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Value tracking in BPF verifier

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About me

Shung-Hsi Yu (pronounced like Shawn see you)

Works at 

About me

Maintains BPF stack of SUSE Enterprise Linux and openSUSE

- BPF subsystem, libbpf, bpftool, bpftrace, bcc, xdp-tools
  - backport CVE fixes (along with selftests)
    - BPF verifier

Wish

The verifier is **simpler** to understand

More people **understand** the verifier

More thorough **testing** of the verifier

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- Agni/Verifying the Verifier
- range bounds tester (reg_bounds.c)

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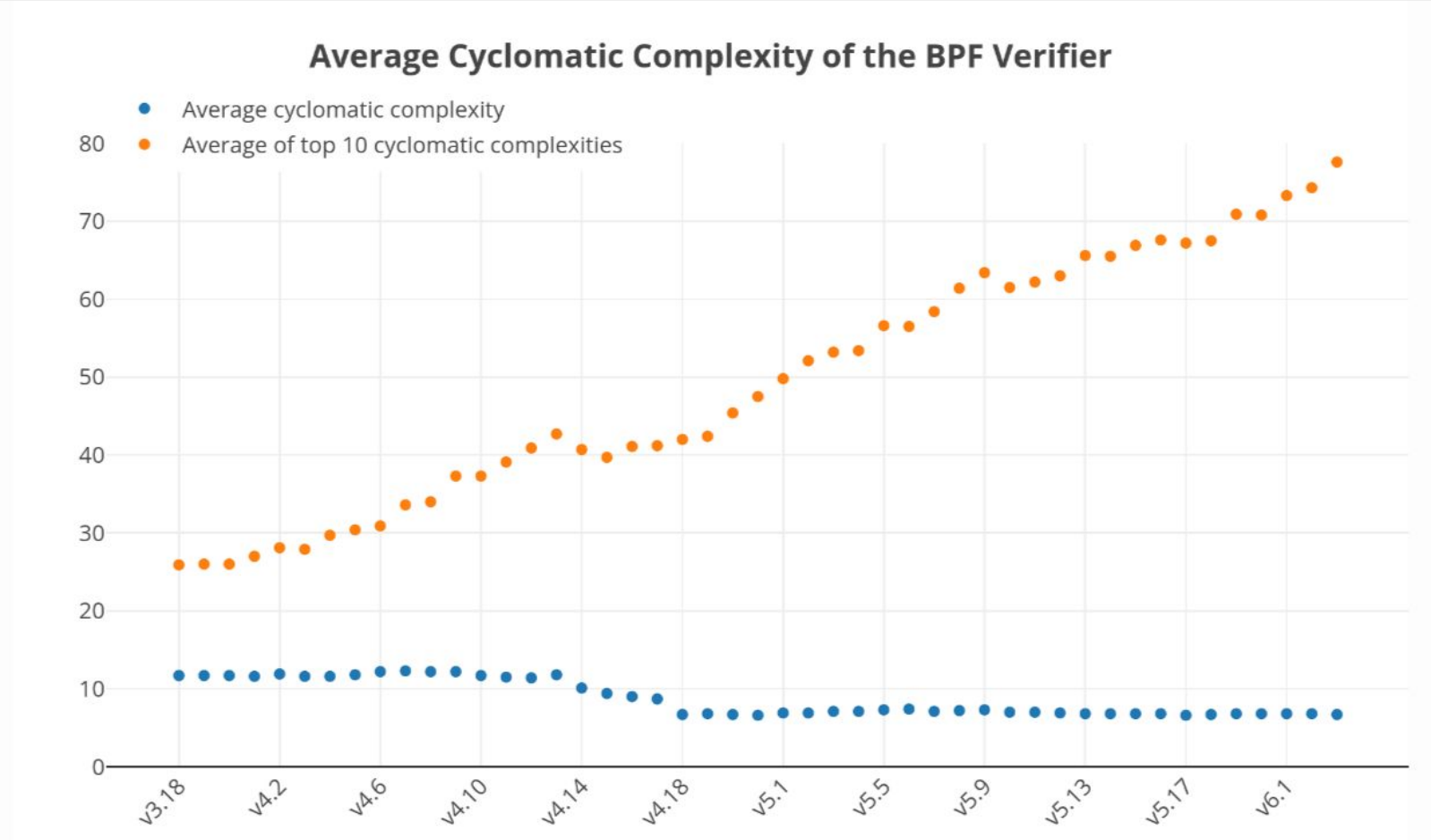

"Complexity of the BPF Verifier" by Paul Chaignon

Focus

I still don’t understand **BPF verifier** as a whole

Focus

BPF verifier

Focus

value tracking

dead code elimination

control flow analysis

BPF verifier

backtracking

spectre mitigation

type tracking

liveness tracking

instruction rewrite

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liveness tracking

instruction rewrite

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Value Tracking

Why it is used

```
e = bpf_map_lookup_elem();
val = *(e + offset); /* out of bound? */
```

```
/* include/linux/bpf_verifier.h */
struct bpf_reg_state {   /* track 5 kinds of bounds */
    struct tnum var_off; /* possible bit pattern */
    s64 smin_value; /* minimum possible (s64)value */
    s64 smax_value; /* maximum possible (s64)value */
    u64 umin_value; /* minimum possible (u64)value */
    u64 umax_value; /* maximum possible (u64)value */
    s32 s32_min_value; /* min (s32)value */
    s32 s32_max_value; /* max (s32)value */
    u32 u32_min_value; /* min (u32)value */
    u32 u32_max_value; /* max (u32)value */
};
```

```
/* include/linux/bpf_verifier.h */
struct bpf_reg_state {   /* back in the days */
    s64 min_value;
    u64 max_value;
    u32 min_align;
    u32 aux_off;
    u32 aux_off_align;
    bool value_from_signed;
};
```

```
/* include/linux/bpf_verifier.h */
struct bpf_reg_state {   /* track 5 kinds of bounds */
    struct tnum var_off; /* possible bit pattern */
    s64 smin_value; /* minimum possible (s64)value */
    s64 smax_value; /* maximum possible (s64)value */
    u64 umin_value; /* minimum possible (u64)value */
    u64 umax_value; /* maximum possible (u64)value */
    s32 s32_min_value; /* min (s32)value */
    s32 s32_max_value; /* max (s32)value */
    u32 u32_min_value; /* min (u32)value */
    u32 u32_max_value; /* max (u32)value */
};
```

```
/* include/linux/bpf_verifier.h */
struct bpf_reg_state {   /* track 5 kinds of bounds */
    struct tnum var_off; /* possible bit pattern */
    s64 smin_value; /* minimum possible (s64)value */
    s64 smax_value; /* maximum possible (s64)value */
    u64 umin_value; /* minimum possible (u64)value */
    u64 umax_value; /* maximum possible (u64)value */
    s32 s32_min_value; /* min (s32)value */
    s32 s32_max_value; /* max (s32)value */
    u32 u32_min_value; /* min (u32)value */
    u32 u32_max_value; /* max (u32)value */
};
```

Tnum

Short for **tri-state number** or **tracked number**

```
struct tnum {
    u64 value; /* which bits are set (if known) */
    u64 mask;  /* which bits are _un_known */
};
```

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Tnum

Short for **tri-state number** or **tracked number**

Tracks knowledge about the bits of a value

- each bit can be either **known (0 or 1)**, or **unknown (x)**

Tnum

Each bit can be either known (0 or 1), or unknown (x)

```
    { 0b00 }     => 00 => mask=0b00, value=0b00
    { 0b01 }     => 01 => mask=0b00, value=0b01
{ 0b00, 0b01 } => 0x => mask=0b01, value=0b00
{ 0b00..0b11 } => xx => mask=0b11, value=0b00
```

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```
/* include/linux/bpf_verifier.h */
struct bpf_reg_state {   /* track 5 kinds of bounds */
    struct tnum var_off; /* possible bit pattern */
    s64 smin_value; /* minimum possible (s64)value */
    s64 smax_value; /* maximum possible (s64)value */
    u64 umin_value; /* minimum possible (u64)value */
    u64 umax_value; /* maximum possible (u64)value */
    s32 s32_min_value; /* min (s32)value */
    s32 s32_max_value; /* max (s32)value */
    u32 u32_min_value; /* min (u32)value */
    u32 u32_max_value; /* max (u32)value */
};
```

```
/* include/linux/bpf_verifier.h */
struct bpf_reg_state {   /* track 5 kinds of bounds */
    struct tnum var_off; /* possible bit pattern */
    s64 smin_value; /* minimum possible (s64)value */
    s64 smax_value; /* maximum possible (s64)value */
    u64 umin_value; /* minimum possible (u64)value */
    u64 umax_value; /* maximum possible (u64)value */
    s32 s32_min_value; /* min (s32)value */
    s32 s32_max_value; /* max (s32)value */
    u32 u32_min_value; /* min (u32)value */
    u32 u32_max_value; /* max (u32)value */
};
```

Range a.k.a interval domain

Tracks **minimum** and **maximum** possible value

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Range a.k.a interval domain

Tracks minimum and maximum possible value

```
  { 0 }  => umin(_value)=0, umax(_value)=0
{ 0, 1 } => umin(_value)=0, umax(_value)=1
```

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```
/* include/linux/bpf_verifier.h */
struct bpf_reg_state {   /* track 5 kinds of bounds */
    struct tnum var_off; /* possible bit pattern */
    s64 smin_value; /* minimum possible (s64)value */
    s64 smax_value; /* maximum possible (s64)value */
    u64 umin_value; /* minimum possible (u64)value */
    u64 umax_value; /* maximum possible (u64)value */
    s32 s32_min_value; /* min (s32)value */
    s32 s32_max_value; /* max (s32)value */
    u32 u32_min_value; /* min (u32)value */
    u32 u32_max_value; /* max (u32)value */
};
```

Value Tracking

Efficient data structure to track a **set** of values

- **in expense** of not being able to track precisely

Value Tracking

In expense of not being able to track precisely

```
  { 1, 3 }    => umin=1, umax=3   =>   { 1, 2, 3 }

{ 0b01, 0b10 } => mask=0b11, val=0b00 =>  { 0b00..0b11 }
```

Value Tracking

Why both tnum and ranges?

```
   { 1, 3 }     =>    umin=1, umax=3     => { 1, 2, 3 }
{ 0b01, 0b11 } => mask=0b10, val=0b01 => { 0b01, 0b11 }
                                       => { 1, 3 }
```

Value Tracking

Why both tnum and ranges?

```
   { 1, 2 } =>   umin=1, umax=2    => { 1, 2 }
{ 0b01, 0b10 } => mask=0b10, val=0b01 => { 0b00..0b11 }
                                      => { 0b01, 0b10 }
```

Value Tracking

Why both signed and unsigned ranges?

```
BPF_LD_IMM64(src, 0xfffffffffffffffe) /* U64MAX-1 */
BPF_JMP_REG(BPF_JLT, dst, src, off)

BPF_LD_IMM64(src, 0xfffffffffffffffe) /* -2 */
BPF_JMP_REG(BPF_JSLT, dst, src, off)
```

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Value Tracking

Why both 64-bit and 32-bit ranges?

```
/* Unsigned comparison of full 64-bit in register */
BPF_JMP_IMM(BPF_JLT, dst, imm, off)

/* Unsigned comparison of lower 32-bit in register */
BPF_JMP32_IMM(BPF_JLT, dst, imm, off)
```

Wish

The verifier is **simpler** to understand

More people **understand** the verifier

Less bounds

Things we do for precision

Propagating the knowledge about possible values

```
static void reg_bounds_sync(struct bpf_reg_state *reg)
{
    /* tnum -> u64, s64, u32, s32 */
    __update_reg_bounds(reg);
    /* u64 -> u32, s32; s64 -> u32, s32
     * u64 -> s64; s64 -> u64
     * u32 -> u64, s64; s32 -> u64, s64 */
    __reg_deduce_bounds(reg);
    __reg_deduce_bounds(reg); /* 2nd time */
    /* u64 -> tnum; u32 -> tnum */
    __reg_bound_offset(reg);
    /* tnum -> u64, s64, u32, s32 */
    __update_reg_bounds(reg);
}
```

```
static void reg_bounds_sync(struct bpf_reg_state *reg)
{
    /* tnum -> u64, s64, u32, s32 */
    __update_reg_bounds(reg);
    /* u64 -> u32, s32; s64 -> u32, s32
     * u64 -> s64; s64 -> u64
     * u32 -> u64, s64; s32 -> u64, s64 */
    __reg_deduce_bounds(reg);
    __reg_deduce_bounds(reg); /* 2nd time */
    /* u64 -> tnum; u32 -> tnum */
    __reg_bound_offset(reg);
    /* tnum -> u64, s64, u32, s32 */
    __update_reg_bounds(reg);
}
```

```
static void reg_bounds_sync(struct bpf_reg_state *reg)
{
    /* tnum -> u64, s64, u32, s32 */
    __update_reg_bounds(reg);
    /* u64 -> u32, s32; s64 -> u32, s32
     * u64 -> s64; s64 -> u64
     * u32 -> u64, s64; s32 -> u64, s64 */
    __reg_deduce_bounds(reg);
    __reg_deduce_bounds(reg); /* 2nd time */
    /* u64 -> tnum; u32 -> tnum */
    __reg_bound_offset(reg);
    /* tnum -> u64, s64, u32, s32 */
    __update_reg_bounds(reg);
}
```

```c
static void __reg64_deduce_bounds(struct bpf_reg_state *reg)
{
    /* u64 -> s64 */
    if ((s64)reg->umin_value <= (s64)reg->umax_value) {
     reg->smin_value = max_t(s64, reg->smin_value, reg->umin_value);
     reg->smax_value = min_t(s64, reg->smax_value, reg->umax_value);
    }
    /* s64 -> u64 */
    if ((u64)reg->smin_value <= (u64)reg->smax_value) {
     reg->umin_value = max_t(u64, reg->smin_value, reg->umin_value);
     reg->umax_value = min_t(u64, reg->smax_value, reg->umax_value);
    }
}
```

```
tnum -> u64, s64, u32, s32
u64 -> s64
s64 -> u64
u64 -> u32, s32
s64 -> u32, s32
u32 -> u64, s64
s32 -> u64, s64
u32 -> s32
s32 -> u32
u64 -> tnum
u32 -> tnum
s64 -> tnum
s32 -> tnum
```

Things we do for precision

Less propagation?

```
/* include/linux/bpf_verifier.h */
struct bpf_reg_state {   /* track 5 kinds of bounds */
    struct tnum var_off; /* possible bit pattern */
    s64 smin_value; /* minimum possible (s64)value */
    s64 smax_value; /* maximum possible (s64)value */
    u64 umin_value; /* minimum possible (u64)value */
    u64 umax_value; /* maximum possible (u64)value */
    s32 s32_min_value; /* min (s32)value */
    s32 s32_max_value; /* max (s32)value */
    u32 u32_min_value; /* min (u32)value */
    u32 u32_max_value; /* max (u32)value */
};
```

```
/* include/linux/bpf_verifier.h */
struct bpf_reg_state {   /* track 3 kinds of bounds */
    struct tnum var_off; /* possible bit pattern */
    u64 min_value; /* allow min > max */
    u64 max_value;
    u32 subreg_min_value; /* allow min > max */
    u32 subreg_max_value;
};
```

Wrapped Range

Tracks the possible starting **from min**, and all value encountered by **iteratively adding 1**, **until umax**

```
min=0xfffffffffffffffe, max=0
                    => { 0, UMAX-1, UMAX }
     inverted range => { 0..UMAX } - { max+1..min-1 }
```

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Wrapped Range

Tracks the possible starting **from min**, and all value encountered by **iteratively adding 1**, **until umax**

```
min=0xfffffffffffffffe, max=0
                    => { 0, UMAX-1, UMAX }
    inverted range => { 0..UMAX } - { max+1..min-1 }
                    => { -2, -1, 0 }
```

```
/* include/linux/bpf_verifier.h */
struct bpf_reg_state {   /* track 3 kinds of bounds */
    struct tnum var_off; /* possible bit pattern */
    u64 min_value; /* allow min > max */
    u64 max_value;
    u32 subreg_min_value; /* allow min > max */
    u32 subreg_max_value;
};
```

```
tnum -> u64, s64, u32, s32
u64 -> s64
s64 -> u64
u64 -> u32, s32
s64 -> u32, s32
u32 -> u64, s64
s32 -> u64, s64
u32 -> s32
s32 -> u32
u64 -> tnum
u32 -> tnum
s64 -> tnum
s32 -> tnum
```

```
tnum -> u64, u32
u64 -> u32
u32 -> u64
u64 -> tnum
u32 -> tnum
```

Reference

RFC Unifying signed and unsigned min/max tracking

Interval Analysis and Machine Arithmetic: Why Signedness Ignorance Is Bliss

```c
static void scalar32_min_max_add(struct bpf_reg_state *dst_reg,
                 struct bpf_reg_state *src_reg)
{
    s32 smin_val = src_reg->s32_min_value;
    s32 smax_val = src_reg->s32_max_value;
    u32 umin_val = src_reg->u32_min_value;
    u32 umax_val = src_reg->u32_max_value;

    if (signed_add32_overflows(dst_reg->s32_min_value, smin_val) ||
     signed_add32_overflows(dst_reg->s32_max_value, smax_val)) {
      dst_reg->s32_min_value = S32_MIN;
      dst_reg->s32_max_value = S32_MAX;
    } else {
      dst_reg->s32_min_value += smin_val;
      dst_reg->s32_max_value += smax_val;
    }
    if (dst_reg->u32_min_value + umin_val < umin_val ||
     dst_reg->u32_max_value + umax_val < umax_val) {
      dst_reg->u32_min_value = 0;
      dst_reg->u32_max_value = U32_MAX;
    } else {
      dst_reg->u32_min_value += umin_val;
      dst_reg->u32_max_value += umax_val;
    }
}
```

```
/* include/linux/bpf_verifier.h */
struct bpf_reg_state {
    struct tnum var_off; /* possible bit pattern */
    struct wrange { /* wrapped range */
        u64 start;
        u64 end;
    } wr64;
    struct wrange32 {
        u32 start;
        u32 end;
    } wr32;
};
```

```
struct wrange32 wrange32_add(struct wrange32 a,
                             struct wrange32 b)
{
    u32 a_len = a.end - a.start;
    u32 b_len = b.end - b.start;
    u32 new_len = a_len + b_len;

    /* the new start/end pair goes full circle
     * so any value is possible */
    if (new_len < a_len || new_len < b_len)
        return WRANGE32(U32_MIN, U32_MAX);
    else
        return WRANGE32(a.start + b.start, a.end + b.end);
}
```

Plan

Make wrapped range fit in the current ecosystem

Plan

1. Create helper that transform current signed and unsigned min/max from/to wrange
2. Use `wrange*_{add,sub,...}` inside `scalar*_min_max_{add,sub,...}` instead
3. Run selftests to check
4. Switch to `wrange` in `struct bpf_reg_state`

Concerns

- Hidden/implicit assumptions of value tracking
  - does umax/umin and smax/smin *always* intersects?
  - …

Abstract value tracking details

Implementation detail

Requires knowing tnum and range to work on verifier

- `umin` or `var_off.value` for minimum value?
- `tnum_is_const()` or `umin == umax`?
- how to get maximum offset? `var_off` or `umax`?
  (don't forget the '`off`' field for base offset)

```
/* include/linux/bpf_verifier.h */
struct bpf_reg_state {   /* track 5 kinds of bounds */
    struct tnum var_off; /* possible bit pattern */
    s64 smin_value; /* minimum possible (s64)value */
    s64 smax_value; /* maximum possible (s64)value */
    u64 umin_value; /* minimum possible (u64)value */
    u64 umax_value; /* maximum possible (u64)value */
    s32 s32_min_value; /* min (s32)value */
    s32 s32_max_value; /* max (s32)value */
    u32 u32_min_value; /* min (u32)value */
    u32 u32_max_value; /* max (u32)value */
};
```

```c
/* include/linux/bpf_verifier.h */
struct bpf_reg_state {
    struct tval val;
    /* ... */
};
```

```
static int is_scalar_branch_taken(
        struct bpf_reg_state *reg1, struct bpf_reg_state *reg2,
         u8 opcode, bool is_jmp32)
{
    /* ... */
    switch (opcode) {
    case BPF_JEQ:
     if (tnum_is_const(t1) && tnum_is_const(t2) &&
         t1.value == t2.value)
         return ALWAYS;
     /* non-overlapping ranges */
     if (umin1 > umax2 || umax1 < umin2)
         return NEVER;
     if (smin1 > smax2 || smax1 < smin2)
         return NEVER;
     return MAYBE;
```

```
static int is_scalar_branch_taken(
      struct bpf_reg_state *reg1,
      struct bpf_reg_state *reg2,
       u8 opcode, bool is_jmp32)
{
    /* ... */
    switch (opcode) {
    case BPF_JEQ:
        intersects = tval_intersect(reg1->val, reg2->val2,
                                    &out);
       if (!intersects)
           return NEVER;
       return tval_eq(reg1->val, reg2->val) ? ALWAYS : MAYBE;
```

```
static void regs_refine_cond_op(
            struct bpf_reg_state *reg1,
            struct bpf_reg_state *reg2,
                u8 opcode, bool is_jmp32)
{
    switch (opcode) {
    case BPF_JEQ:
        reg1->umin_value = max(reg1->umin_value, reg2->umin_value);
        reg1->umax_value = min(reg1->umax_value, reg2->umax_value);
        reg1->smin_value = max(reg1->smin_value, reg2->smin_value);
        reg1->smax_value = min(reg1->smax_value, reg2->smax_value);
        reg2->umin_value = reg1->umin_value;
        reg2->umax_value = reg1->umax_value;
        reg2->smin_value = reg1->smin_value;
        reg2->smax_value = reg1->smax_value;
        reg1->var_off = tnum_intersect(reg1->var_off, reg2->var_off);
        reg2->var_off = reg1->var_off;
```

```
static int regs_refine_cond_op(
            struct bpf_reg_state *reg1,
            struct bpf_reg_state *reg2,
             u8 opcode, bool is_jmp32)
{
    switch (opcode) {
    case BPF_JEQ:
    if(!tval_intersect(reg1->val, reg2->val, &out))
            return -EINVAL; /* should not happen */
    reg2->val = reg1->val = out;
    /* ... */
```

tval helpers

```
/* copy tnum */
tval_{add,sub,mul,div}()
tval_{and,or,xor}()
tval_{l,r,ar}shift()
/* minimum and maximum */
tval_{u,s}{min,max}()
```

```
/* with __must_check */
tval_intersect()
tval_diff()
tval_union()
```

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Question

- How much abstraction is too much?
- `__must_check` semantic too verbose?
- …

Other topics

Other verifier topics

- **Documentation** improvement
- Simplification/refactoring of codebase
- Removing `tnum` from `bpf_reg_state`
- Tracks complexity metric of verifier

Other verifier topics

- Standardization for verifier
- Testing across different verifier
- Further reducing loop/branch states
- Lazier precision tracking
- …

Thank you! and ...

Shameless plug

BPF BoF in Asia

Taipei

- (TBD) COSCUP, August 3-4th

Tokyo

- (TBD) OSS Japan, October 28-29th
- (TBD) openSUSE Asia Summit, November 2-3rd

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