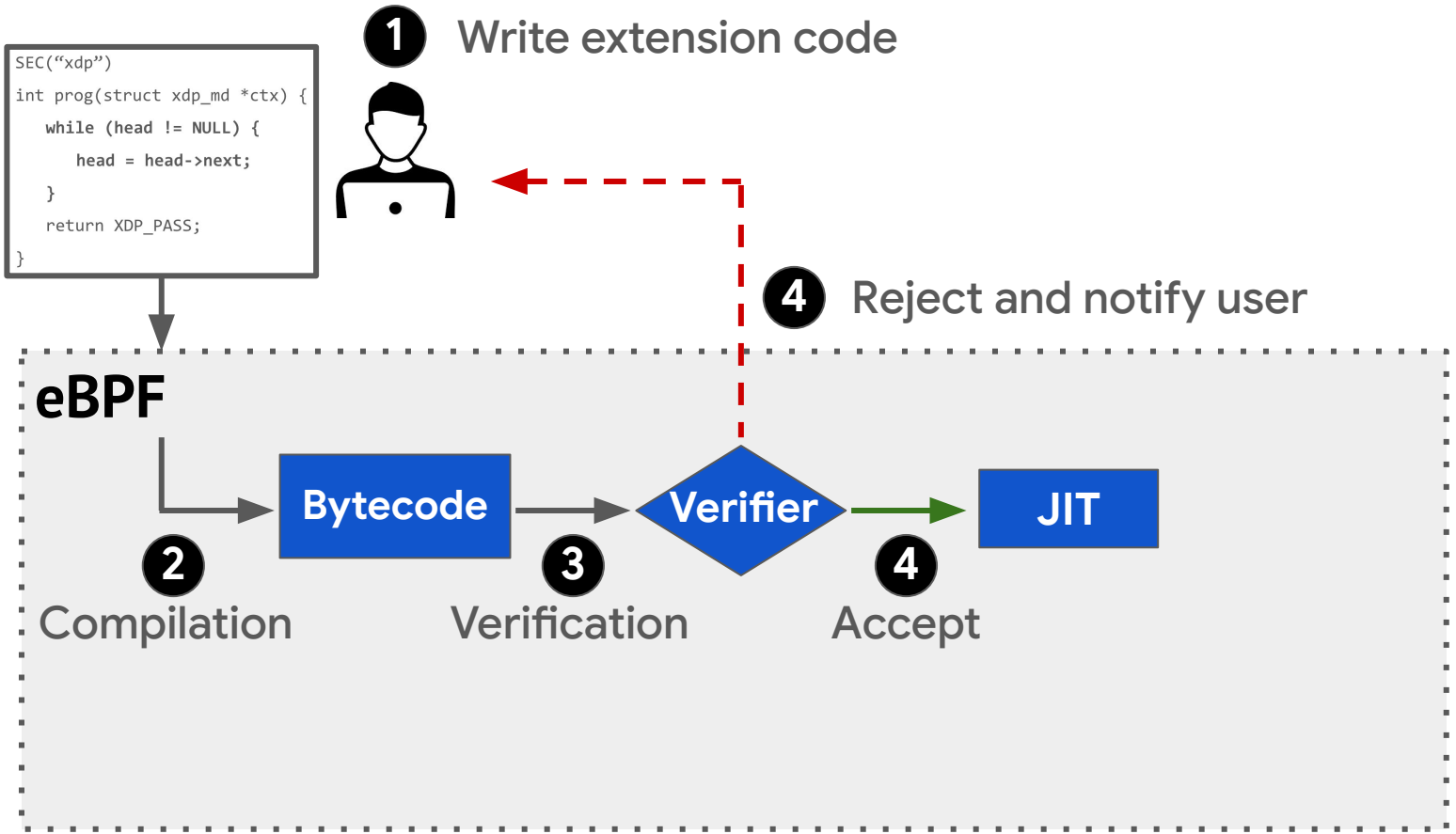
Runtime checks

Eliminate runtime overhead with co-design of runtime checks and verification

KFlex overview



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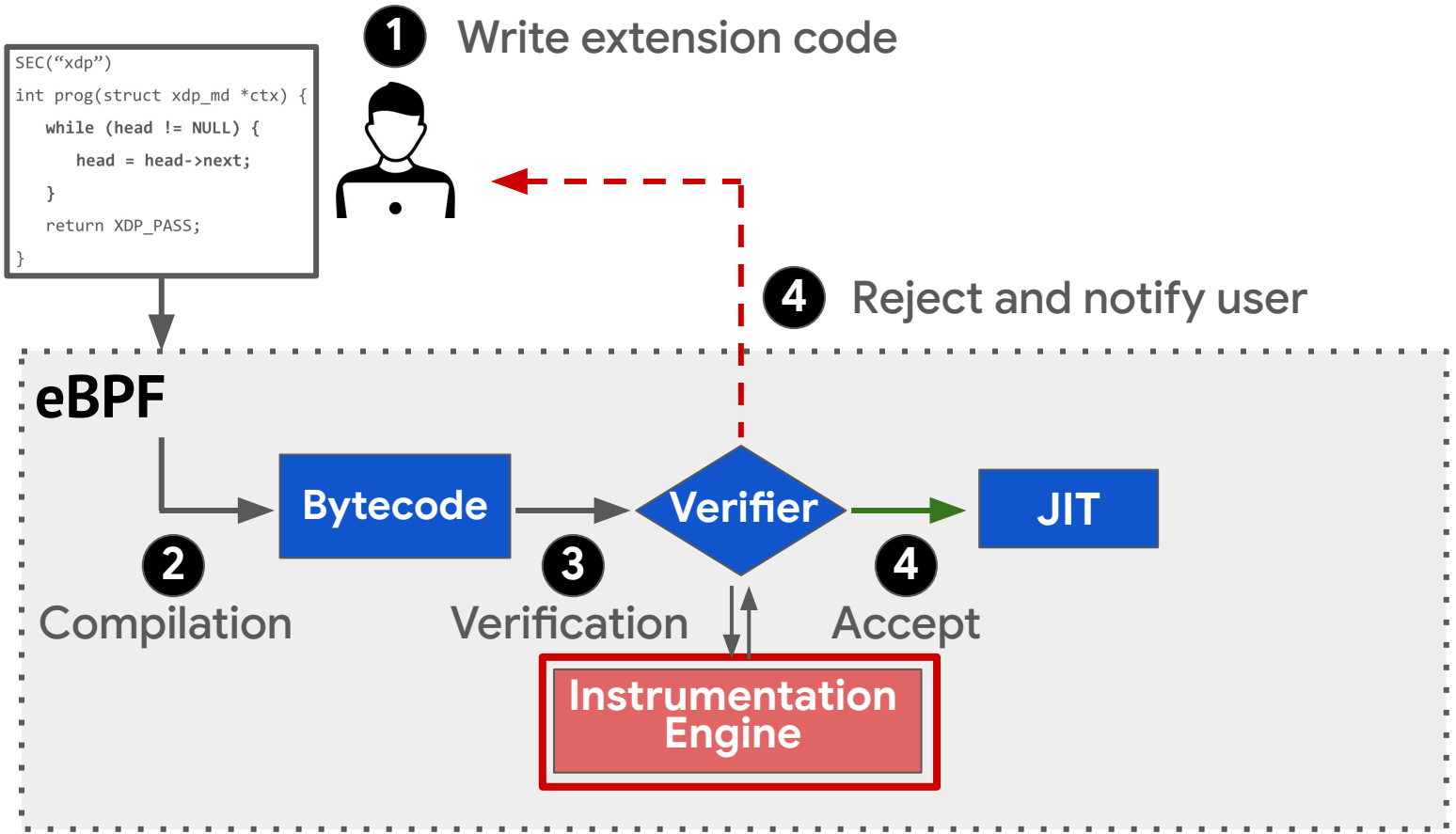

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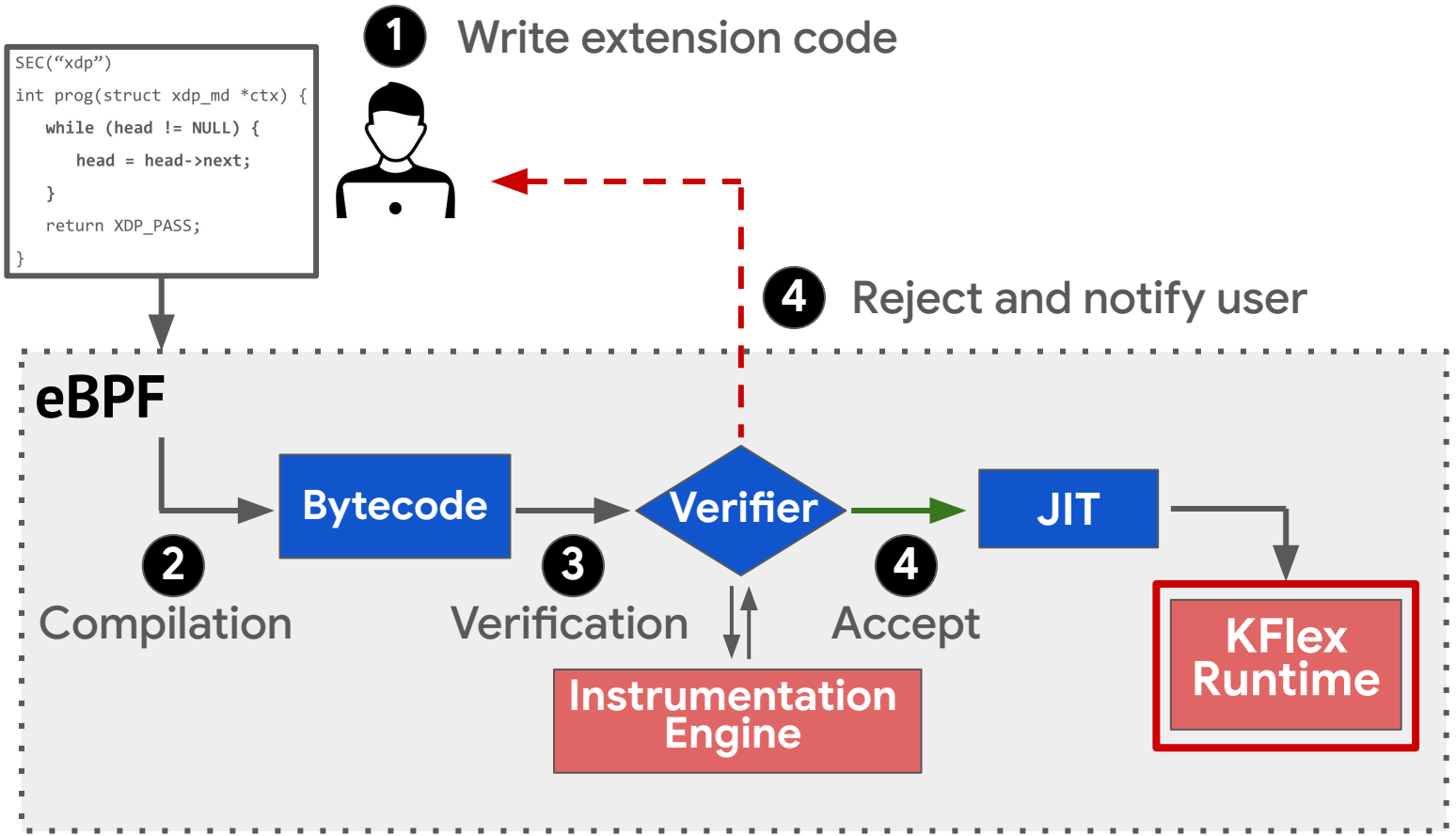


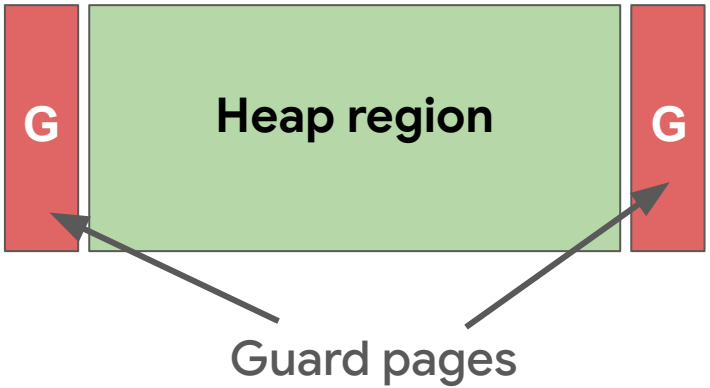
Extension correctness with runtime checks

- Memory safety for extension-owned data
- Safe termination to ensure forward progress

Memory safety using sandboxing

Dedicated region for extension-owned memory

- All extension data lives in heap
- Pages can be allocated and deallocated on demand
- Surrounded by guard pages that trap out-of-bounds accesses



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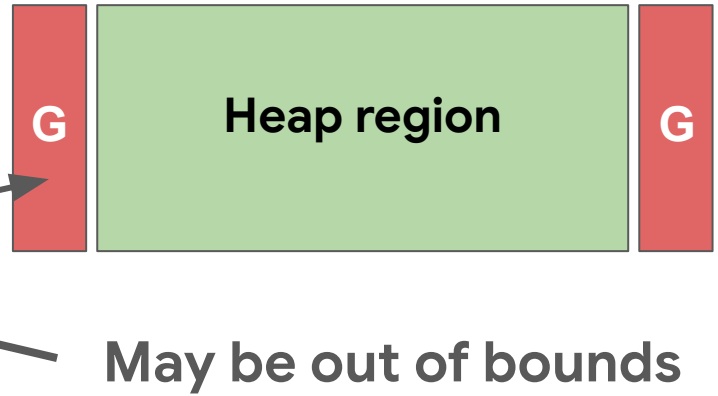

Memory safety using sandboxing

```
int prog(struct xdp_md *ctx) {
    while (head != NULL) {
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```

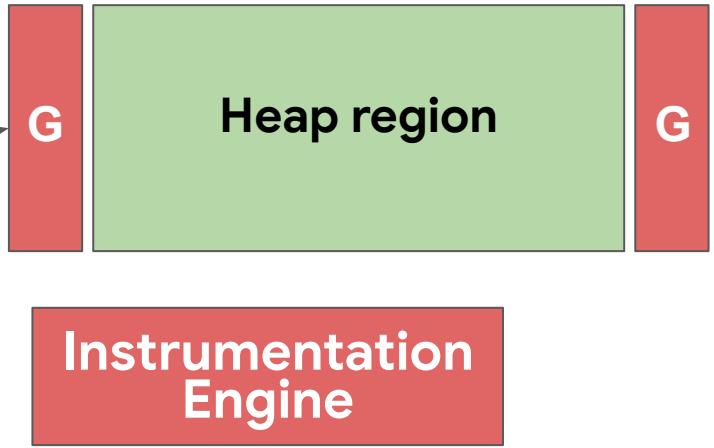

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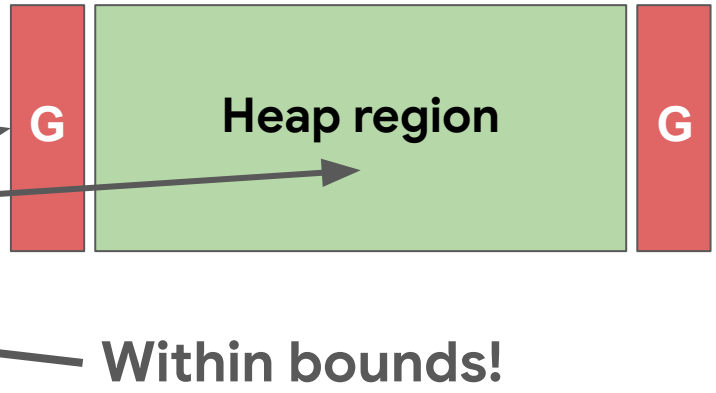

Extension cancellations

- Safely terminate an extension at a given point in bounded time

Safe termination using extension cancellations

- Find non-terminating loops

```
while (head != NULL) {

   head = head->next;

}
```

Safe termination using extension cancellations

- Find non-terminating loops
- Instrument loop back-edges

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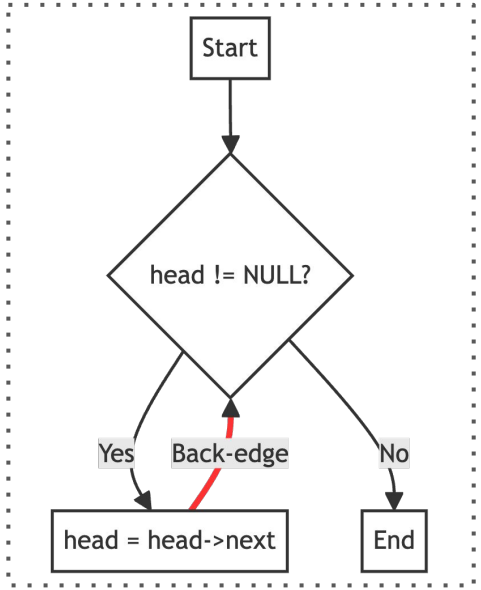

Safe termination using extension cancellations

- Find non-terminating loops
- Instrument loop back-edges
- Terminate and release kernel resources on a stall

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while (head != NULL) {

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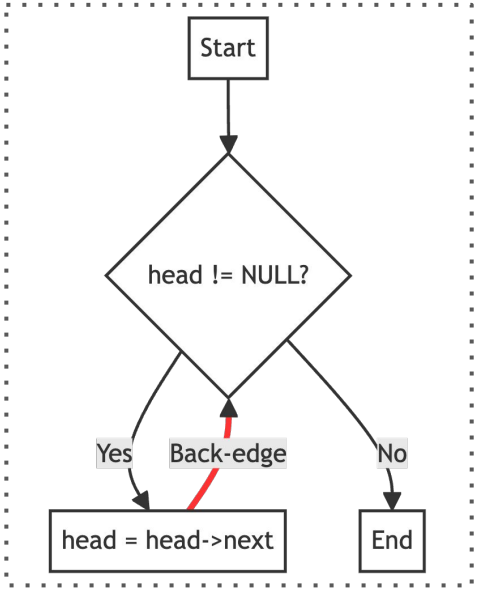

Safe termination using extension cancellations

```
void prog(struct xdp_md *ctx) {
    sk = bpf_sk_lookup(...);
    while (head != NULL) {
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    }
    bpf_sk_release(sk);
    return bpf_redirect(...);
}
```

Safe termination using extension cancellations

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void prog(struct xdp_md *ctx) {
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Instrumentation Engine

Safe termination using extension cancellations

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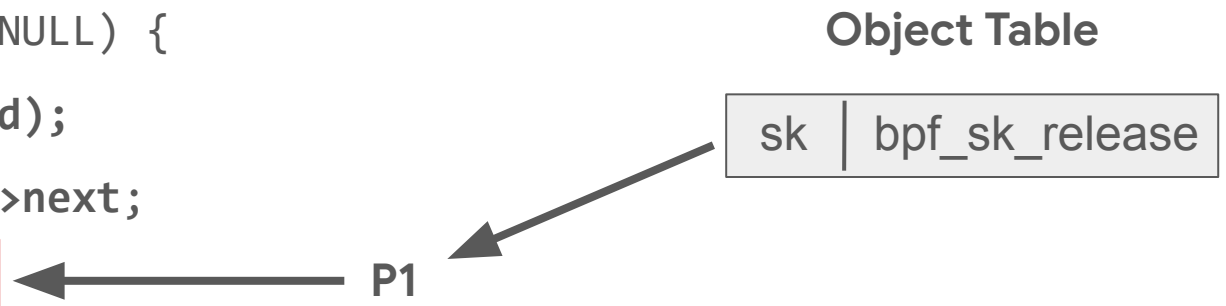

Recovery of the kernel

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KFlex Runtime

Recovery of the kernel

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Page fault!

Recovery of the kernel

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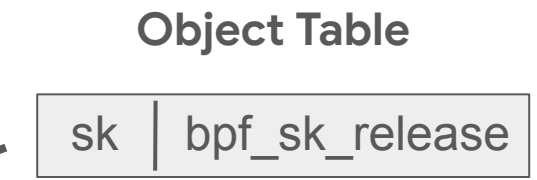
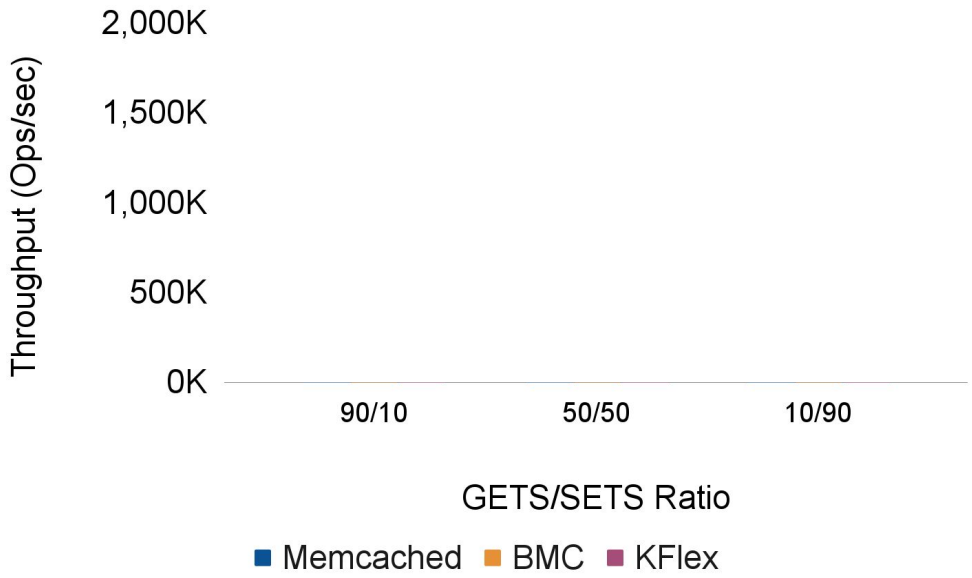


Evaluation

- Can KFlex improve end-to-end performance for applications?
- Can KFlex enable flexibility with low overhead?

Memcached in XDP



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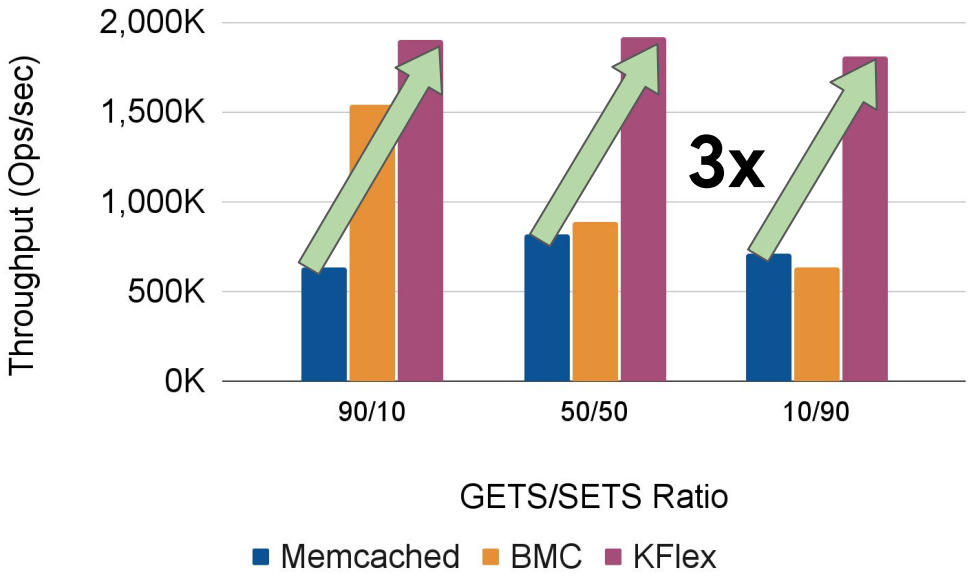

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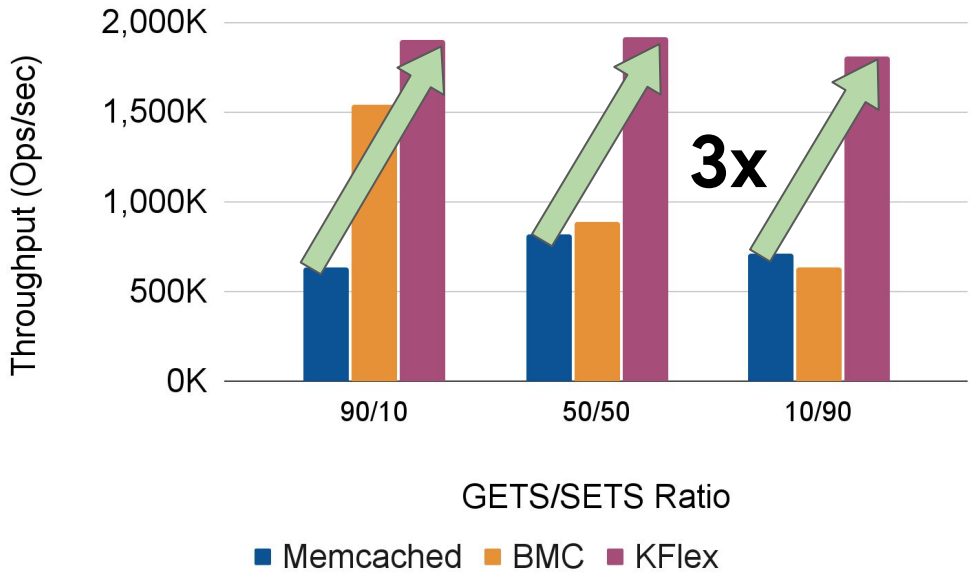
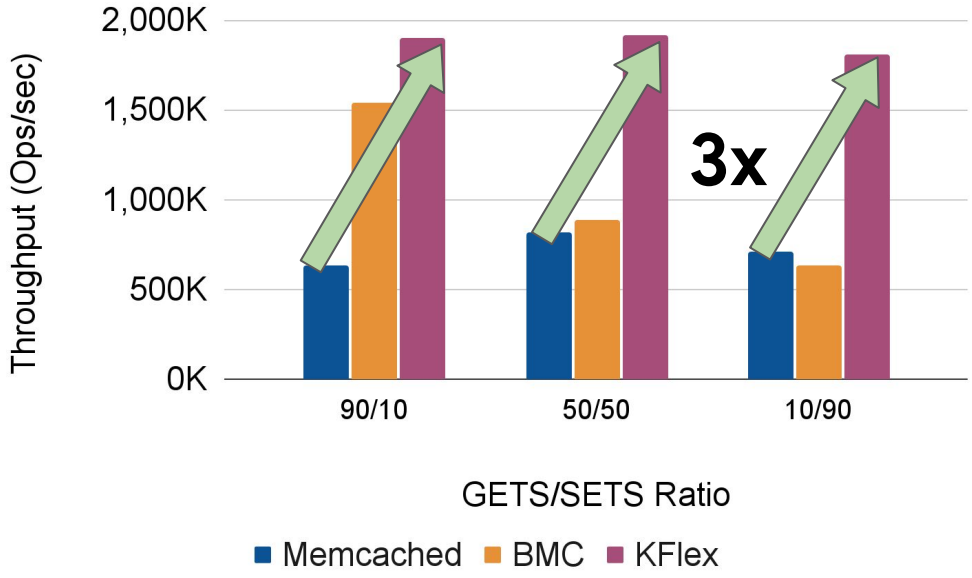


Allows both SETS/GETS

No memory waste

Low overhead

Memcached in XDP



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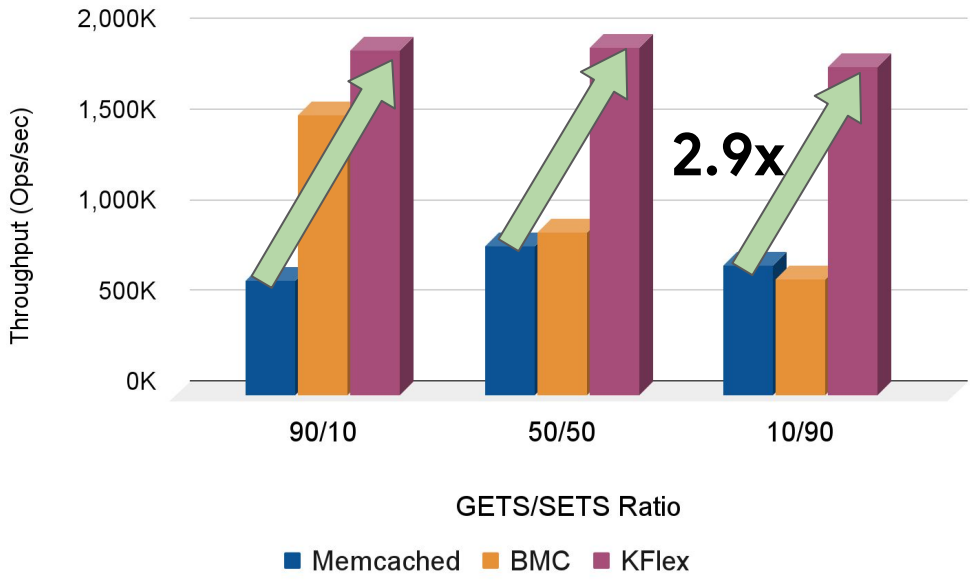
KFlex enables significant throughput improvements

Memcached with GC in user space



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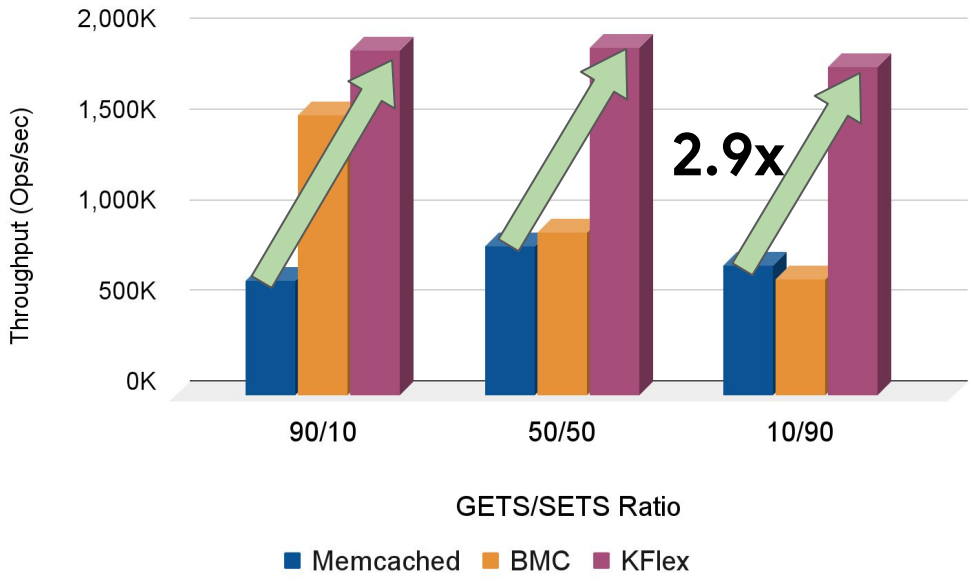

Share data structures

Memory conservation

Synchronization

Auxiliary functionality can be implemented in user space

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Share data structures

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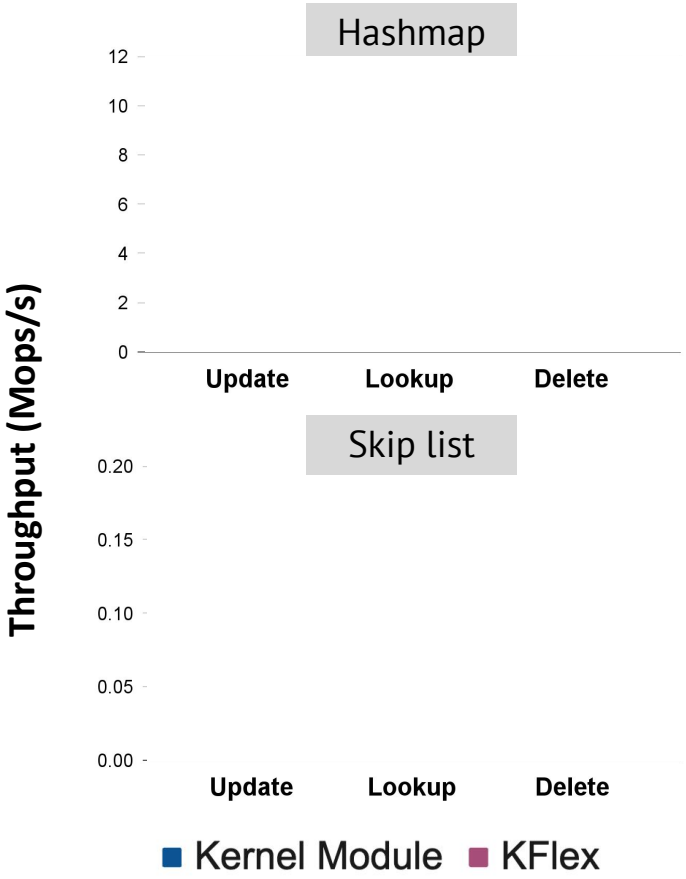
Data Structures



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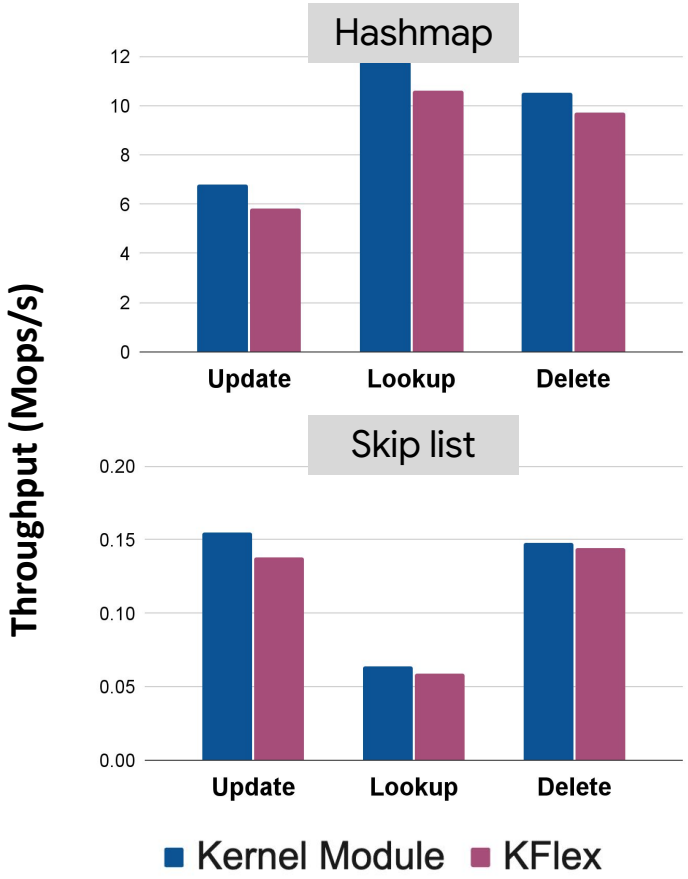
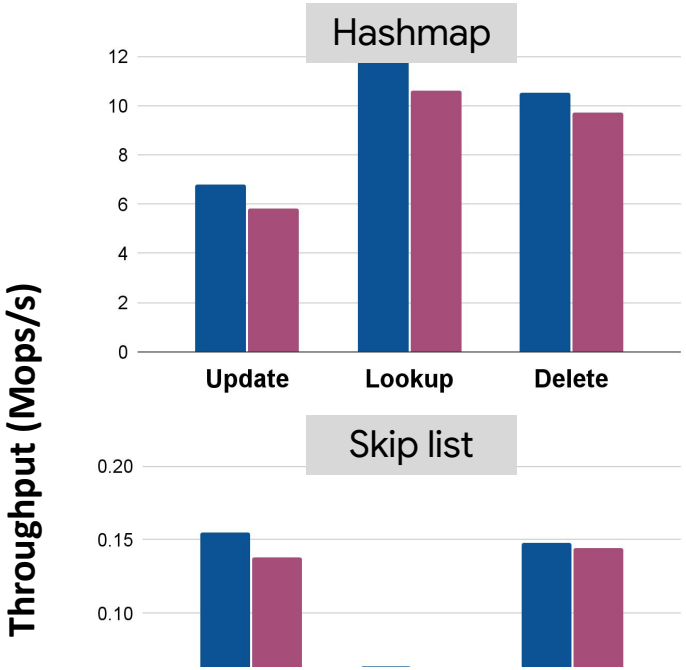


Offload arbitrary data structures

7% throughput overhead

30% latency overhead

Data Structures



Offload arbitrary data structures

7% throughput overhead

30% latency overhead

Implement infeasible functionality at low overhead

More results in the paper!

Latency numbers for Memcached

Throughput + latency numbers for Redis

Impact of co-designing runtime mechanisms with verification

KFlex: fast, flexible, and practical kernel extensions

- Separate kernel safety into two sub-properties
  - Use distinct, bespoke mechanisms to enforce each sub-property
  - Co-design runtime mechanisms with verification to reduce overhead

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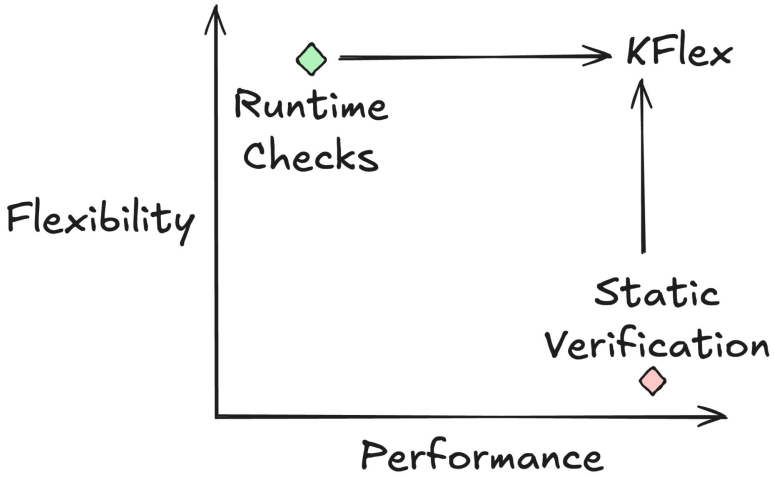
  - Use distinct, bespoke mechanisms to enforce each sub-property
  - Co-design runtime mechanisms with verification to reduce overhead
- Integrated into the upstream Linux kernel



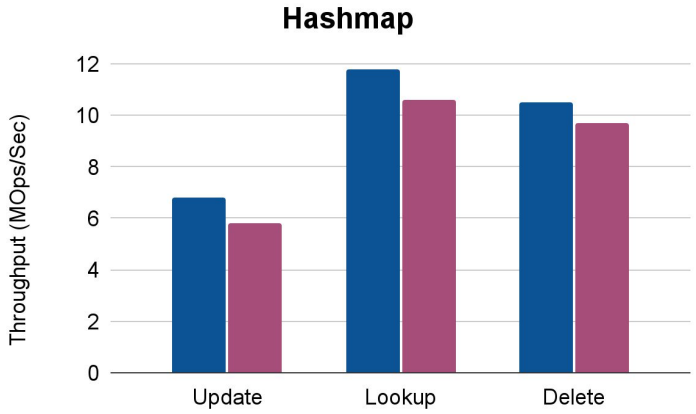
Project website

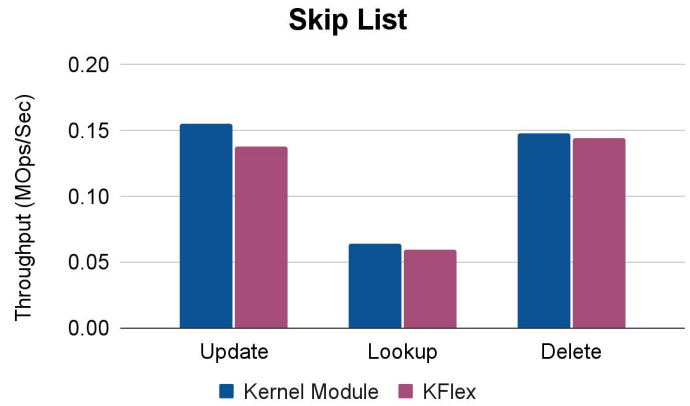
Backup Slides

KFlex vs State of the art

Approach	Flexibility	Performance	Practicality
Safe programming language (SPIN)	✓	✓	×
Software Fault Isolation (VINO)	✓	×	✓
Static verification (eBPF)	×	✓	✓
Static verification + Runtime checks (KFlex)	✓	✓	✓

Data Structures - Overhead





Static analysis reduces overhead

Elides 76% “sanitize” instructions

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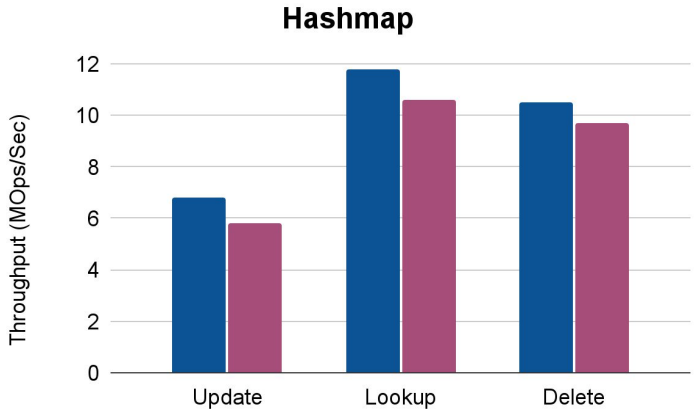


Static analysis reduces overhead

Elides 76% “sanitize” instructions

Co-design of runtime mechanisms reduces overhead

Translation

- Extension heaps allow bi-directional access to memory from user space and kernel
- Pointers escaping into heaps are translated to user space addresses
- Pointers loaded from the heap are translated back to kernel addresses

Performance mode

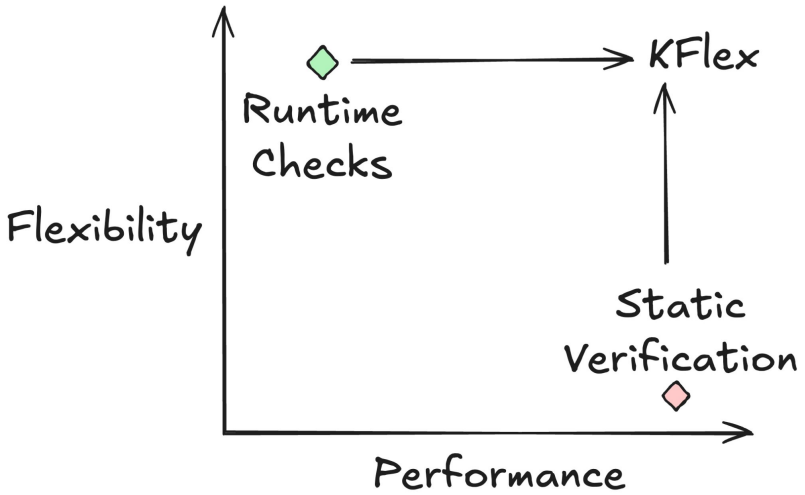
- Elide guard emission when reading from heap pointers
- Arbitrary kernel memory can be read, requires root access
- Tradeoff confidentiality for performance

Co-designing extensions with user space

- Holding locks from both user-space and the kernel
- Translation of pointers for bi-directional data access
- Introduce support to disable preemption in extensions
- MCS lock implemented in the extension over heaps

KFlex

- **Idea:** Separate kernel safety into two sub-properties
  - Use distinct bespoke mechanisms to enforce each sub-property
  - Co-design runtime mechanisms with verification to reduce overhead



Co-designing extensions with user space

- Holding locks from both user-space and the kernel
- Translation of pointers for bi-directional data access
- Introduce support to disable preemption in extensions
- MCS lock implemented in the extension over heaps

Two examples:

- Extension memory allocator (malloc)
- Memcached in XDP (kernel), with GC in user space

Time slice extension

- User space may be preempted within a critical section
- Set a bit in a memory region shared with CPU scheduler
- When bit is set, user space is granted a one-time extension

Time slice extension

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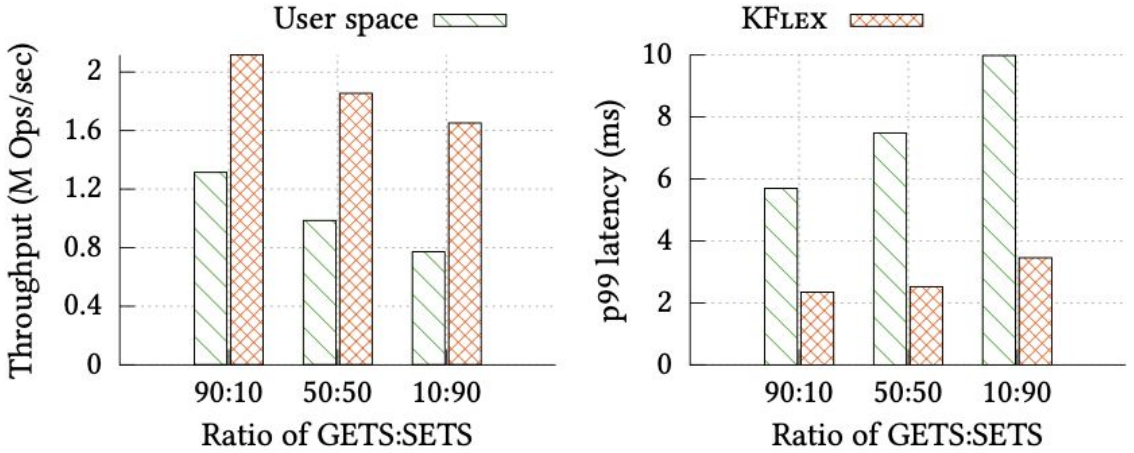
Anomalies:

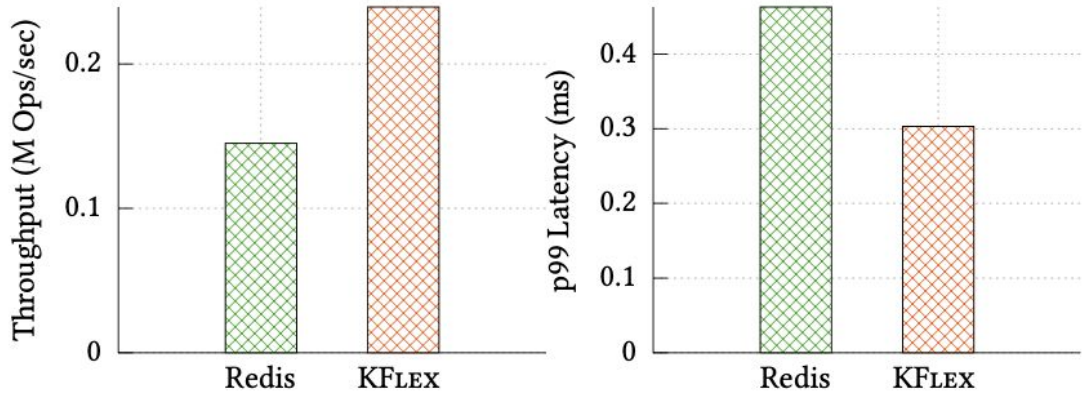
- What if user space is hung or killed while holding the lock?
  - Extensions will wait spinning, and eventually be cancelled
  - User space will be forcefully preempted after the first extension
- What if user space corrupts the lock?
  - Random memory corruption occurs, but only affects extension data

Redis in sk_skb - GETS/SETS



Up to 2x more throughput, up to 3x lower p99 latency

Redis in sk_skb - ZADD



1.6x more throughput than user space, 30% reduction in p99 latency

Co-design of SFI with verification

- Pointer manipulation of heap pointers changes pointer value
- In general, needs sanitization before access
- Co-design SFI with eBPF verifier's range analysis tracking
- 76% of guard emissions elided on pointer manipulations
- For some data structures, 100%!