AN ANALYSIS OF SPECULATIVE TYPE CONFUSION VULNERABILITIES IN THE WILD

<u>Ofek Kirzner</u>

Adam Morrison

Blavatnik School of Computer Science

Tel Aviv University

SPECTRE VARIANT 1: BOUNDS CHECK BYPASS

Goal: Leak data from the victim address space

foo(valid_x)

foo(&secret – array1)

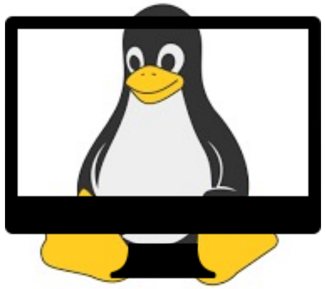
Training:
if taken

Misprediction:
out of bounds

```
void foo(long x) {
    // ...
    if (x < array1_len) {
        y = array1[x];
        z = array2[y * 4096];
    }
    // ...
}
```

The secret is leaked

SPECTRE VARIANT 1: BOUNDS CHECK BYPASS



Attacker – unprivileged user

Victim – the kernel

foo(&secret – array1)

```
void function_called_from_syscall(long x) {
    // ...
    if (x < array1_len) {
        y = array1[x];
        z = array2[y * 4096];
    }
    // ...
}
```

The secret is leaked

Read from kernel → Read any physical address

MITIGATION IN THE LINUX KERNEL

A special API to ensure bounds checks are respected under speculation

```
void function_called_from_syscall(long x) {
    // ...
    if (x < array1_len) {
        y = array1[x];
        z = array2[y * 4096];
    }
    // ...
}
```

```
void function_called_from_syscall(long x) {
    // ...
    if (x < array1_len) {
        y = array_index_nospec(array1[x], array1_len);
        z = array2[y * 4096];
    }
    // ...
}
```

SPECTRE V1 IS MORE THAN BOUNDS CHECK BYPASS

Quoting from the Spectre paper [Kocher et al., 2019]:

> **Variant 1: Exploiting Conditional Branches.** In this variant of Spectre attacks, the attacker mistrains the CPU's branch predictor into mispredicting the direction of a branch, causing the CPU to temporarily violate program semantics by executing code that would not have been executed otherwise.

SPECULATIVE TYPE CONFUSION

Misspeculation makes the victim execute with some variables holding values of the wrong type, and thereby leak memory content

SPECULATIVE TYPE CONFUSION - EXAMPLE

Speculation:
Type confusion

```
void syscall_helper(struct Base* obj) {
    if (obj->type == TYPE1) {
        struct Type1* o = (struct Type1*) obj;
        leak(o->value);
    }
    if (obj->type == TYPE2) {
        ...
    }
}
```

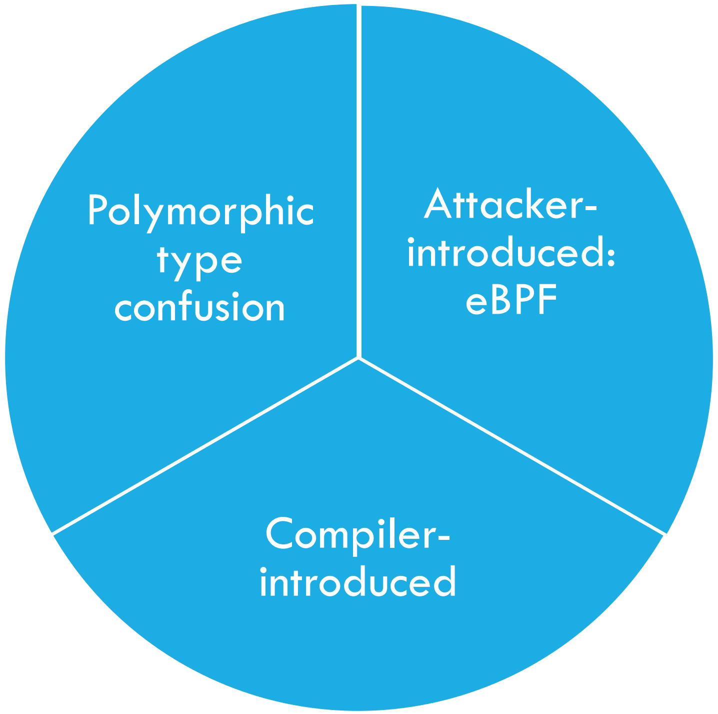
```
struct Base {
    enum Type type;
};

struct Type1 {
    struct Base base;
    ...
    uint32_t value;
};
```

CONTRIBUTIONS

Observation: speculative type confusion may be much more prevalent than previously hypothesized.

We analyzed the Linux kernel, looking for speculative type confusion.

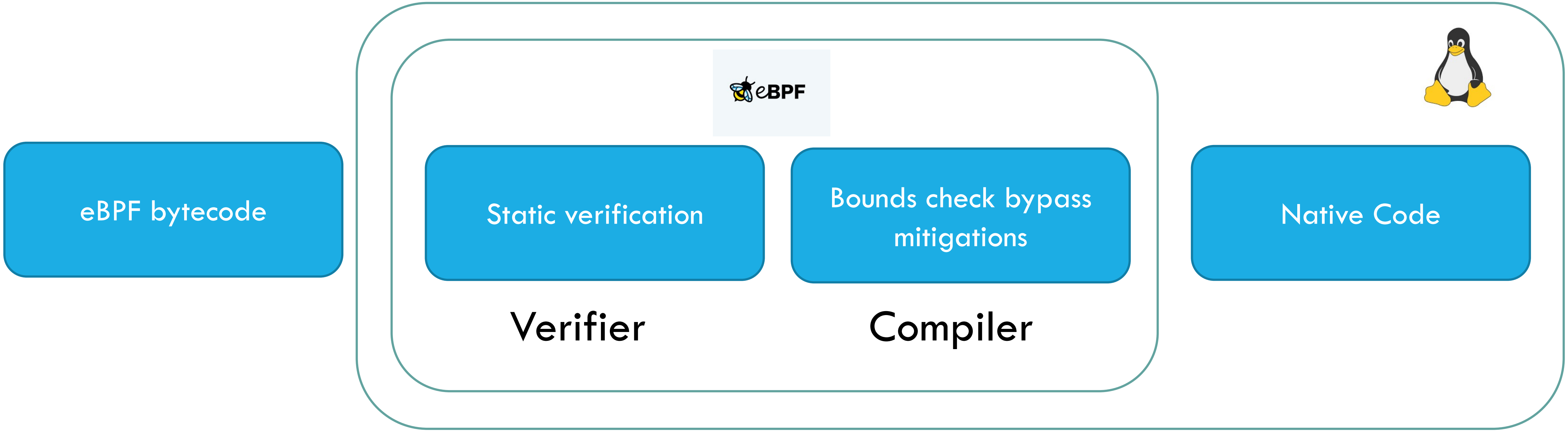
Found new types of speculative type confusion.



EBPF: SPECULATIVE TYPE CONFUSION

EBPF

Linux subsystem, enabling user-defined programs in kernel



EBPF VERIFIER VULNERABILITY

```
r0 = *(u64 *)(r0)
A: if r0 != 0x0 goto B
          r6 = r9
B: if r0 != 0x1 goto D
          r9 = *(u8 *)(r6)
C:        r1 = M[(r9 & 1) * 512]
D:...
```

Flows considered by eBPF verifier

r0 == 0

```
r0 = *(u64 *)(r0)
A: if r0 != 0x0 goto B
          r6 = r9
B: if r0 != 0x1 goto D
          r9 = *(u8 *)(r6)
C:        r1 = M[(r9 & 1) * 512]
D:...
```

r0 == 1

```
r0 = *(u64 *)(r0)
A: if r0 != 0x0 goto B
          r6 = r9
B: if r0 != 0x1 goto D
          r9 = *(u8 *)(r6)
C:        r1 = M[(r9 & 1) * 512]
D:...
```

otherwise

```
r0 = *(u64 *)(r0)
A: if r0 != 0x0 goto B
          r6 = r9
B: if r0 != 0x1 goto D
          r9 = *(u8 *)(r6)
C:        r1 = M[(r9 & 1) * 512]
D:...
```

EBPF VERIFIER VULNERABILITY

```
// r0 = ptr to an array entry (verified != NULL)
// r6 = ptr to stack slot (verified != NULL)
// r9 = scalar value controlled by attacker
```

```
r0 = *(u64 *)(r0)
A: if r0 != 0x0 goto B
        r6 = r9
B: if r0 != 0x1 goto D
        r9 = *(u8 *)(r6)
C:      r1 = M[(r9 & 1) * 512]
D:...
```

Predicted taken (A: if r0 != 0x0 goto B)

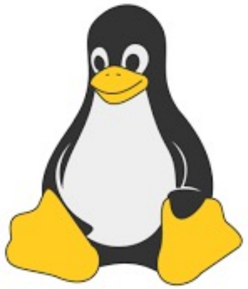
Predicted taken (B: if r0 != 0x1 goto D)

```
if r0 == 0x0 and r0 == 0x1
    r6 = r9
    r9 = *(u8 *)(r6)
    r1 = M[(r9 & 1) * 512]
```

Speculative flows are not verified

TRAINING MUTUALLY EXCLUSIVE BRANCHES

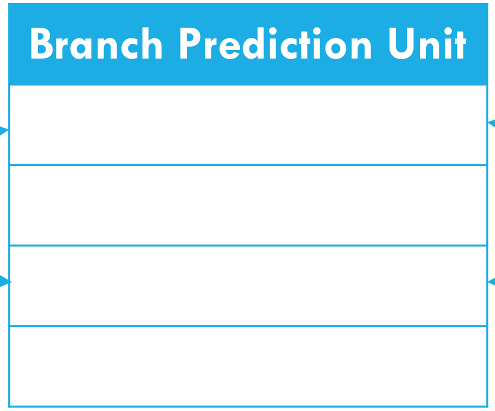
Unprivileged process can read arbitrary memory addresses at a rate of ~6.5 KB/sec



Shadow gadget

Can both be taken

```
A: if r0 != 0x0 goto B
       r6 = r9
B: if r0 != 0x0 goto D
       r9 = *(u8 *)(r6)
```



Mutually exclusive

```
A: if r0 != 0x0 goto B
       r6 = r9
B: if r0 != 0x1 goto D
       r9 = *(u8 *)(r6)
```

Manipulating the branch predictor (details in the paper)

COMPILER INTRODUCED SPECULATIVE TYPE CONFUSIONS

COMPILERS MIGHT CREATE SPECULATIVE TYPE CONFUSION

Innocent looking code is compiled in a way that inroduces vulnerability

Compiler reasoning:
Branches are mutually exclusive

(trusted) ptr argument held in x86 register %rsi

Attacker-controlled

```
void syscall_helper(cmd_t* cmd, char* ptr, long x)
{
    cmd_t c = *cmd;
    if (c == CMD_A)
    {
        ... // %rsi = x
    }
    if (c == CMD_B)
    {
        y = *ptr; // y = *%rsi
        z = array[y * 4096];
    }
    // ...
}
```

code during which x moves to %rsi

CAN WE FIND IT IN THE WILD?

Binary level analysis of Linux

Focused on system calls, which have well-defined user-controlled interface

The leakage mechanism is out of scope: aiming at finding speculative attacker-controlled memory dereference

compiler	flags	# vulnerable syscalls
GCC 9.3.0	-Os	20
GCC 9.3.0	-O3	2
GCC 5.8.2	-Os	0
GCC 5.8.2	-O3	0

A pattern in syscalls the receive an optional untrusted user pointer (details in paper)

SPECULATIVE POLYMORPHIC TYPE CONFUSION

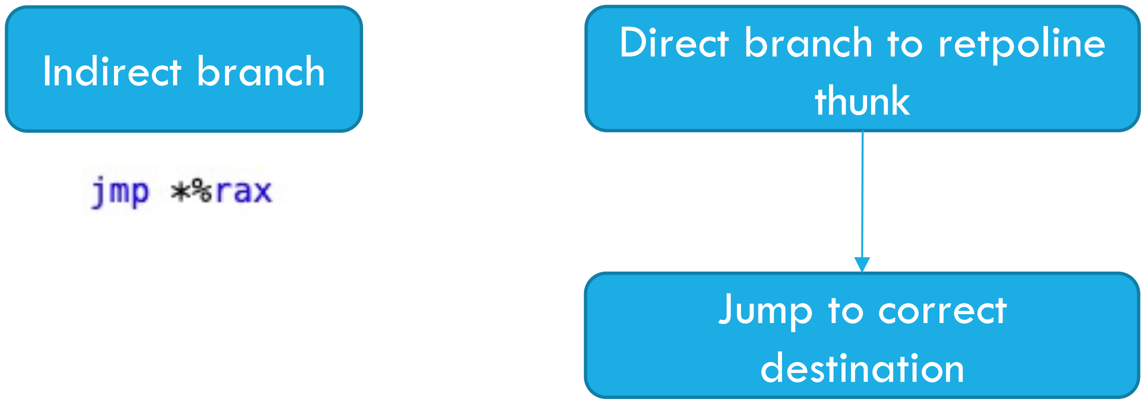
SPECTRE V2 MITIGATIONS

Spectre v2 exploits misprediction of indirect branch target addresses

Retpolines: block indirect branch prediction

Optimization: restrict speculation to valid targets [Linux, Amit et al., 2019]

Might create speculative type confusion vulnerabilities




```
# %rax = branch target
cmp $0xXXXXXXXX, %rax # target1?
jz $0xXXXXXXXX
cmp $0xYYYYYYYY, %rax # target2?
jz $0xYYYYYYYY
...
jmp ${fallback} # jmp to retpoline thunk
```

SPECULATIVE POLYMORPHIC TYPE CONFUSION

```
struct Common { void (*foo) (void*); };
struct A { struct Common common; char* ptr; };
struct B { struct Common common; long user_controlled_scalar; };
```

```
void some_code_path(struct Common* common) {
    /* ... */
    common->foo(common);
}
```

```
void foo_A(struct Common* common) {
    char x = *((struct A*) common)->ptr;
    leak(x);
}
```

B→user_controlled_scalar

ANALYSIS

Analysis

- Linux code analysis - looking at ways in which polymorphism can lead to speculative type confusion

Results

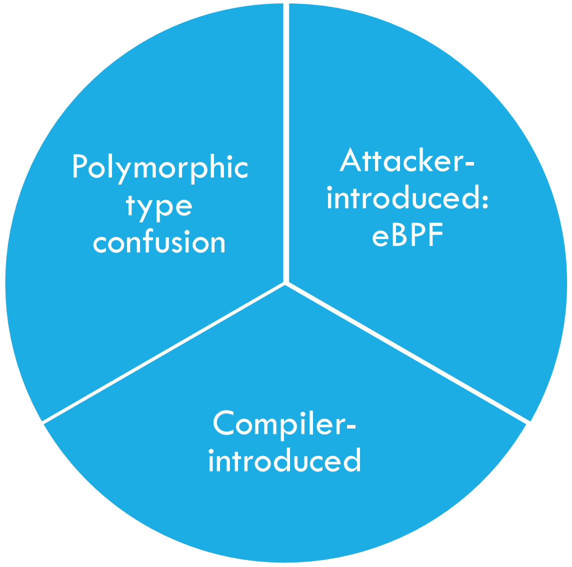
- Thousands - flagged potentially vulnerable
- Hundreds - ”array indexing” instances
- All - limited speculation window or limited control on user value

Conclusion

- Were a conditional branch-based mitigation used instead of retpolines, the kernel’s security would be on shaky ground

SUMMARY

Analysis



Conclusion

Speculative type confusion is prevalent

Discussion

Mitigation is difficult and requires rethinking

(Discussion in paper)

ofekkir@gmail.com

mad@cs.tau.ac.il