hexhive

Memory corruption: Why we can’t have nice things

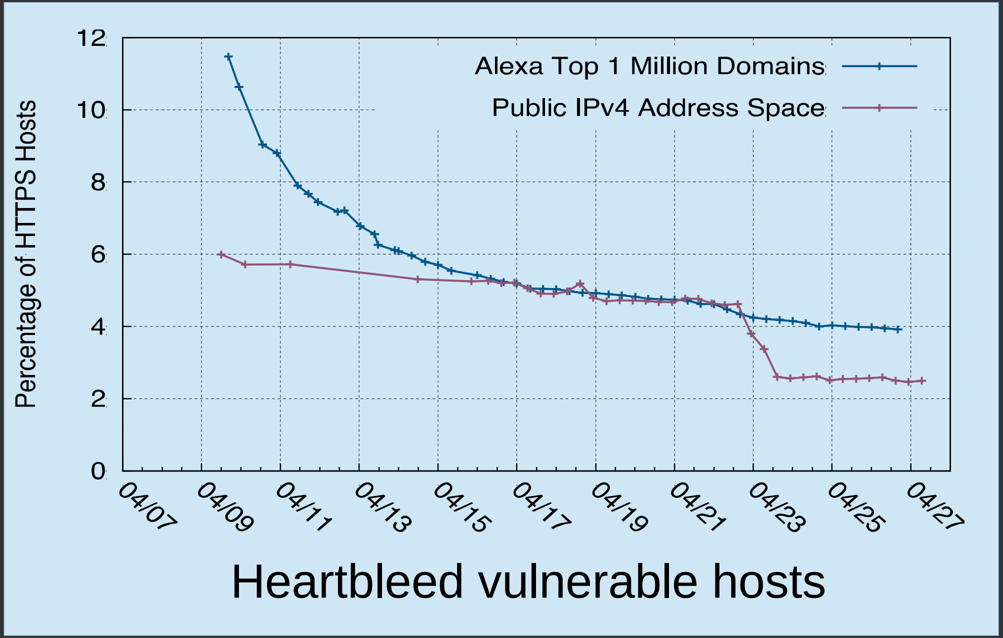
Mathias Payer (@gannimo)
http://hexhive.github.io

Software is unsafe and insecure

- Low-level languages (C/C++) trade type safety and memory safety for performance
  - Programmer responsible for all checks
- Large set of legacy and new applications written in C / C++ prone to memory bugs
- Too many bugs to find and fix manually
  - Protect integrity through safe runtime system

Heartbleed: patching observations

- 11% of servers remained vulnerable after 48 hours
- Patching plateaued at 4%
- Only 10% of vulnerable sites replaced certificates
- 15% of replaced cert's used vulnerable cryptographic keys



Heartbleed vulnerable hosts

Zakir Durumeric, James Kasten, J. Alex Halderman, Michael Bailey, Frank Li,
Nicholas Weaver, Bernhard Amann, Jethro Beekman, Mathias Payer, Vern Paxson,
"The Matter of Heartbleed", ACM IMC'14 (best paper)

Heartbleed: patching observations

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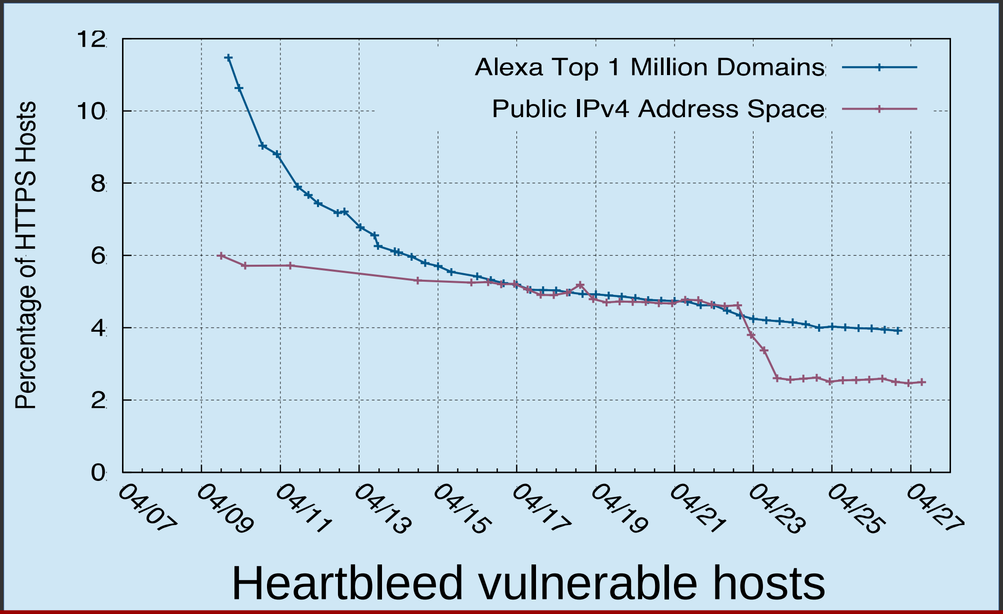


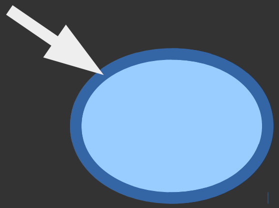
Heartbleed vulnerable hosts

Update process is slow, incomplete, and incorrect

Memory (Un-)safety

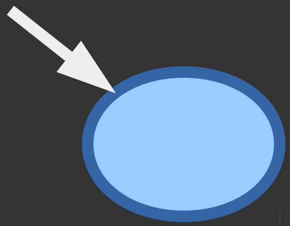
Memory (un-)safety: invalid dereference

Dangling pointer:
(temporal)



```
free(foo);
*foo = 23;
```

Out-of-bounds pointer:
(spatial)

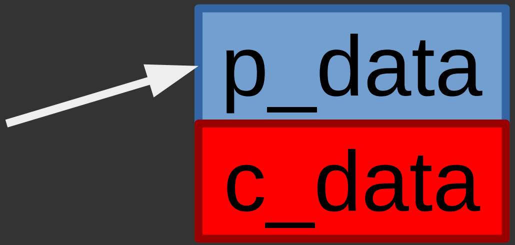


```
char foo[40];
foo[42] = 23;
```

Violation iff: pointer is read, written, or freed

Memory (un-)safety: type confusion

```
class P {
  int p_data;
};
class C: public P {
  int c_data;
};
P *Pptr = new P;
C *Cptr = static_cast<C*>(Pptr);
Cptr->c_data; // Type confusion!
```



p_data

c_data

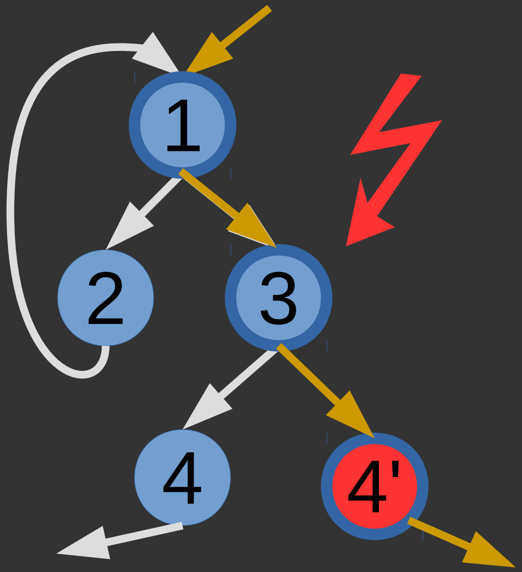
Two types of attack

- Control-flow hijack attack
  - Execute Code

- Data-only attack
  - Change some data used along the way

Let’s focus on code execution

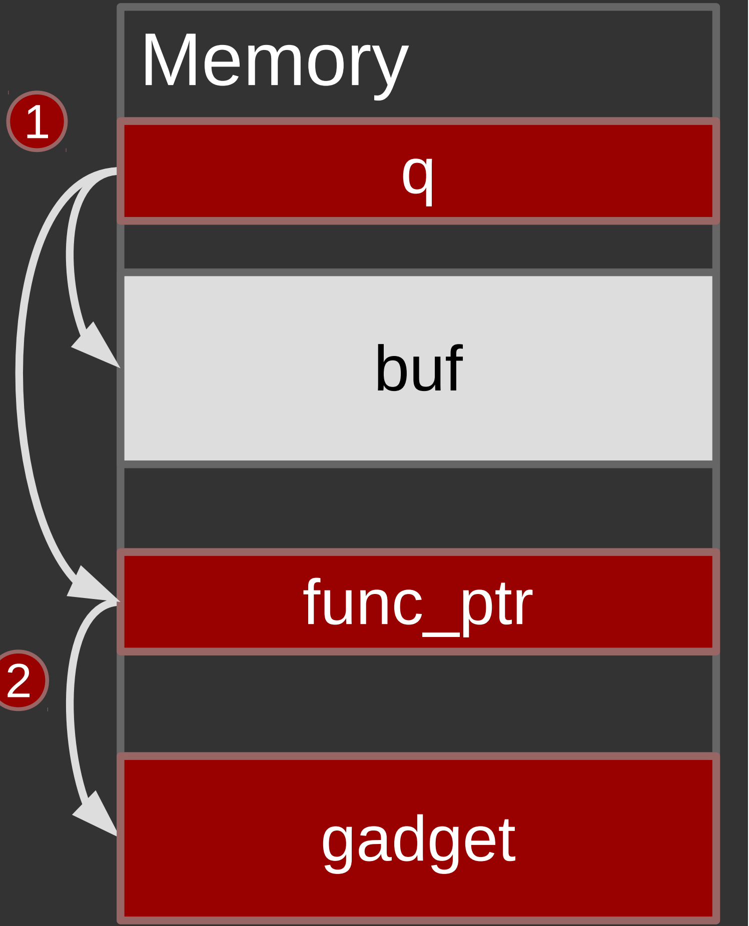
Control-flow hijack attack



- Attacker modifies ***code pointer***
  - Return address on the stack
  - Function pointer in C
  - Object’s VTable pointer in C++
- Control-flow leaves ***valid graph***
- Reuse existing code
  - Return-oriented programming
  - Jump-oriented programming

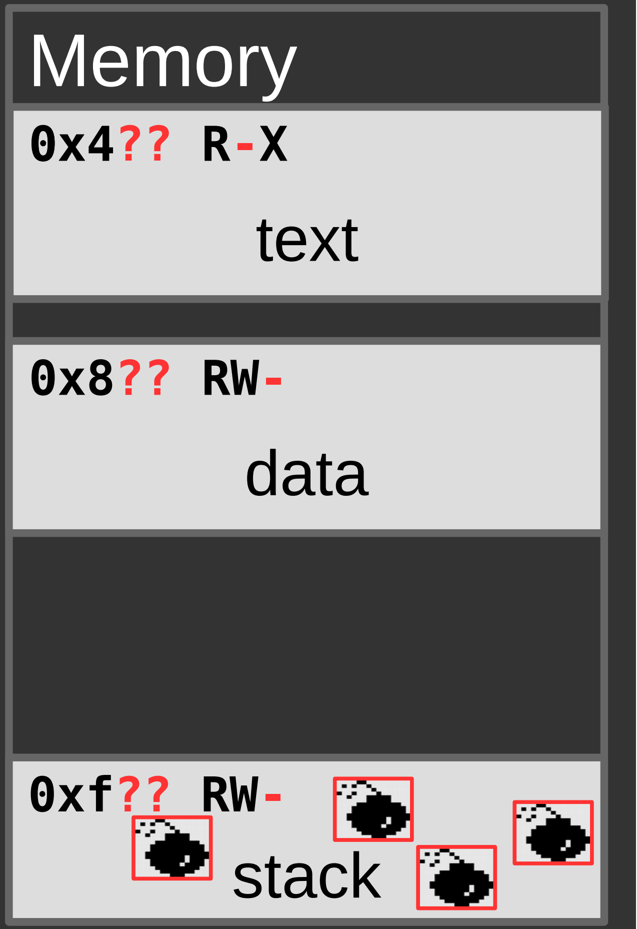
Control-Flow Hijack Attack

```
int vuln(int usr, int usr2){
  void *(func_ptr)();
1 int *q = buf + usr;
  …
  func_ptr = &foo;
  …
2 *q = usr2;
  …
3 (*func_ptr)();
}
```



Status of deployed defenses

- Data Execution Prevention (DEP)
- Address Space Layout Randomization (ASLR)
- Stack canaries
- Safe exception handlers



Status of deployed defenses

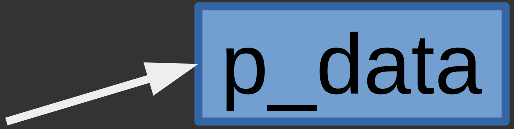
- ASLR and DEP only effective in combination
- ***Breaking*** ASLR enables code reuse
  - On desktops, information leaks are common
  - On servers, code reuse attacks have decreased
  - For clouds: CAIN attack at WOOT'15
  - For OS: Dedup Est Machine at S&P’16
  - For browsers: Flip Feng Shui at SEC’16

Type Safety,
Stack Integrity,
and
Control-Flow Integrity

Type Safety

```
class P {
  int p_data;
};
class C: public P {
  int c_data;
};
P *Pptr = new P;
C *Cptr =  check_cast<C*>(Pptr);
//          ^- Type confusion detected
```

Object	Type
Pptr (& of object)	P



Istvan Haller, Yuseok Jeon, Hui Peng, Mathias Payer, Cristiano Giuffrida, Herbert Bos, Erik van der Kouwe
“TypeSan: Practical Type Confusion Detection”. In CCS’16

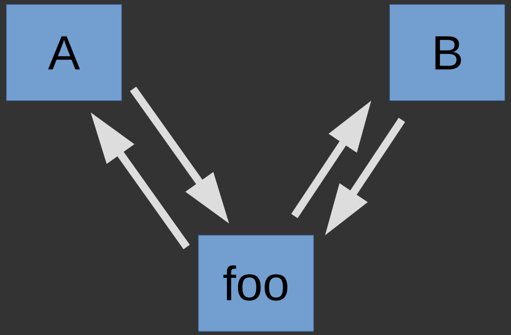
Stack integrity

- Enforce dynamic restrictions on return instructions
- Protect return instructions through shadow/safe stack

```
void a() {
  foo();
}

void b() {
  foo();
}

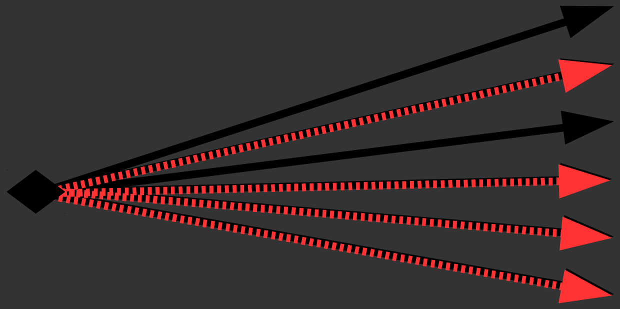
void foo();
```



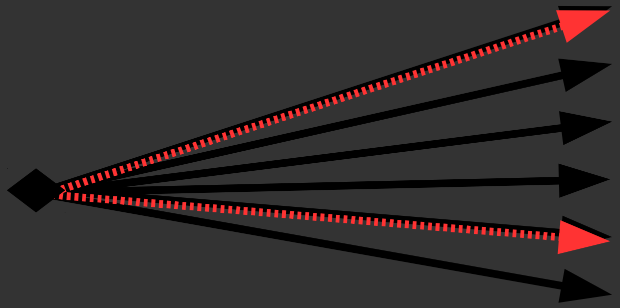
Volodymyr Kuznetsov, Laszlo Szekeres, Mathias Payer, George Candea, Dawn Song, R. Sekar
“Code Pointer Integrity”. In OSDI’14

Control-Flow Integrity (CFI)

```
CHECK(fn);
(*fn)(x);
```



```
CHECK_RET();
return 7;
```



Control-Flow Integrity (CFI)

```
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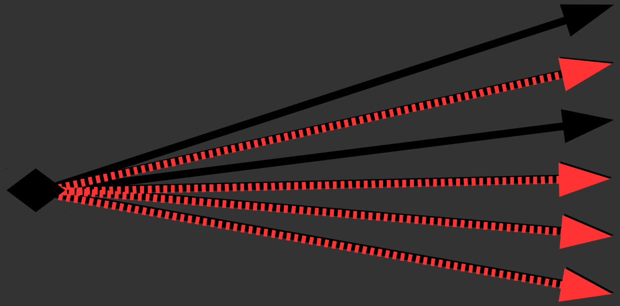


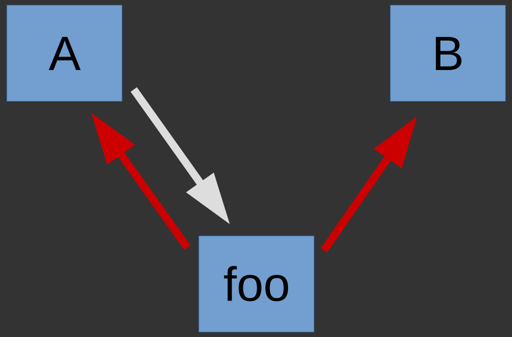
Attacker may write to memory, code ptrs. verified when used

CFI on the stack

```
void a() {
  foo();
}

void b() {
  foo();
}

void foo();
```



Novel
Code Reuse
Attacks

Control-Flow Bending

- Attacker-controlled execution along “***valid***” CFG
  - Generalization of non-control-data attacks
- Each individual control-flow transfer is valid
  - Execution trace may not match non-exploit case
- Circumvents static, fully-precise CFI

Nicholas Carlini, Antonio Barresi, Mathias Payer, David Wagner, and Thomas R. Gross
“Control-Flow Bending”, Usenix SEC'15

CFI's limitation: statelessness

- Each state is verified without context
  - Unaware of constraints between states

- Bending CF along valid states undetectable
  - Search path in CFG that matches desired behavior

Weak CFI is broken

- ***Out of Control: Overcoming CFI***
  Goektas et al., Oakland '14
- ***ROP is still dangerous: breaking modern defenses***
  Carlini et al., Usenix SEC '14
- ***Stitching the gadgets: on the effectiveness of coarse-grained CFI protection***
  Davi et al., Usenix SEC '14
- ***Size does matter: why using gadget-chain length to prevent code-reuse is hard***
  Goektas et al., Usenix SEC '14

Weak CFI is broken

Microsoft's Control-Flow Guard is an instance of a weak CFI mechanism

- ***Size does matter: why using gadget-chain length to prevent code-reuse is hard***
  Goektas et al., Usenix SEC '14

Strong CFI

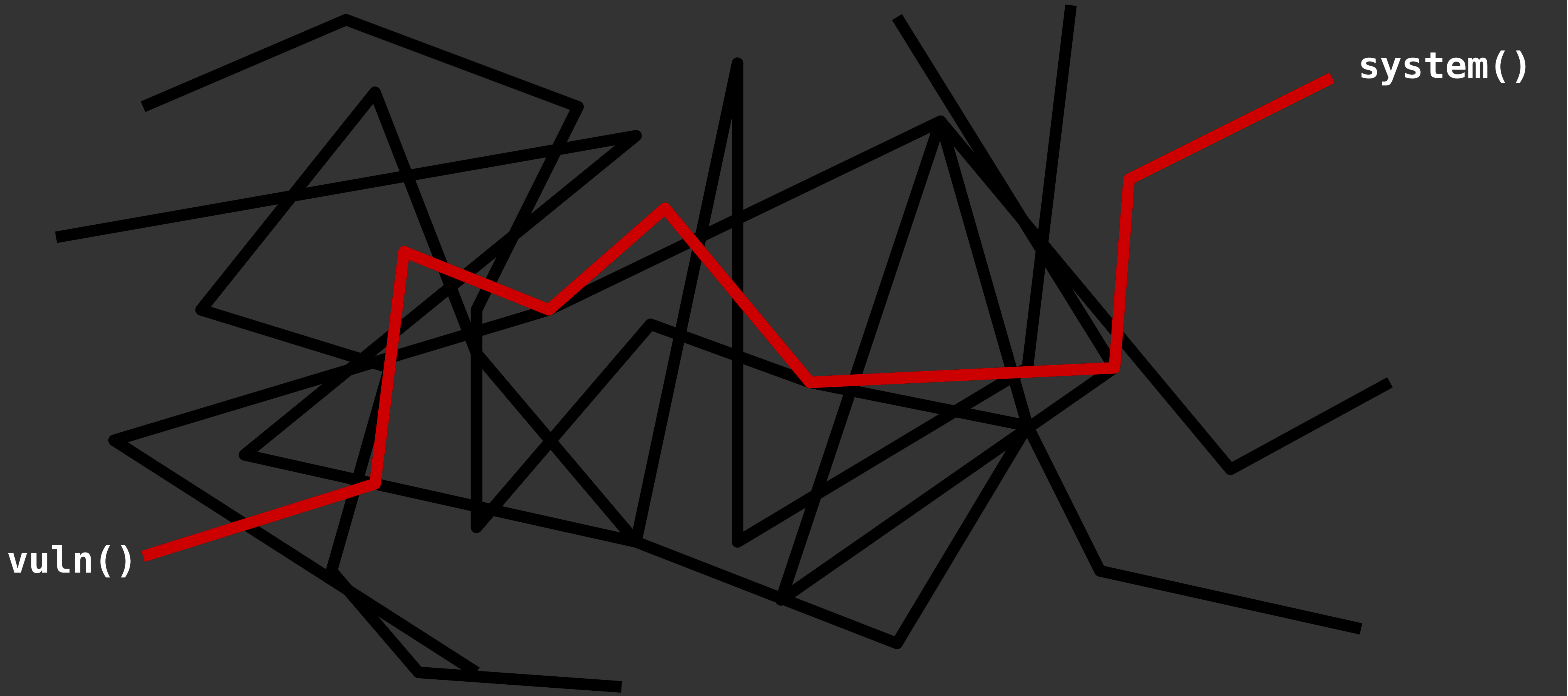
- Precise CFG: no over-approximation
- Stack integrity (through shadow stack)
- Fully-precise static CFI: a transfer is only allowed if some benign execution uses it

- How secure is CFI?
  - With and without stack integrity

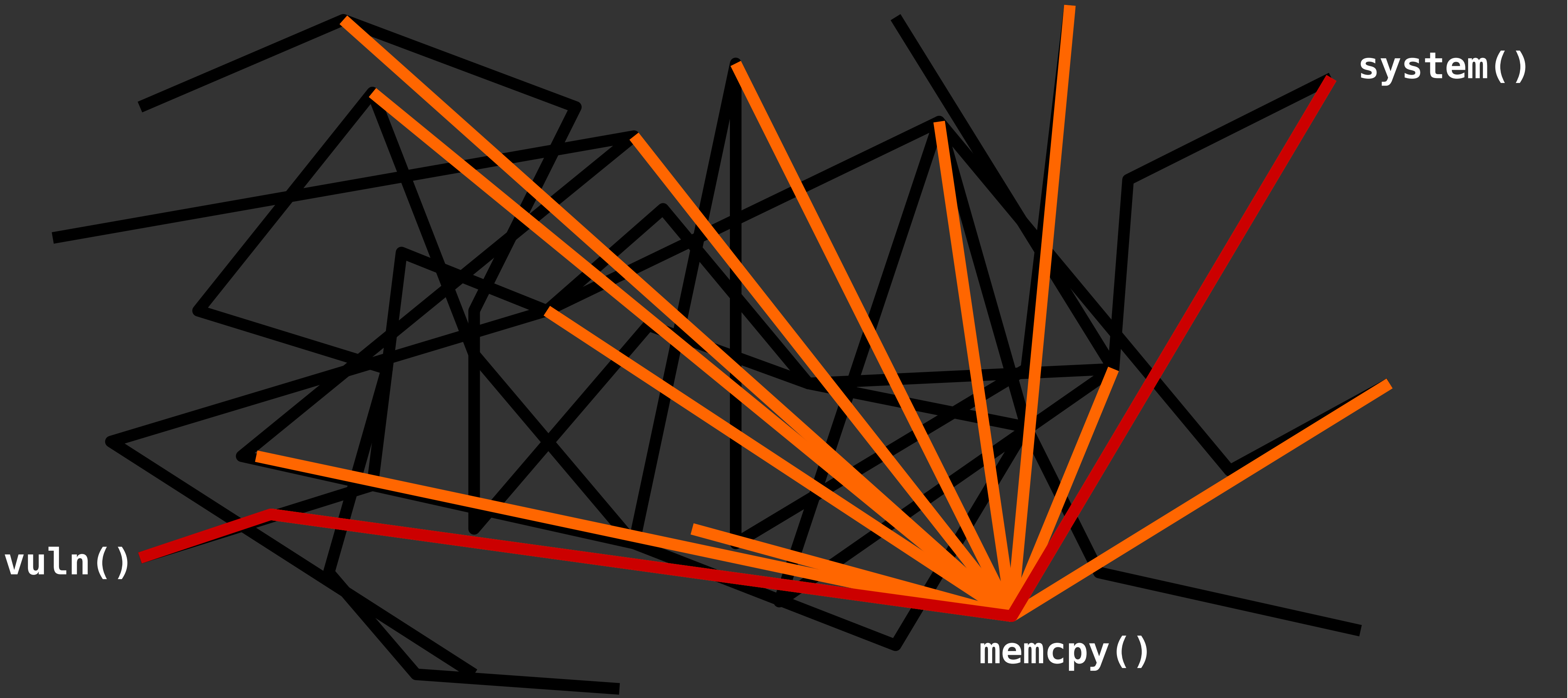
CFI, no stack integrity: ROP challenges

- Find path to **`system()`** in CFG.
- Divert control-flow along this path
  - Constrained through memory vulnerability
- Control arguments to **`system()`**

What does a CFG look like?

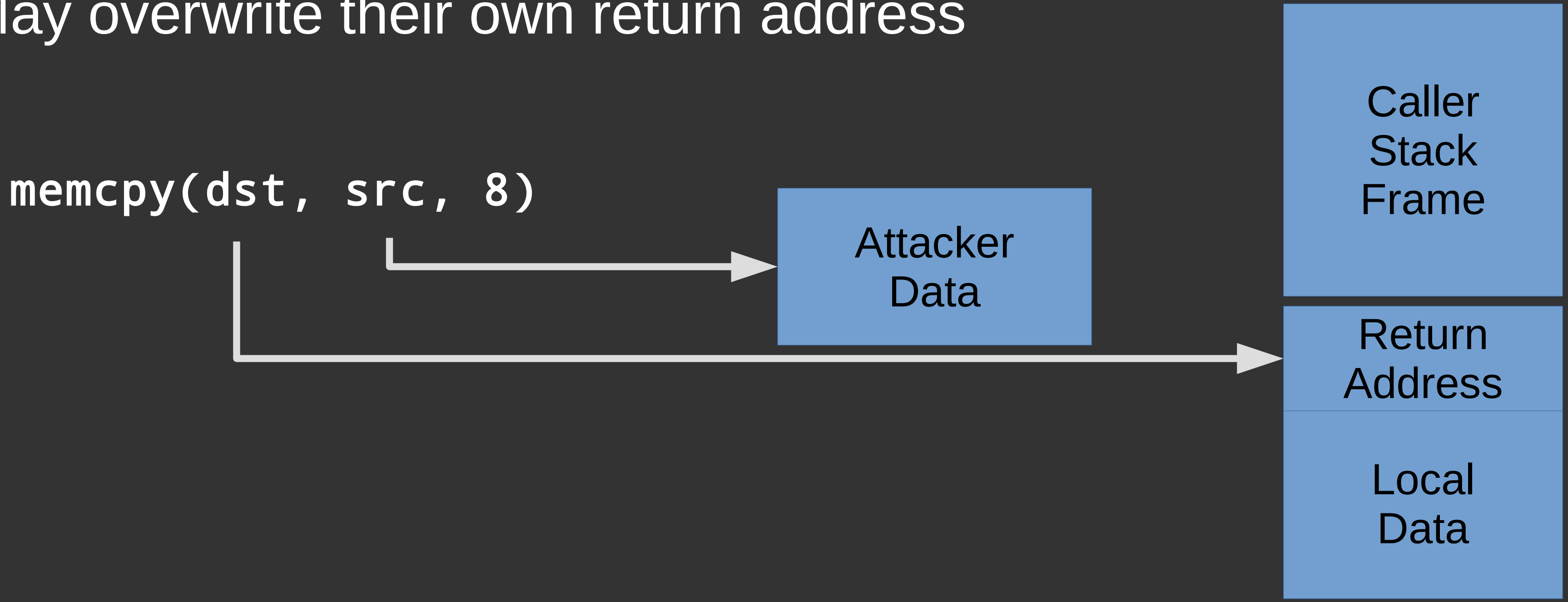


What does a CFG look like? Really?



Dispatcher functions

- Frequently called
- Arguments are under attacker's control
- May overwrite their own return address



```
memcpy(dst, src, 8)
```

Attacker Data

Caller Stack Frame

Return Address

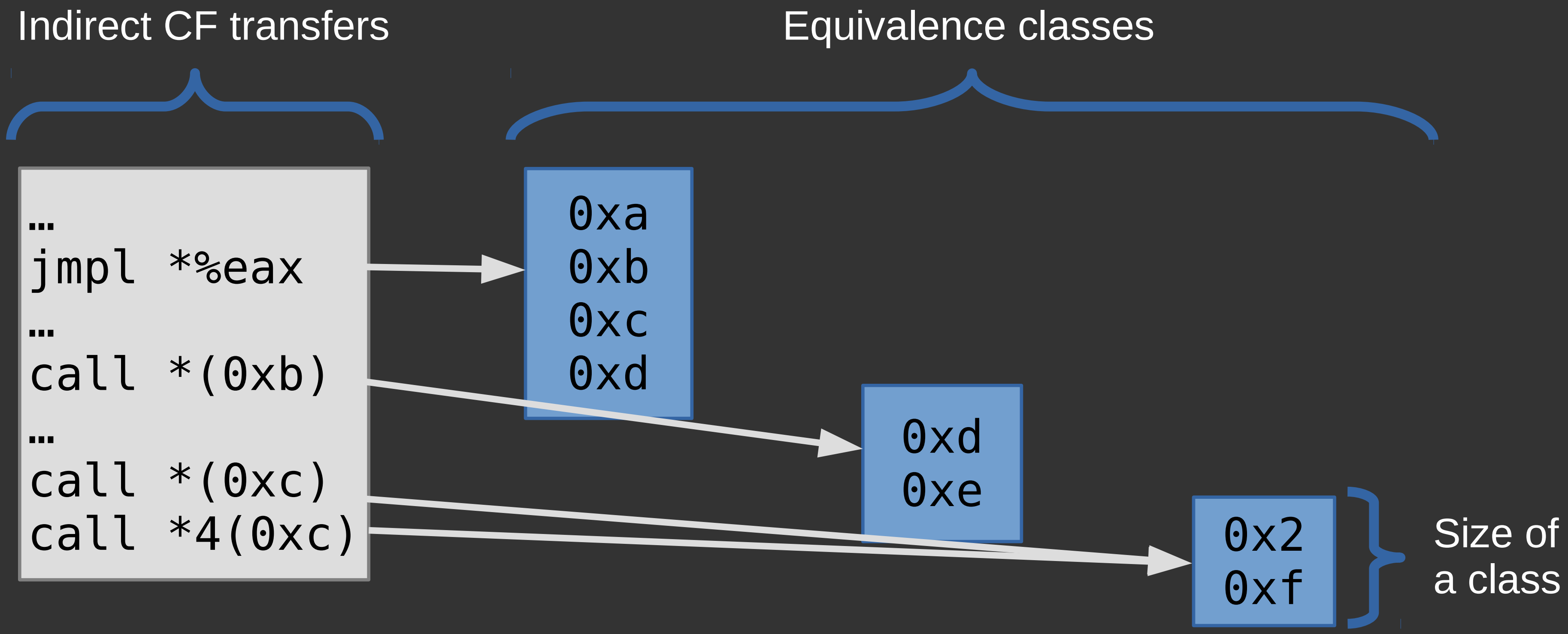
Local Data

Control-Flow Bending, no stack integrity

- CFI without stack integrity is broken
  - Stateless defenses insufficient for stack attacks
  - Arbitrary code execution in all cases

- Attack is program-dependent, harder than w/o CFI

Remember CFI?



```
…
jmpl  *%eax
…
call  *(0xb)
…
call  *(0xc)
call  *4(0xc)
```

Existing CFI mechanisms

CFI mechanism	Forward Edge	Backward Edge	CFB
Google IFCC	~	✗	🟥💣
MS CFG	~	✗	🟥💣
LLVM-CFI	✓	✗	🟥💣
MCFI/piCFI	✓	~	🟧💣
Lockdown	~+	✓	🟨💣

What if we have stack integrity?

- ROP no longer an option
- Attack becomes harder
  - Need to find a path through virtual calls
  - Resort to “restricted COOP”

- An interpreter would make attacks much simpler…
  - Lets automate!

`printf()`-oriented programming*

- Translate program to format string
  - Memory reads: %s
  - Memory writes: %n
  - Conditional: %.*d
- Program counter becomes format string counter
  - Loops? Overwrite the format specific counter
- Turing-complete domain-specific language

* Direct fame towards Nicholas Carlini, blame to me

Ever heard of brainfuck?

>	== dataptr++	%1$65535d%1$.*1$d%2$hn
<	== dataptr--	%1$.*1$d %2$hn
+	== *dataptr++	%3$.*3$d %4$hhn
-	== *datapr--	%3$255d%3$.*3$d%4$hhn
.	== putchar(*dataptr)	%3$.*3$d%5$hn
,	== getchar(dataptr)	%13$.*13$d%4$hn
[	== if (*dataptr == 0) goto ']'	%1$.*1$d%10$.*10$d%2$hn
]	== if (*dataptr != 0) goto '['	%1$.*1$d%10$.*10$d%2$hn

```
void loop() {
  char* last = output;
  int* rpc = &progn[pc];

  while (*rpc != 0) {
    // fetch -- decode next instruction
    sprintf(buf, "%1$.*1$d%1$.*1$d%1$.*1$d%1$.*1$d%1$.*1$d%1$.*1$d%1$.*1$d%1$.*1$d%2$hn",
      *rpc, (short*)(&real_syms));

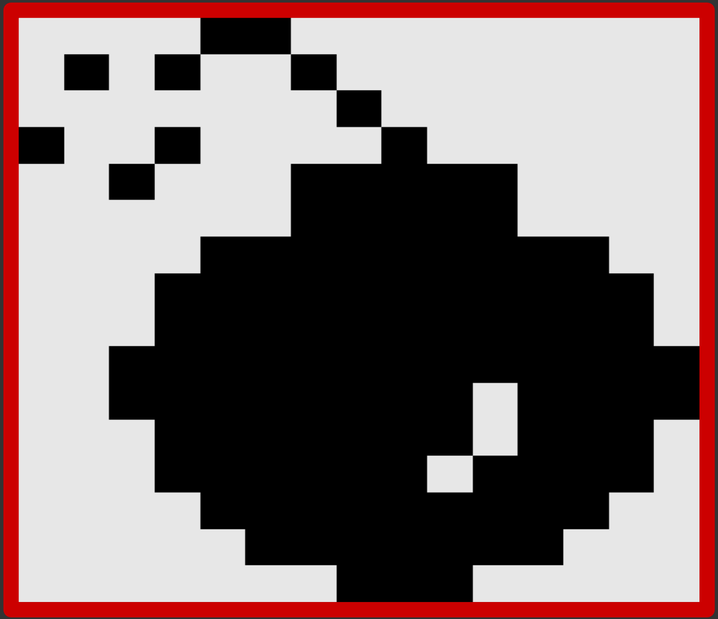
    // execute -- execute instruction
    sprintf(buf, *real_syms,
      ((long long int)array)&0xFFFF, &array, // 1, 2
      *array, array, output, // 3, 4, 5
      ((long long int)output)&0xFFFF, &output, // 6, 7
      &cond, &bf_CGOTO_fmt3[0], // 8, 9
      rpc[1], &rpc, 0, *input, // 10, 11, 12, 13
      ((long long int)input)&0xFFFF, &input // 14, 15
      );

    // retire -- update PC
    sprintf(buf, "12345678%.*d%hn", (int)(((long long int)rpc)&0xFFFF), 0, (short*)&rpc);

    // for debug: do we need to print?
    if (output != last) { putchar(output[-1]); last = output; }
  }
}
```

Presenting: printbf*

- Turing complete interpreter
- Relies on format strings
- Allows you to execute *“stuff”*



http://github.com/HexHive/printbf

* Direct fame to Nicholas Carlini, blame to me

Conclusion

Conclusion

- Low level languages are here to stay
  - ... and they are full of opportunities
- Defenses require careful design
  - Current defenses are broken (too weak)
  - Without stack integrity they can be mitigated
- CFI makes attacks harder but is no panacea
  - We need principled defenses: memory and type safety

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Thank you!
Questions?

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