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Improving eBPF Complexity with a Hardware-backed Isolation Environment

Zhe Wang

$whoami

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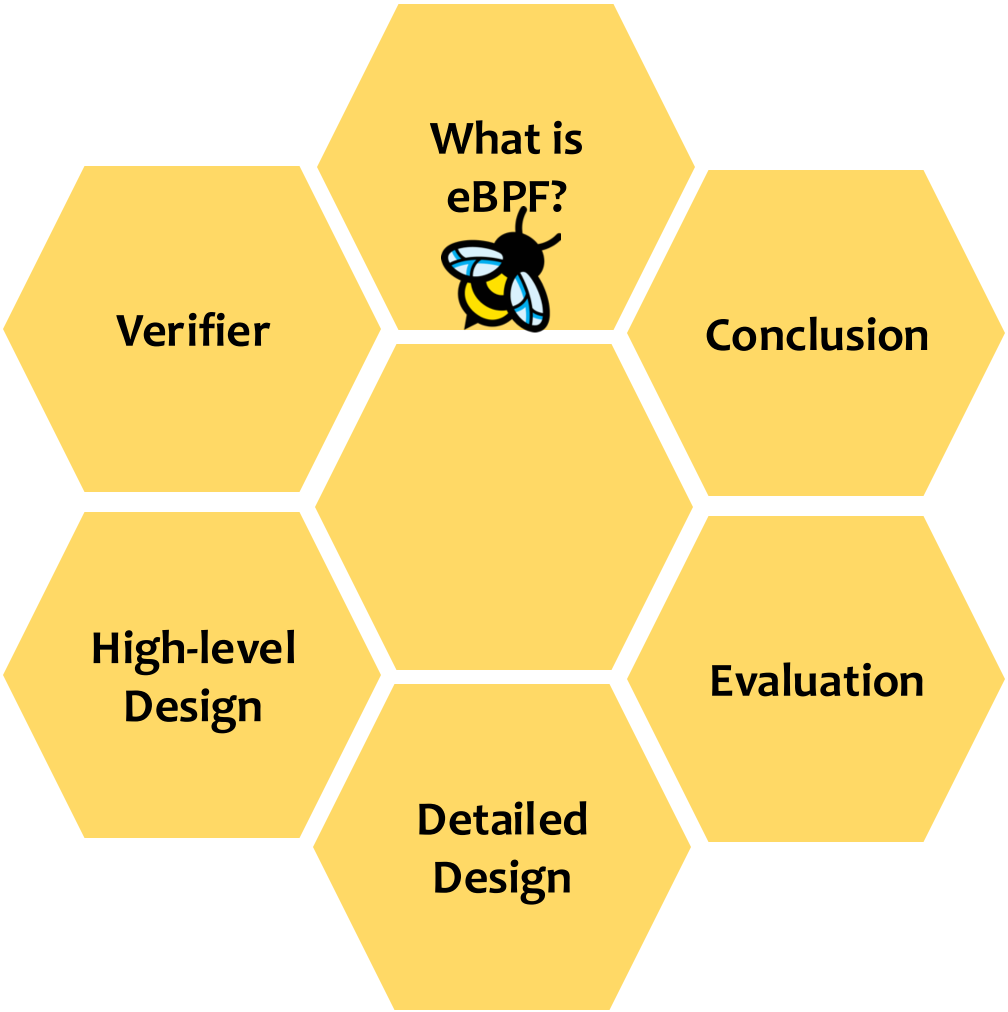
- **Research Interests**
  - System Security: Attacks & Defenses Techniques
  - Operating System, Compiler, System Virtualization, Computer Architecture.

- **Publications**
  - A lot of papers published in top conferences/journals in the fields of security and systems.
  - Including IEEE Security and Privacy (Oakland), USENIX Security, ACM CCS, and USENIX OSDI.

Outline

- What is eBPF?
- Verifier
- High-level Design
- Detailed Design
- Evaluation
- Conclusion

Outline


What is eBPF?
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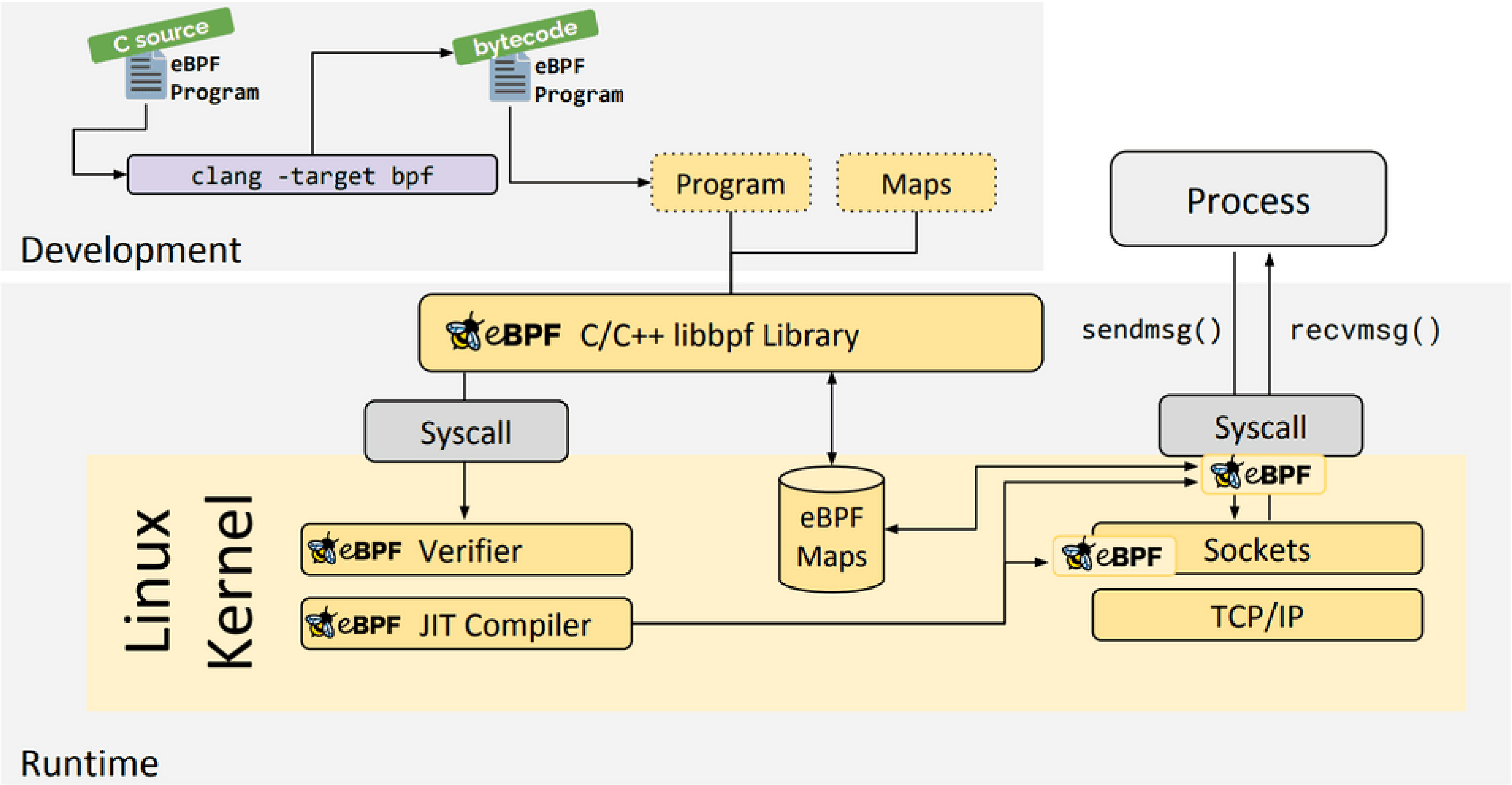
What is extended Berkeley Packet Filter (eBPF) ?

eBPF can be used to safely extend the kernel without requiring to change source code or load kernel modules.



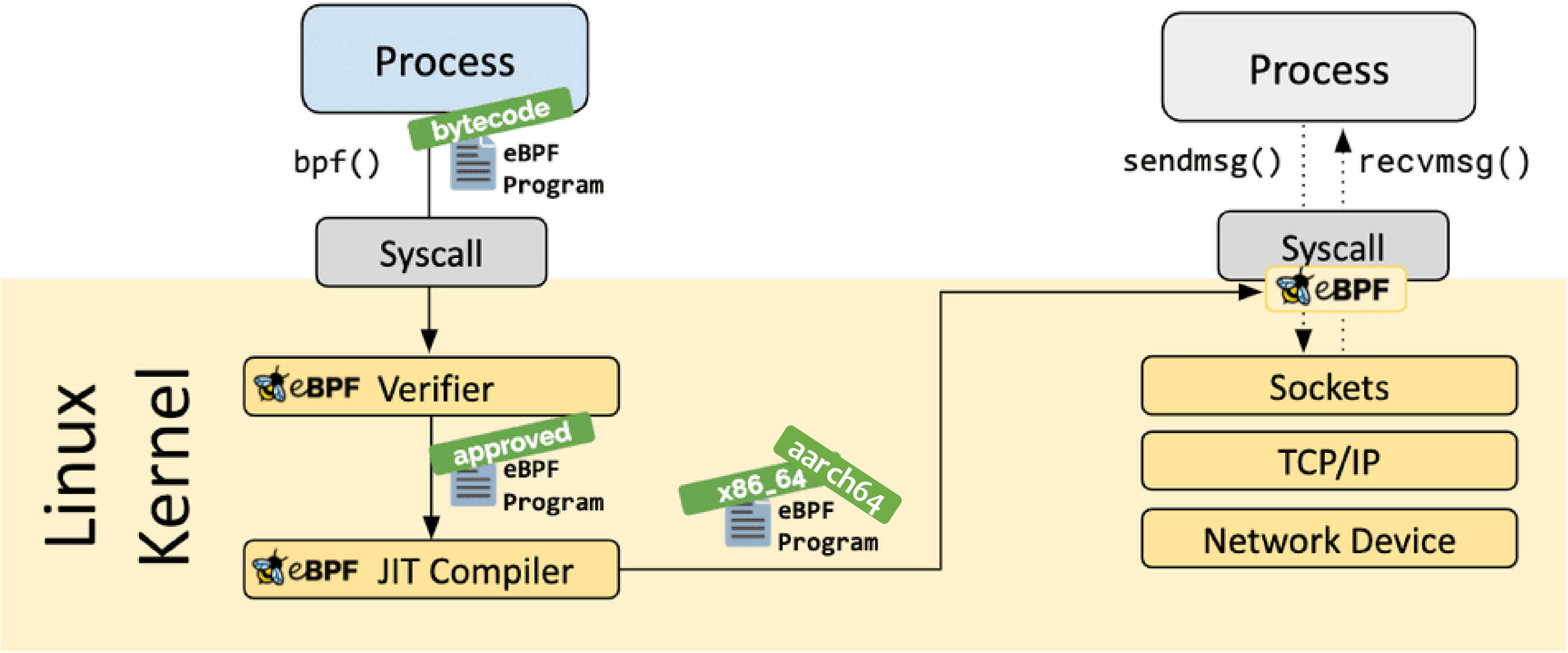
How could eBPF do?

- Security Controls
- Events Tracing
- Kernel Profiling
- Kernel Monitoring

……

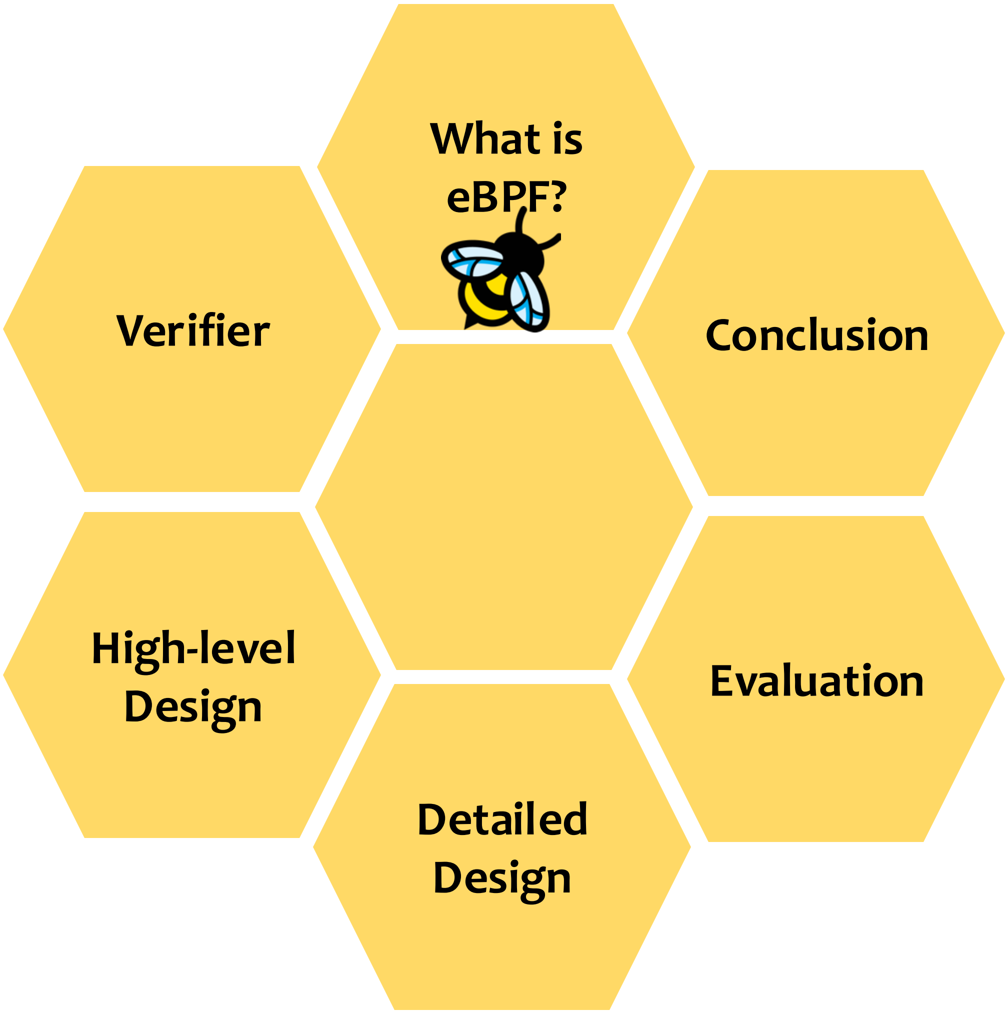
What is extended Berkeley Packet Filter (eBPF) ?

Kernel provides an execution environment for BPF programs.



- Registers (r0-r10)
- Program Context
- Maps (key-value)
- Helper Functions
- BPF (Kernel) Stack

Outline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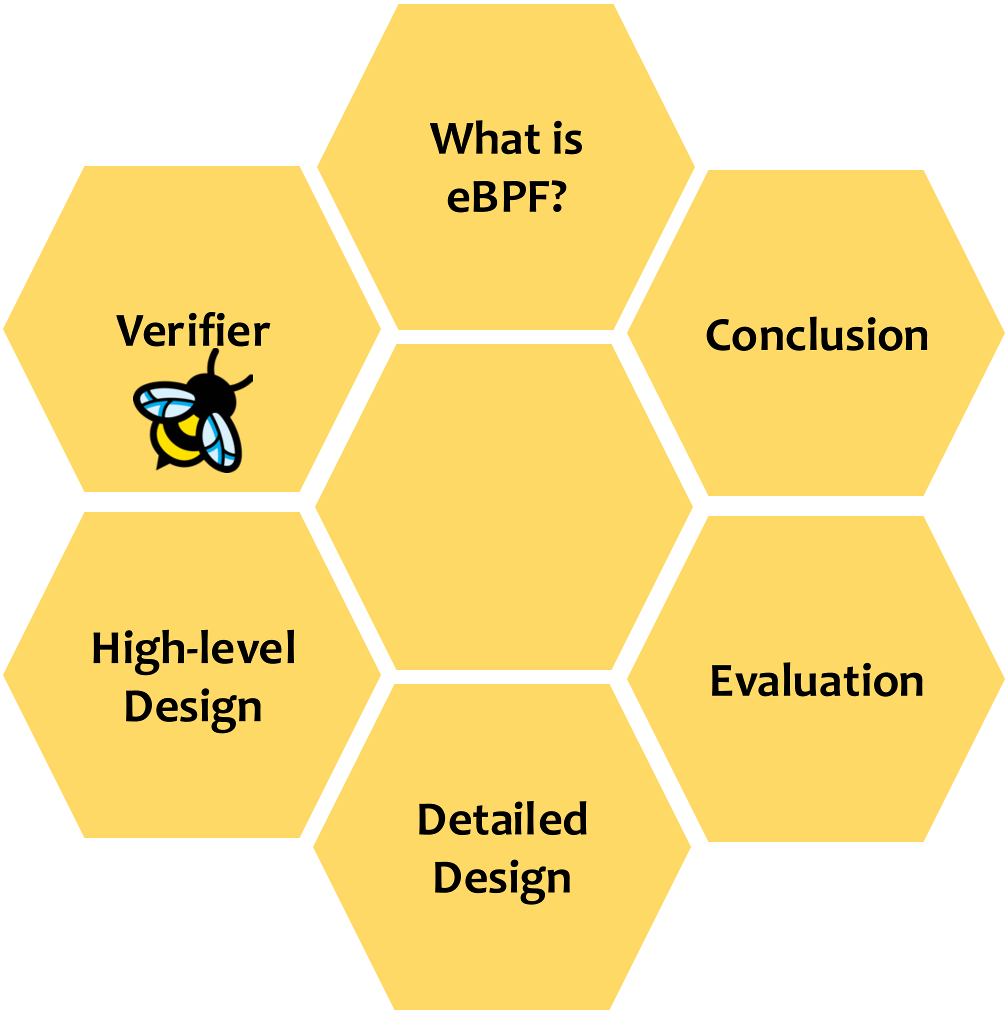
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Evaluation
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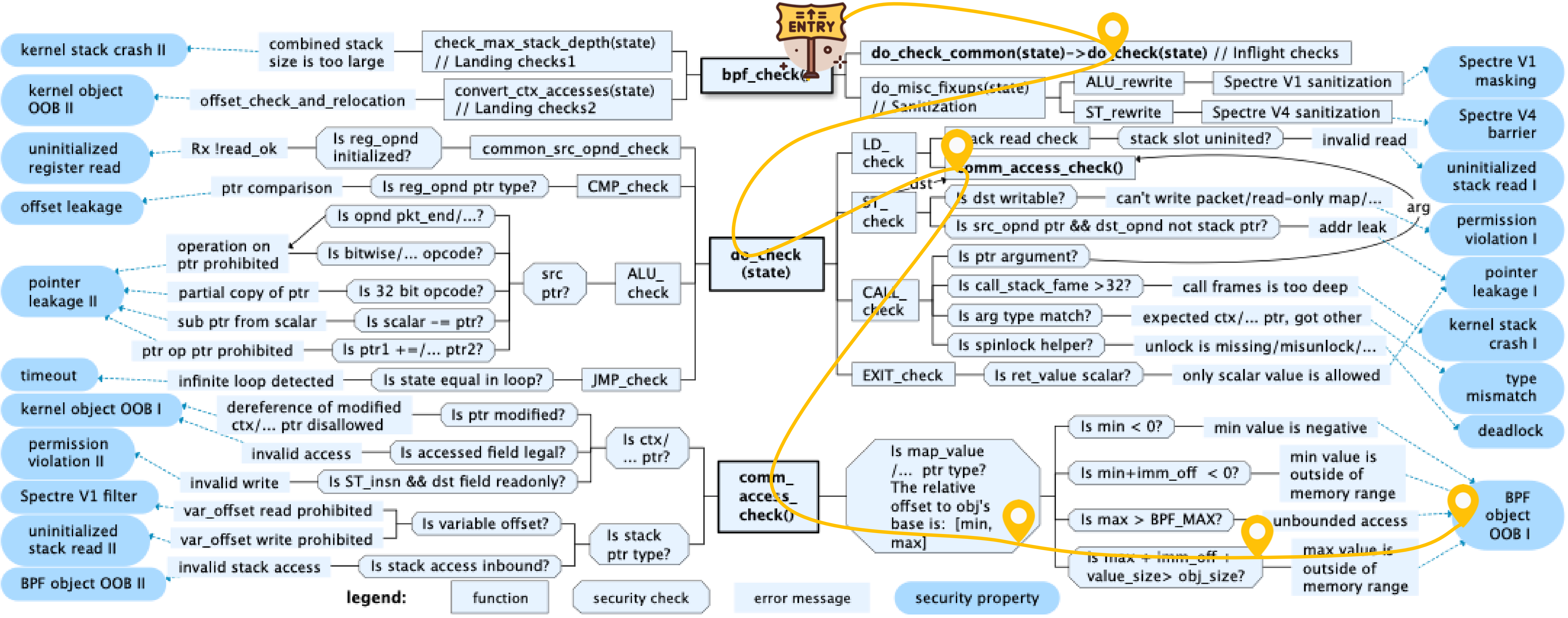
Security properties ensured in the verifier

We analyzed all (400+) security checks and summarized them into 20 security properties.



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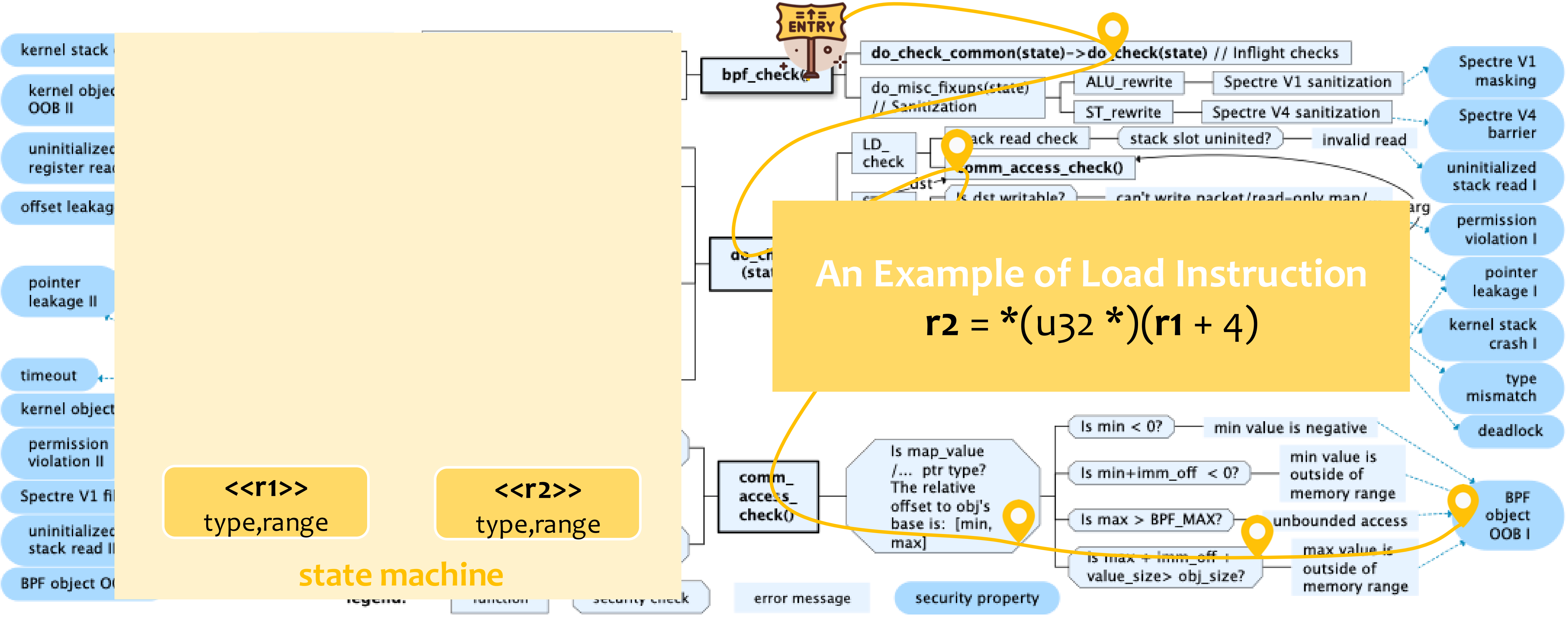

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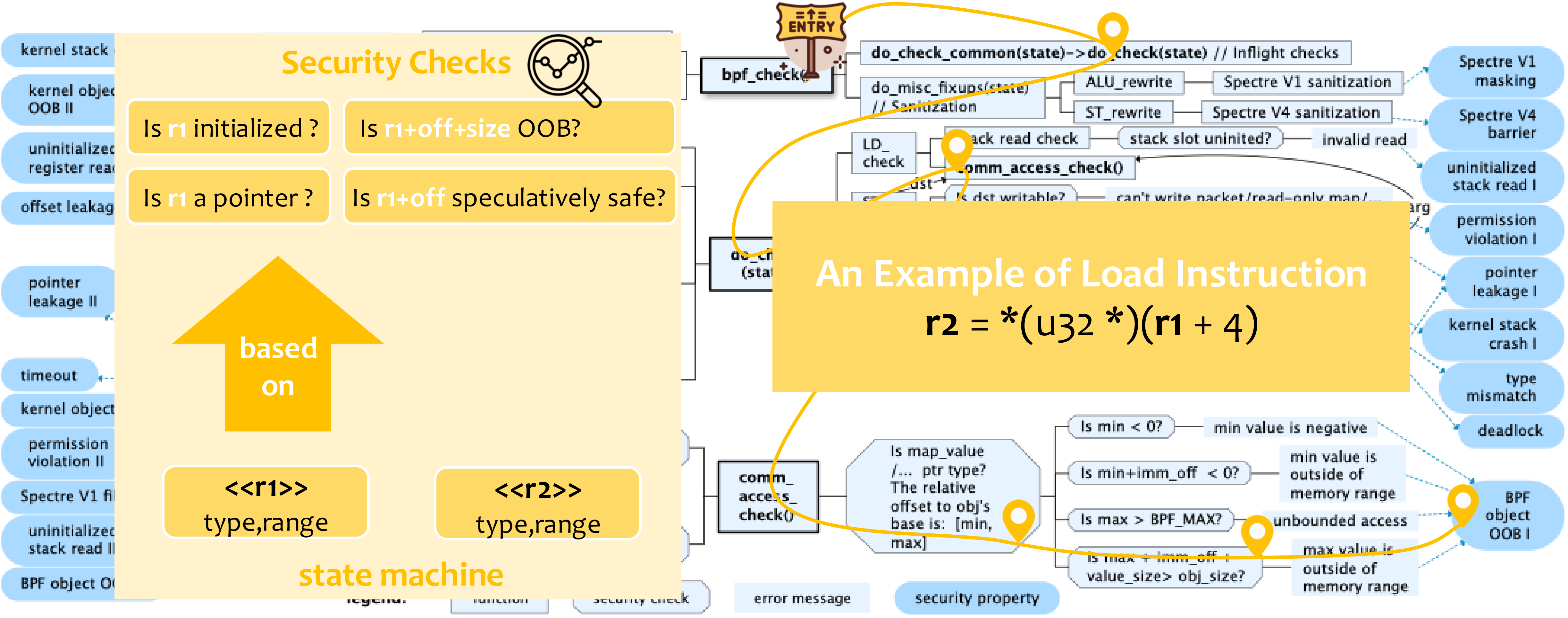

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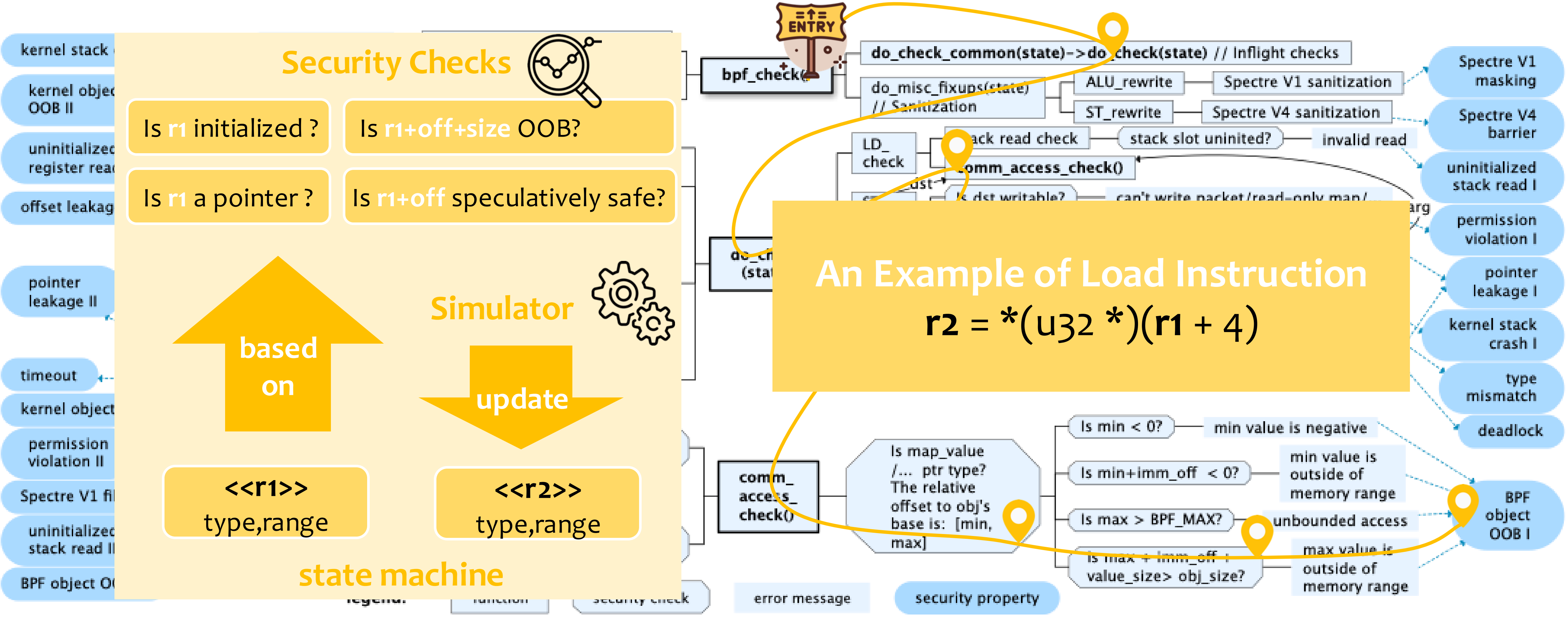


Security goals at design level

Integrity **Confidentiality** **Availability**

Three security goals: memory/type safety, information leakage prevention, and DoS prevention.

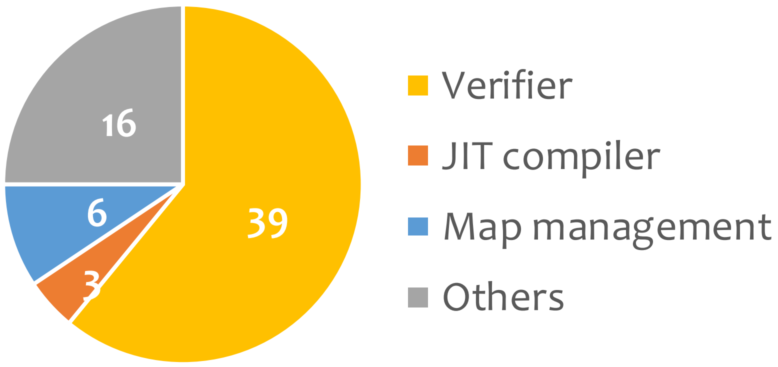
Security Goal	Description	Against Attacks	Corresponding Security Properties
SG-1: Memory/ Type Safety	Program can only access BPF memory, and specific kernel objects such as context.	OOB Access	BPF object OOB I/II, kernel object OOB I/II, permission violation I/II, *type mismatch*
SG-2: Information Leakage Prevention	Program cannot write pointers into maps, and calculation among pointers is not allowed.	Layout Leakage	pointer leakage I/II, offset leakage, *type mismatch*
	Program cannot read uninitialized information.	Uninitialized Read	uninit register read, uninit stack read I/II
	Program cannot speculatively access areas outside the BPF program's memory.	Spectre	Spectre V1 filter/masking, Spectre V4 barrier
SG-3: DoS Prevention	Program cannot execute for too long.	Denial-of-Service	time out, deadlock
	Program cannot crash while executing.	Crash Kernel	kernel stack crash I, kernel stack crash II

Dilemma of Static Analysis in Verifier

The verification-based method has become the bottleneck of eBPF.

Correctness dilemma:
unsafe programs can pass the verification

Capability dilemma:
complex programs can not pass the verification



Verifier contributes the most of CVEs

State Explosion

Outline

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Conclusion

High-level Design

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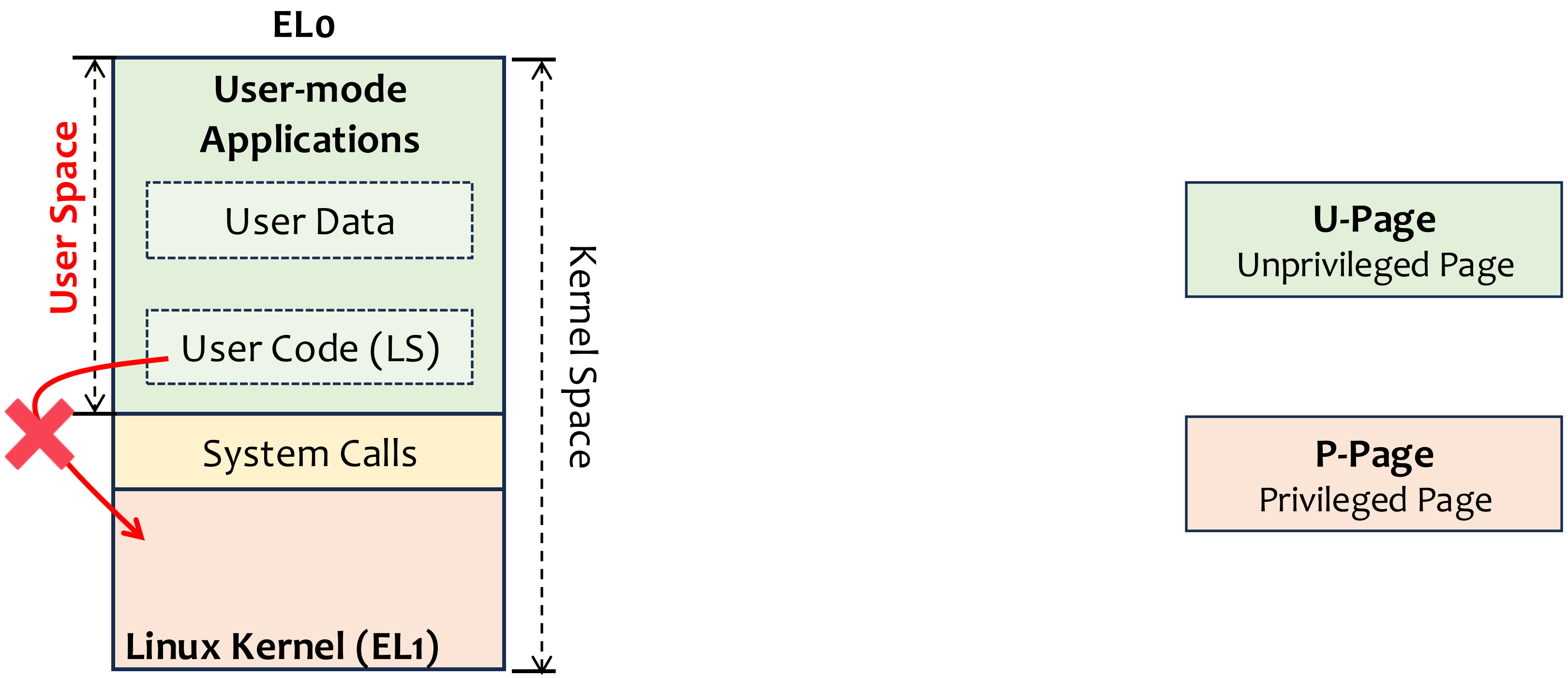
How does the kernel prevent threats from user programs?

ISOLATION not verification!!!

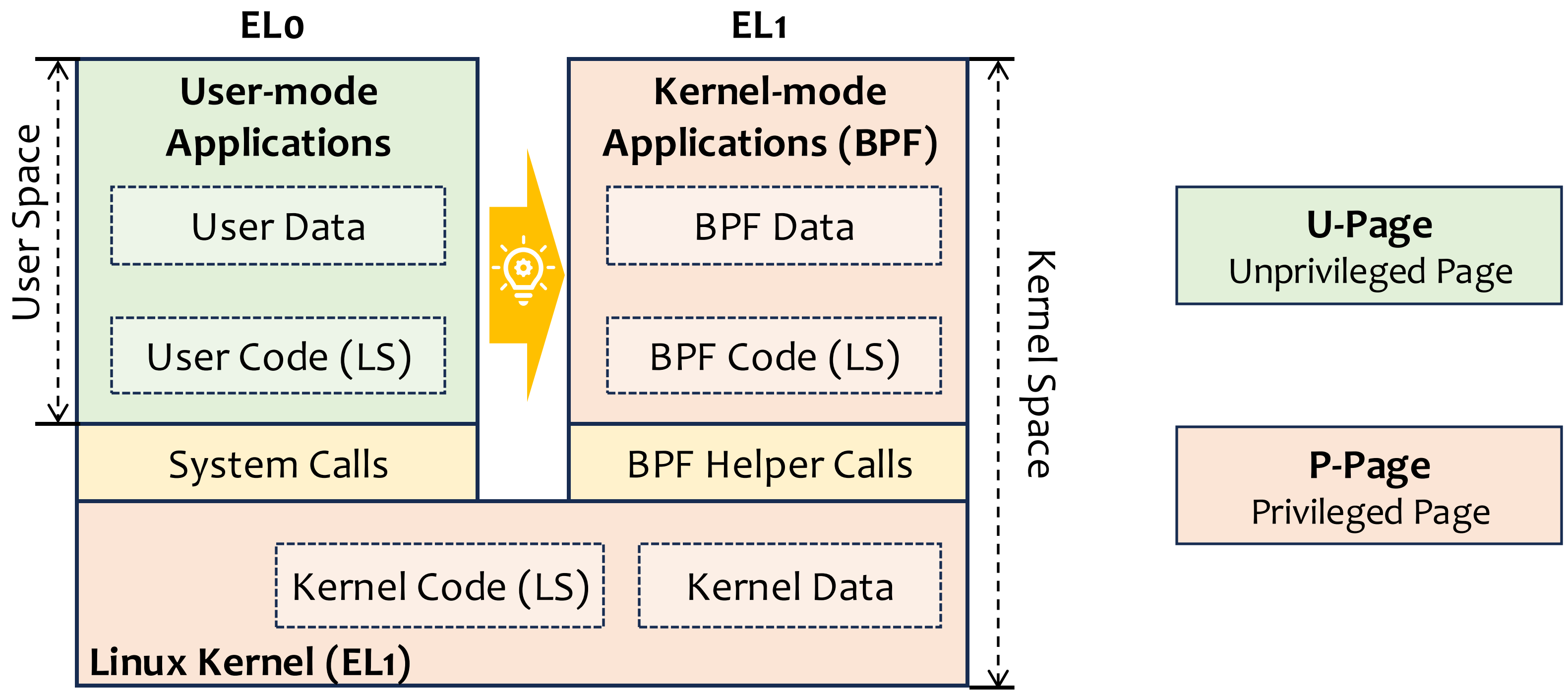
(1) EL-based memory isolation, (2) Independent address space, (3) Crash isolation



EL-based memory isolation on AArch64: the code runs at EL0 cannot access the privileged memory pages (P-Page).

Our Key Insight——BPF programs are kernel mode applications

Kernel security should be achieved by isolating BPF programs.



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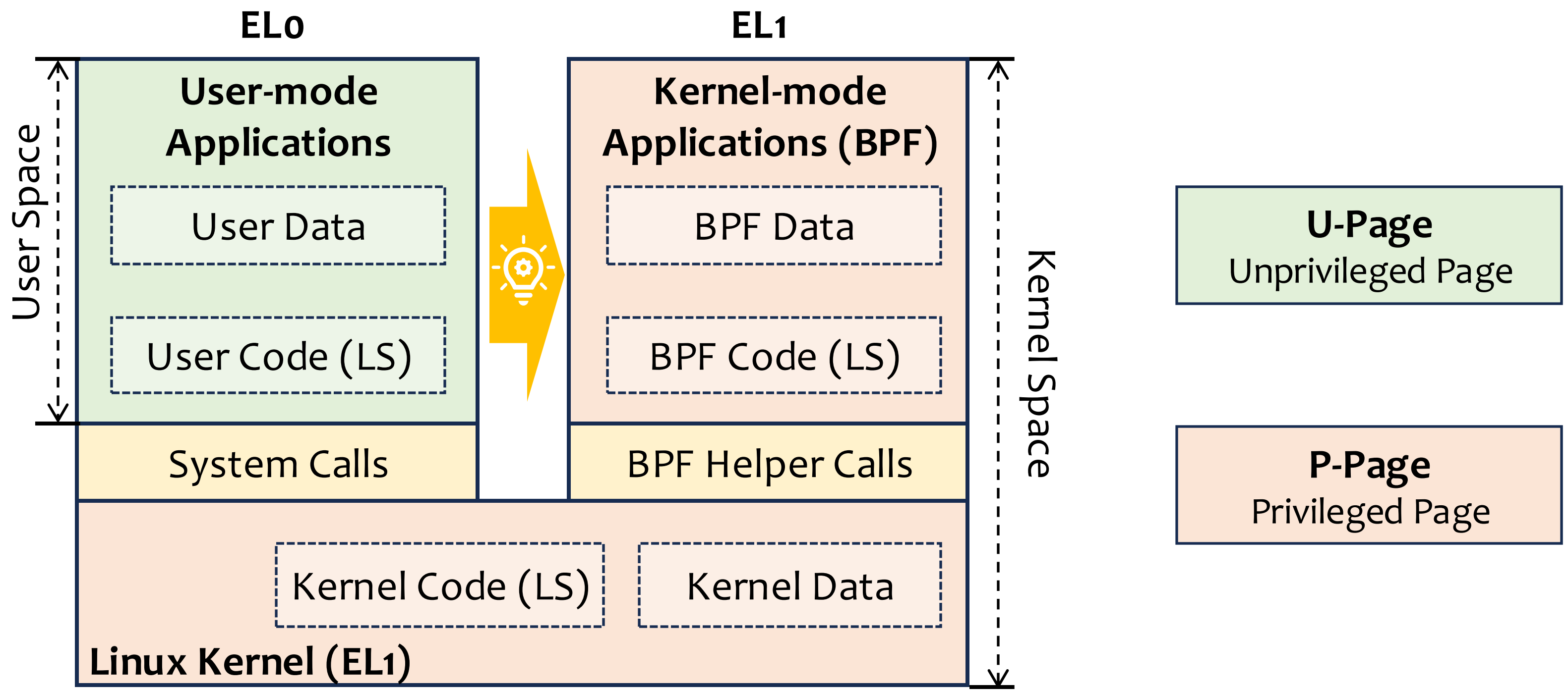


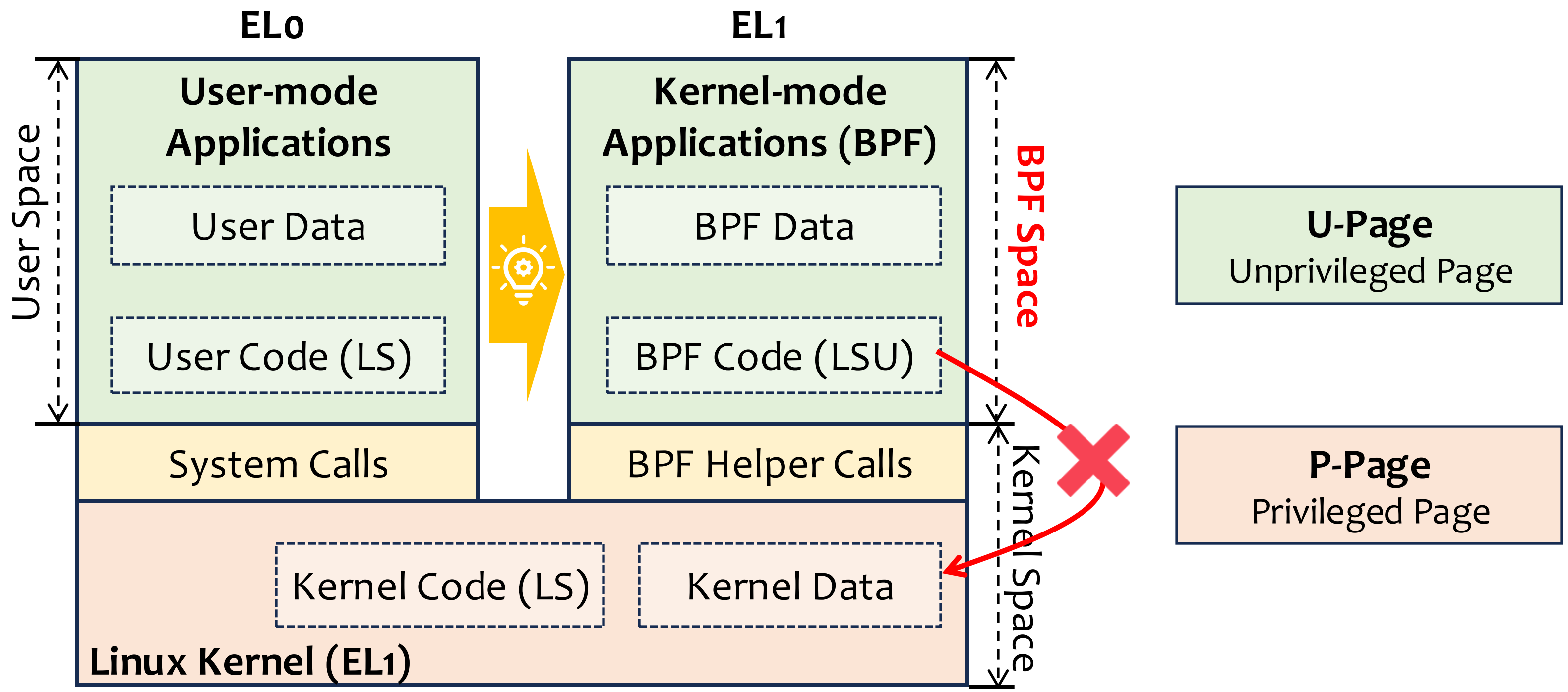
How do we isolate BPF programs efficiently as well as user programs?

Our Key Idea: Build an isolation execution environment——HIVE

De-privileged BPF programs!!!

(1) EL-based memory isolation with LSU, (2) Independent BPF address space, (3) Exception roll-back

SG-1 SG-2 SG-3



* **Load/store unprivileged (LSU) instructions** are treated as if at EL0, no matter which EL they are executed at.

Challenges——BPF programs are highly coupled to Linux kernel

- ***BPF objects*** **require object-grained isolation.**
  - Metadata (e.g., pointers) is embedded in BPF objects and should not be accessed.
  - EL-based memory isolation cannot provide such sub-page protection.

- ***Kernel objects*** **need to be accessed securely.**
  - BPF programs can directly access specific (discontinuous) fields of kernel objects.
  - EL-based memory isolation prevents such access and cannot provide such fine-grained protection.

- ***Kernel pointers*** **cannot be leaked due to they contain the kernel layout information.**
  - Tracking the propagation of pointers is not practical.

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Verifier

Conclusion

High-level Design

Evaluation

Detailed Design

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Evaluation

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eBPF Pointer Types: *BPF pointer* and *kernel pointer* Types

BPF pointer types (10)

ptr_to_buf *ptr_to_stack* *ptr_to_packet*
ptr_to_mem *ptr_to_packet_meta*
ptr_to_tp_buffer *ptr_to_packet_end*
ptr_to_flow_keys *ptr_to_map_value*
ptr_to_map_key

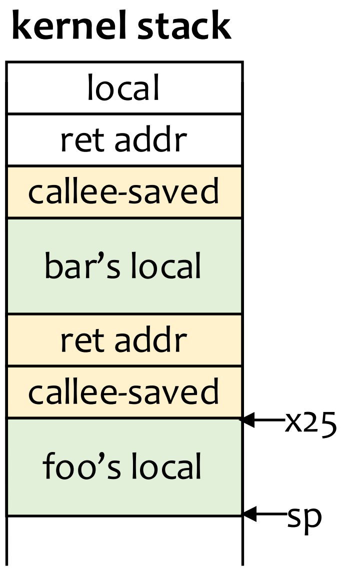
Kernel pointer types (8)

ptr_to_tcp_sock *ptr_to_socket*
ptr_to_sock_common *ptr_to_xdp_sock*
ptr_to_ctx *ptr_to_btf_id*
ptr_to_map *ptr_to_func*

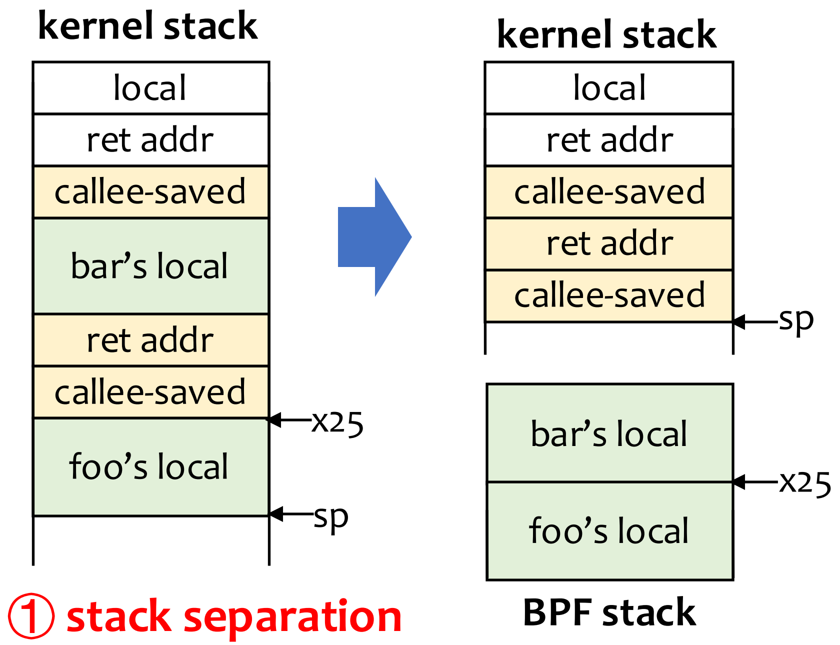
We analyze the eBPF type system and deal with BPF and kernel Pointers separately.

Handling BPF pointers

BPF objects contain BPF-inaccessible metadata



Handling BPF pointers – Compartmentalization (SG-1)



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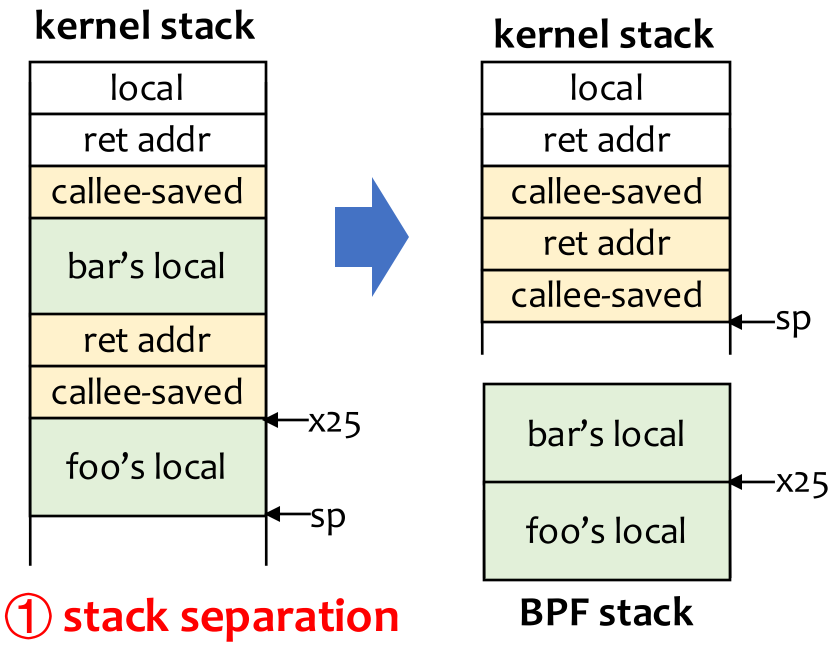
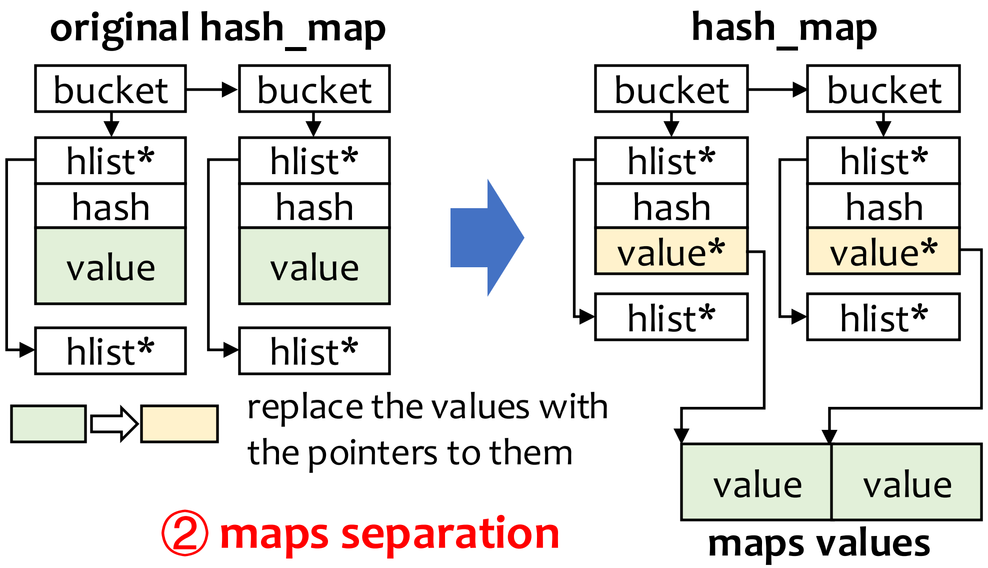
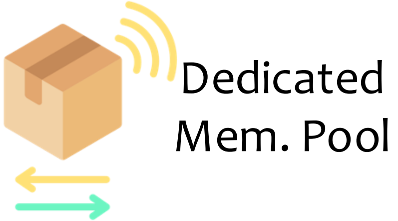


① stack separation

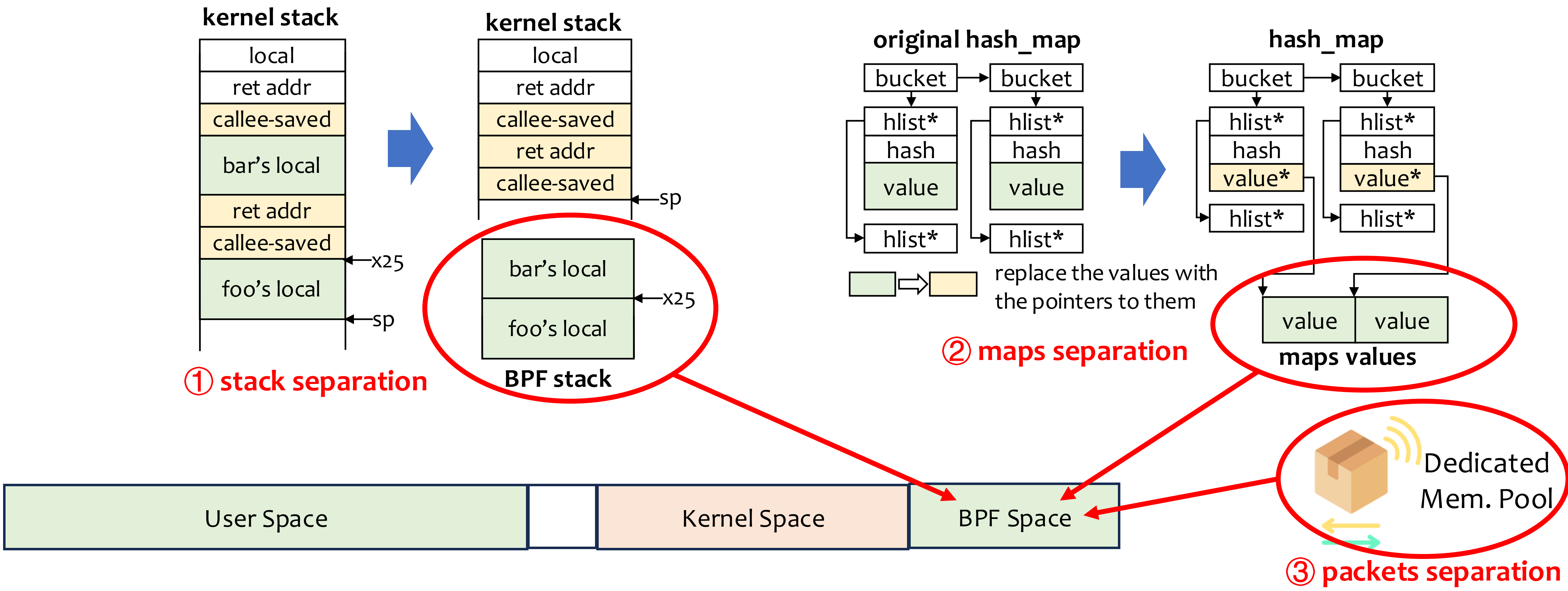


② maps separation



③ packets separation

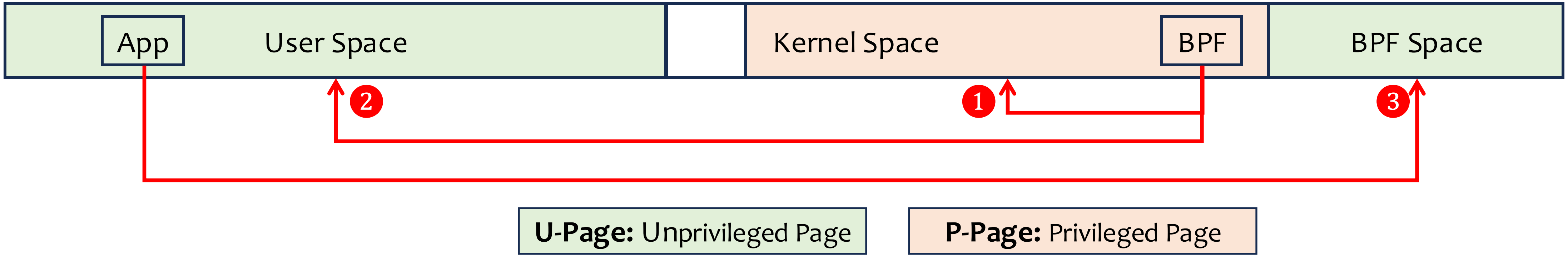
Handling BPF pointers – Compartmentalization (SG-1)



Isolation for the BPF Space (SG-1)

Isolation of direct memory access

1. **BPF program cannot access the kernel space.**
   - due to LSU cannot access P-pages
2. **BPF program cannot access the user space.**
   - E0PD0 forbids unprivileged access to lower half space
3. **User program cannot access the BPF space**
   - E0PD1 forbids unprivileged access to higher half space



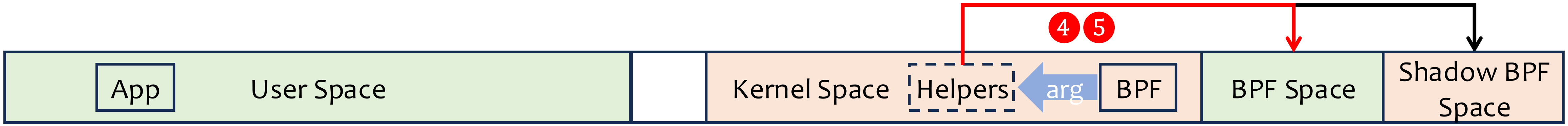
Isolation for the BPF Space (SG-1)

Sanitization of helpers' parameters

4. **Helpers cannot be abused to access the kernel space.**
   - pointer parameters are masked when calling helpers

5. **Helpers can access unprivileged BPF space transparently.**
   - pointers are redirected to the shadow BPF space

Only need 1 instruction: *orr x_n, $mask_{1TB}$*



U-Page: Unprivileged Page

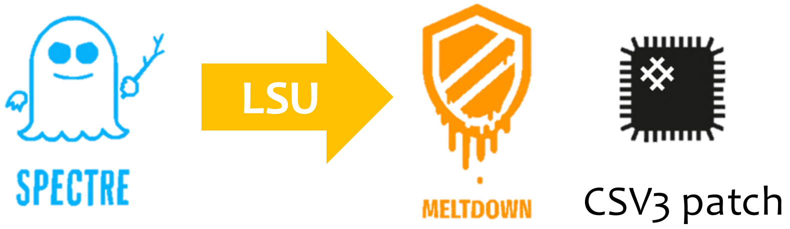
P-Page: Privileged Page

Preventing Information Leakage (SG-2)

Independent address space (SG-2.1)

BPF pointers does not contain kernel layout information.

mov x_n, xzr



Use after initialization (SG-2.2)

BPF space is Initialized during BPF program loading.
All BPF-used registers are cleared when helper returns.

Convert Spectre to Meltdown (SG-2.3)

The CSV3 patch forbids the speculatively loaded data with a permission fault to be used to form an address.

Secure and Passive DoS Prevention (SG-3)

Exceptions Capturing
HIVE passively captures all triggered exceptions, rolls back the state to the entry point of the program, and unloads it.

preventing kernel crash

Execution Timing
HIVE maintains a timetable for each executing BPF program to track their execution time.

preventing execution without terminating

Handling Kernel Pointers in BPF Program --- Our Insight

Characteristic of kernel pointers

New solution for SG-1 and SG-2

1. These kernel pointers **cannot be modified.**
2. De-referenced points must be **exclusive.**
3. Accessing the kernel object in **privileged-pages.**

ARM Pointer Authentication (PA) can ensure the pointer integrity.

+

Regular Load/Store Instruction can access the kernel space normally.

How do we identify memory access to kernel objects?
How do we prevent attacks against PA (e.g., substitute, Spectre)?
How do we prevent kernel pointers from being leaked?

Please read our paper (HIVE[USENIX Security 2024]) if you are interested.

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Security Evaluation

Security equivalence analysis

Security Properties	Equal?
BPF object OOB I, BPF object OOB II	√
kernel object OOB I, kernel object OOB II	√
permission violation I, permission violation II	√
pointer leakage I/II, offset leakage	√
type mismatch	√
uninitialized register rd, uninitialized stack rd I/II	√
Spectre V1 filter/masking, Spectre V4 barrier	√
kernel stack crash I, kernel stack crash II	√
time out, deadlock	√

Real attacks against the security properties

CVE ID	Root Cause	Target Property	Status[1]
2020-27194	Incorrect bound of `OR` insn.	dead loop	●
2021-3490	Incorrect 32-bit bound of bitwise.	BPF obj OOB	●
2021-31440	Incorrect bounds of 32-64 convert.	pointer leakage	●
2022-23222	Mischeck of `*_OR_NULL` Pointer.	kernel obj OOB	●
2020-8835	Incorrect 32-bit Bound.	kernel stack crash	●
2021-4204	Improper input validation.	offset leakage	●
2023-2163	Incorrect branch pruning.	type mismatch	●
2021-34866	Lack map pointer validation.	permission violation	●
2021-33624	Mispredicted branch speculation.	Spectre V1	❍

[1] ●: the attack is mitigated by HIVE, ❍: CVE is confirmed but lacks exploit.

Performance Evaluation

We selected 161 BPF programs from BCC and Tracee.

Table 7: The experimental results of real-world applications when running BPF programs with and w/o HIVE.

App.	config	baseline		eBPF-Tracee			eBPF-BCC			HIVE-Tracee			HIVE-BCC			HIVE/eBPF-O/H[4]		exe_cnt/req[5]	
		THRU[1]	%CPU[2]	THRU[1]	O/H[3]	%CPU[2]	THRU[1]	O/H[3]	%CPU[2]	THRU[1]	O/H[3]	%CPU[2]	THRU[1]	O/H[3]	%CPU[2]	Tracee	BCC	Tracee	BCC
Apache	**32KB**	18.50	98.6	10.48	76.6	98.4	6.17	199.9	99.1	10.11	82.9	98.6	6.03	206.9	99.1	3.48	2.28	555.1	568.8
	64KB	16.17	98.9	8.80	83.8	99.0	5.32	203.9	98.9	8.54	89.5	98.9	5.27	206.9	98.6	3.02	0.99	654.1	693.3
	128KB	12.52	99.0	6.65	88.3	99.0	3.60	248.1	99.1	6.42	95.0	99.4	3.46	262.2	98.4	3.46	3.90	809.6	1028.6
	256KB	7.70	99.6	4.41	74.6	98.5	2.01	282.2	98.1	4.26	80.8	98.5	2.01	282.8	98.1	3.44	0.16	1171.5	1749.5
	Geomean	-	-	-	80.6	-	-	231.1	-	-	86.9	-	-	237.4	-	**3.34**	**1.08**	**766.1**	**917.9**
Nginx	**32KB**	27.25	99.0	13.94	95.5	99.3	5.52	393.8	100.0	13.41	103.3	99.3	5.42	402.7	99.9	3.82	1.77	481.3	701.7
	64KB	23.96	99.0	12.34	94.1	99.5	4.48	434.8	99.9	11.86	102.1	99.8	4.40	444.8	99.8	3.95	1.83	584.6	823.9
	128KB	19.95	99.4	9.07	119.9	99.5	3.30	505.3	99.6	8.67	130.0	99.5	3.25	513.1	99.8	4.37	1.28	761.9	704.6
	256KB	12.98	93.4	5.85	121.8	99.5	2.26	474.9	98.0	5.58	132.5	99.0	2.19	492.5	99.5	4.60	2.97	1089.0	1912.4
	Geomean	-	-	-	107.1	-	-	450.2	-	-	116.1	-	-	461.2	-	**4.18**	**1.87**	**695.1**	**939.5**
Memc-ached	**32B**	1584.39	98.5	941.77	68.2	99.3	471.06	236.3	99.9	907.77	74.5	99.4	459.56	244.8	99.9	3.61	2.44	8595.7	13117.5
	64B	1583.11	98.6	939.88	68.4	99.3	467.08	238.9	99.9	906.88	74.6	99.4	458.95	244.9	99.8	3.51	1.74	8602.8	13110.0
	128B	1577.85	98.4	938.74	68.1	99.8	464.41	239.8	99.8	906.19	74.1	99.5	452.39	248.8	99.5	3.47	2.59	8647.7	13119.9
	256B	1551.61	98.6	923.09	68.1	99.5	461.82	236.0	99.6	883.12	75.7	99.3	455.12	240.9	99.6	4.33	1.45	8685.5	13115.6
	Geomean	-	-	-	68.2	-	-	237.7	-	-	74.7	-	-	244.8	-	**3.71**	**2.00**	**8632.9**	**13115.8**
Redis	**32B**	1342.35	88.7	861.30	55.9	90.0	698.98	92.0	66.7	836.33	60.5	81.0	689.23	94.8	67.9	2.90	1.39	975.9	1088.0
	64B	1304.76	100.0	861.96	51.4	81.7	663.63	96.6	65.7	836.59	56.0	82.0	659.54	97.8	64.6	2.94	0.62	1028.6	1399.3
	128B	1300.93	90.0	858.71	51.5	82.0	664.15	95.9	66.1	827.77	57.2	79.3	657.55	97.8	69.8	3.60	0.99	1020.9	1398.1
	256B	1292.59	90.0	855.05	51.2	90.0	656.88	96.8	70.0	821.67	57.3	80.0	652.03	98.2	68.0	3.90	0.74	1015.0	1408.2
	Geomean	-	-	-	52.4	-	-	95.3	-	-	57.7	-	-	97.2	-	**3.31**	**0.89**	**1009.9**	**1315.8**

[1] The application's throughput (thousands of requests per second). [2] The CPU utilization (%). [3] The overhead (%) of vanilla eBPF and HIVE compared to baseline which does not load BPF programs.
[4] The overhead (%) of HIVE compared to the vanilla eBPF, which is calculated using the throughput directly. [5] The average number of times BPF programs are executed per request.

Complexity Evaluation

The ultimate goal of eBPF is to "replace kernel modules as the de-facto means of extending the kernel".

	BPF	HIVE		eBPF			KLEE				
Kernel Module	**#insn**	**exec time**	**load time**	**rejected cause**	**Ainsn**	**Astate**	**Ainsn**	**Astate**	**Icov**	**Bcov**	**exporing time**
polynomial	126	0.5μs	1.0ms	loop	1M	9K	10.5M	16.9K	99	75	4h 54min
crc-ccitt	134	0.1μs	1.1ms	loop	1M	9.5K	79.9K	2K	61	67	2min 27s
libarc4	265	8.1μs	1.7ms	loop	1M	34.5K	1.7M	21.5K	100	100	21h 25min
prime_numbers	378	0.6μs	2.4ms	branch	141K	1.9K	45.7M	23.9K	71	56	4h 54min
ghash	734	6.7μs	7.9ms	loop	1M	9.7K	21.5M	4.1K	50	55	17h 16min
sha3	1028	32.9μs	11.8ms	loop	1M	1.2K	158.5M	587	98	91	8h 3min
xxhash	1158	1.3μs	7.2ms	pointer ALU	38	1	26M	49.5K	40	39	7h 27min
libchacha	1421	4.4μs	2.9ms	loop	1M	2.6K	79.6M	131.1K	94	83	12h 6min
libsha256	1445	16.7μs	13.6ms	loop	1M	9.5K	50.6M	2.1K	91	85	12min 1s
des	1751	5.2μs	26.4ms	pointer ALU	39	1	7.4M	1K	100	95	1min 15s

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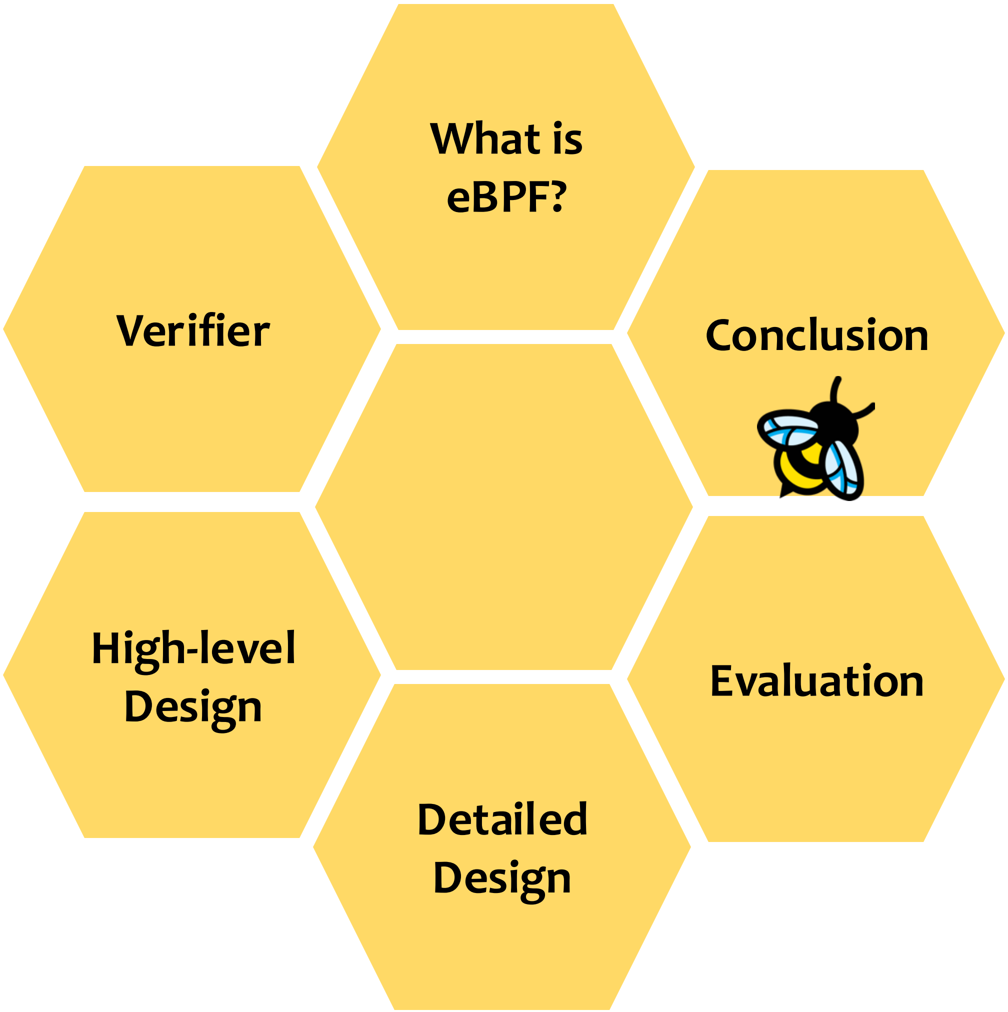
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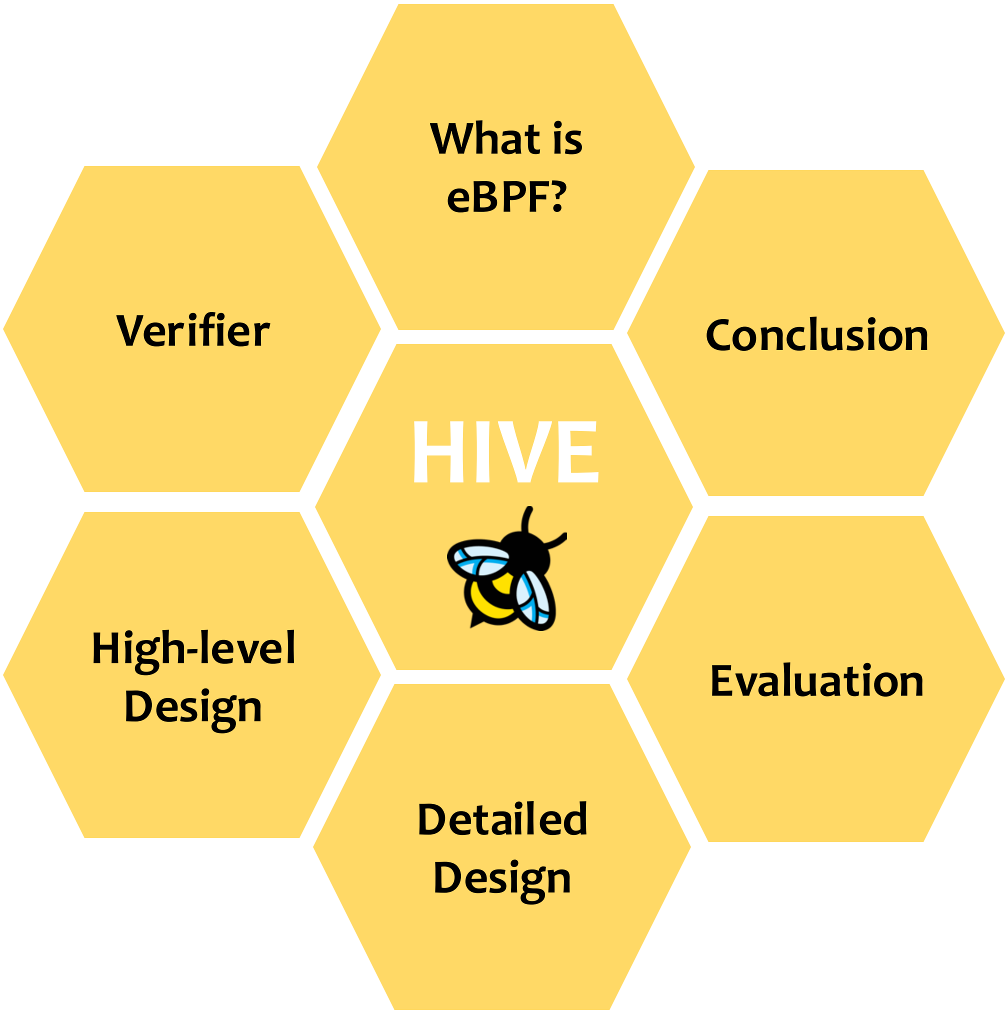
Conclusion

- **Verification-based method has become the bottleneck of eBPF.**
- **We provide a hardware-backed isolation environment – Hive.**
  - De-privilege and decoupled BPF.
  - Special design for accessing kernel objects.
- **Hive can provide the same security guarantees with low runtime overhead.**
- **Now BPF programs can be as complex as they want.**

Thanks



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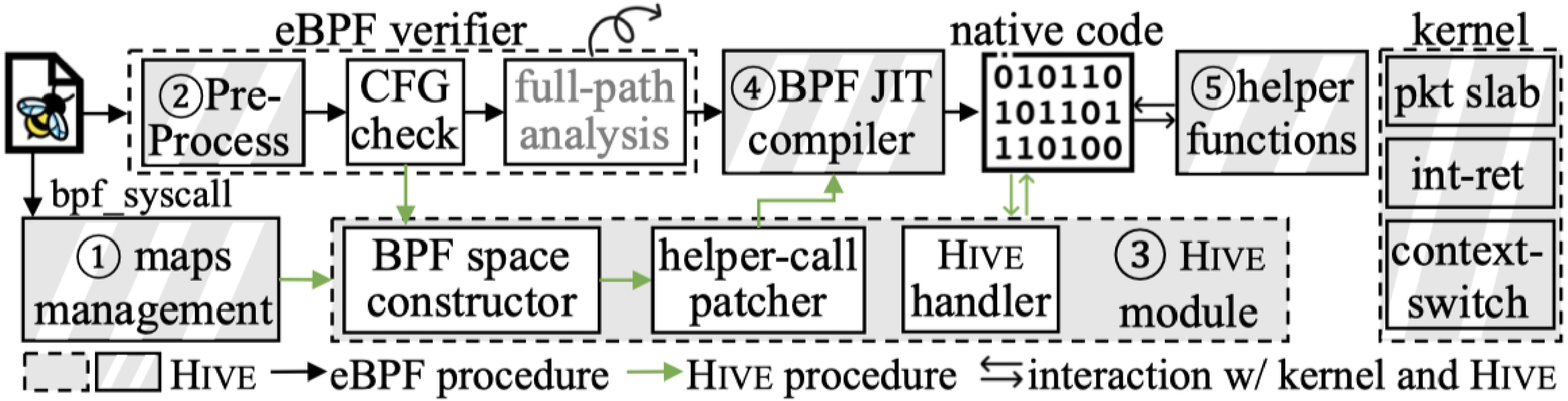
Some Implementation Details



The workflow of HIVE

Inter-BPF isolation via switching page table with ASID

Additional 11 helpers rewriting (e.g., lock)

Concurrent and reentrant safe code patching method

Security property customization

eBPF Pointer Types: *BPF* and *Kernel Pointer* Types

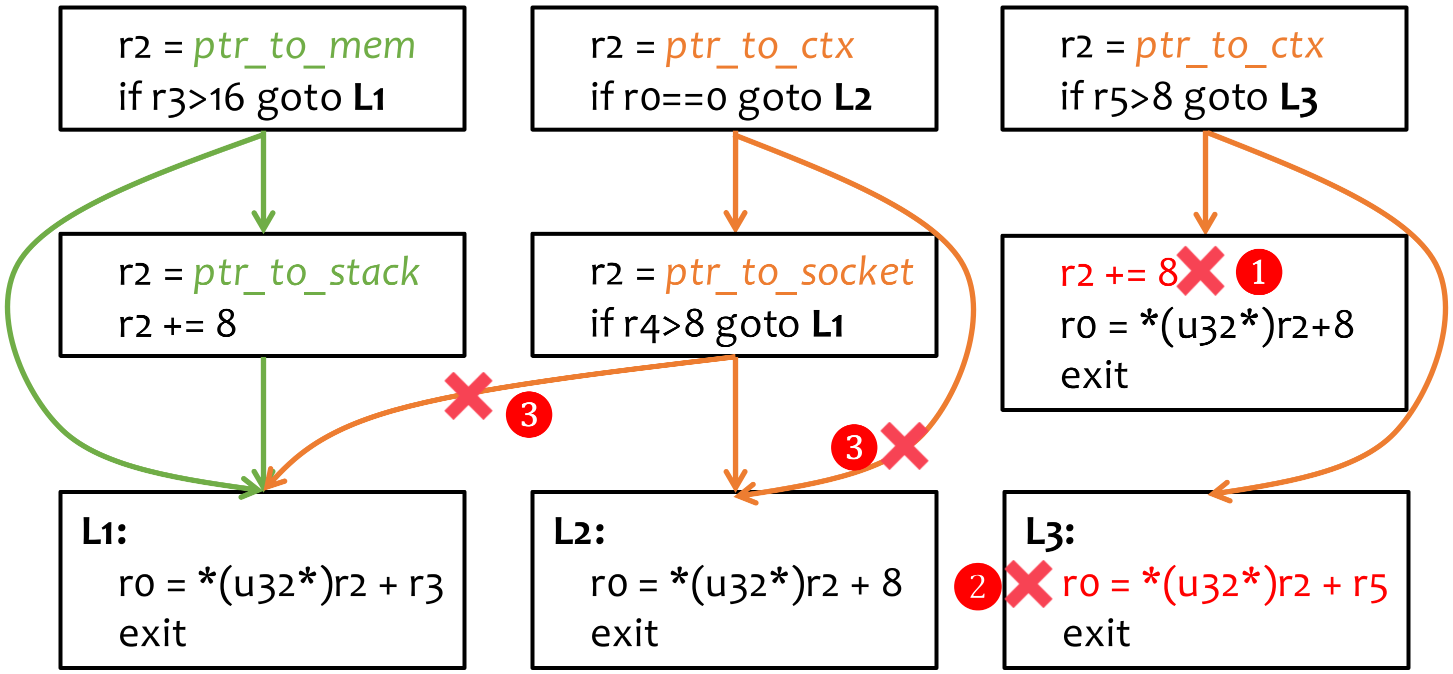
bpf_pointer_type (10)

ptr_to_buf *ptr_to_stack* *ptr_to_packet*
ptr_to_mem *ptr_to_packet_meta*
ptr_to_tp_buffer *ptr_to_packet_end*
ptr_to_flow_keys *ptr_to_map_value*
ptr_to_map_key

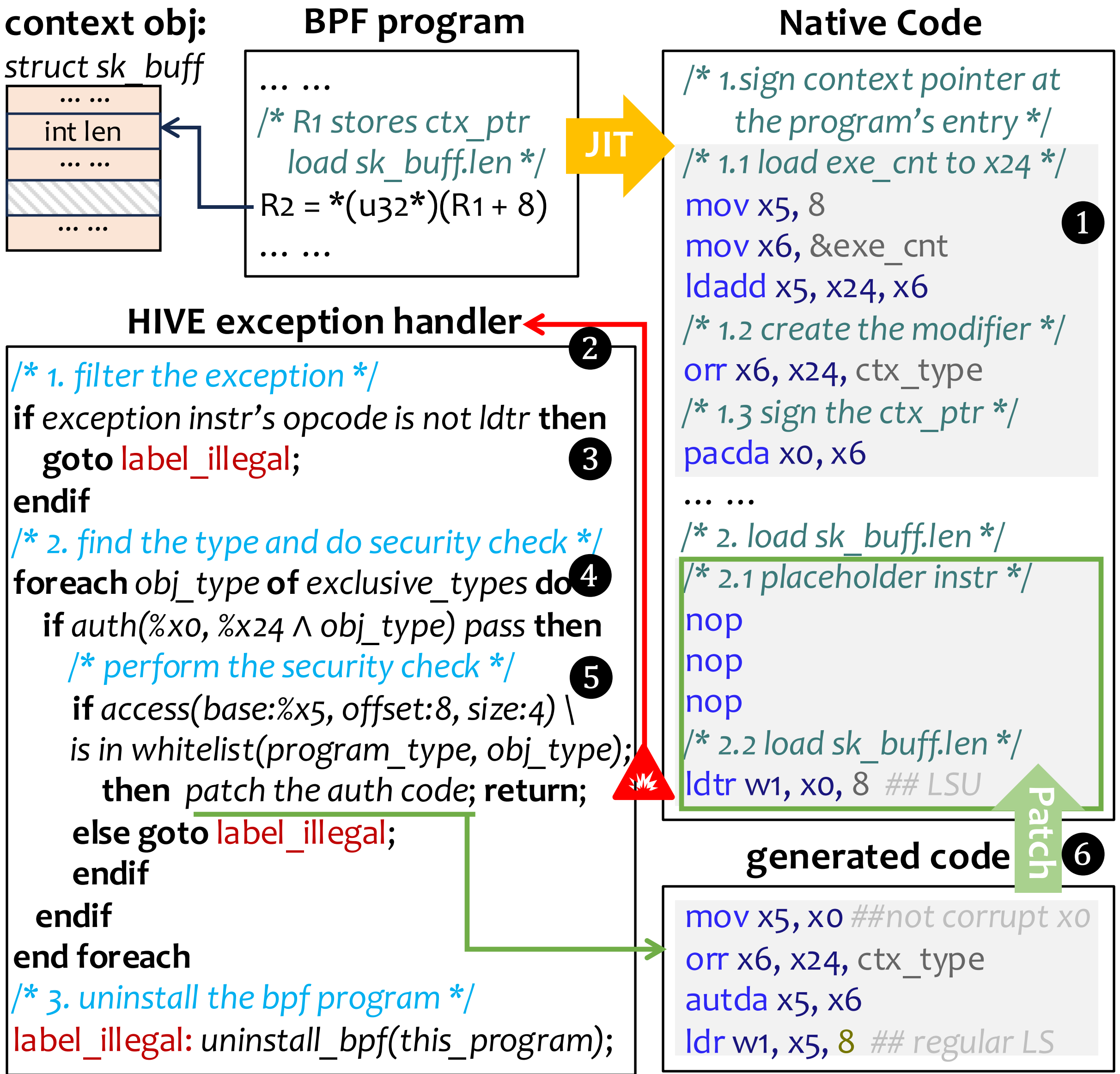
kernel_pointer_type (8)

ptr_to_tcp_sock *ptr_to_socket*
ptr_to_sock_common *ptr_to_xdp_sock*
ptr_to_ctx *ptr_to_btf_id*
ptr_to_map *ptr_to_func*

Types	Point to	Can be Modified	De-reference: Access form	De-reference: Pinned Loc.
Bpf...	BPF object	✓	Arbitrary form	✗
Kernel...	Kernel object	① ✗	② constant offset	③ ✓



Handling Kernel Pointer Types——Point-of-use Probing (SG-1)



Security Method

Trust on the first access to kernel object

Create Unique Modifier

to avoid the pointer substitution attacks.

Check Legality

to lock the access to the target object.

Trigger Permission Fault

when access the kernel space via LSU.

Patch Generated Code

to bind the access to the kernel object.

Handling Kernel Pointer Types——Type Descriptor Table (SG-2)

```
nop                  ## placeholder
nop                  ## placeholder
nop                  ## placeholder
ldtr w1, x0, 8       ## LSU instr.
```

Patch

```
mov x5, x0                  ## not corrupt x0 register
orr x6, x24, ctx_type       ## create the modifier
autda x5, x6                ## perform authentication
ldr w1, x5, 8               ## regular LS instruction
```

x0: pointer

a real kernel pointer

The patched code is enforced to access the legal field of the target kernel object.

Kernel Object:

struct sk_buff

x0 →

… …
int len
… …

Handling Kernel Pointer Types——Type Descriptor Table (SG-2)

The PACed pointers still contain the kernel address information that could be leaked by malicious BPF programs (SG-2.1).

```
nop              ## placeholder
nop              ## placeholder
nop              ## placeholder
ldtr w1, x0, 8   ## LSU instr.
```

Patch

```
mov x5, x0                 ## not corrupt x0 register
orr x6, x24, ctx_type      ## create the modifier
autda x5, x6               ## perform authentication
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Kernel Object:
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… …
int len
… …

Handling Kernel Pointer Types——Type Descriptor Table (SG-2)

SPECTRE

PAC is vulnerable to Spectre attacks(SG-2.3)

```
nop                 ## placeholder
nop                 ## placeholder
nop                 ## placeholder
ldtr w1, x0, 8      ## LSU instr.
```

Patch

```
mov x5, x0                  ## not corrupt x0 register
orr x6, x24, ctx_type       ## create the modifier
autda x5, x6                ## perform authentication
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Kernel Object:
struct sk_buff

x0 →

… …
int len
… …

Handling Kernel Pointer Types——Type Descriptor Table (SG-2)

Inspired by the file descriptor design in Linux,
we design a type descriptor table for each kernel type

```
nop                ## placeholder
nop                ## placeholder
nop                ## placeholder
ldtr w1, x0, 8     ## LSU instr.
```

Patch

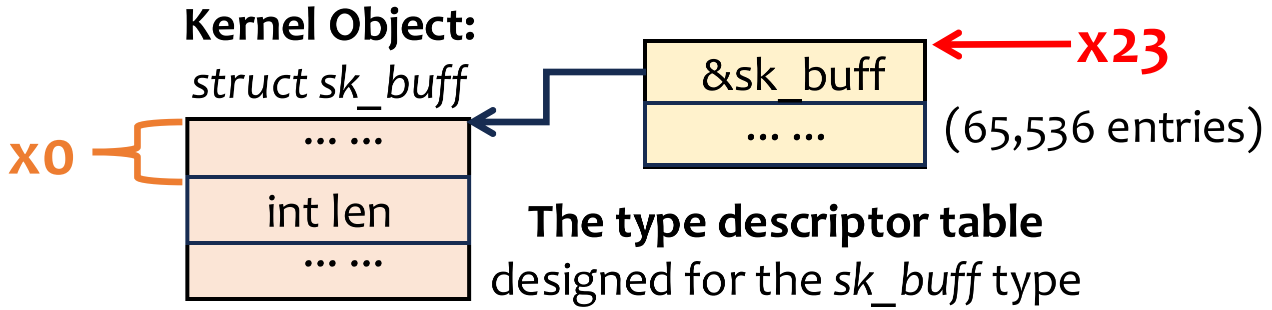
```
... x5 ...                ## not corrupt x0 register
o... 24, ctx_type         ## create the modifier
a... x6                   ## perform authentication
... w1, ... 8             ## regular LS instruction
```

The patched code is enforced to access the legal field of the target kernel object.

x0: pointer
a real kernel pointer

convert

x0: descriptor
an index of a table



Handling Kernel Pointer Types——Type Descriptor Table (SG-2)

Inspired by the file descriptor design in Linux,
we design a type descriptor table for each kernel type

```
1:  nop                ## placeholder
2:  nop                ## placeholder
3:  nop                ## placeholder
4:  ldtr w1, x0, 8     ## LSU instr.
```

Patch

```
1: … x5 …                          ## not corrupt x0 register
2: o… …24, ctx_type                ## create the modifier
3: a… … x6                         ## perform authentication
4: … w1, … 8                       ## regular LS instruction
```

x0: pointer
a real kernel pointer

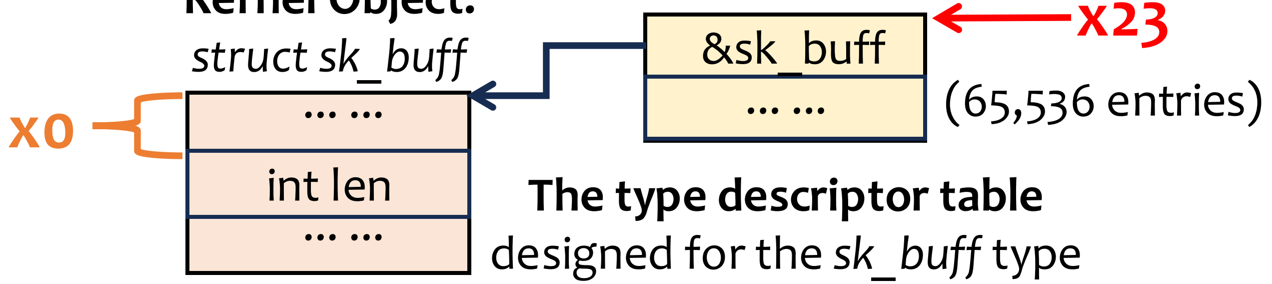
convert

x0: descriptor
an index of a table

The patched code is enforced to access the legal field of the target kernel object.

```
1: and x5, x0, 0xffff         ## mask table index
2: ldr x5, x23, x5            ## load pointer from table
3: ldr w1, x5, 8              ## regular LS instruction
```

Kernel Object:
struct sk_buff



The type descriptor table
designed for the *sk_buff* type

Handling Kernel Pointer Types——Type Descriptor Table (SG-2)

Inspired by the file descriptor design in Linux, we design a type descriptor table for each kernel type

```
1: nop                ## placeholder
2: nop                ## placeholder
3: nop                ## placeholder
4: ldtr w1, x0, 8     ## LSU instr.
```

Patch

```
1: ...v x5                  ## not corrupt x0 register
2: o...24, ctx_type         ## create the modifier
3: a... x6                  ## perform authentication
4: ... w1, ..., 8           ## regular LS instruction
```

x0: pointer
a real kernel pointer

convert

The patched code is enforced to access the legal field of the target kernel object.

```
1: and x5, x0, 0xffff       ## mask table index
2: ldr x5, x23, x5          ## load pointer from table
3: ldr w1, x5, 8            ## regular LS instruction
```

x0: descriptor
an index of a table

prevent OOB access speculatively