MOAT: Towards Safe BPF Kernel Extention

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Background

What is (e)BPF?

Extended Berkeley Packet Filter:

- Kernel Virtual Machine
- Introduced in Linux 3.15 (2014)

- Extended from classic BPF (cBPF), which dates back to FreeBSD (1992)
- Packet Filter → Tracing/Network/Security…

Why eBPF?

- **Fast**: Run in JITed native code.
- **Portable**: Stable kernel API (named helpers).

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

Sounds good, but?

BPF Security is a concern.

BPF verifier alone is NOT enough to ensure BPF's security.

And…

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

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

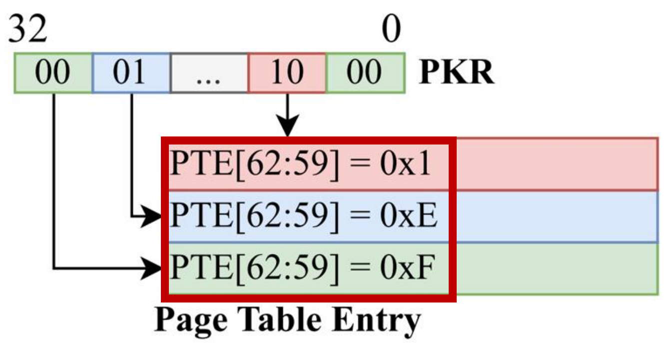
Hardware Isolation!

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?

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



PKR Entry Options	
00	Access Enabled (AE)
01	Access Disabled (AD)
10	Write Disabled (WD)
11	Access Disabled (AD)

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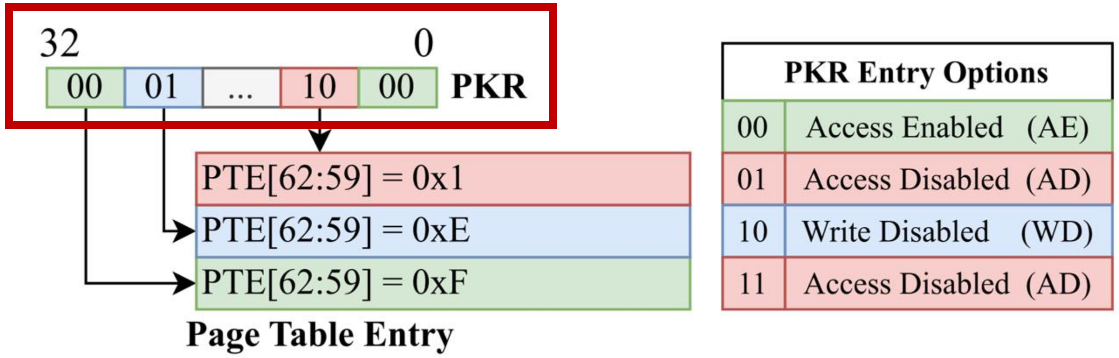


Method

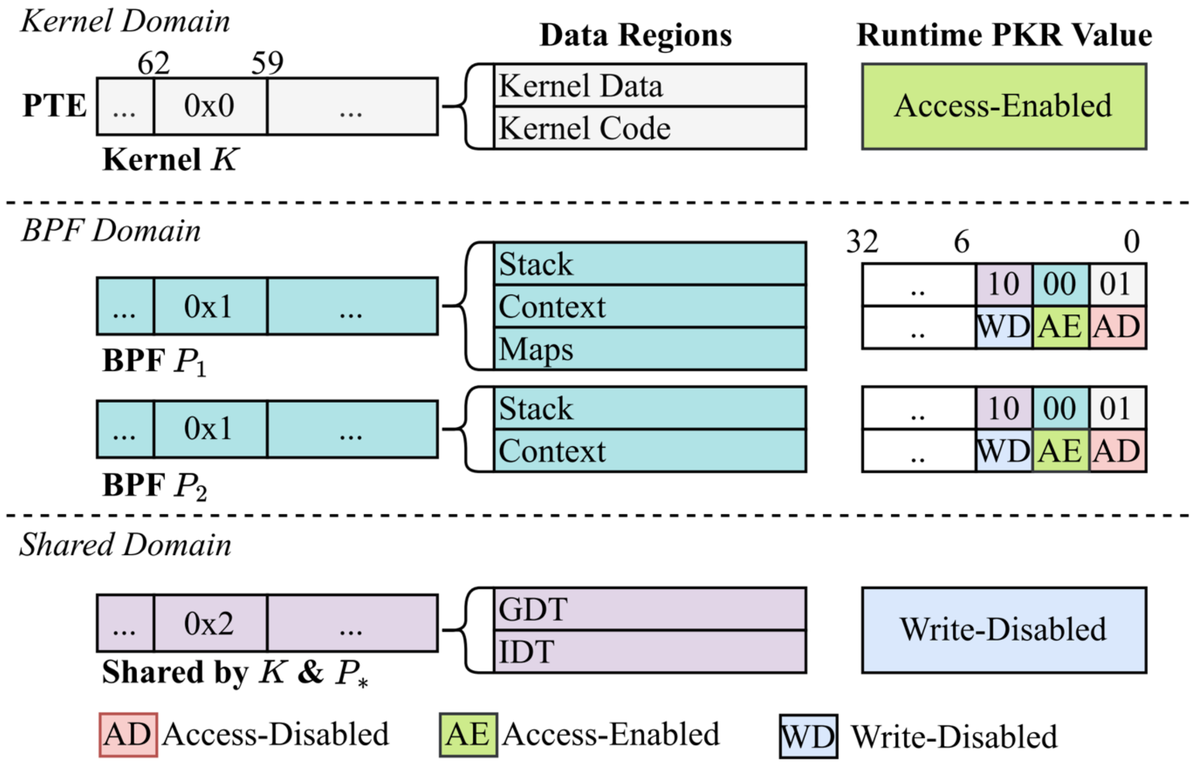
Limited MPK Tags

MPK is...

- Only 16 tags
- Lightweight

So... *bad* for multiple BPF programs.

But... *good* for isolating kernel/BPF.



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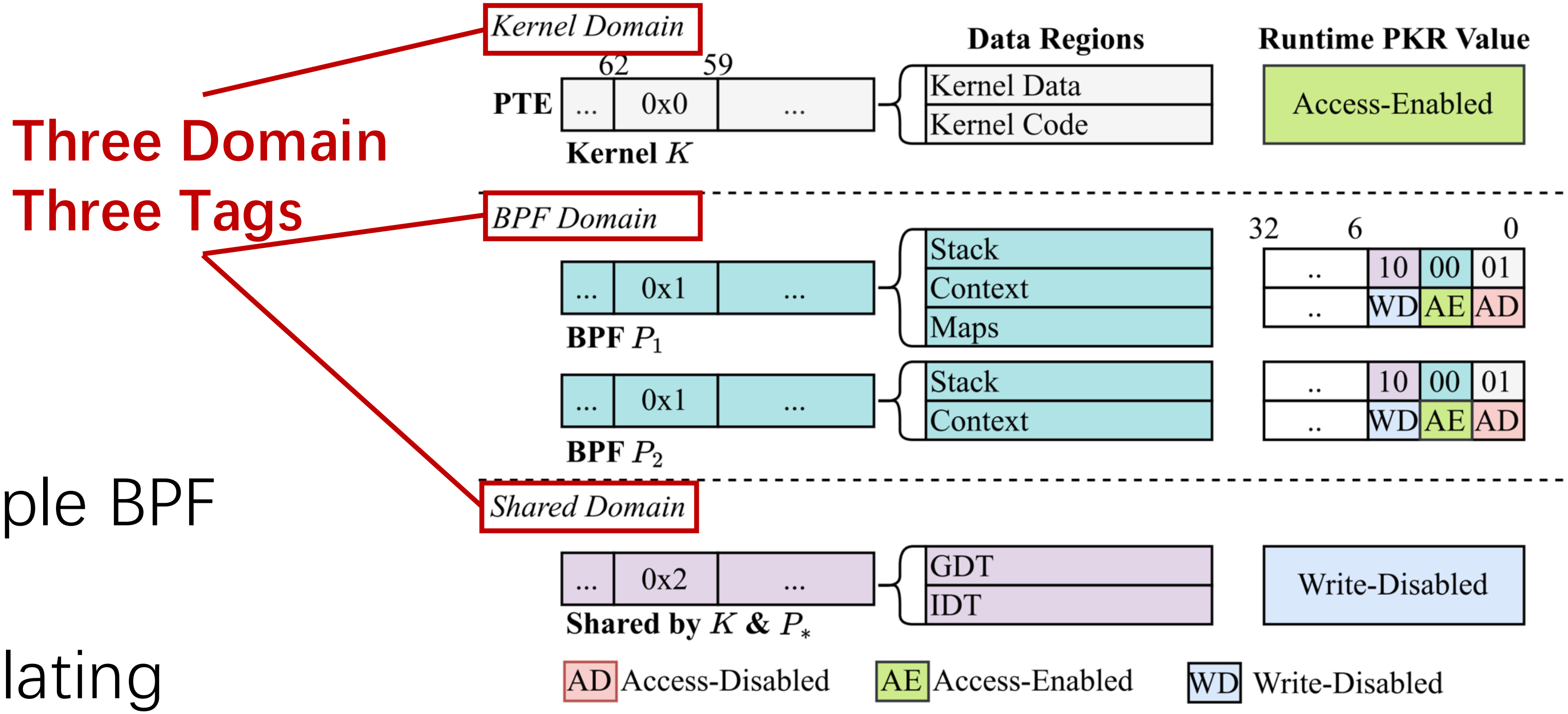

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Constrain ALL BPF programs

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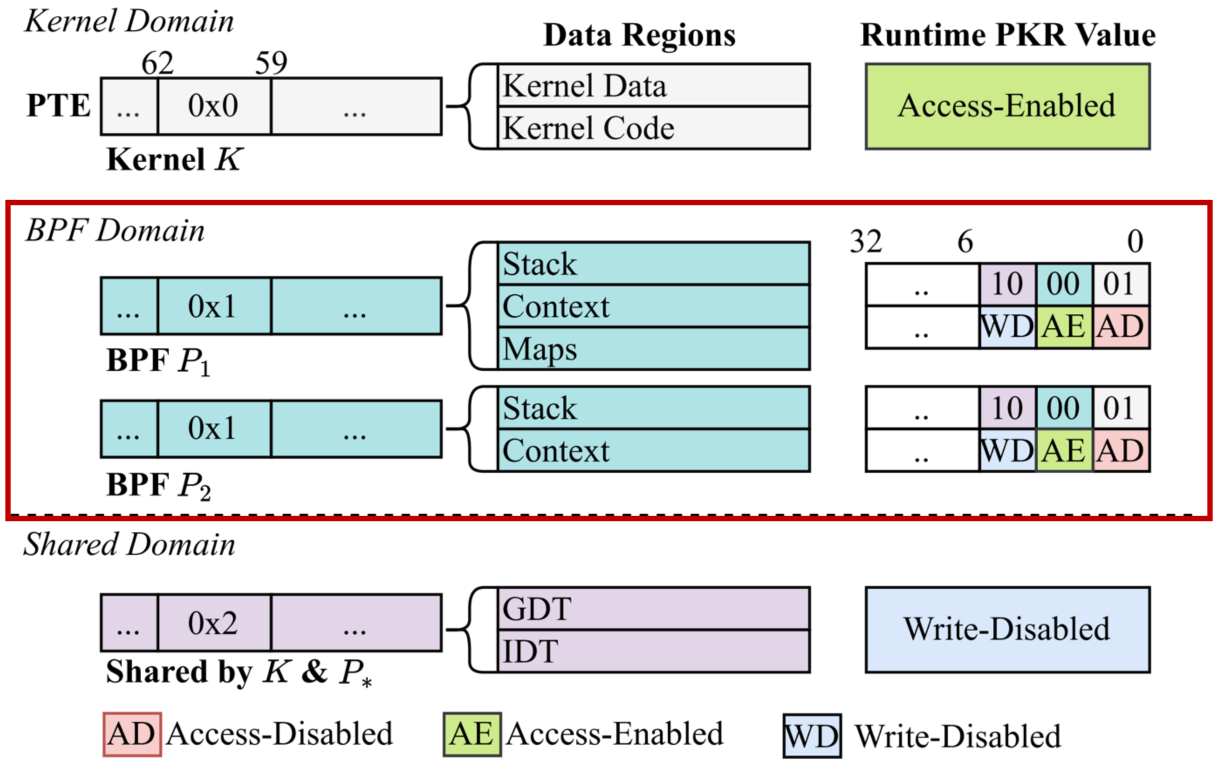

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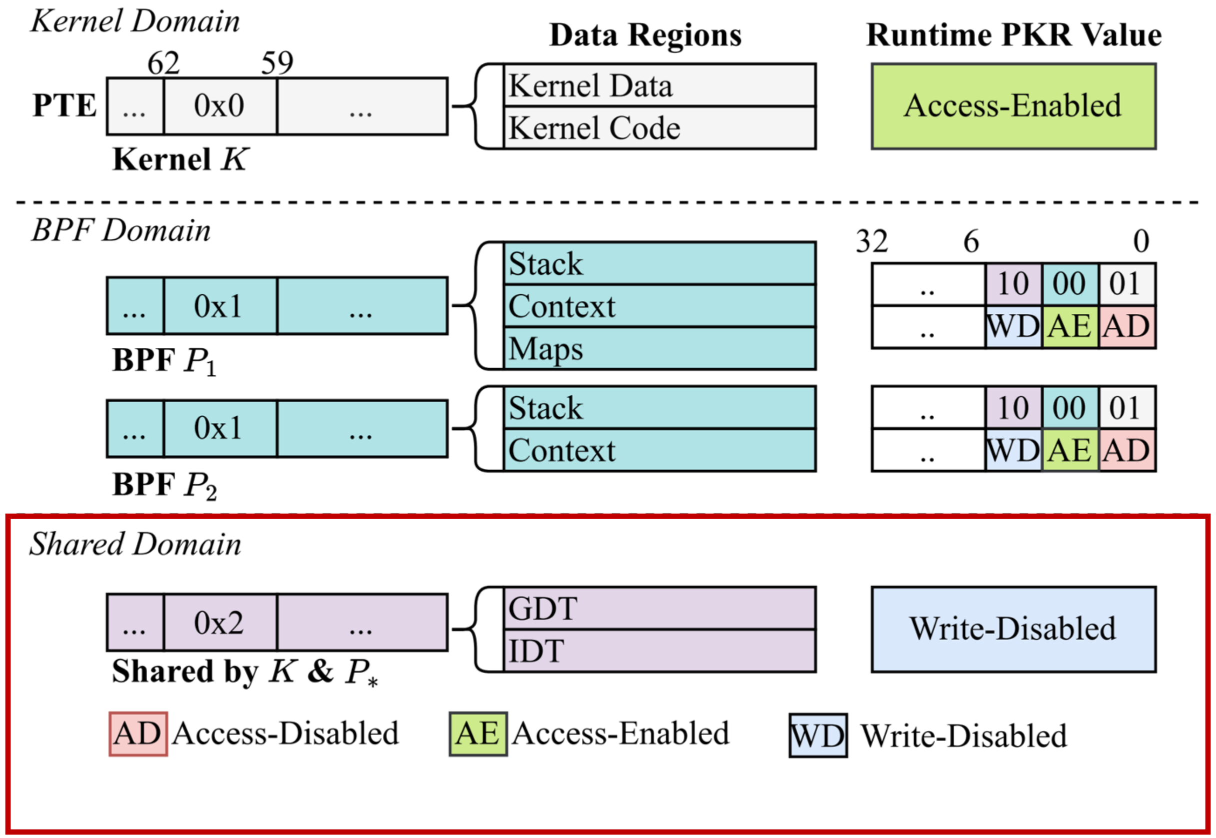


Things both BPF & Kernel need

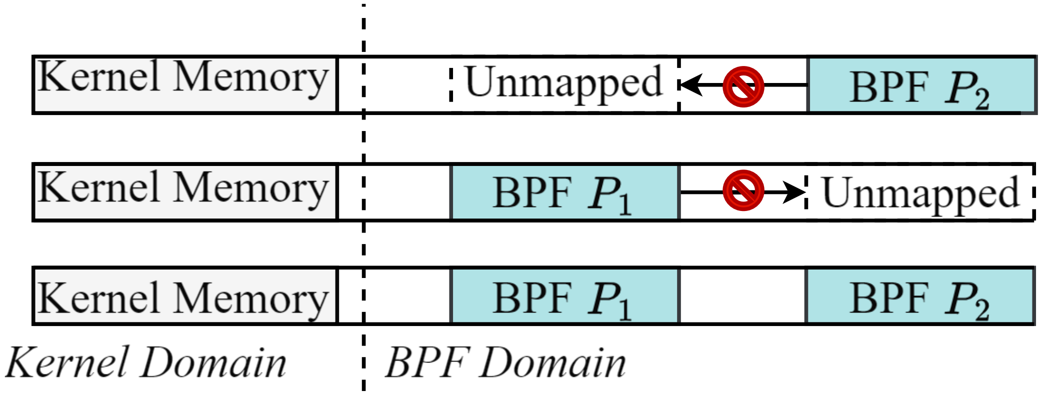
Intra-BPF exploitation

Problem:

Bad BPFs attack the good ones.

MOAT isolates them by address spaces.

TLB flush is slow?



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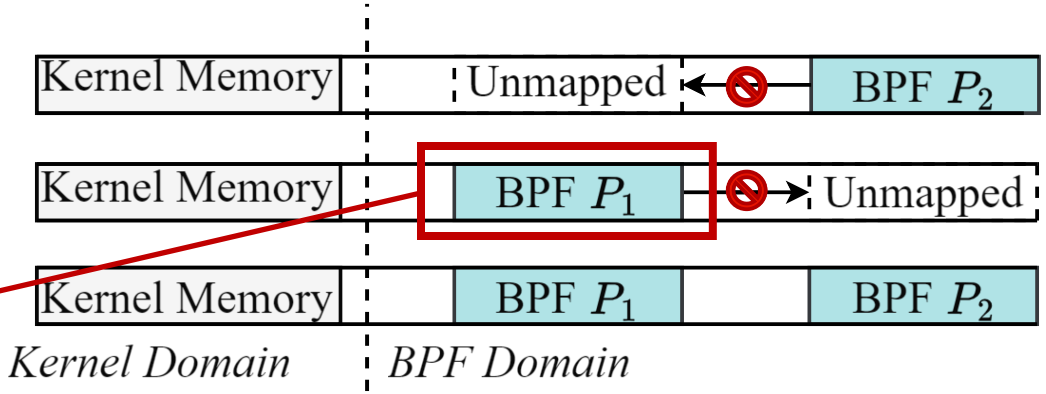
- BPF has **small** memory footprints.
- We use PCID to minimize #flushes.



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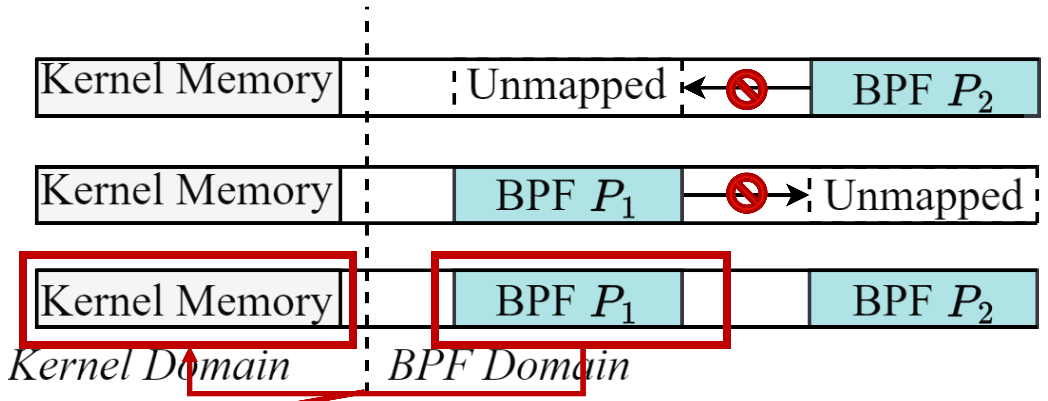


Avoid unnecessary flushes

Kernel API Security

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

MOAT does…

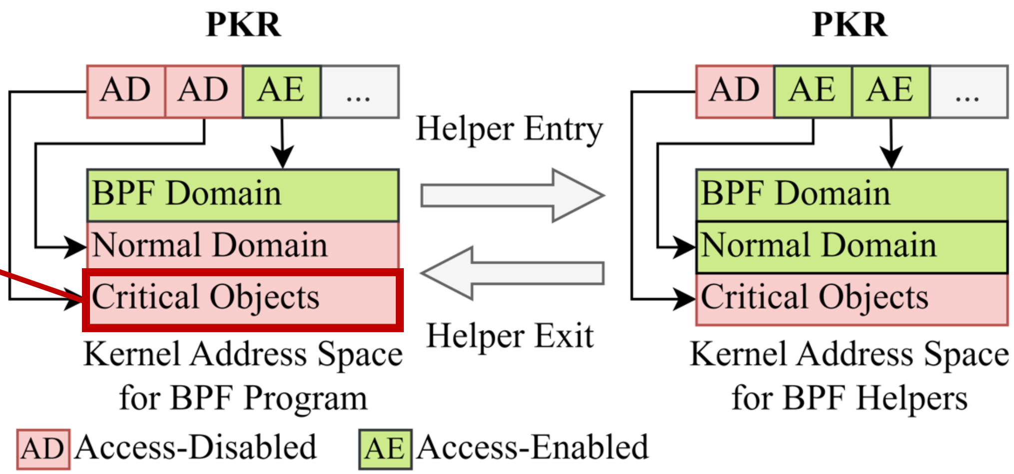
- Isolate **easy-to-exploit** structures from helpers.
- Check parameters against **verified bounds**.

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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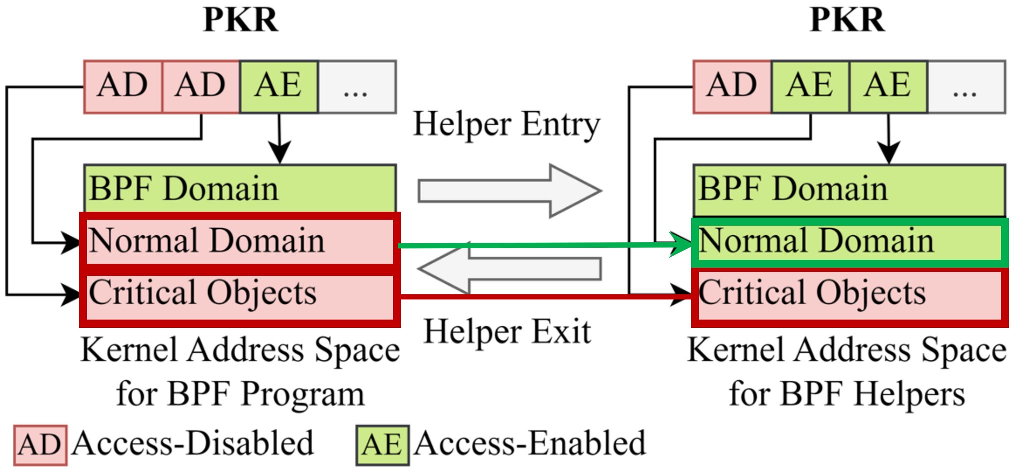

Dynamic Parameter Auditing

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

BPF Instructions	Static Register Value Inferred by Verifier	Runtime Register Values for Each Instruction: r0	r1	
`r0 = 0x10`	**r0 = 0x10**	**0x10**	0xbe	...
`r1 = r0 + 0x1`	r0 = 0x10 **r1 = 0x11**	0x10	**0x11**	...
`call BPF_HELPER`	**r0 = 0x10 r1 = 0x11**	**0x10**	**0x11**	...

Why verifier is trustworthy now?

- *Bad* deduced values $\boldsymbol{D}$.
- *Good* bounds $\boldsymbol{E}$ for helpers.

- $\boldsymbol{E}$ never deviates from ground truth $\boldsymbol{T}$ in practice.

	R	D	E	T	**State**
1	0x10	0x10	[0,0x20]	[0,0x20]	✓
2	**0xba**	0xba	[0,0x20]	[0,0x20]	$✓_V$
3	**0xba**	**0x10**	[0,0x20]	[0,0x20]	$✓_M$
4	**0xba**	**0xba**	**[0,0xba]**	[0,0x20]	✗

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r0 = 0x10	**r1 = 0x11**

Static Register Value Inferred by Verifier

r0	r1	
0x10	0xbe	...
0x10	**0x11**	...
0x10	**0x11**	...

Runtime Register Values for Each Instruction

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Runtime Value

	R	D	E	T	**State**
1	`0x10`	`0x10`	`[0,0x20]`	`[0,0x20]`	✓
2	**`0xba`**	`0xba`	`[0,0x20]`	`[0,0x20]`	$✓_V$
3	**`0xba`**	**`0x10`**	`[0,0x20]`	`[0,0x20]`	$✓_M$
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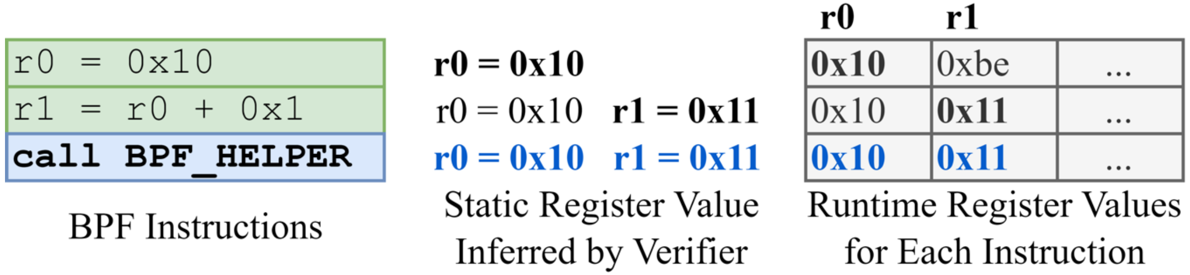

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Deduced Value

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Dynamic Parameter Auditing

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

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r0 = 0x10
r1 = r0 + 0x1
call BPF_HELPER
```

BPF Instructions

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r0 = 0x10 **r1 = 0x11**
r0 = 0x10 r1 = 0x11

Static Register Value Inferred by Verifier

r0	r1	
0x10	0xbe	...
0x10	**0x11**	...
0x10	**0x11**	...

Runtime Register Values for Each Instruction

Why verifier is trustworthy now?

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

- E never deviates from ground truth T in practice.

Expected Safe Value

	R	D	E	T	State
1	0x10	0x10	[0,0x20]	[0,0x20]	✓
2	**0xba**	0xba	[0,0x20]	[0,0x20]	$✓_V$
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Runtime Register Values for Each Instruction

Why verifier is trustworthy now?

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Truly Safe Value

	R	D	E	T	State
1	0x10	0x10	[0,0x20]	[0,0x20]	✓
2	**0xba**	0xba	[0,0x20]	[0,0x20]	$✓_V$
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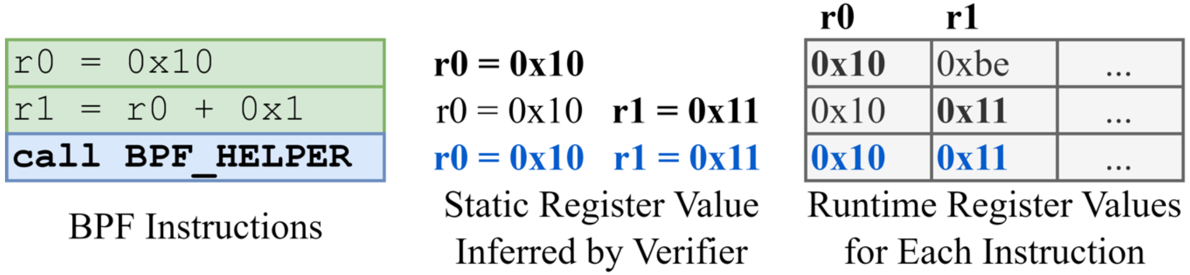

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- $\boldsymbol{E}$ never deviates from ground truth $\boldsymbol{T}$ in practice.

Evaluation

Security Evaluation

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

- 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
```

Security Evaluation

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

- L5: `MOD32` *forgets* to track upper bits
- `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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Security Evaluation

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- MOAT saves the day!

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r5 = <bad addr>
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  exit(1)
r5 = r5 | 0        // R:r5=<bad addr> V: r5=0x1
*(ptr+r5)=0xbad    // PKS violation
```

Performance Evaluation

In sum…

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

And many more…

- Numerous BPF programs…
- Comparison with SandBPF…
- Microbenchmark…

Takeaways.

- BPF is powerful but its **security** is a concern.

- BPF security can benefit from **hardware features**.

- Good protection is **multi-folded**.
  (Software + Hardware & Memory + API)

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

Thank You!

My Homepage

Email Me

Project Site