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Advancing Kernel Control Flow Integrity with eBPF

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```
void key_revoke(struct key *key)
{
  ...
  if(key->type->revoke)
    key->type->revoke(key);
  ...
}
```

```
void
keyring_revoke(struct key *key)
{
  ...
}
```

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void key_revoke(struct key *key)
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  ...
  if(key->type->revoke)
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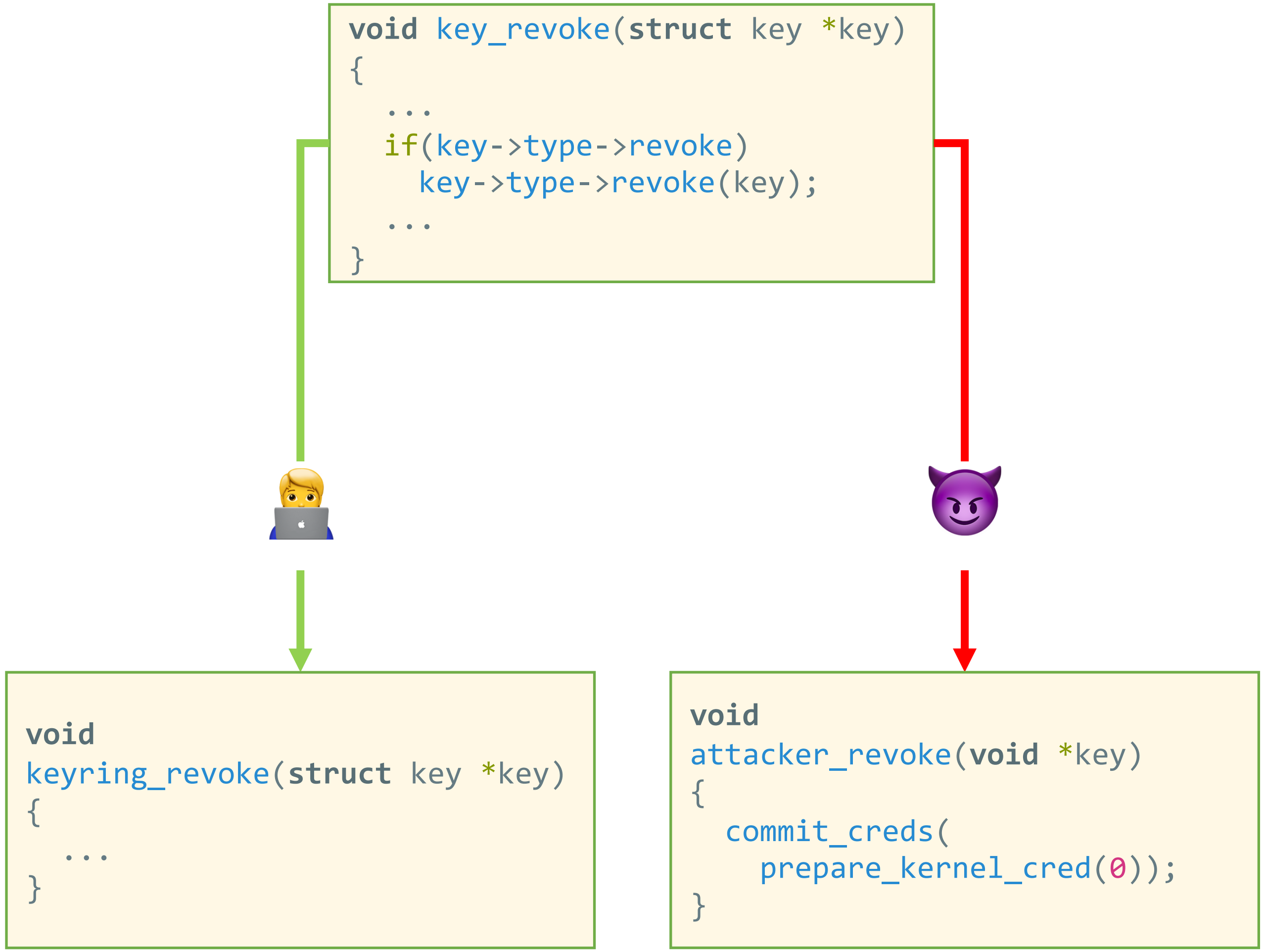
  ...
}
```

```
void
keyring_revoke(struct key *key)
{
  ...
}
```

```
void
attacker_revoke(void *key)
{
  commit_creds(
    prepare_kernel_cred(0));
}
```

Control-flow integrity

- Restricting program execution to its control-flow graph (CFG)
- Verifies validity of **indirect** control flow transfers
  - Indirect calls
  - Returns
- CFG can be generated via either *static or dynamic* analysis



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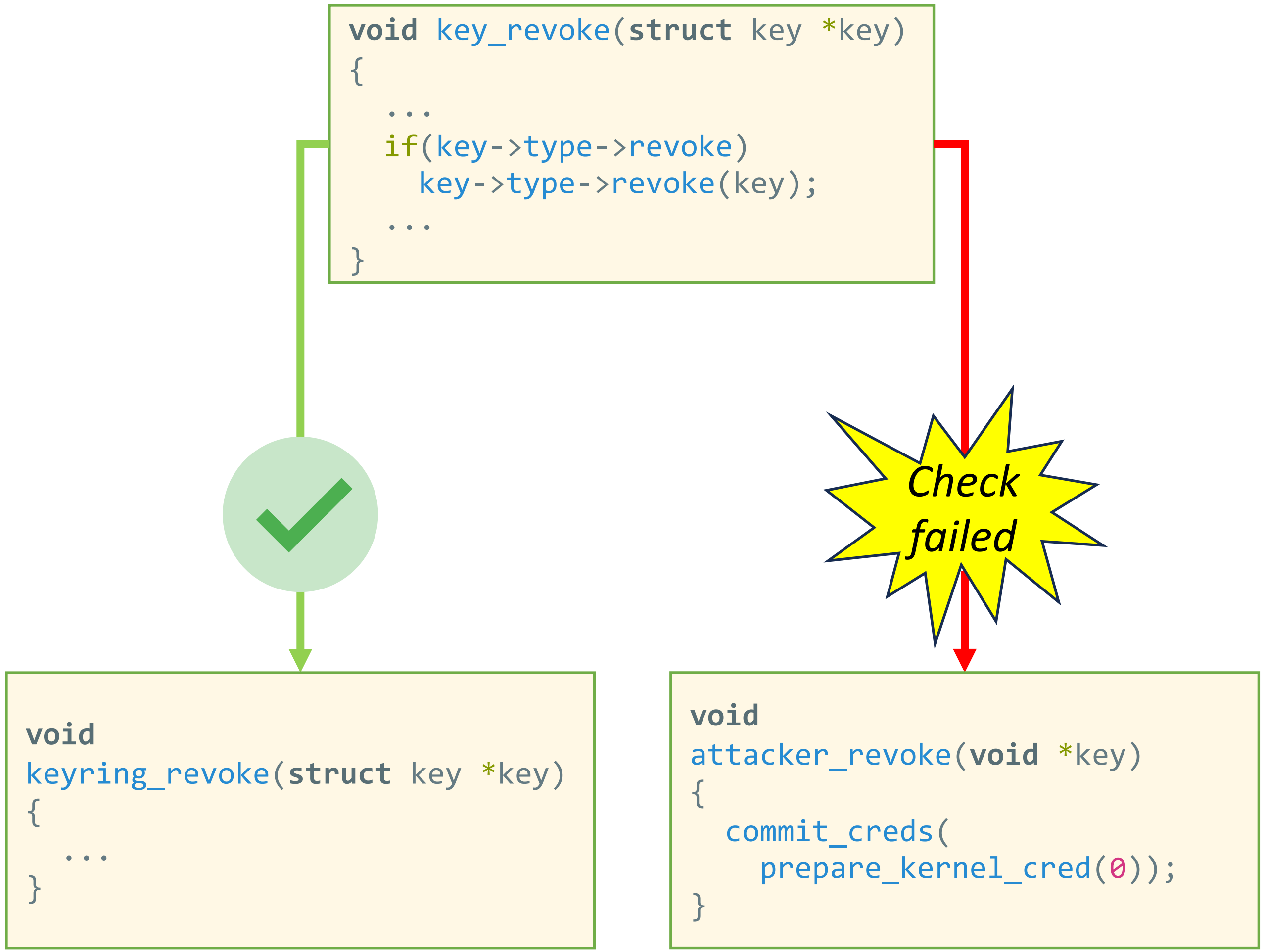

Inflexibility of existing KCFI approaches

- State-of-the-Practice: LLVM-based KCFI in Linux
  - Static policy based on function prototypes
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Inflexibility of existing KCFI approaches

- State-of-the-Practice: LLVM-based KCFI in Linux
  - Static policy based on function prototypes
  - Enabling/disabling KCFI requires rebuild the kernel

- KCFI policies are *statically* defined
  - Hard to catch the moving target of state-of-the-art CFI techniques
  - Policy change requires kernel rebuild and reboot
    - Service disruption
    - Increased mitigation time
  - Difficult to make use of runtime context

eBPF can be a powerful tool for KCFI

- **Easy to deploy**
  - KCFI policies can be enabled/disabled/switched at runtime
  - No kernel rebuilding/rebooting
- **Expressiveness and observability**
  - Support for dynamic policies that leverage context information
  - Observability superpower
- **Flexibility and fine granularity**
  - Selectively attaching eBPF checks to different indirect call sites

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Kernel CFI

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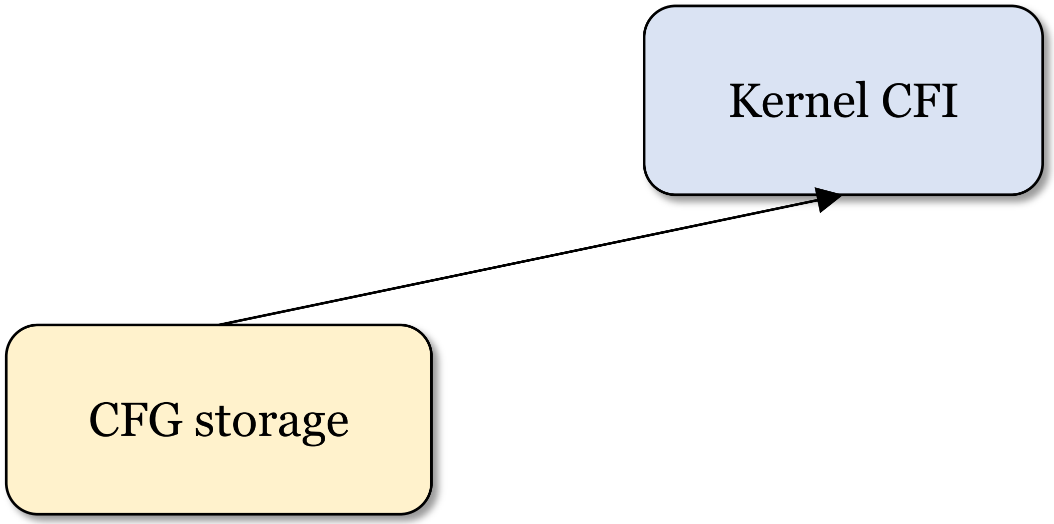

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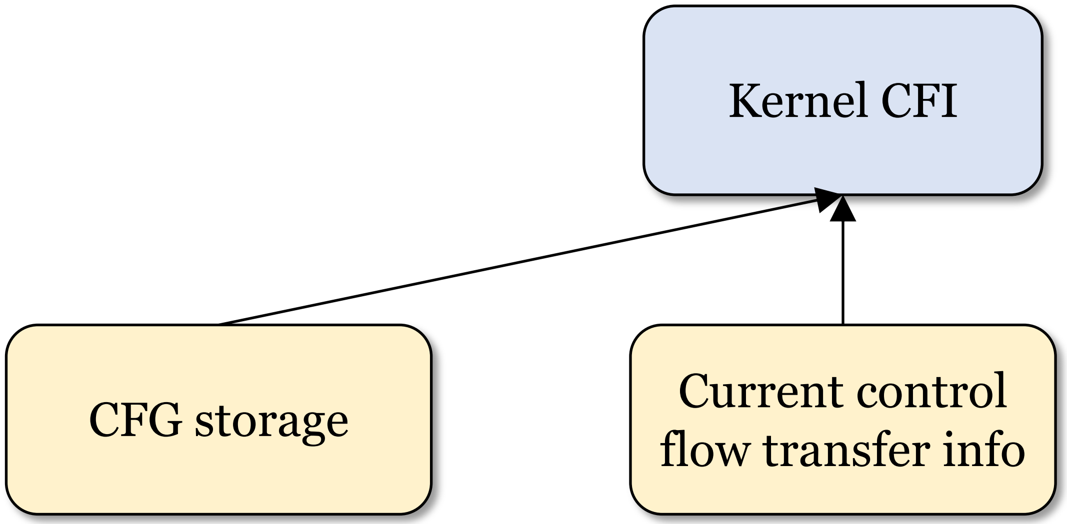

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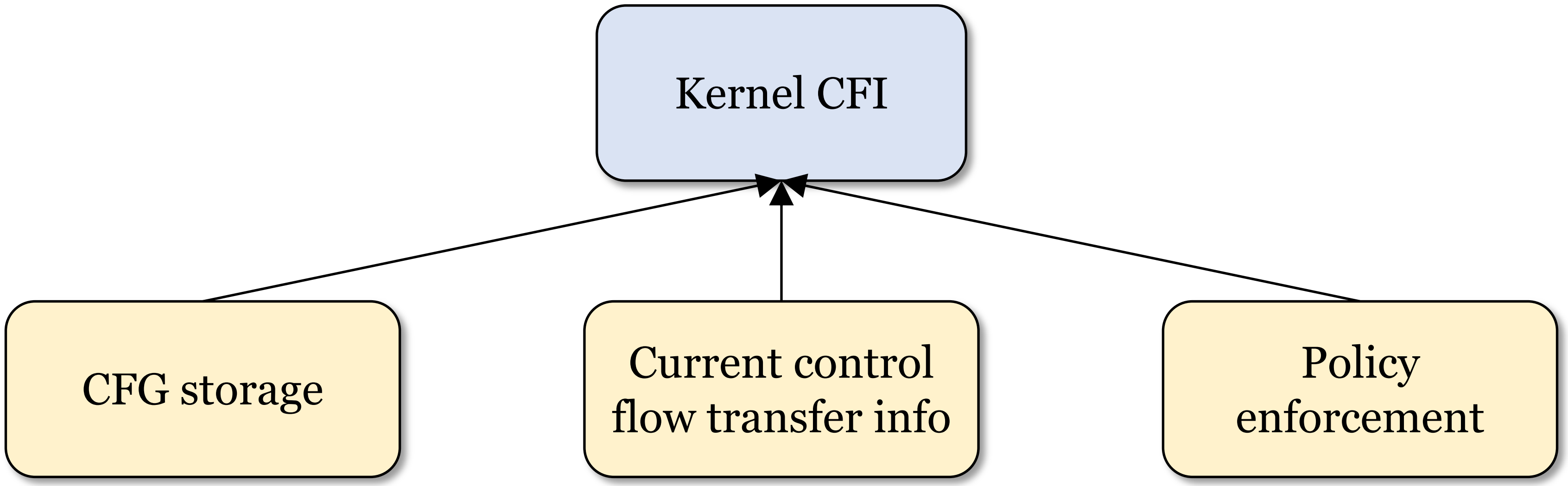

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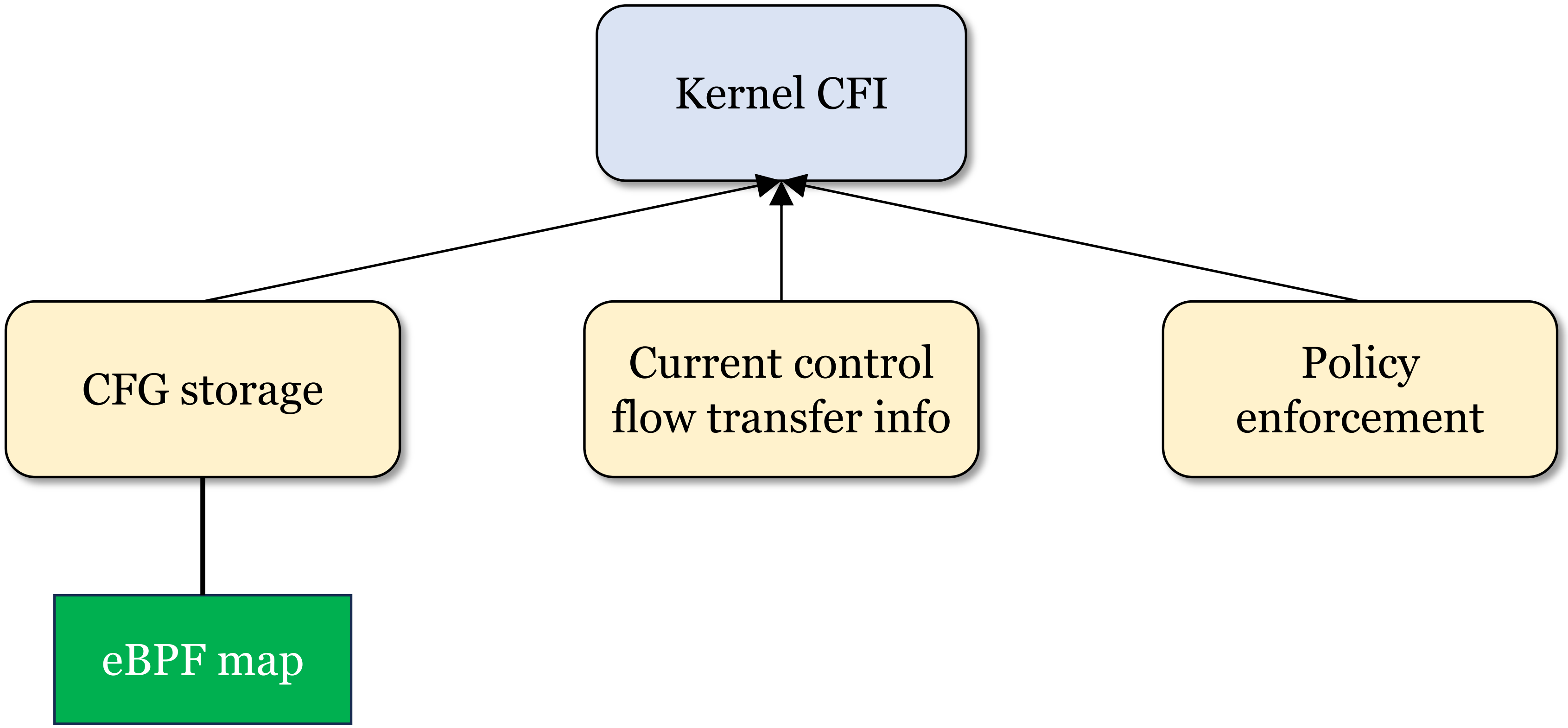

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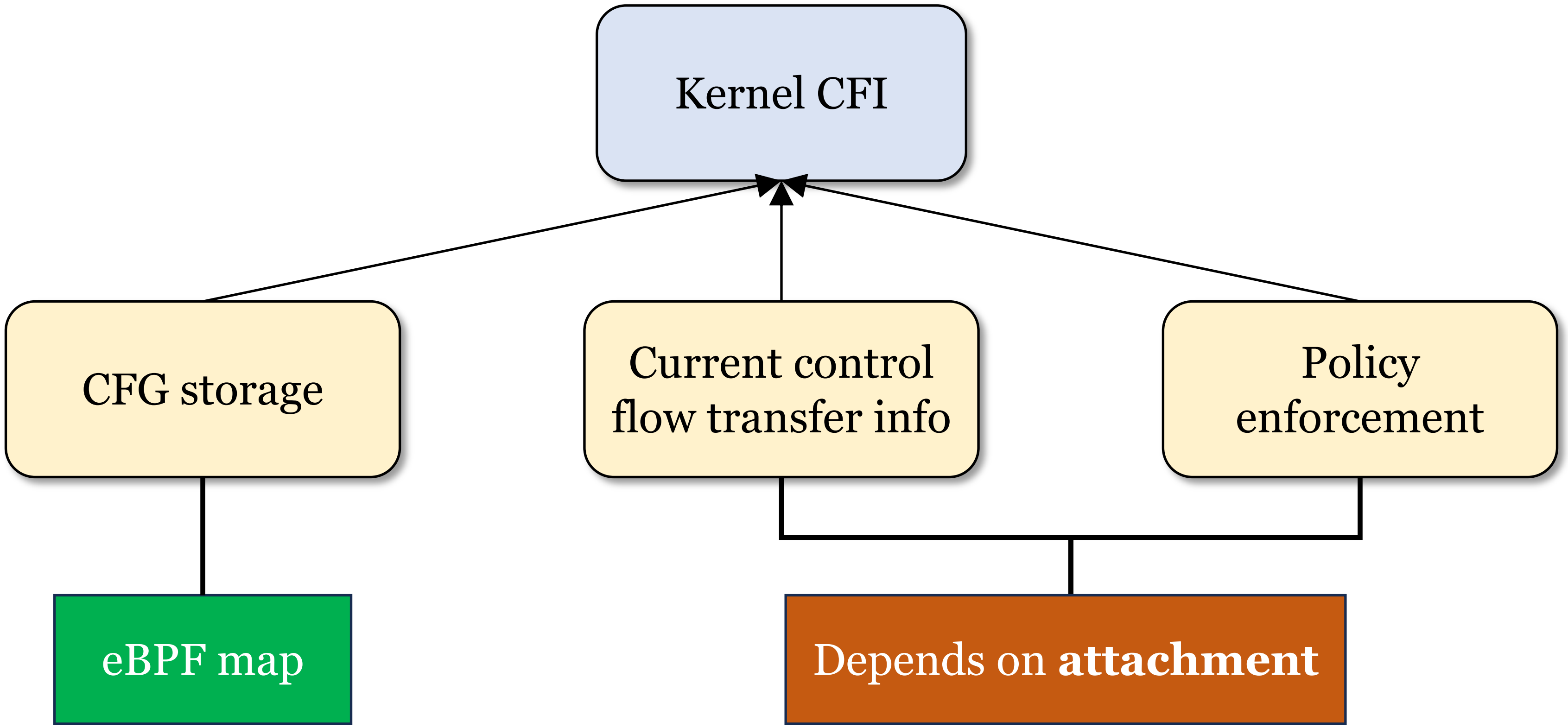

Scope and Threat Model

- The kernel is benign, but may contain vulnerabilities
- The attacker attacks the kernel by issuing system calls or by sending network packets
- The eBPF-based KCFI infrastructure is trusted
- Our current focus is on indirect function calls

A kprobe-based Approach

- Attach to indirect calls
  - `kprobe` attaches to most kernel text address

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48 89 44 24 08 mov  %rax,0x8(%rsp)
31 ff          xor  %edi,%edi
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SEC("kprobe")
int kcfi_prog(struct *pt_regs ctx)
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  return 0;
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- Attach to indirect calls
  - `kprobe` attaches to most kernel text address
- Obtain source and target from registers
- Use `bpf_send_signal` to terminate offending task
- **Problem:** `kprobe` uses interrupt by default
  - Significant context switch overhead
  - **~26x** on QEMU for a single indirect call

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What about jump optimization?

- Optimizes `kprobe` instrumentation into a synchronous jump

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  - `call` instructions are not boost-able

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74 02             je   ffffffff8106b991
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```

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- Attaching to LLVM-KCFI instructions?
  - LLVM-KCFI instrumentations are special :(
  - KCFI failure handler decodes these instructions
  - Overwriting the instruction with `kprobe` breaks the handler

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Is there a more efficient solution?

An `fprobe`-based approach

- Derived from Daniel Borkmann's suggestion on using `fentry`.
- `BPF_TRACE_KPROBE_MULTI` allows attaching to functions via `fprobe`
  - program is executed under the same context when the function is called
  - More efficient than interrupts :)

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ff d3                call *%rbx # indirect call
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  - callee is the currently probed function
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- Requires using LLVM-KCFI

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```

Limitations of using `fprobe`

- Less coverage than LLVM-KCFI
  - `noinstr`/`notrace` functions
  - Tracing subsystem and library functions are compiled without `fprobe` support
  - **~10K** (out of 59K) functions cannot be attached
- `fprobe` doesn't distinguish between direct and indirect calls
  - The program always executes when the function is invoked
  - **258K** direct calls vs. **15K** indirect calls
  - **7x** slowdown for LEBench on QEMU

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Mechanism	Hook point	eBPF invocation	Overhead	KCFI coverage
`kprobe`	Indirect call	Interrupt	Context switch	Same as LLVM-KCFI*
`fprobe`	Function entry	Synchronous call	Function call	17% less than LLVM-KCFI

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- A new attachment mechanism is desired:
  - Synchronous invocation
  - Instrument precisely indirect call sites covered by LLVM-KCFI

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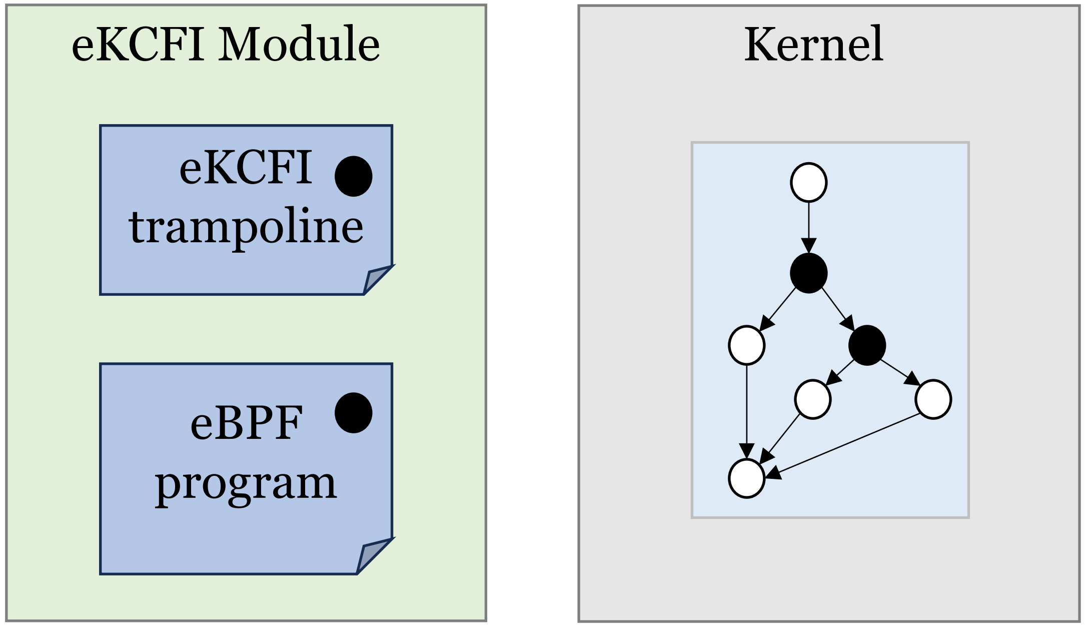
eKCFI Overview

- A new way to hook eBPF programs to indirect call sites
  - Instrument kernel code to create hooking point at indirect calls
  - Allows synchronous invocation of eBPF programs
- The policy program decides whether to allow the control-flow transfer
  - Continue execution
  - Kernel panic



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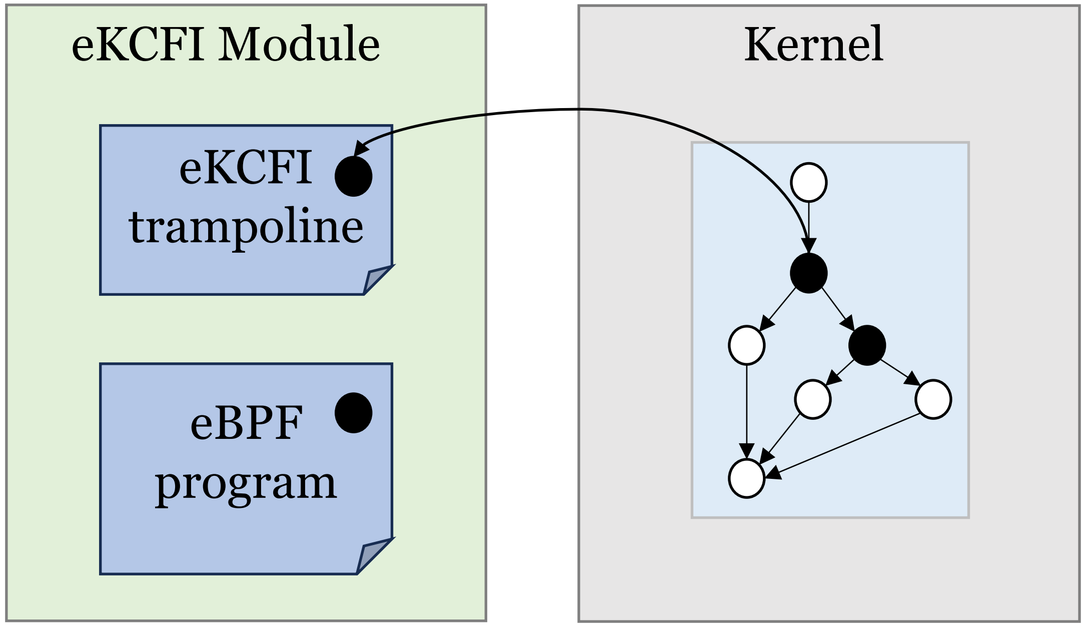

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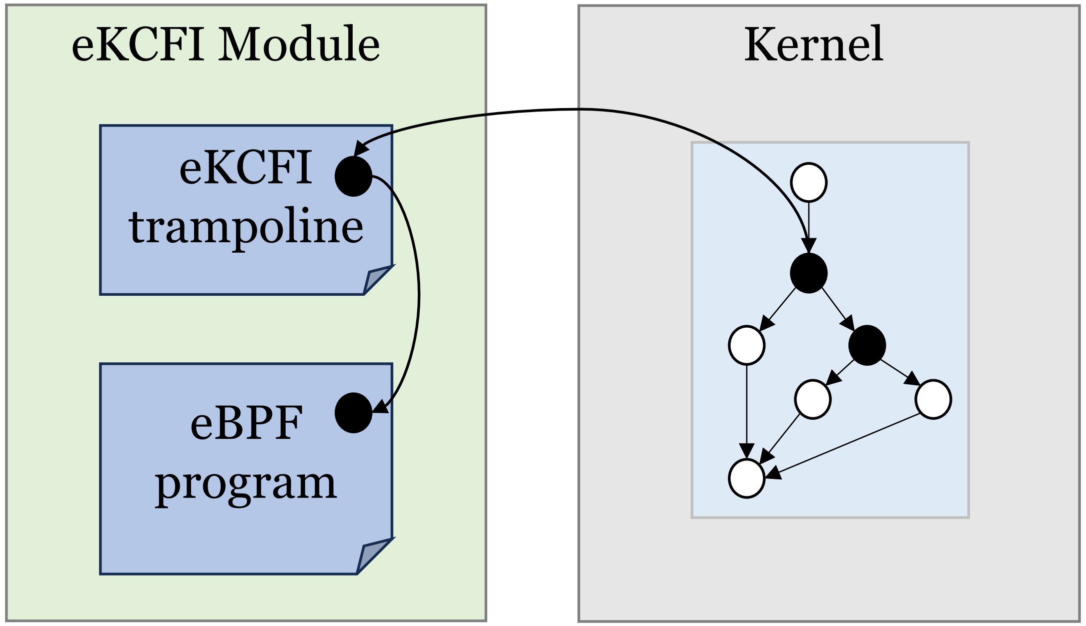

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- ✓ Invokes eBPF program with kCFI context

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- ✓ Saves registers
- ✓ Obtains callee from `rax`, caller from its return address
- ✓ Prevents recursive kCFI instrumentation
- ✓ Invokes eBPF program with kCFI context
- ✓ Interprets return value of eBPF program

Instrumenting kernel code

- `eKCFI` trampoline invokes the eBPF policy program

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Instrumenting kernel code

- `eKCFI` trampoline invokes the eBPF policy program

- The trampoline provides caller and callee information in context

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Instrumenting kernel code

- eKCFI trampoline invokes the eBPF policy program
- The trampoline provides caller and callee information in context
- Enforcement implemented by program return value
  - interpreted by trampoline

```
...
48 89 44 24 08 mov %rax,0x8(%rsp)
31 ff          xor %edi,%edi
31 f6          xor %esi,%esi
48 89 d8       mov %rbx,%rax
e8 d7 00 00 00 call *0xd7(%rip) #trampoline
ff d3          call *%rbx # indirect call
...
```

```
SEC("ekcfi")
int kcfi_prog(struct *ekcfi_ctx ctx)
{
  u64 caller = ctx->caller;
  u64 callee = ctx->callee;

  if (!call_allowed(caller, callee))
    return EKCFI_RET_PANIC;

  return EKCFI_RET_ALLOW;
}
```

Adding eKCFI to the design space

Mechanism	Hook point	eBPF invocation	Overhead	KCFI coverage
`kprobe`	Indirect call	Interrupt	Context switch	Same as LLVM-KCFI
`fprobe`	Function entry	Synchronous call	Function call	17% less than LLVM-KCFI

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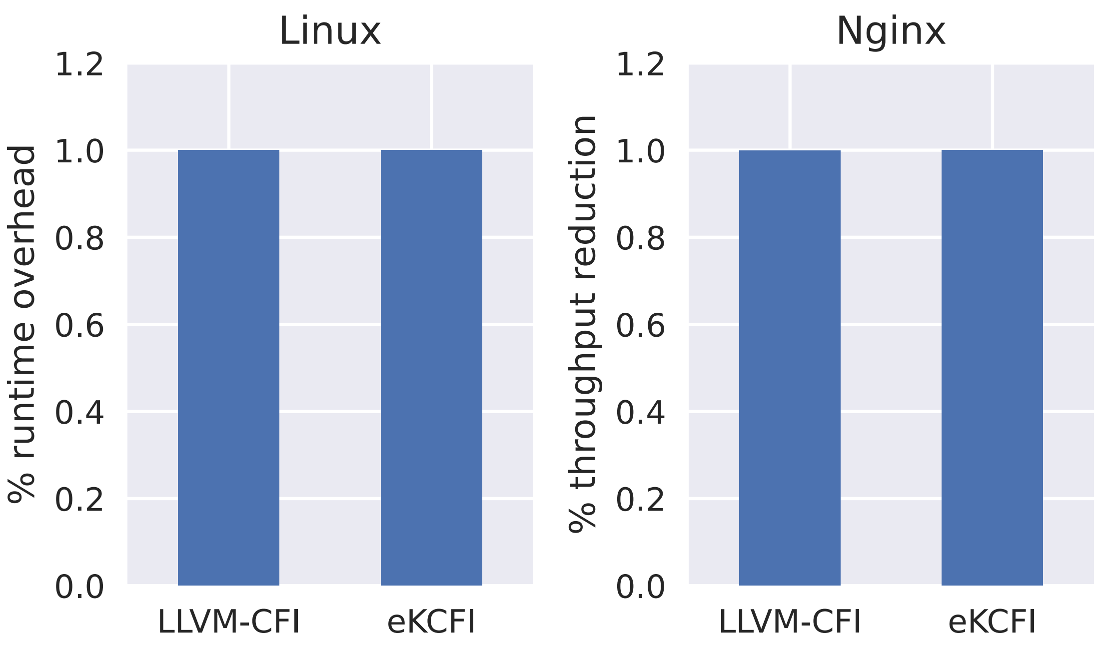
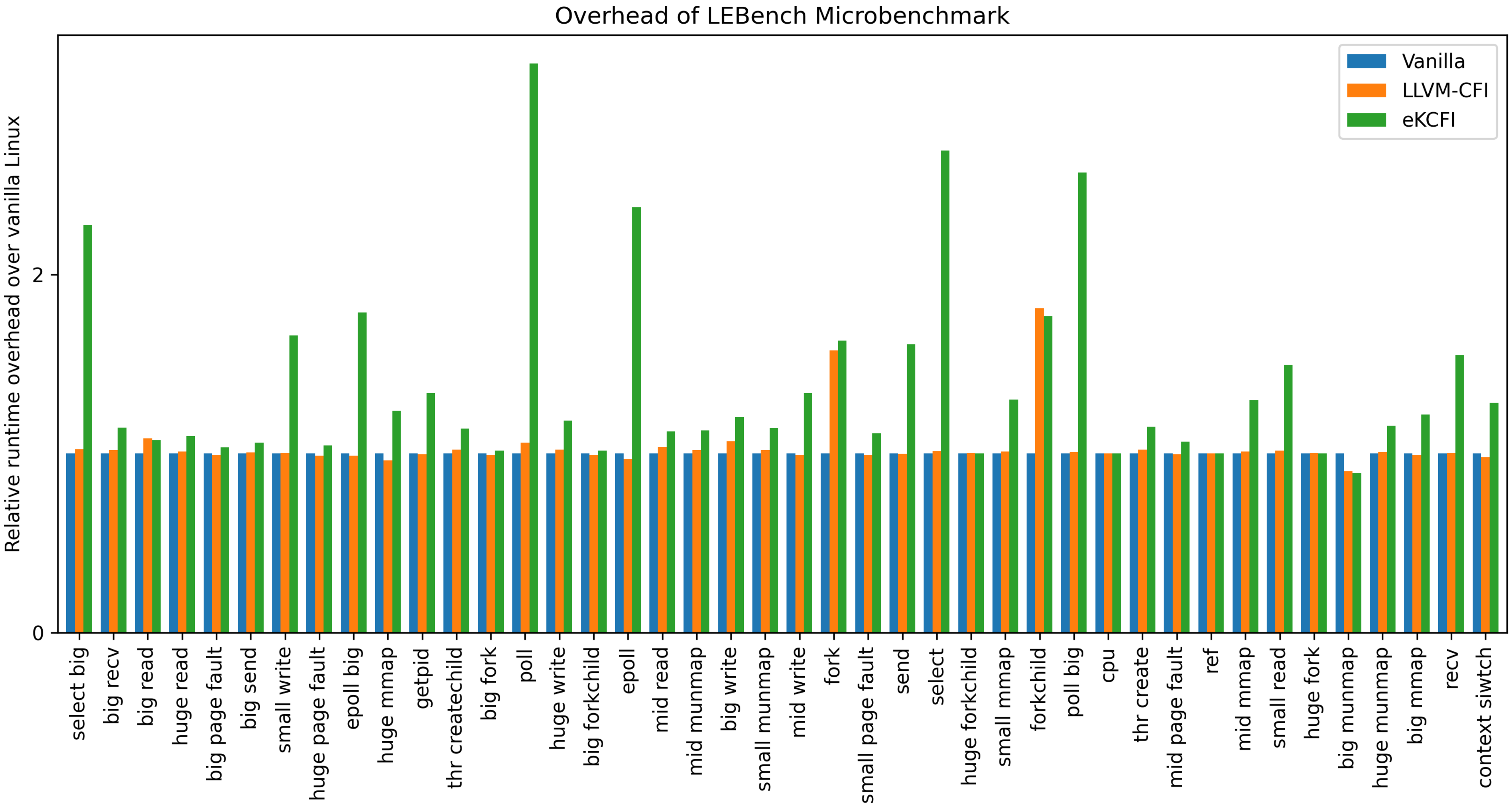
`eKCFI`	Indirect call	Synchronous call	Function call	Same as LLVM-KCFI

Application Performance

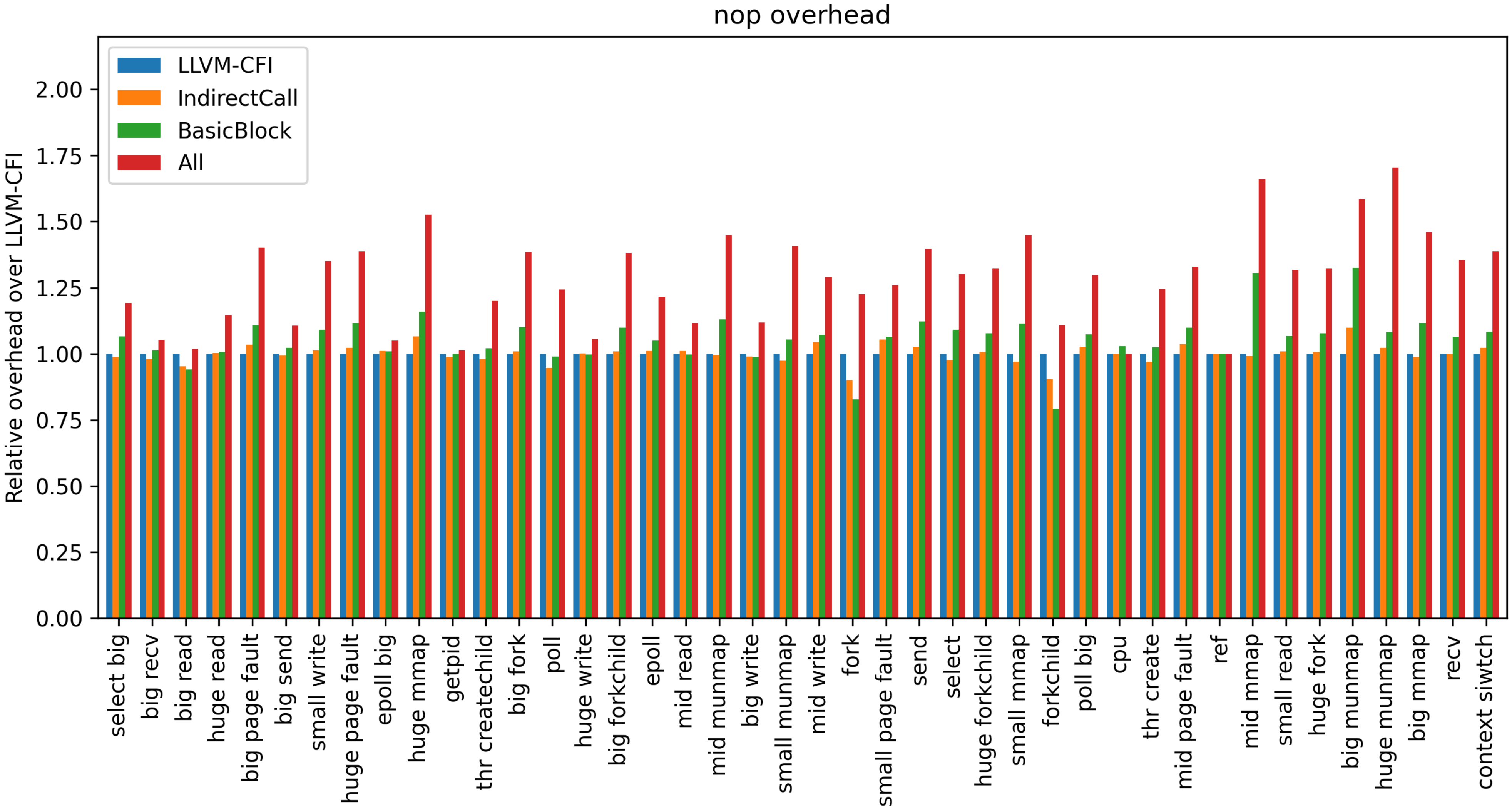
- Evaluate on NGINX and Linux kernel compilation
- Policy: enforce a fine-grained CFG from dynamic traces
- `eKCFI` achieves roughly the same performance comparing to LLVM-KCFI



Microbenchmark Performance



Nops overhead



Discussion and Limitation

- Limitations of `eKCFI` (or eBPF-based KCFI in general)
  - Need to trust the eBPF subsystem
  - Attackers may be able to corrupt memory of helper code or map content
- Protection and Mitigation
  - Hardware-based mechanisms (e.g. MPK) might be useful for maps
  - Protecting helper functions is still hard
    - helpers call deep into core kernel code
- Complements LLVM-KCFI, not necessarily replace

Conclusion

- eBPF can make kernel CFI (KCFI) more flexible and usable.
- Existing eBPF mechanism is insufficient for practical KCFI
  - Performance and hook point limitations
- We develop `eKCFI`, an eBPF-based KCFI framework
  - A new hooking mechanism for efficient indirect call checking

Backup slides

Call site equivalence classes

# of targets	LLVM-KCFI	eKCFI
1	18.5%	70.8%
≤ 5	48.2%	95.6%
≥ 100	10.9%	0.1%

Comparison of equivalent classes for different KCFI techniques considering 742 dynamically traced call sites.