Flexible and Concise Spectre Mitigations for BPF

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FGBS Spring 2023 - March 7, 2023 - Dresden, Germany

Motivation: High-Performance IO

- **Problem:** User-/kernel switching overhead too high for packet processing, NVME disks, tracing, ...
- **Approaches:** System-call batching (e.g. io_uring, aio), kernel-bypass (e.g. DPDK), **software-based isolation (BPF)**

eBPF

- Un-/privileged users load bytecode into the kernel
- Verified for type-/memory-safety and a bounded execution time
- JIT-compiled and invoked in kernel mode
- BPF program can call kernel helpers (≈ system calls)

- **Problem:** Expressiveness and performance are limited by mitigations against speculative side-channel attacks

Speculative Side-Channel Attacks

- **„Hardware bugs“ not considered:** Meltdown, load-value injection
- **Software-based mitigation:** Bounds-check bypass, speculative-store bypass, speculative type-confusion
- Non cache-based side-channels
- Secrets are encoded into side-channels on speculative paths

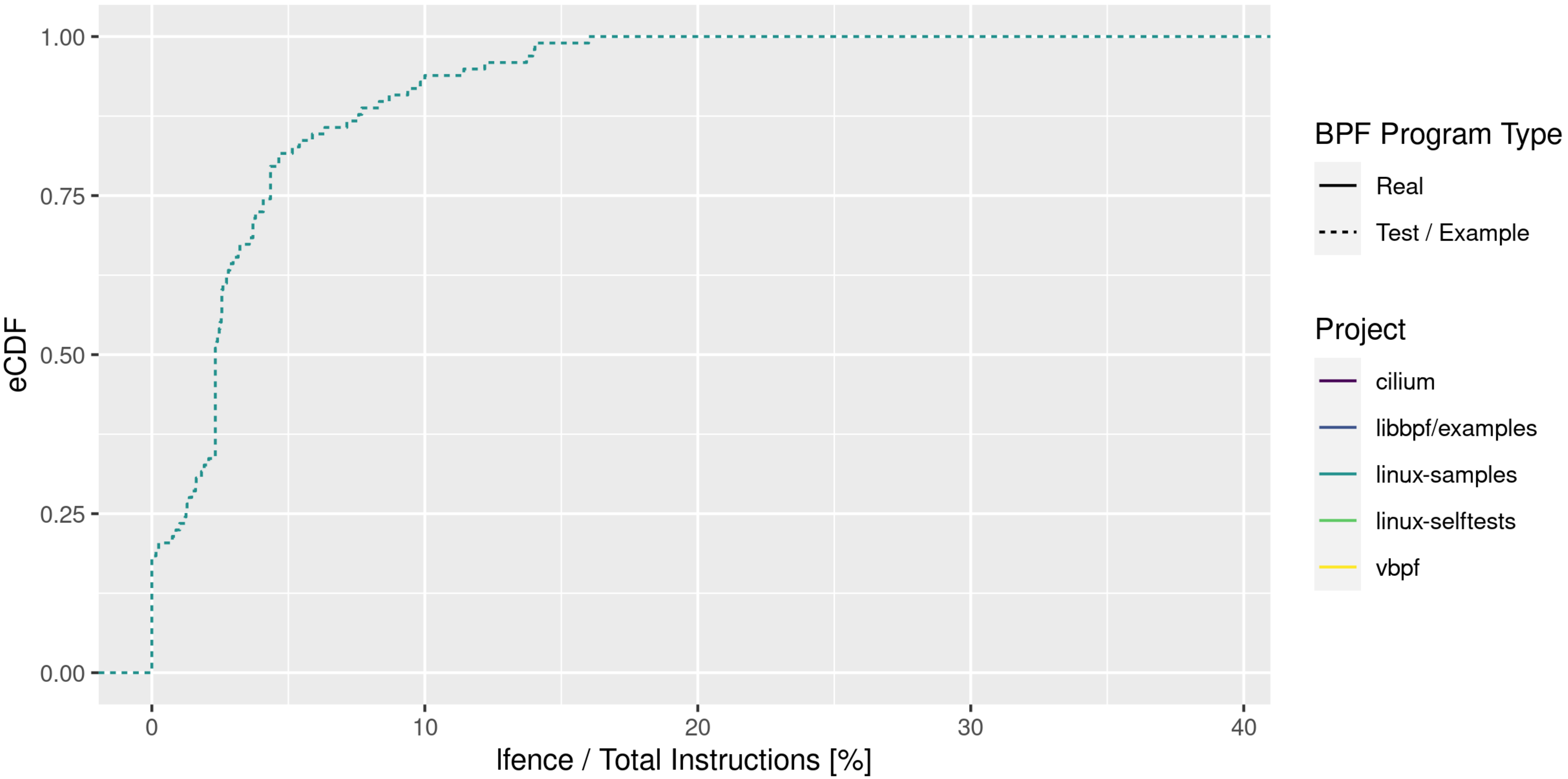
BPF Verifier

- Memory-safety: Only access borrowed/owned memory
- Type-safety: Only perform operations valid for the type (pointer/scalar/…)
- Pointers are secrets: Unprivileged programs can not cast pointers to scalars or encode them into side-channel

BPF Spectre Mitigations

- **Speculative Store-Bypass (v4) →** Fences
- **Speculative Bounds-Check Bypass (v1)** → Reject / Masking
- **Speculative Type Confusion (v1)** → Reject

- **Evaluation:** Collected over 350 programs from 4 projects and analyzed the number of fences and rejections



eCDF
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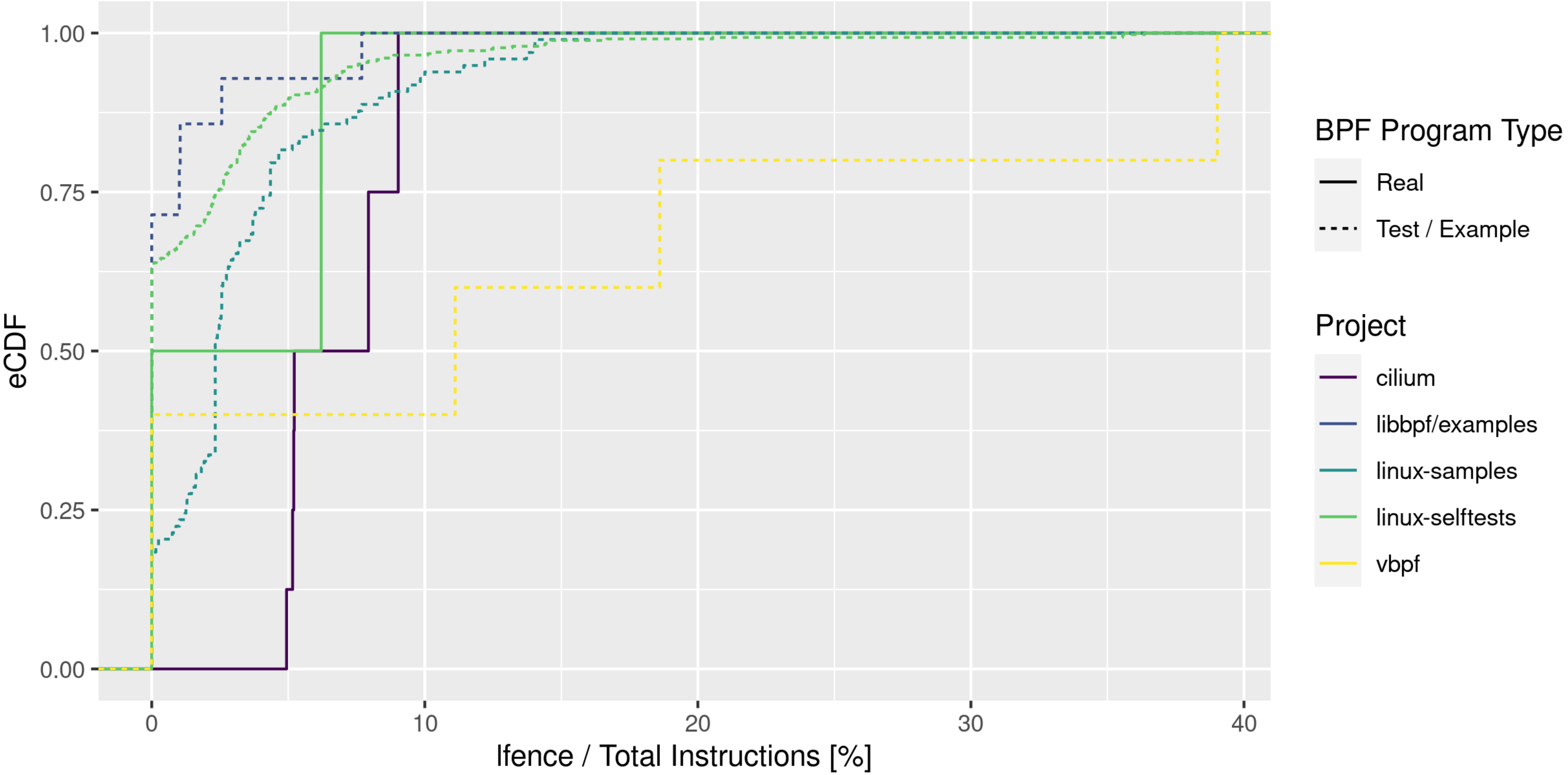
BPF Program Type
Real
Test / Example
Project
cilium
libbpf/examples
linux-samples
linux-selftests
vbpf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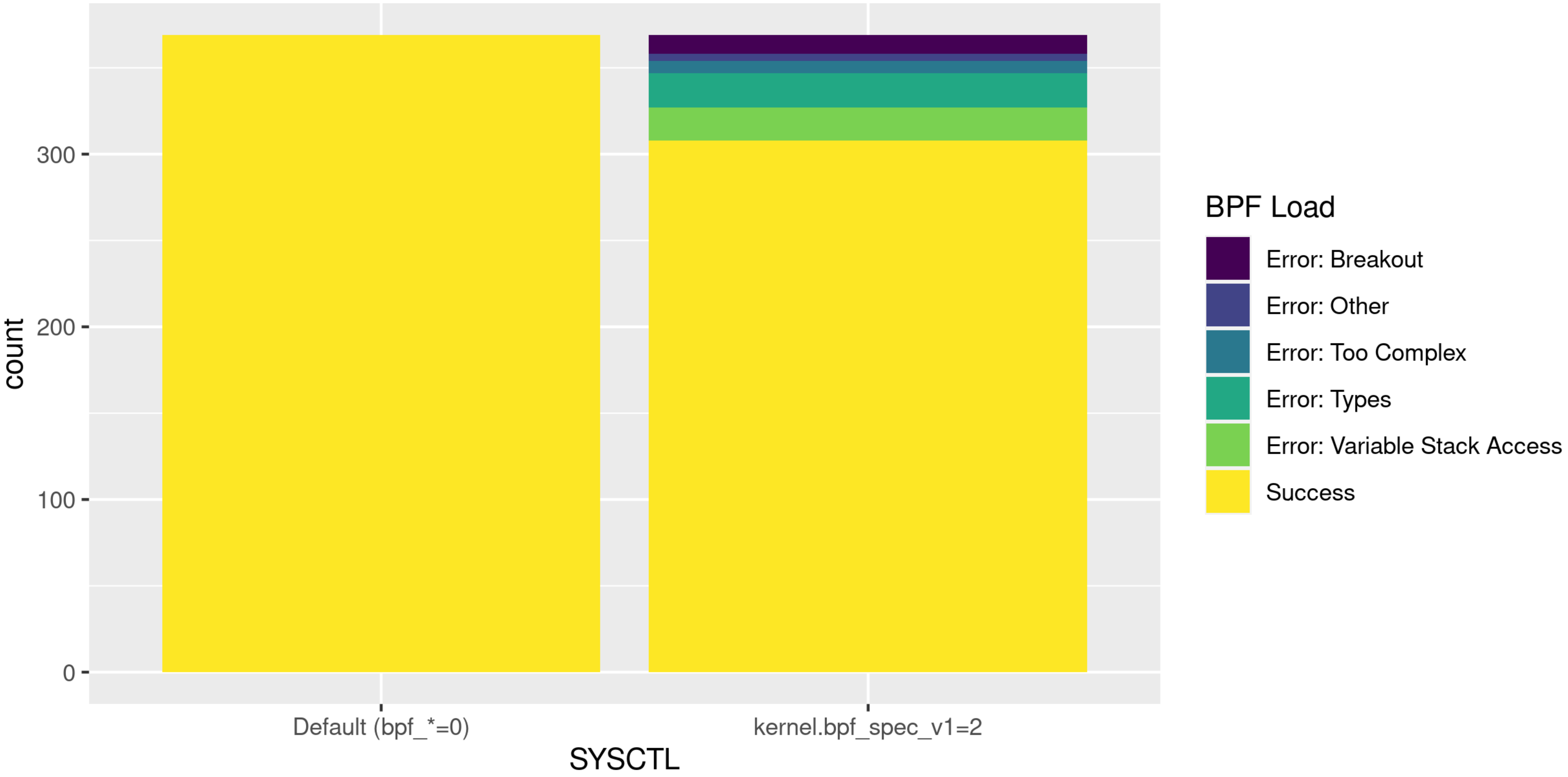

count
300
200
100
0
Default (bpf_*=0)
kernel.bpf_spec_v1=2
SYSCTL
BPF Load
Error: Breakout
Error: Other
Error: Too Complex
Error: Types
Error: Variable Stack Access
Success

BPF Spectre Mitigations Limitations

- **Unprivileged:** Hardcoded policy (no speculative breakout with speculative constant-time for pointers) → Limited expressiveness and performance
- **Privileged:** Only some mitigations active → Easily introduce vulnerabilities
- **Privileged and unprivileged:** Secrets unknown to compiler completely unprotected

- **Approaches:** Refine kernel implementation or create an extensible architecture

Approach: Refine Kernel Mitigations

- Replace „no speculative breakout“ with „relative constant-time“ policy
- Improves expressiveness
- Makes the verifier more complex (currently already 13k SLoC)

Approach: Extensible Mitigations

- Introduce BPF instructions to prevent/restrict speculation
- Exposes speculation in Userspace ABI
- Privileged userspace services: Apply concise mitigations to unprivileged programs
- Compilers and programmers: Precisely control mitigations for privileged programs

Summary

- BPF is the only production-ready system for software-fault isolation that fully mitigates Spectre
- Speculative bounds-check bypass and type-confusion mitigations **limit expressiveness** while speculative store-bypass **limits performance**
- We will attempt to refine the current mitigation-approach, and create an architecture that allows for **flexible and concise user-defined mitigations**

Appendix

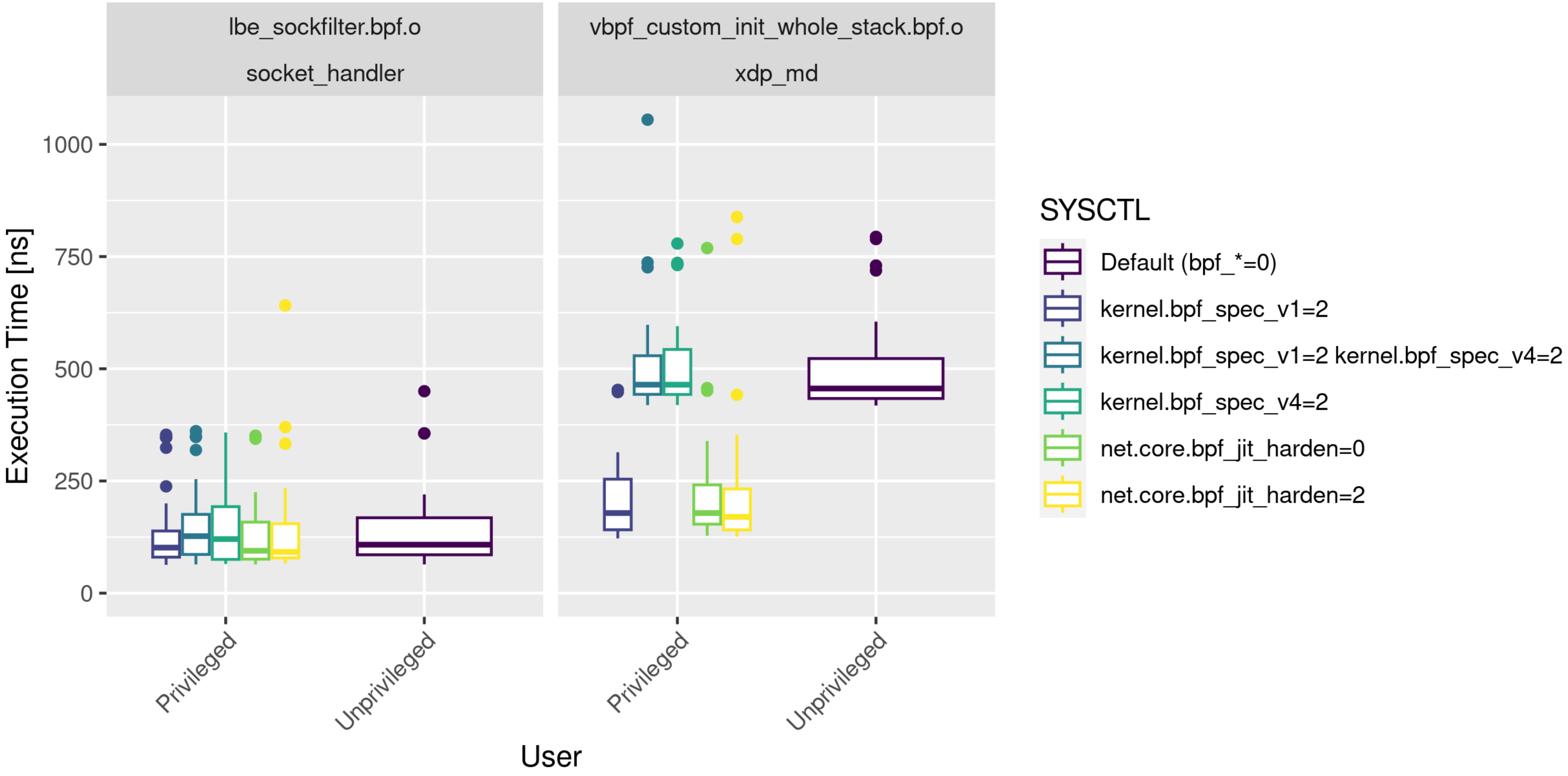
Speculation Policies

Security depends on system context and hardware

- **Leakage model:** Which instructions (e.g. load) leak which information (e.g. data address)?
- **Attacker model:** None, only remote, local unprivileged users
- **Leakage** + **attacker model → speculation policy:** No speculation, no speculative breakout, speculative constant-time, relative constant-time, …, *no Spectre*, arbitrary speculation

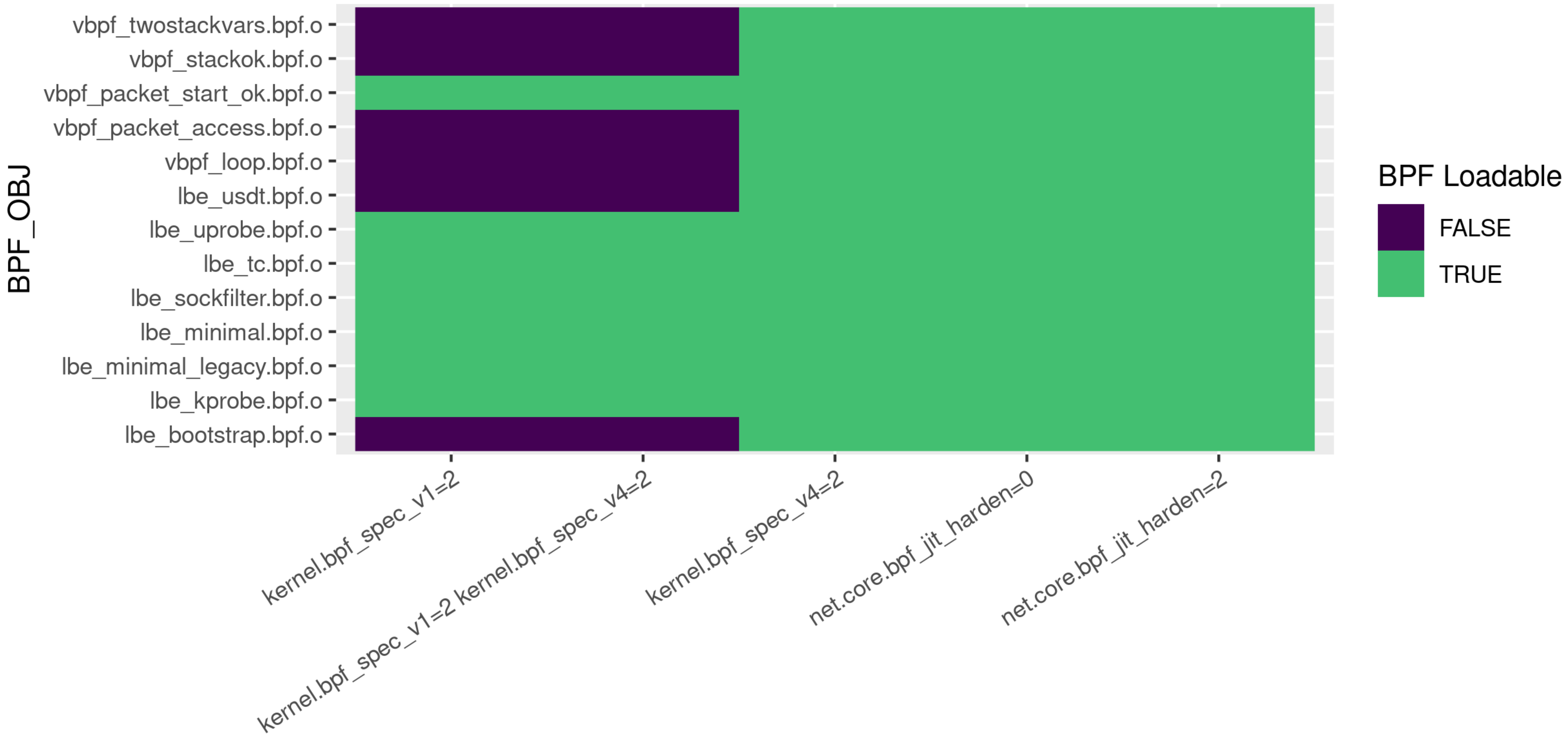
Limited Performance

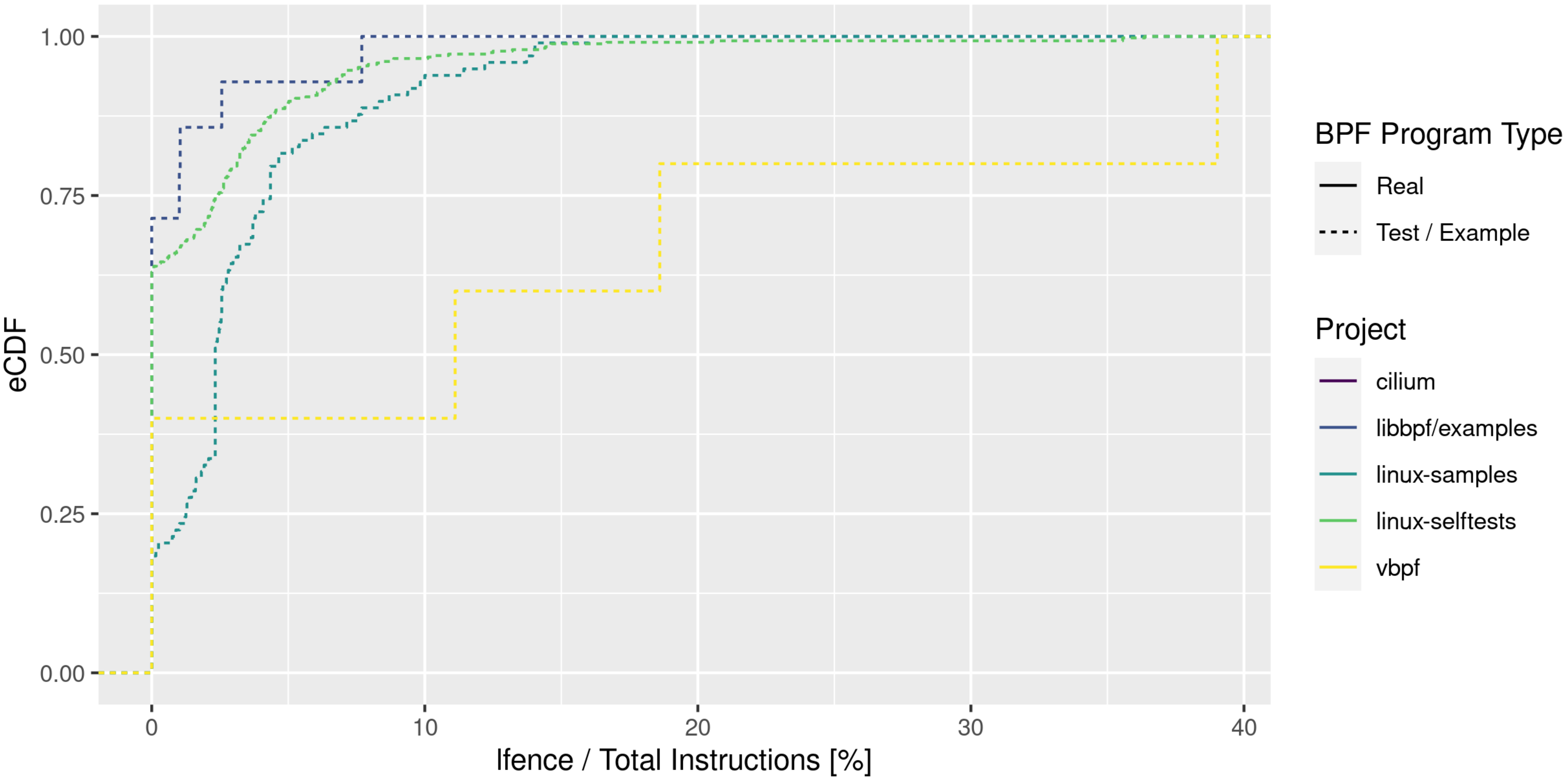
Difference measureable, real-world programs WIP



Limited Expressiveness

Even for small example programs: Many can not be mitigated

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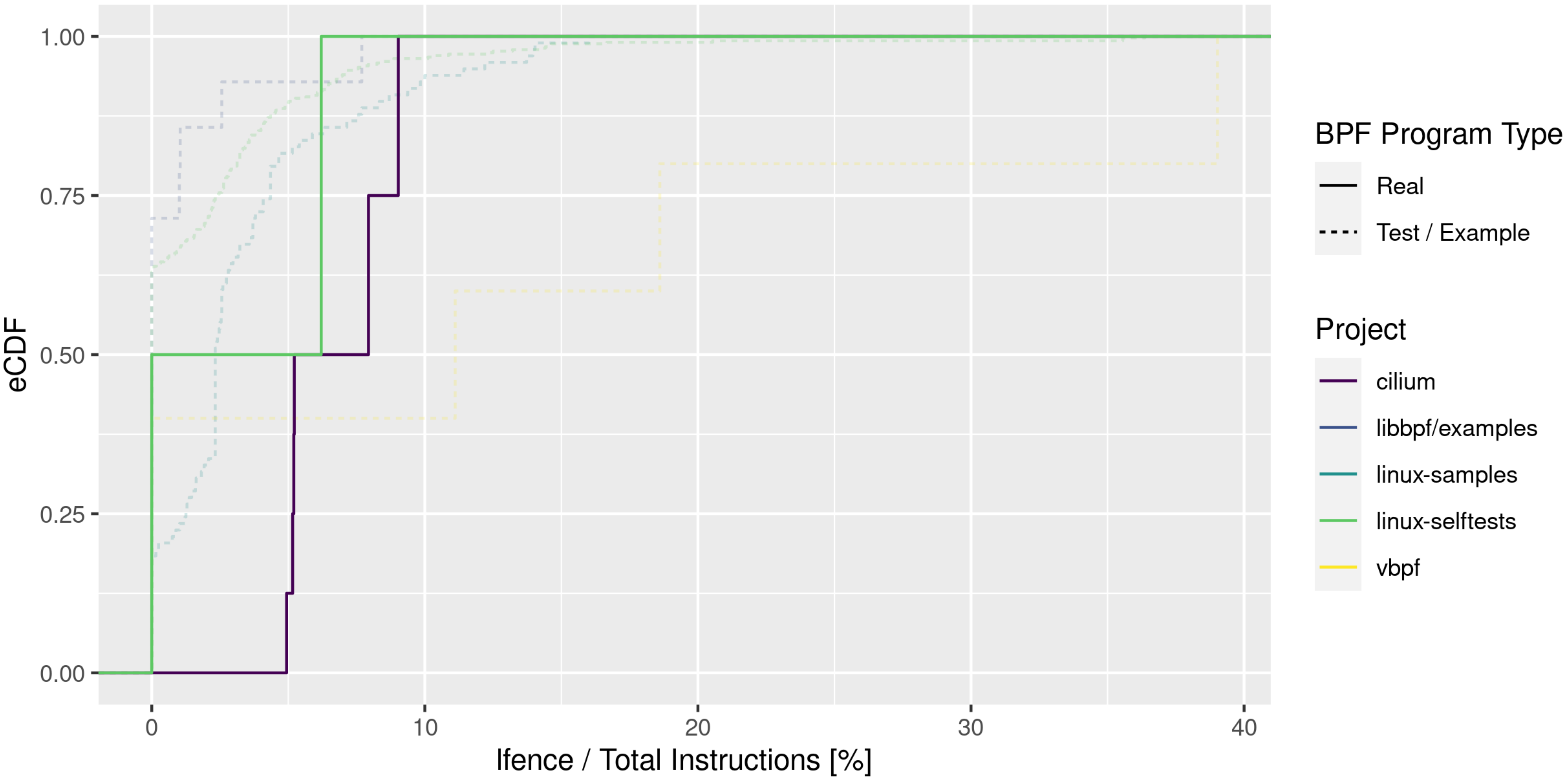
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