南方科技大学
SOUTHERN UNIVERSITY OF SCIENCE AND TECHNOLOGY

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COMPASS Lab
COMPuter And System Security Lab

MOAT: Towards Safe BPF Kernel Extention

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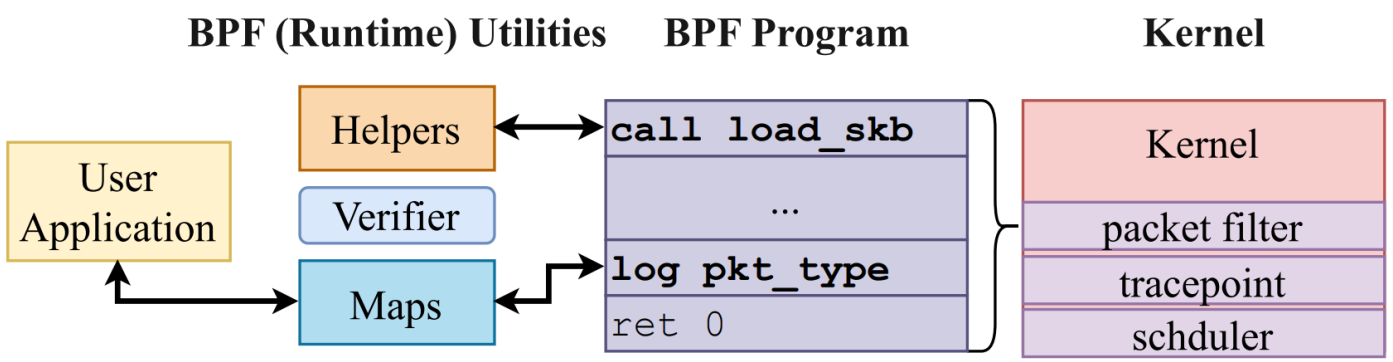
Background

What is (e)BPF?

Extended Berkeley Packet Filter:

- Kernel Virtual Machine



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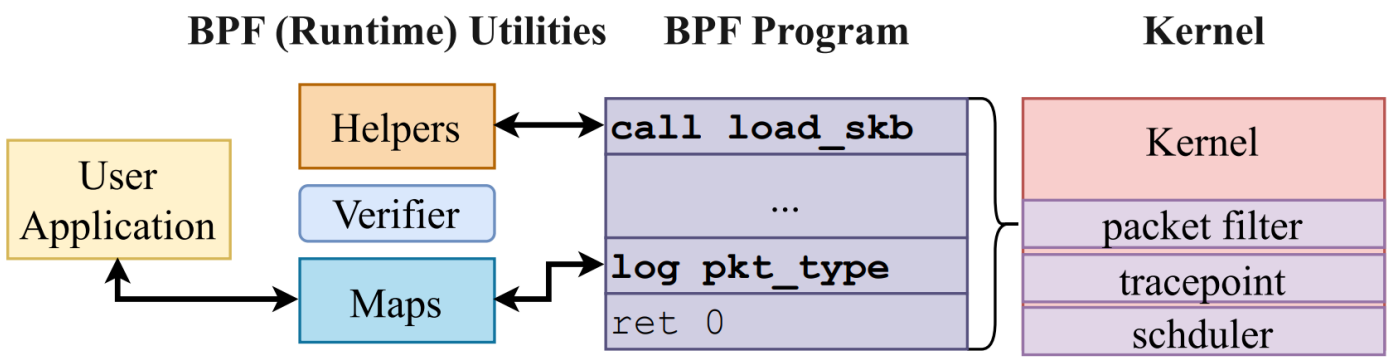

- Extended from classic BPF (cBPF), introduced to Linux in 2014.
- Packet Filter ⟶ Tracing/Network/Security…

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- **Robust**: Does NOT crash your kernel; eBPF is statically checked by a *verifier*.

Verifier: Do not load it, or your kernel will go kaboom!

Sounds good, but?

BPF security is a concern.

(**26** arbitrary R/W CVEs).

Because…

CVE ID
2016-2383, 2017-16995, 2017-16996, 2017-17852, 2017-17853, 2017-17854, 2017-17855, 2017-17856, 2017-17857, 2017-17862, 2017-17863, 2017-17864, 2018-18445, 2020-8835, 2020-27194, 2021-34866, 2021-3489, 2021-3490, 2021-20268, 2021-3444,2021-33200, 2021-45402, 2022-2785, 2022-23222, 2023-39191, 2023-2163

BPF CVEs

Sounds good, but?

BPF memory safety is a concern.

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- Static analysis is **hard**.

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BPF CVEs

Sounds good, but?

BPF memory safety is a concern.

Because…

- Static analysis is **hard**.
- BPF is **rapidly** developed.

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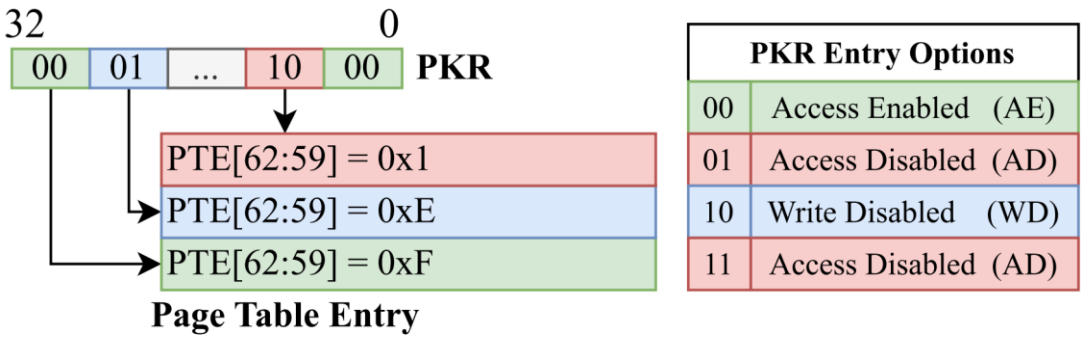
BPF CVEs

Hardware Isolation!

We therefore propose MOAT.
MOAT uses **hardware features** (e.g., MPK) to isolate BPF programs.
And… resolves a set of challenges, like **limited MPK and BPF API security**.

Hardware Isolation!

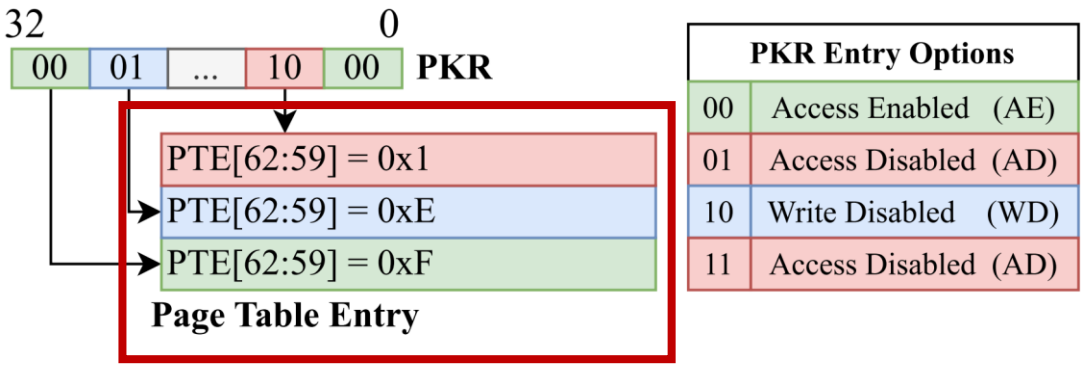
Wait..., what is Intel MPK?



Hardware Isolation!

Wait..., what is Intel MPK?

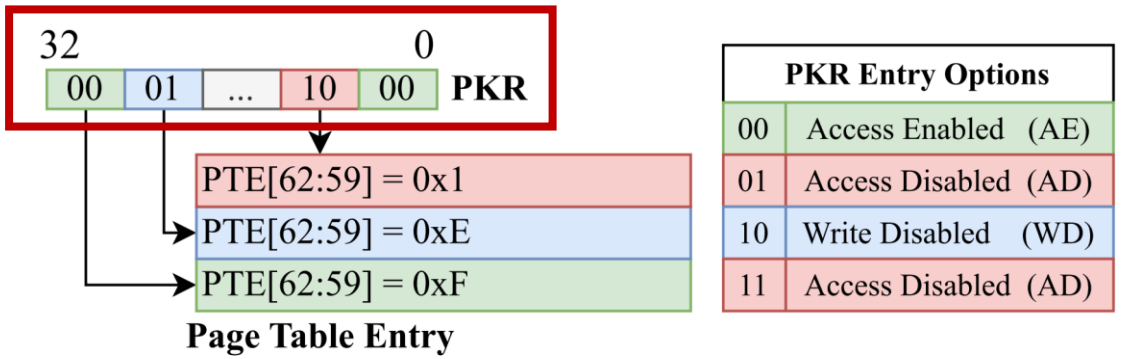
- Add a **4-bit tag** to PTEs (16 tags).



Hardware Isolation!

Wait..., what is Intel MPK?

- Add a 4-bit tag to PTEs (16 tags).
- **Toggle PTEs** with the same tag.



Method

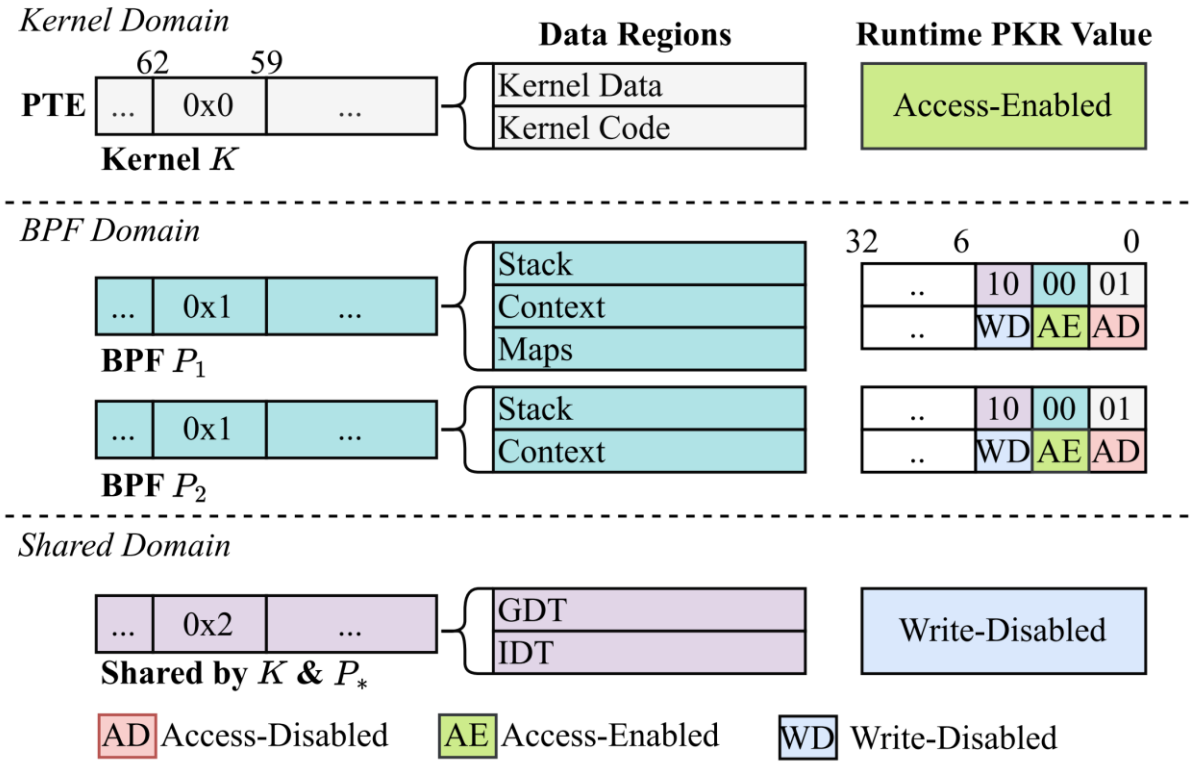
Limited MPK Tags

MPK is…

- Only 16 tags
- Lightweight

So… ***insufficient*** for multiple BPF programs.

But… ***abundant*** for isolating kernel/BPF.



Limited MPK Tags

MPK is…

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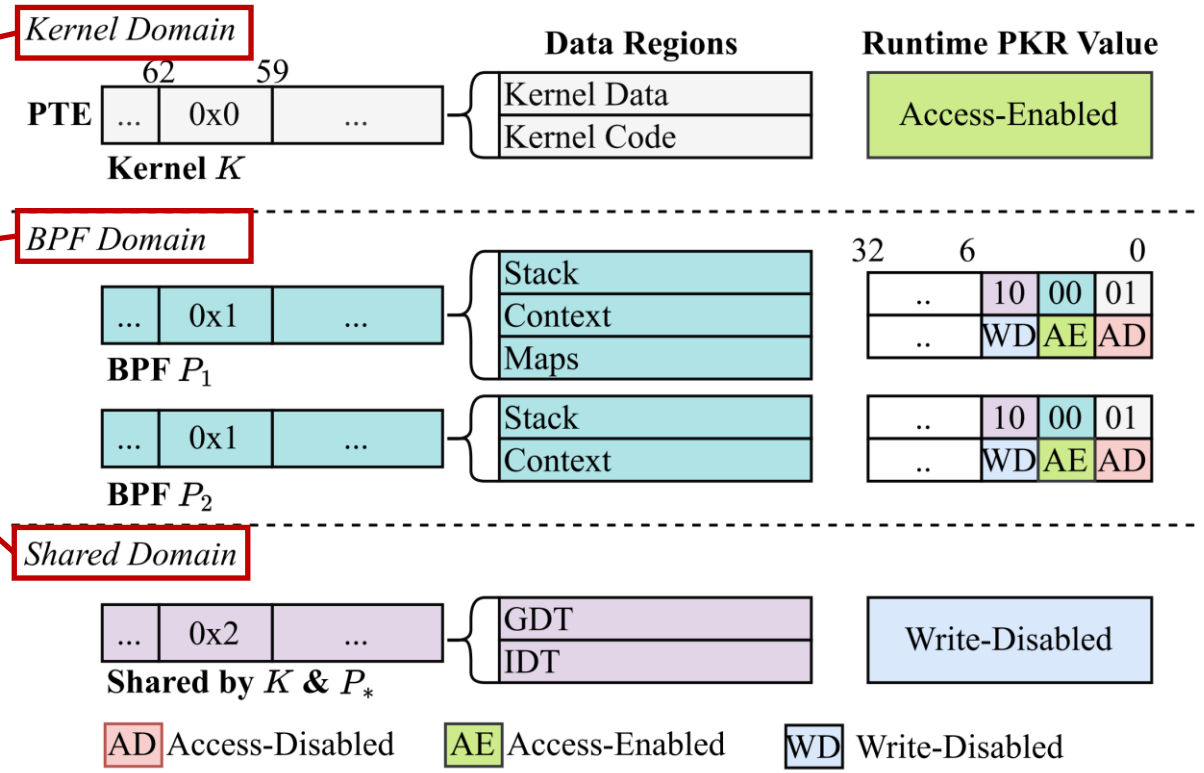
So… *bad* for multiple BPF programs.

But… *good* for isolating kernel/BPF.

Three Domain Three Tags



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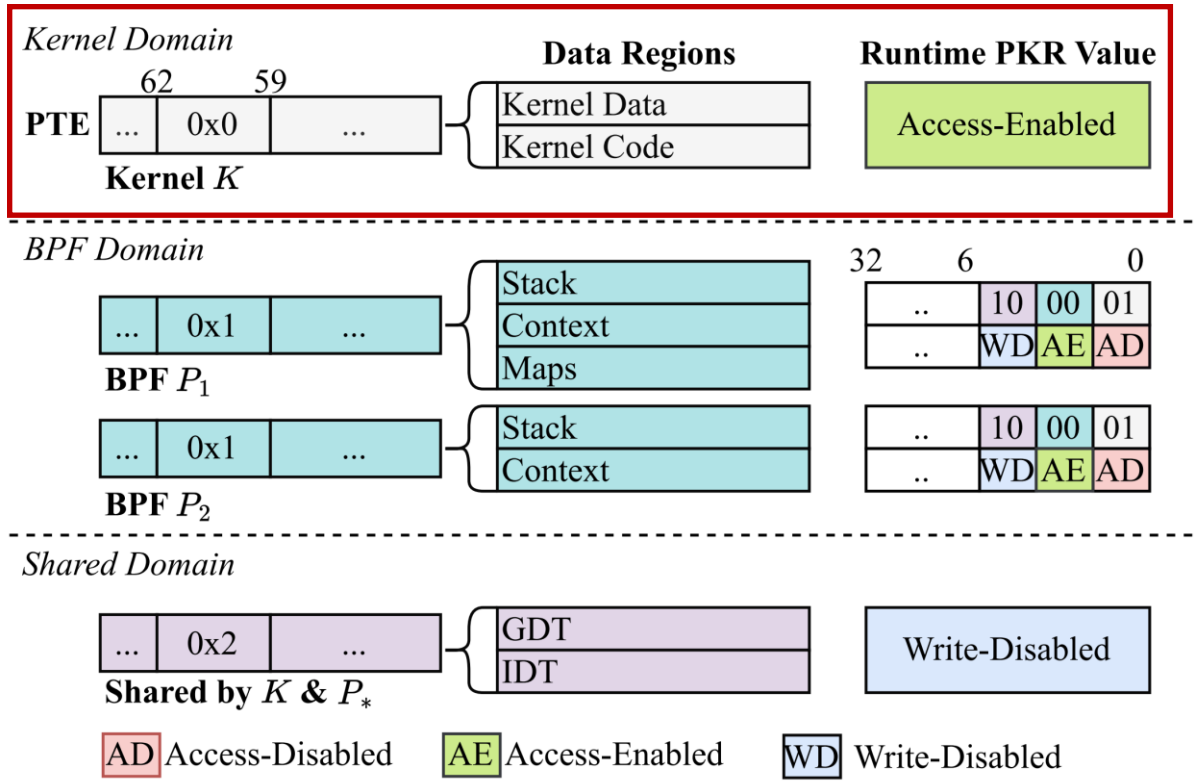
Kernel Stuff



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Constrain ALL BPF programs

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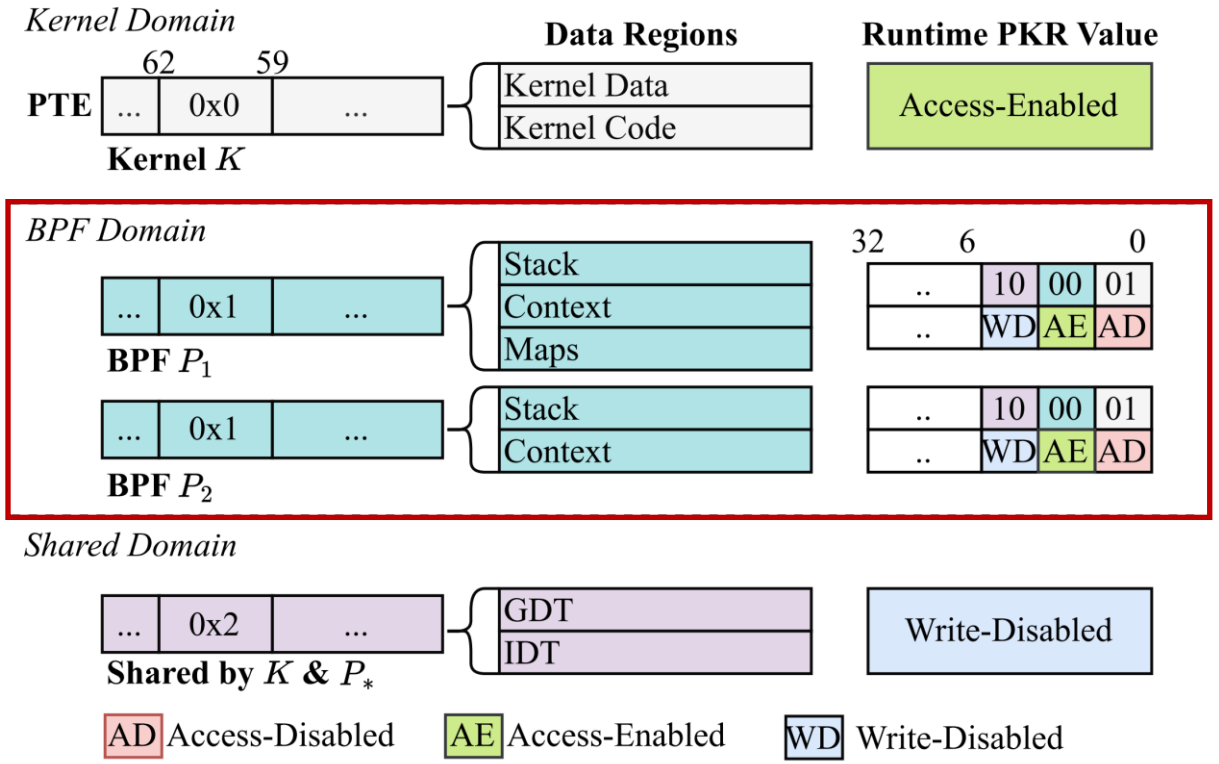

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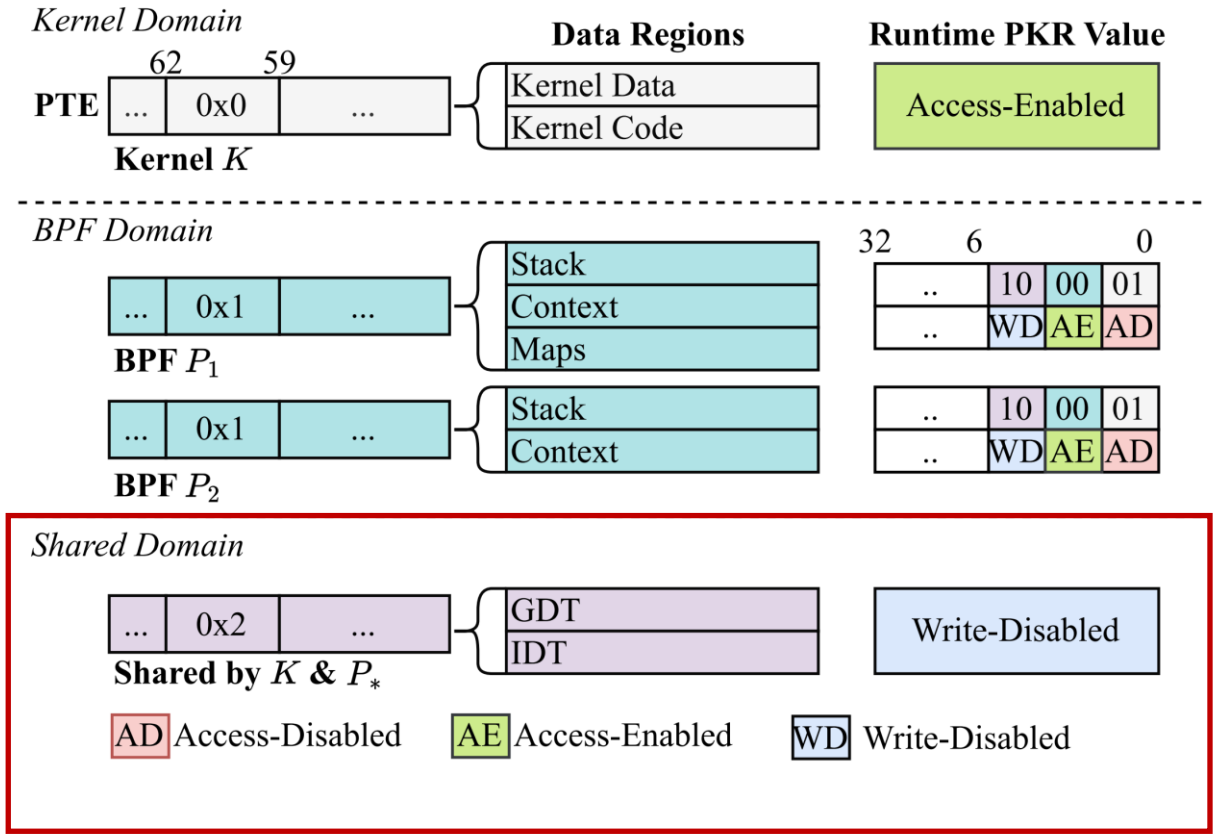
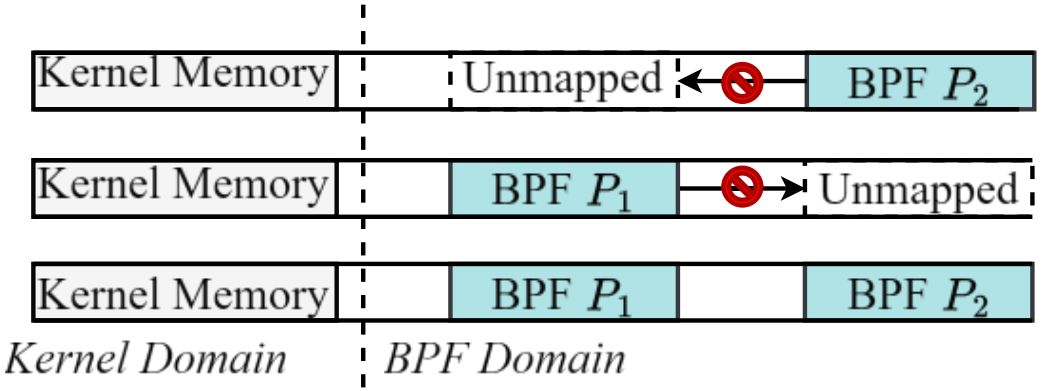


Things both BPF & Kernel need

Intra-BPF exploitation

Problem:

Bad BPFs attack the good ones.



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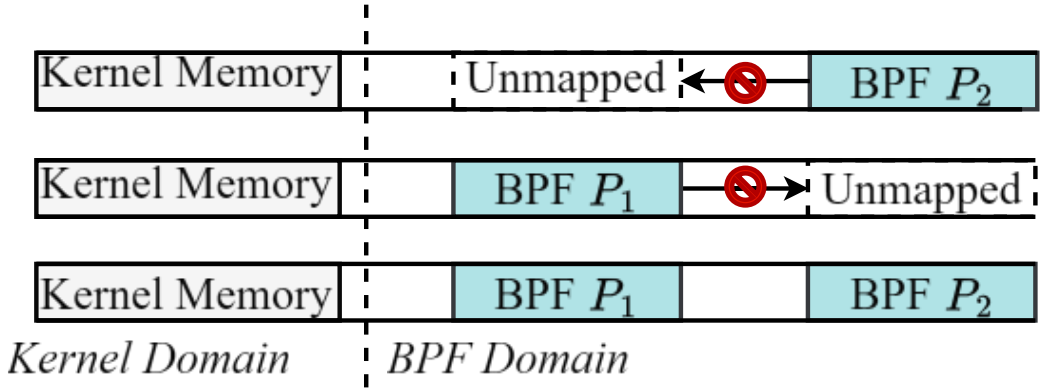

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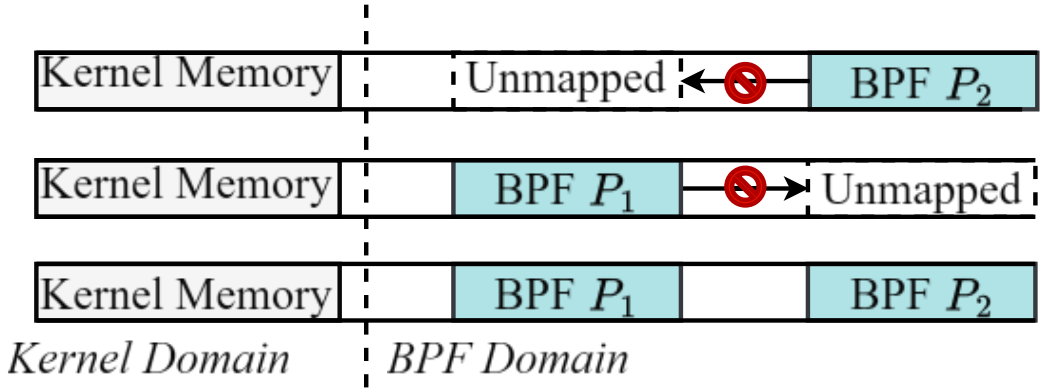
Issue: Slow TLB flushes



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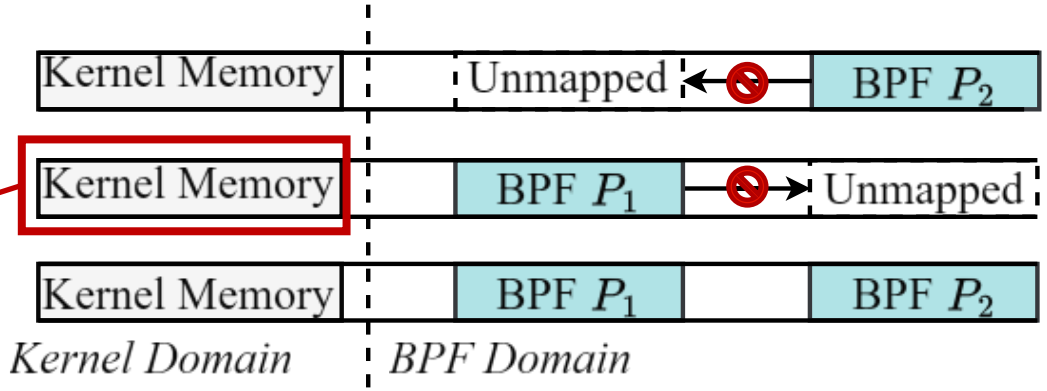


TLB flush is slow?

- **Constant kernel** mapping
- We use PCID to minimize #flushes.

Intra-BPF exploitation

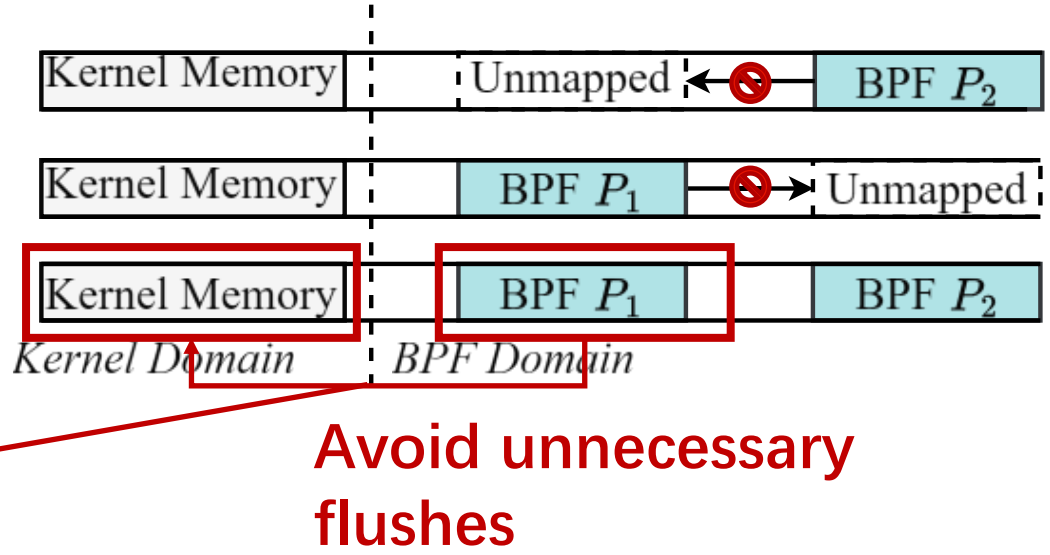
Problem:

Bad BPFs attack the good ones.

MOAT isolates them by address spaces.

TLB flush is slow?

- BPF has **small** memory footprints.
- We use **PCID** to minimize #flushes.



Kernel API Security

BPF is isolated, but it might still access kernel via its API (BPF Helpers)

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- Isolate **easy-to-exploit** structures from helpers.

Kernel API Security

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MOAT does...

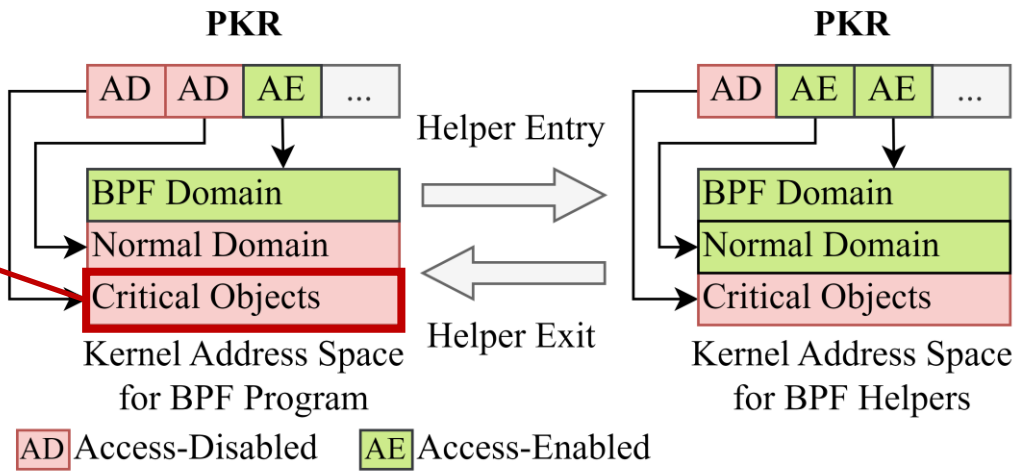
- Isolate **easy-to-exploit** structures from helpers.
- Check parameters against **verified bounds**.

Critical Object Protection

We studied kernel objects that were **previously exploited** via BPF.

In sum, **44** of these are identified;

MOAT protects them with an extra MPK tag.



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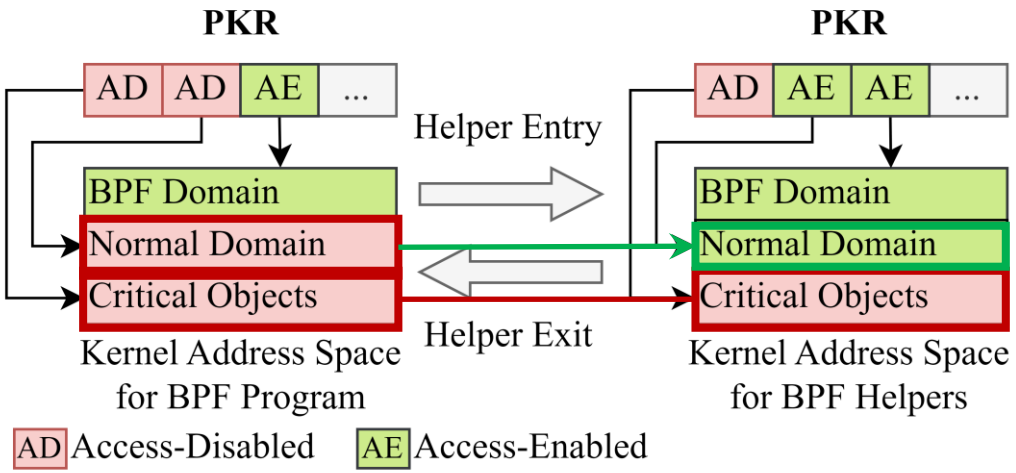
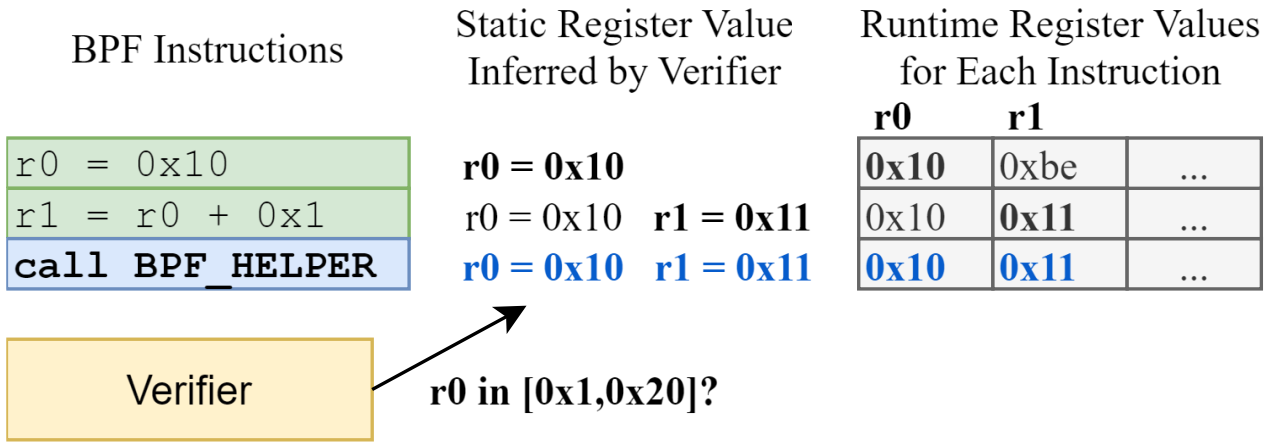


Dynamic Parameter Auditing

MOAT uses the verifier's bounds to double-check the helper's arguments.

Why verifier is **trustworthy** now?



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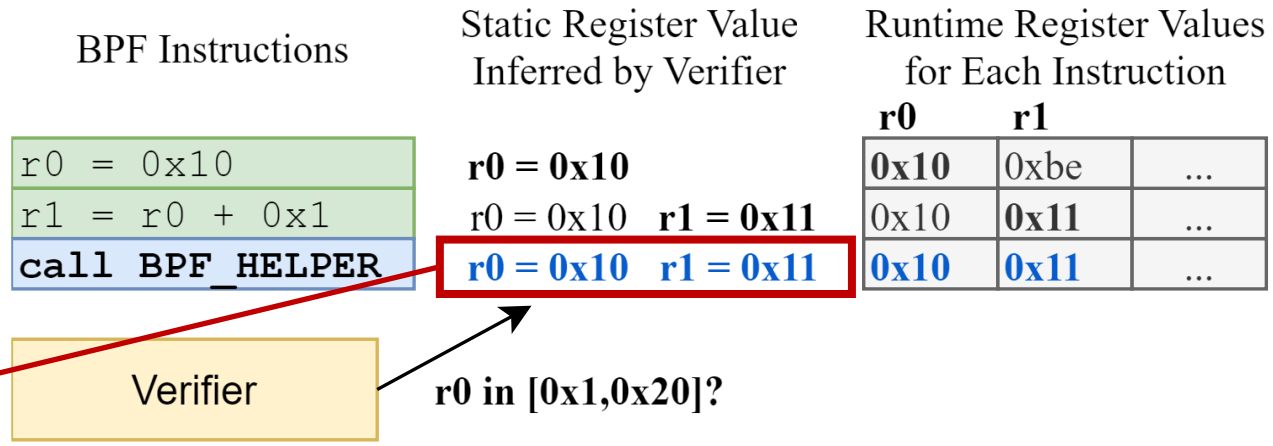

Dynamic Parameter Auditing

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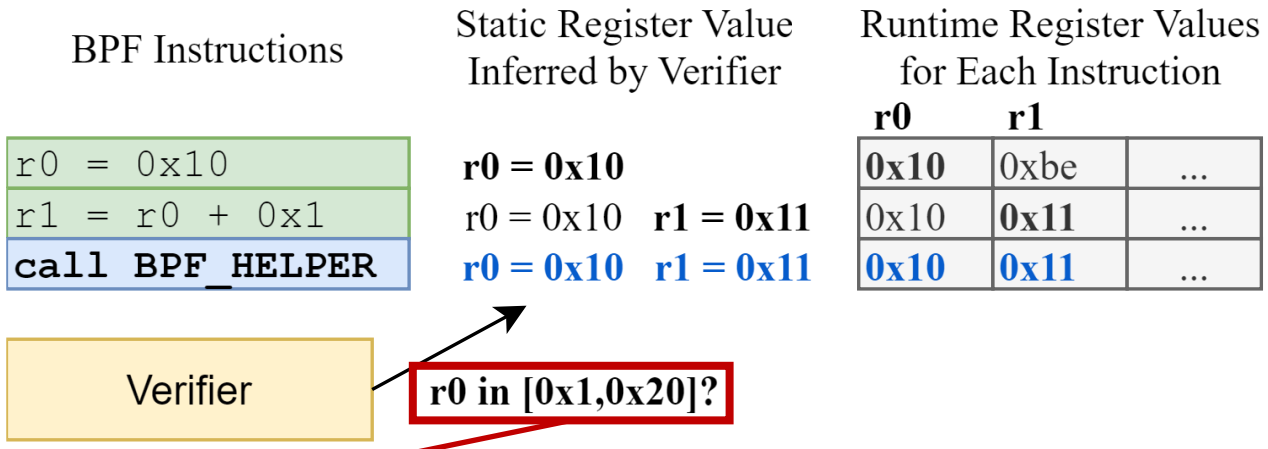
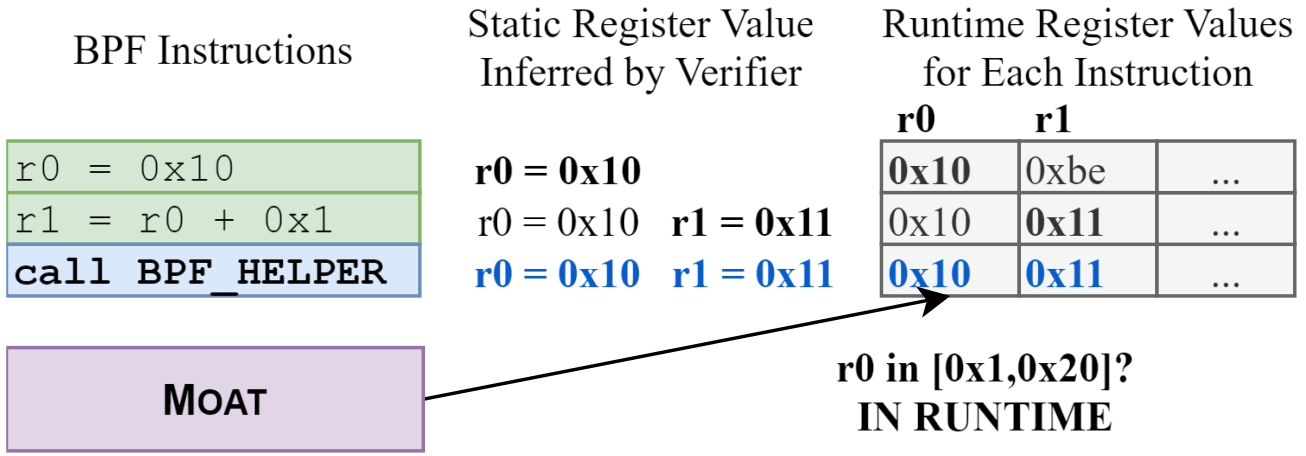
Why verifier is **trustworthy** now?

- *Bad* deduced values.
- ***Good*** bounds for helpers.



Dynamic Parameter Auditing

MOAT uses the verifier's bounds to double-check the helper's arguments **in runtime**.



Evaluation

Security Evaluation

We verified that MOAT mitigates all **26** BPF CVEs within MOAT's scope

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Security Evaluation

Now, let's go through one in detail.

- L3: verifier deduces `r5`

```
1 r5 = <bad addr>
2 r6 = 0x600000002
3 if (r5>=r6||r5<=0) // R&V:0x1<=r5<=0x600000001
4   exit(1)
5 r5 = r5 | 0        // R:r5=<bad addr> V: r5=0x1
6 *(ptr+r5)=0xbad    // PKS violation
```

R: Runtime Value V: Verifier Deduced Value

Security Evaluation

We verified that MOAT mitigates all **26** memory-related BPF CVEs

- L5: `OR32` performed a wrong truncation
- `r5` is mis-deduced to 0x1

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3 if (r5>=r6||r5<=0) // R&V:0x1<=r5<=0x600000001
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- MOAT saves the day!

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Performance Evaluation

In sum…

- **Network filtering: <2%.**
- System profiling: **<13%**.
- Seccomp (cBPF): **<3%**

Throughput (TPPS)	drop	byte	pkt	trim	flow	all
Baseline	594.39 (99.70%)	594.67 (99.73%)	594.26 (99.66%)	594.74 (99.73%)	594.39 (99.68%)	587.22 (98.47%)
MOAT	593.10 (99.46%)	594.31 (99.66%)	594.43 (99.68%)	594.69 (99.73%)	593.10 (99.46%)	575.33 (96.48%)

Throughput (TPPS)	xdp1	xdp2	adj	rxq1	rxq2
Baseline	560.58 (99.84%)	557.78 (99.34%)	531.11 (99.66%)	528.36 (99.15%)	530.52 (99.55%)
MOAT	560.15 (99.76%)	557.76 (99.33%)	530.65 (99.58%)	527.57 (99.00%)	527.66 (99.05%)

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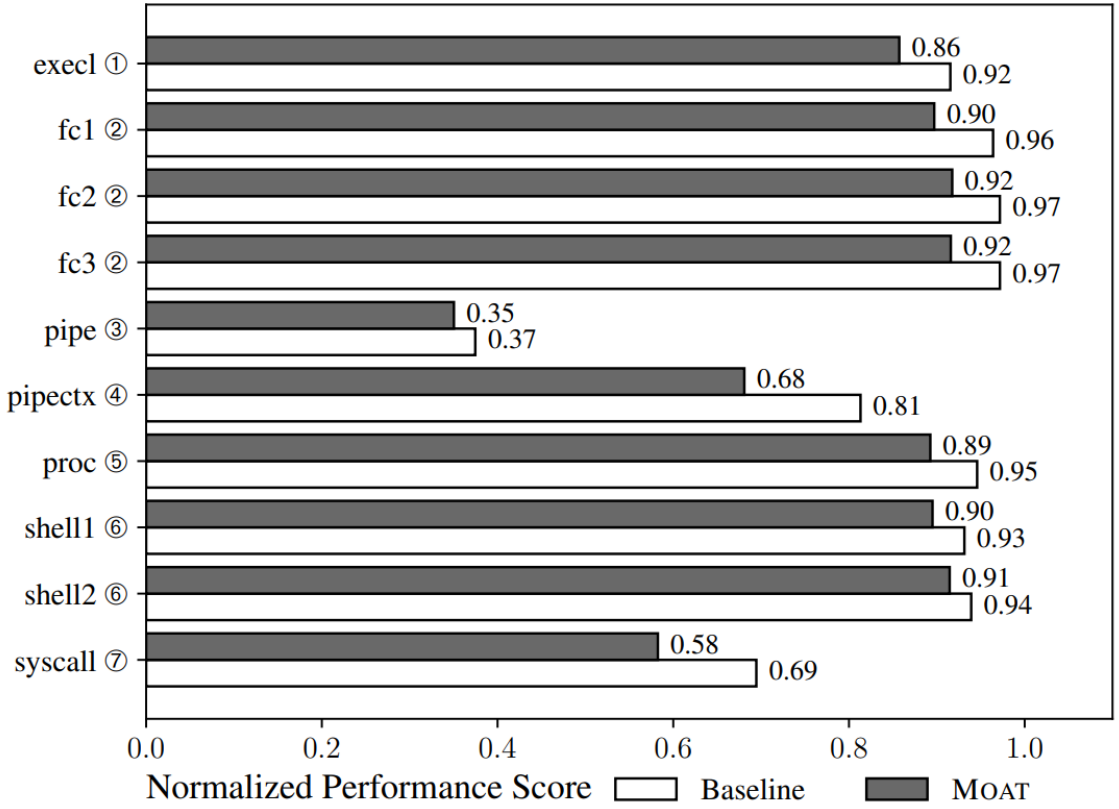

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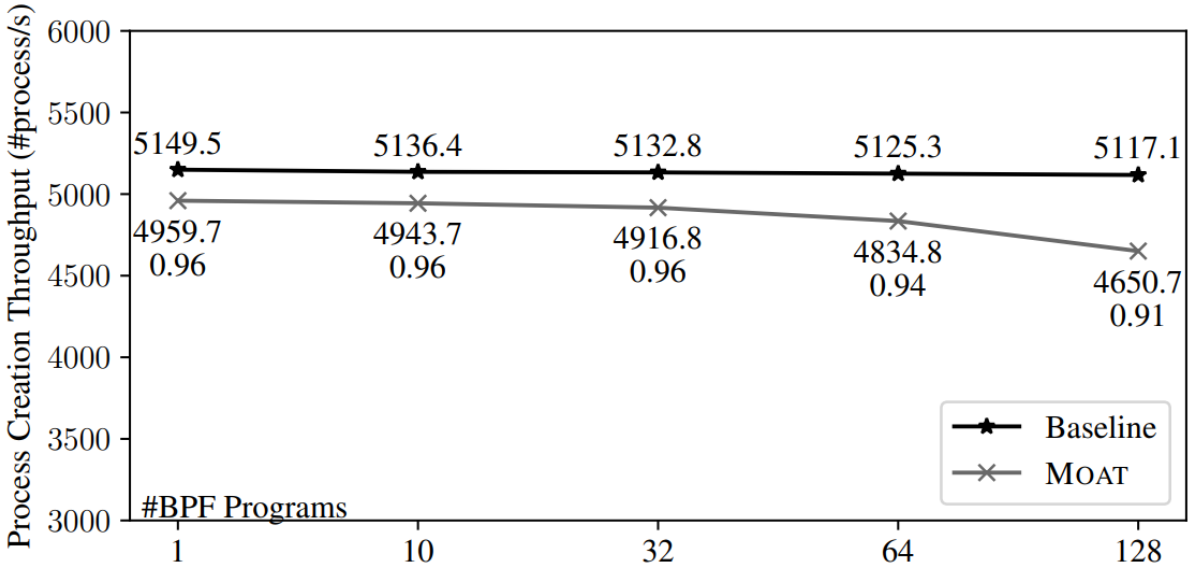
Throughout (Treq/s)	1 worker	2 worker	3 worker
Vanilla (no `seccomp-BPF`)	148.1 (100%) ±12.81	179.5 (100%) ± 8.35	165.2 (100%) ±4.72
Baseline	147.2 (99.4%) ±9.56	171.3 (95.4%) ±8.08	160.5 (97.2%) ±5.28
MOAT	142.3 (96.1%) ±8.77	166.3 (92.6%) ±6.70	158.0 (95.6%) ±4.48

Performance Evaluation

Comparing with SFI-based SandBPF

Test #Conn (req./s)	XDP				Socket Filter			
	Base	MOAT	Rel.	Ref.	Base	MOAT	Rel.	Ref.
Apache 20	34,303	33,689	2%	**0%**	40,666	40,286	**1%**	4%
Apache 100	31,929	30,726	**4%**	8%	37,998	36,546	**4%**	4%
Apache 200	27,751	26,657	**4%**	5%	32,652	31,344	4%	**3%**
Apache 500	24,786	24,439	**1%**	7%	30,262	29,423	**3%**	7%
Apache 1000	24,597	24,470	**1%**	6%	29,545	28,961	**2%**	7%
Nginx 20	22,688	21,892	**3%**	7%	23,359	23,530	**0%**	10%
Nginx 100	21,492	20,689	**4%**	7%	22,870	22,482	**2%**	8%
Nginx 200	19,972	19,216	**4%**	6%	21,562	20,984	**3%**	8%
Nginx 500	18,470	17,814	**4%**	6%	19,421	18,713	**4%**	7%
Nginx 1000	17,024	16,735	**2%**	3%	17,392	17,098	**2%**	6%

1->128 BPF programs at the same time



Takeaways.

- BPF is powerful but its **security** is a concern.
- BPF security can benefit from **hardware features**.
- MOAT protection is **multi-folded**.
  (Software + Hardware & Memory + API)

My Wife (Yuqi Qian) & Me (Hongyi Lu)

Thank You!

My Homepage

Email Me

Project Site