a simple way to check returns?

observation: places we return to usually after call instructions

exception: 'tail calls' — we'll ignore this for now

we could check for one...

replace return with:

```
return address ← PopFromStack()
if DecodeInstruction(return address - 5) == "call thisFunction":
    goto return address
else:
    CRASH
```

a simple way to check returns?

more practical: `label $ID` instruction with encoding:

TWO-BYTE-OPCODE FOUR-BYTE-CONSTANT

(real version: can reuse some sufficiently nop-like instruction)

```
...
    call foo
    label $0xf19279bb // random ID for function foo
...
```

```
foo:
...
    pop %rdx                // RDX <- return address
    cmp $0xf19279bb, 2(%rdx)
    jne CRASH
    jmp *%rdx
```

looks like canaries? (1)

what attacks does this stop that canaries don't?

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ID does not need to be secret!

- assuming non-executable writeable memory, no!
- attacker can't write new places for return to go

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avoids "stack pivoting" attacks

- attacker can't make stack pointer point to wrong part of stack...
- and expect it to return differently

looks like canaries? (2)

what attacks does this NOT stop that canaries don't?

example: SortList can be called from `Innocent`,
then return from `Dangerous`

> assumption: attacker can overwrite return address at right time
> (running on another core? problem with sortFunc1?)

```
void Innocent() {
  ...
  SortList(someList1,
           sortFunc1);
  Use(someList1);
  ...
}
```

```
void Dangerous() {
  ...
  SortList(someList2,
           sortFunc2);
  UseDangerously(someList2);
  ...
}
```

checking a VTable call

```
class A { public:
  virtual void bar() { ... }
};
class B : public A { public:
  void bar() { ... }
};
void example(A *obj) {
  obj->bar();
}
```

```
example:
  // rax <- vtable address
  movq (%rdi), %rax
  // rdx <- first vtable entry
  movq (%rax), %rax
  // call using vtable entry
  call *%rax
```

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example uses VTable to call method
target for memory corruption attacks
just like return addresses
so, apply same strategy

checking a VTable call

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class A { public:
  virtual void bar() { ... }
};
class B : public A { public:
  void bar() { ... }
};
void example(A *obj) {
  obj->bar();
}
```

```
A::bar():
  label $0xe0c5df0b
  ...
B::bar():
  label $0xe0c5df0b
  ...
```

```
example:
  // rax <- vtable address
  movq (%rdi), %rax
  // rdx <- first vtable entry
  movq (%rax), %rax
  // call using vtable entry
  call *%rax
```

```
example:
  movq (%rdi), %rax
  movq (%rax), %rax
  cmpq $0xe0c5df0b, 2(%rax)
  jne CRASH
  call *%rax
  ...
```

checking a VTable return

```
A::bar():
   label $0xe0c5df0b
   ...
   pop %rdx // RDX <- return address
   cmp $0x64a0cfe3, 2(%rdx)
   jne CRASH
   jmp *%rdx
B::bar():
   label $0xe0c5df0b
   ...
   pop %rdx // RDX <- return address
   cmp $0x64a0cfe3, 2(%rdx)
   jne CRASH
   jmp *%rdx
```

```
example:
   movq (%rdi), %rax
   movq (%rax), %rax
   cmpq $0xe0c5df0b, 2(%rax)
   jne CRASH
   call *%rax
   label $0x64a0cfe3
   ret
```

if we want to use this label-checking on the return

calls through function pointers

```
typedef int (*CompareFnType)(const char*, const char*)
void SortFunction(const char **items, CompareFnType compare) {
    ...
    (*compare)(a, b);
    ...
}
```

here: call through explicitly passed function pointer

want to do the same thing we did for VTable calls

- all the compare functions have the same label
- all the returns form compare functions have the same label

yes, if we can somehow label all the compare functions

calls through function pointers

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CFI overhead

Abadi et al's 2004 paper:

- used label-based approach
- 0-45% time overhead on SPECcpu2000 benchmarks
- best: compression program
- worst: chess engine

Tice et al's 2014 paper (clang-style impl, sometimes in GCC, sometimes in Clang)

- could seperately enable different parts
- in tests on SPECcpu 2006 benchmarks:
- 0–10% slowdown for VTable dereference checks
  - but 20% without tuning
- 0-6% for other indirect call checking

looks like canaries? (2)

what attacks does this NOT stop that canaries don't?

example: SortList can be called from `Innocent`, then return from `Dangerous`

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> (running on another core? problem with sortFunc1?)

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}
```

```
void Dangerous() {
  ...
  SortList(someList2,
           sortFunc2);
  UseDangerously(someList2);
  ...
}
```

concept: labels and control flow graph

```
bool lt(int x, int y) {
    return x < y;
}

bool gt(int x, int y) {
    return x > y;
}

sort2(int a[], int b[], int len)
{
    sort( a, len, lt );
    sort( b, len, gt );
}
```

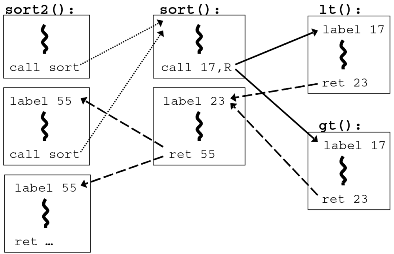


Figure 1: Example program fragment and an outline of its CFG and CFI instrumentation.

control flow graph

nodes = blocks of code

edges = *potential jump/call*

assigning labels: every in-edge needs to check same label at source

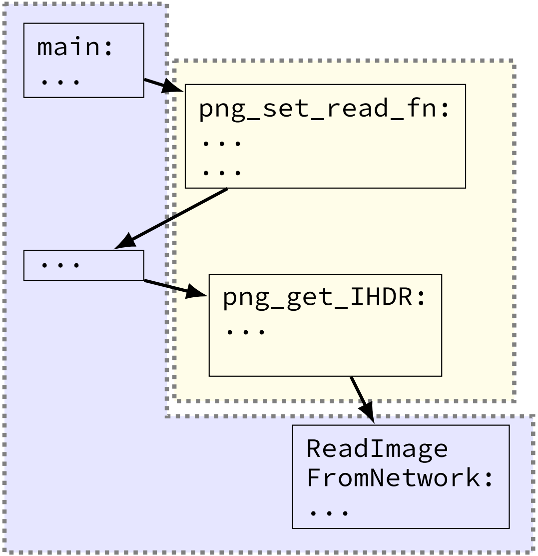
figure from Abadi et al, "Control-Flow Integrity: Principles, Implementations and Applications" (CCS 2005)

library-crossing CFGs

main.c

```
#include <png.h>
void ReadImageFromNetwork(
    png_structp libpng_handle,
    unsigned char *bytes,
    size_t size
) { ...  }

int main() {
    /* init libpng */
    png_structp libpng_handle = ...;
    /* tell libpng how to read image data */
    png_set_read_fn(
        libpng_handle, ...,
        ReadImageFromNetwork
    )
    ...
    /* extract "header"
       information from image */
    png_get_IHDR(libpng_handle, ...)
    ...
}
```



CFGs will be imprecise

```
FunctionPtr p = functionA;
Example() {
  while (true) {
    ...
    if (SomethingComplicated()) {
      (*p)();
    } else if (SomethngElseComplicated()) {
      foo();
    }
    ...
  }
}
foo() {
  ...
  if (AnotherComplexThing()) {
    p = functionB;
  }
}
```

finding possible function pointer values?

given call using function pointers

how do we find the **legitimate** possible values?

one high-level idea:

```
for each fptr constant X:
    PossibleValues[X] = {X}
for each fptr variable X:
    PossibleValues[X] = empty set
until PossibleValues stops changing:
    for each fptr assignment LHS=RHS:
        for each fptr variable/constant Y
                that RHS could evaluate to:
            PossibleValues[LHS] = Union(
                PossibleValues[LHS],
                PossibleValues[Y]
            )
```

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given call using function pointers

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        for each fptr variable/constant Y
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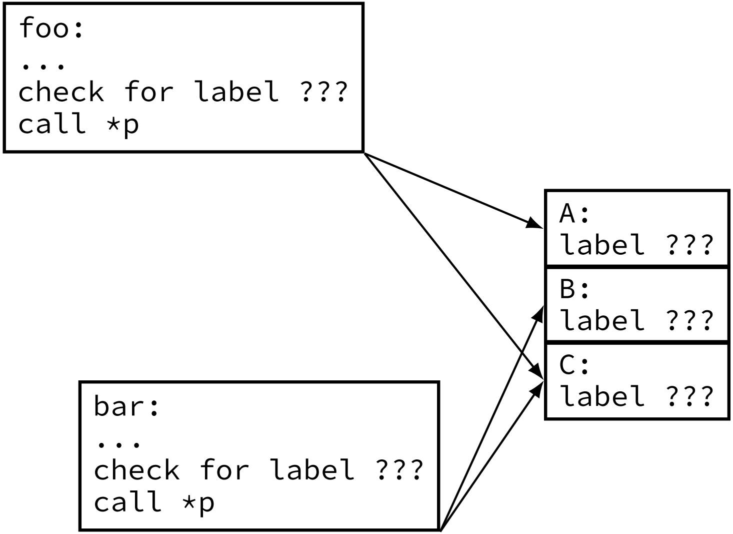
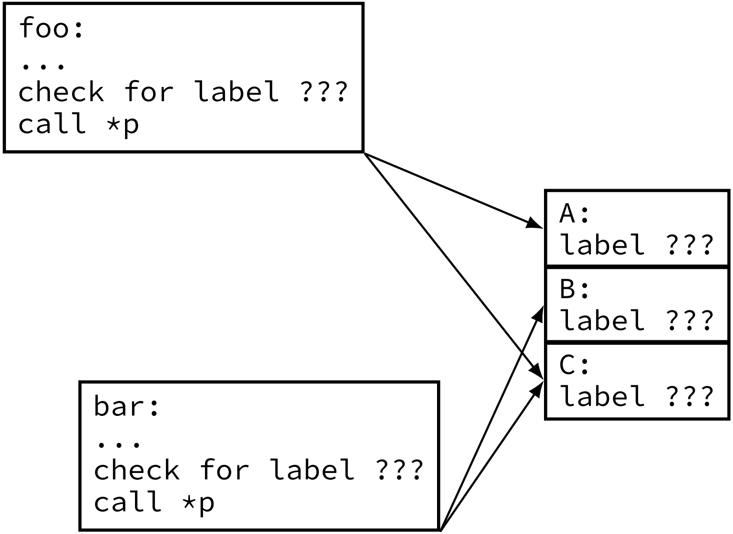
                PossibleValues[LHS],
                PossibleValues[Y]
            )
```

labels aren't enough?



labels aren't enough?



two possible fixes:

make checks scan for multiple labels (more overhead)

allow foo to call B and bar to call A (easier to attack)

clang's CFI implementation

`https://clang.llvm.org/docs/ControlFlowIntegrity.html`

also `https://www.usenix.org/conference/usenixsecurity14/technical-sessions/presentation/tice`

only checks calls via VTables or function pointers

stable implementation requires libraries compiled with support

label information is placed in separate data structure

- looked up using function or VTable addresses

trick: keep functions in one region of memory

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only checks calls via VTables or function pointers

stable implementation requires libraries compiled with support

label information is placed in separate data structure

looked up using function or VTable addresses

trick: keep functions in one region of memory

clang idea for CFI indirect calls

```
start_funcs_with_two_string_args:
.align 8
compare_alpha:
  jmp real_compare_alpha
.align 8
run_command_with_arg:
  jmp real_run_command_with_arg
.align 8
print_two_strings:
  jmp real_print_two_strings
.align 8
move_file:
  jmp real_move_file
.align 8
compare_reverse_alpha:
  jmp real_compare_reverse_alpha
end_funcs_with_two_sting_args:
```

functions of same type placed together

every func's address is multiple of 8

clang idea for CFI indirect calls

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start_funcs_with_two_string_args:
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  jmp real_compare_alpha
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  jmp real_move_file
.align 8
compare_reverse_alpha:
  jmp real_compare_reverse_alpha
end_funcs_with_two_sting_args:
```

check pseudocode:
round fptr to multiple of 8
if fptr $<$ start or fptr $>$ end:
    CRASH
allowed $\leftarrow$ [1,0,0,0,1]
    'mask' for compare funcs
offset $\leftarrow$ fptr - start
if bit (offset/8) of allowed
    is not set:
    CRASH

clang idea for VTables

check VTable element address instead of function address

otherwise

- place all VTables for related classes together
- check start/end address for VTables
- bit mask indicating which VTable entries are okay for call

CFI prevents?

```
class Foo { public:
    virtual void f() { }
};
class Bar : public Foo { public:
    virtual void f() { g(1); }
};
class Quux : public Foo { public:
    virtual void f() { }
};
void g(int x) {
    if (x == 0) { danger(); }
}
int h(int x) { return 0; }
int (*ptr)(int) = &h;
```

with clang's CFI, which likely can end up calling `danger()` if an attacker can first write to arbitrary memory locations?

A. `(*ptr)(1);`

B. `(*ptr)(0);`

C. `Foo *q = attacker_controlled(); q->f()`

CFI prevents?

```
class Foo { public:
    virtual void f() { }
};
class Bar : public Foo { public:
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void g(int x) {
    if (x == 0) { danger(); }
}
int h(int x) { return 0; }
int (*ptr)(int) = &h;
```

with clang's CFI, which likely can end up calling `danger()` if an attacker can first write to arbitrary memory locations?

A. `(*ptr)(1);`

B. `(*ptr)(0);` *if compiler thinks ptr set to g ever, yes; otherwise, no*

C. `Foo *q = attacker_controlled(); q->f()` *can only call*