Protecting C++ Dynamic Dispatch Through VTable Interleaving

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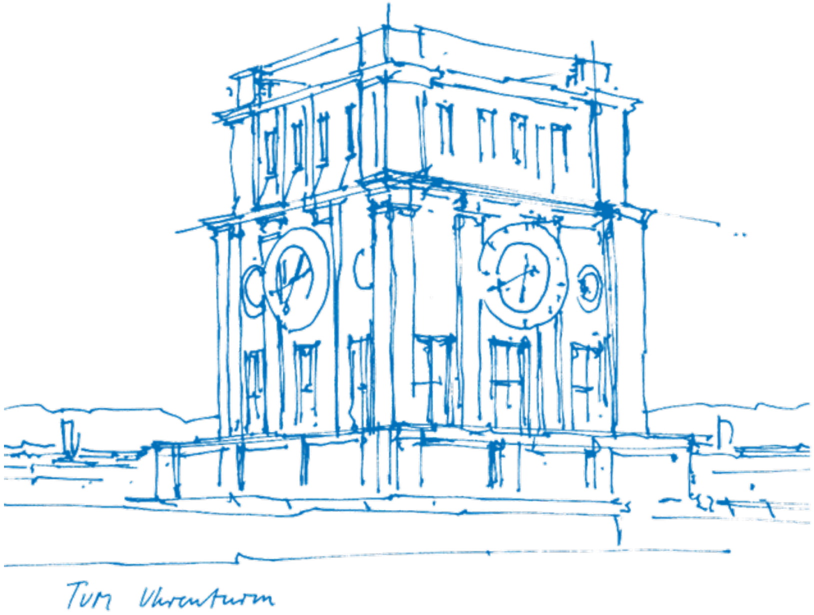

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Outline

Dynamic Dispatch in C++
- Virtual Functions in C++

VTable Hijacking

Protecting Dynamic Dispatches
- VTable Ordering
- VTable Interleaving
- Multiple Inheritance
- Optimization

Benchmarks

Comparison with other Approaches

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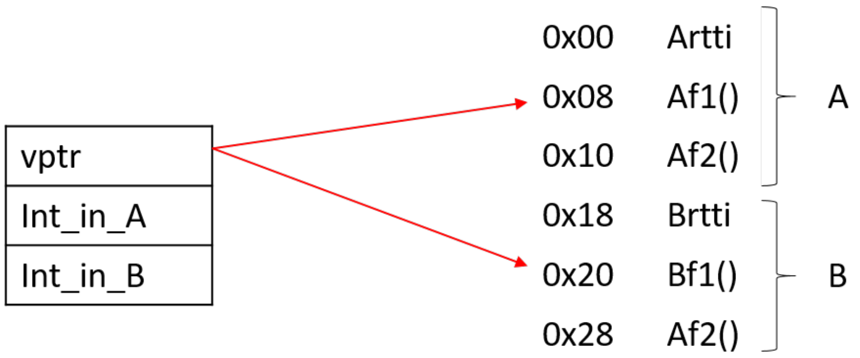
Virtual Functions in C++

```
class A {
        public:
        void f0() {}
        virtual void f1() {}
        virtual void f2() {}
        int int_in_A;
};

class B : public A {
        public:
        void f1() {} //override f1
        int int_in_B;
};
```

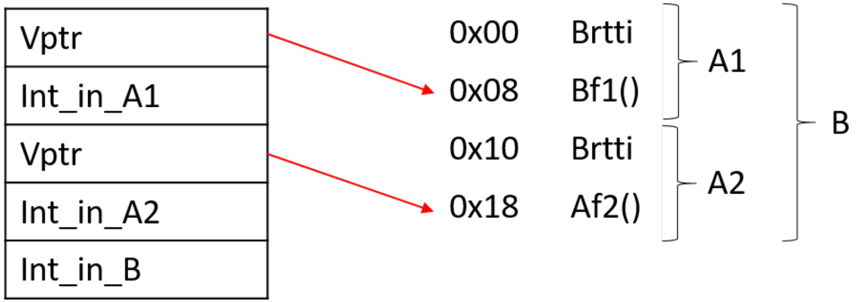


Multiple Inheritance

```
class A1 {
        public:
        void f0() {}
        virtual void f1() {}
        int int_in_A1;
};

class A2 {
        public:
        virtual void f2() {}
        int int_in_A2;
};

class B : public A1, public A2 {
        public:
        void f1() {} //override f1
        int int_in_B;
};
```



VTable Hijacking

- Exploting memory corruption, for example use after free.
- VTables are stored in read only memory, vptr in writable memory.
- Changing vptr to take control over program flow.
- Either code injection or reuse attacks possible.

Assumptions made by the authors:

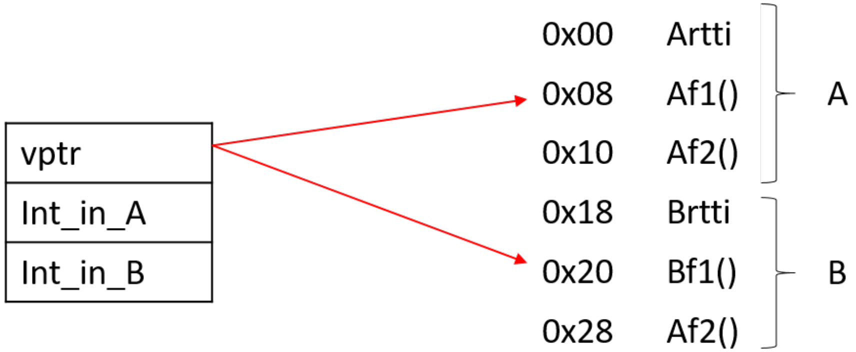
- Hacker capable of modifying the Heap.
- Registers are safe.

Protecting Dynamic Dispatches

- Most strategies use **Inline Reference Monitors** (IRMs) before dynamic dispatch calls.
- Example for semantic of IRMs:

$$vptr \in \{0x08, 0x20\} \tag{1}$$

⇒ Differences are in the implementation.



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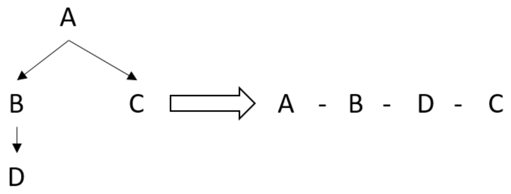
VTable ordering (OVT)

- Preorder traversal of the class hierarchy.
- Padding added, so that VTable addresses are 2^n Bytes aligned.
- Address point ranges are stored.
- Example[1]:




```
0x18  Artti      ]
0x20  Afoo       ]  A
0x28  <padding>
0x30  <padding>
0x38  Brtti      ]
0x40  Bfoo       ]  B
0x48  Bbar       ]
0x50  <padding>
0x58  Drtti      ]
0x60  Dfoo       ]  D
0x68  Bbar       ]
0x70  Dboo       ]
0x78  Crtti      ]
0x80  Afoo       ]  C
0x88  Cbaz       ]
```

Class	Start	End	Alignment
A	0x20	0x80	0x20
B	0x40	0x60	0x20
C	0x80	0x80	0x20
D	0x60	0x60	0x20

[1] Bounov, Kici, and Lerner 2016.

VTable Ordering (OVT)

- Simple range check and alignment check before dispatch call.

Problems of VTable Ordering:

- Takes more memory than necessary because of padding.
- Especially an issue in systems with limited memory (embedded systems).

⇒ VTable Interleaving

VTable Interleaving (IVT)

- Interleaving of different VTables, by making them sparse, to save memory.
- Saving different functions offsets.
- Example[2]:

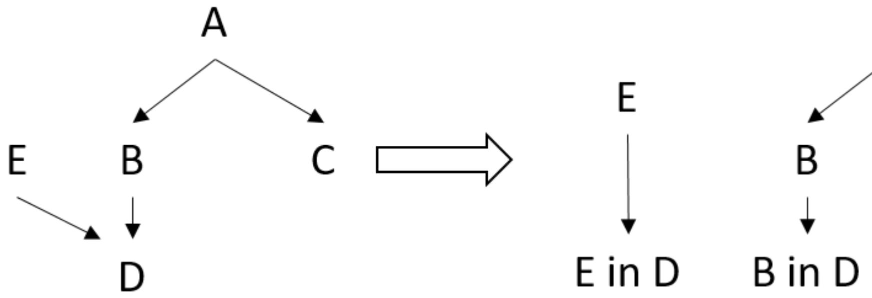
```
      A      B      D      C
0x00  Artti
0x08         Brtti
0x10                Drtti
0x18                       Crtti
0x20  Afoo
0x28         Bfoo
0x30                Dfoo
0x38                       Afoo
0x40         Bbar
0x48                Bbar
0x50                Dboo
0x58                       Cbaz
```

VTable Entry	Old Offset	New Offset
rtti	-0x8	-0x20
foo	0	0
bar	0x8	0x18
boo	0x10	0x20
baz	0x8	0x20

[2] Bounov, Kici, and Lerner 2016.

Handling Multiple Inheritance

- Multiple Inheritance can be decomposed into several single inheritances.
- Each single inheritance is managed individually.



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Implementation of IRMs

- Checking necessary if $vptr \in [a, b]$ and $vptr \mod 2^n = 0$.

Trivial implementation:

```
cmp $vptr, $a
jlt FAIL
cmp $vptr, $b
jgt FAIL
and $vptr,1111...n
cmp $vptr, 0
jne FAIL
... ;Success
```

Enhanced implementation:

```
$diff = $vptr - $a
$diffR = rotr $diff,n
cmp $diffR, ($b-$a) >> n
jgt FAIL
... ;Success
```

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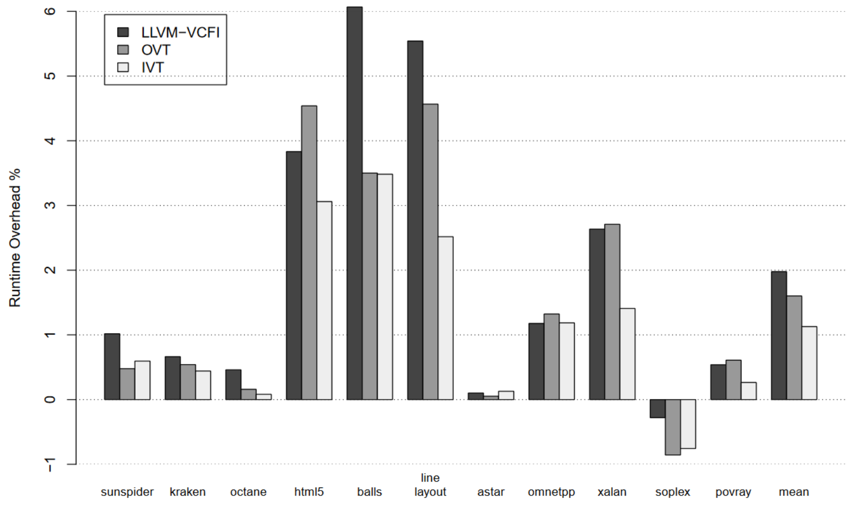
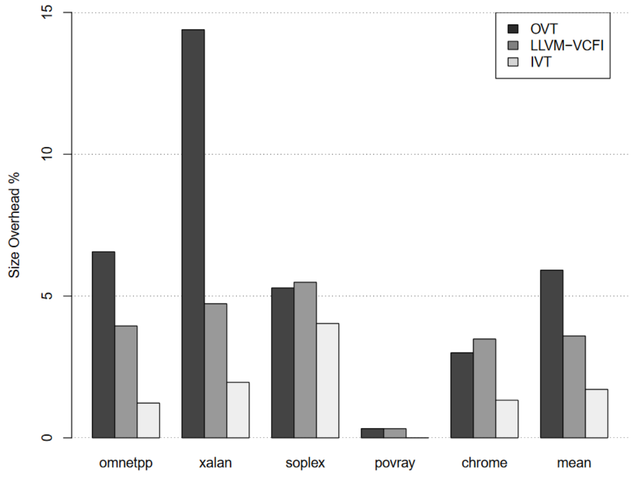
Benchmarks

- Implemented approaches into the LLVM compiler.

Runtime overhead[3]:



Binary size overhead[4]:



[3] Bounov, Kici, and Lerner 2016.
[4] Bounov, Kici, and Lerner 2016.

Other Approaches

- Other compiler based techniques (SafeDispatch[5], VTV[6]).
  → Similar runtime and binary overhead.
- General CFI which protect all control transfers (also normal function pointers and returns).
  → Bigger runtime overhead.

[5] Jang, Tatlock, and Lerner 2014.
[6] Tice et al. 2014.

References

- Bounov, D., R. G. Kici, and S. Lerner (2016). “Protecting C++ Dynamic Dispatch Through VTable Interleaving.”. In: *NDSS*.
- Jang, D., Z. Tatlock, and S. Lerner (2014). “SafeDispatch: Securing C++ Virtual Calls from Memory Corruption Attacks.”. In: *NDSS*.
- Tice, C. et al. (2014). “Enforcing Forward-Edge Control-Flow Integrity in GCC & LLVM.”. In: *USENIX Security Symposium*, pp. 941–955.