There and back again Binary Analysis with mcsema

Andrew Ruef

~~There and back again~~
Street Fighting Binary Analysis with mcsema

Andrew Ruef

Hi

- Now:
  - PhD Programming Languages
  - Advised by Mike Hicks
  - Research at Trail of Bits
- Before:
  - Startups
  - Defense contractors
  - Big companies

Introduction

Problem: binary programs

What if humans didn't read it?

- We ask machines to do everything else
- Let's have them read native instructions and analyze them just like they analyze other programs
- What new problems show up?
- What existing problems are magnified?
- Does anything get easier?

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- What new problems show up?
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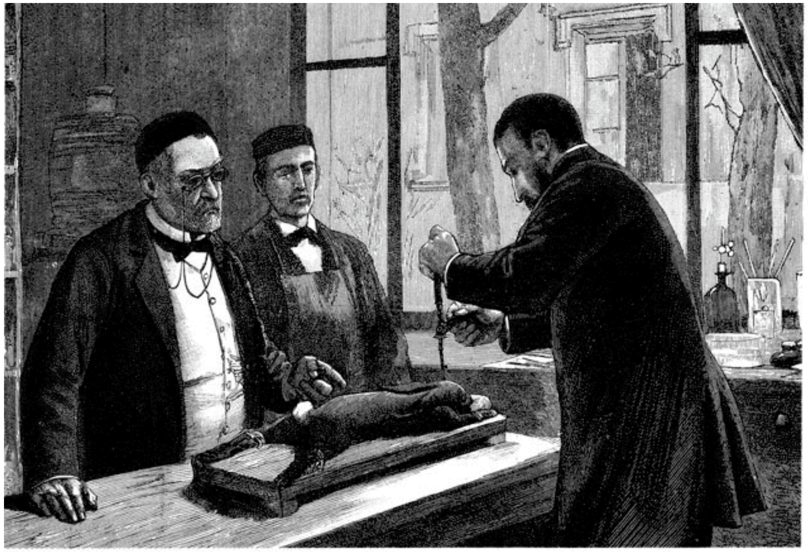
- Does anything get easier?
  - Trick question, nothing ever gets easier

Native Instructions

What’s in machine code?



“I’ve never seen the inside of a rabbit’s brain before. What’s in there, anyway?”

“Nobody knows yet. Johnson and I are hoping it’s cupcakes.”

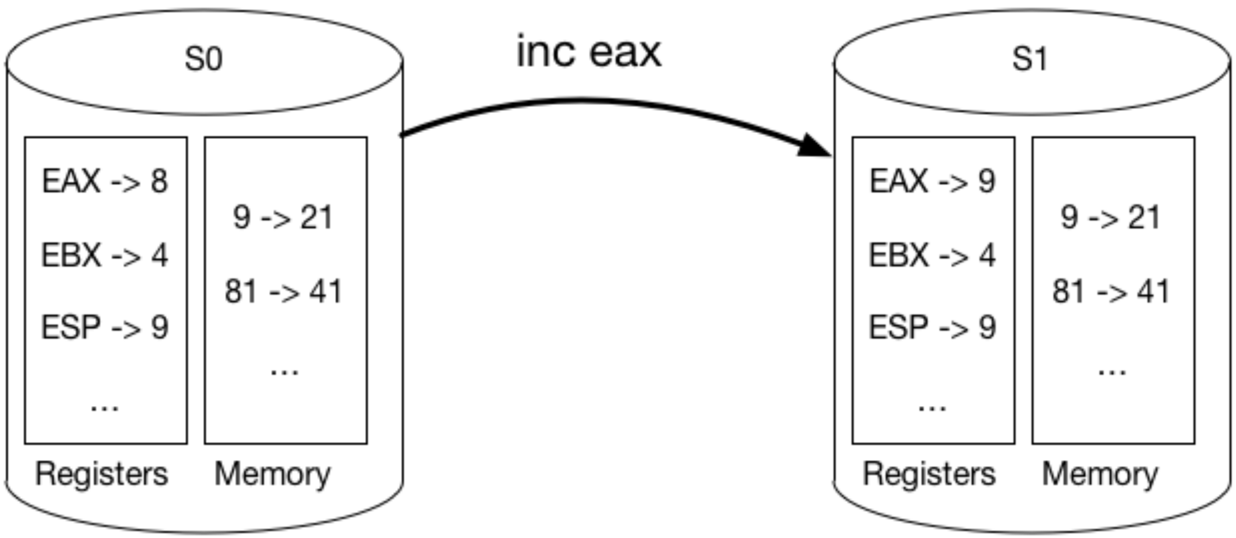
What's in machine code?

- Statements that look like this

```
mov      eax, [ebp-4]
movzx    eax, byte ptr [eax]
mov      [ebp-9], al
cmp      byte ptr [ebp-9], 0
```

- The code that contains those statements itself
- Some entry point

What's in machine code?



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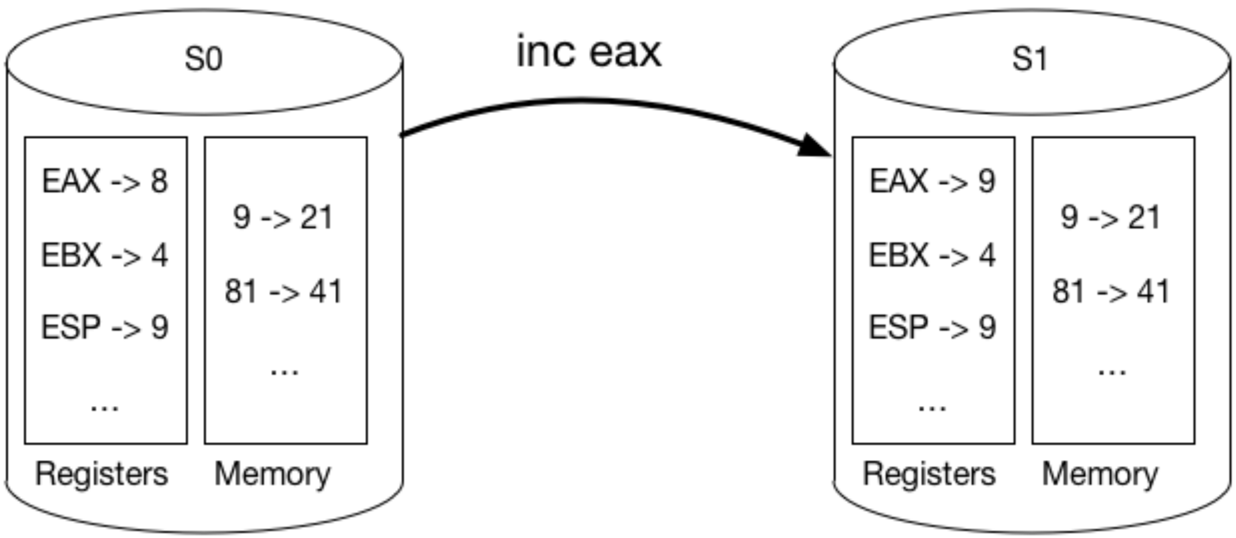


Not stack or heap, just "memory"

What instructions does this miss?

- Does your model include multiple threads?
  - If no, then you miss xbegin / xcommit / xabort
- Does your model include devices and privilege levels?
  - If no, then you miss (some of) the behavior of iret and friends
- What about individual page permissions and virtual memory?
  - Then you miss implicit exceptions due to page permissions

Can we make instructions explicit?

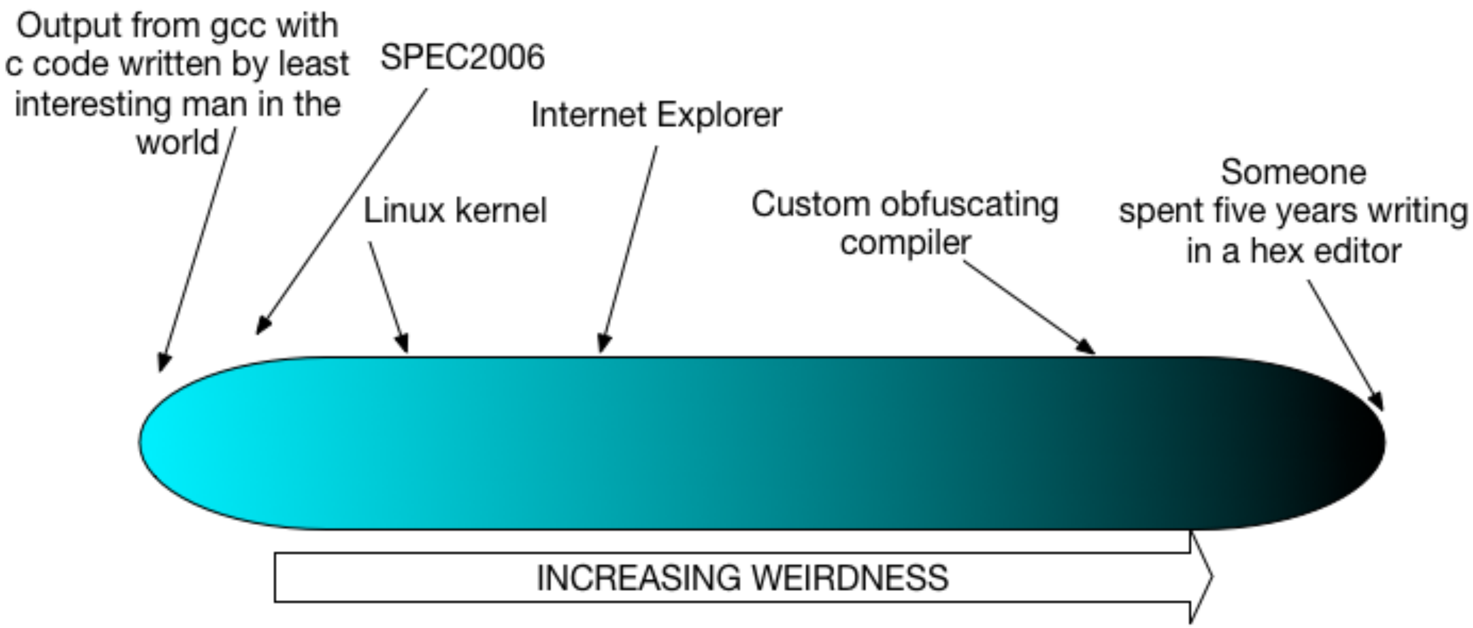
- What if we used some pure, core language to represent transitions on states?
- Spoiler alert – this is what everyone does
- We'll use LLVM for this language, for reasons I will defend later

Compilers and other instruction sources

Provenance

- What produces instructions? Compilers, right?
  - That’s a big assumption
- What rules do compilers have to play by?
  - ~~Their own~~ The ABI
- What’s the gap between what compilers *must* do and what they *frequently* do?
  - Significant

Binary or compiler output analysis?



… more simply

Compilers / configurations you've seen before
Everything else
INCREASING WEIRDNESS

Don’t be these people

Kaspersky Lab Experts Discover Unknown Programming Language in the Duqu Trojan; Appeal to Programming Community for Support in Analysis

11 Mar 2012
Virus News

The language, which DuQu used to communicate with command-and-control servers, turns out to be a special type of C code compiled with the Microsoft Visual Studio Compiler 2008.

Why should you care?

- Compromise is the essence of ~~diplomacy~~ having a working / scalable system
- You can’t handle all the weirdness that the system has to offer
- Know the gaps
- Also know where systems will fail?

Breaking assumptions

- Undefined flags used in control decisions
- Lots of control flow through memory
- No stack / all data accesses through push and pop

Motivating mcsema

mcsema

- Translate X86 into IR
- LLVM translation
- Function identification
- Stack translation
- KLEE

Goal: take X86, put it into an IR

- Sub goals:
  - Have collaborators
  - Produce executable from IR
  - Do some static analysis
- What IR to use?
  - Use an existing one
  - Make our own

What about VEX?

- Valgrind is a dynamic binary translator
- DBTs have the same problems we do
- Valgrind represents the semantics of native programs as VEX
- VEX is nasty
  - Small number of expressions and statements
  - ~1600 values in the binop op enumerator

Tradeoffs we'll make

- Fewer fancy abstractions like memory
  - No assumptions about stack or heap
- Some assumptions about code
  - Immutable
- An interconnected mass of ~~pulsating maggots~~ components

- Take native code and print it as LLVM

Why LLVM?

- Lots of thought went into the design of the IR
  - If not LLVM, then we would reproduce this thought and surely get something wrong
- Lots of tools exist to work with this IR
  - Symbolic executors, abstract interpreters, code generators, optimizers
- The type system of the IR is already close to what the machine is
  - No signed / unsigned types, integer bit vector machines
- Existing LLVM expertise is transferrable
- Some of these reasons are political, some are engineering

Anatomy of a decoder

- Machine state is represented as an LLVM record type
  - Registers are field members
- Translated instructions are sequences of LLVM instructions that modify the machine state
- Machine state is spilled to the stack on function entry, synced on function call and function return

Flags

- EFLAGS is broken out as a sequence of 1-bit virtual registers in the machine state
- Instructions set registers, now they also set flag registers

- Lots of flag assignment code is dead by construction
- Conservative DCE removes “lots” of flag assignment code

- Undefined flags set to LLVM undefined value

Translation example

`and ebx, `**`0x44444`**

Translation example

```
%79 = load i64* %RBX_val
%80 = trunc i64 %79 to i32

%81 = and i32 %80, 279620

%82 = lshr i32 %81, 31
%83 = trunc i32 %82 to i1
store i1 %83, i1* %SF_val
%84 = icmp eq i32 %81, 0
store i1 %84, i1* %ZF_val
%85 = trunc i32 %81 to i8
%86 = call i8 @llvm.ctpop.i8(i8 %85)
%87 = trunc i8 %86 to i1
%88 = xor i1 %87, true
store i1 %88, i1* %PF_val
store i1 false, i1* %OF_val
store i1 false, i1* %CF_val
store i1 undef, i1* %AF_val

%89 = zext i32 %81 to i64
store i64 %89, i64* %RBX_val
```

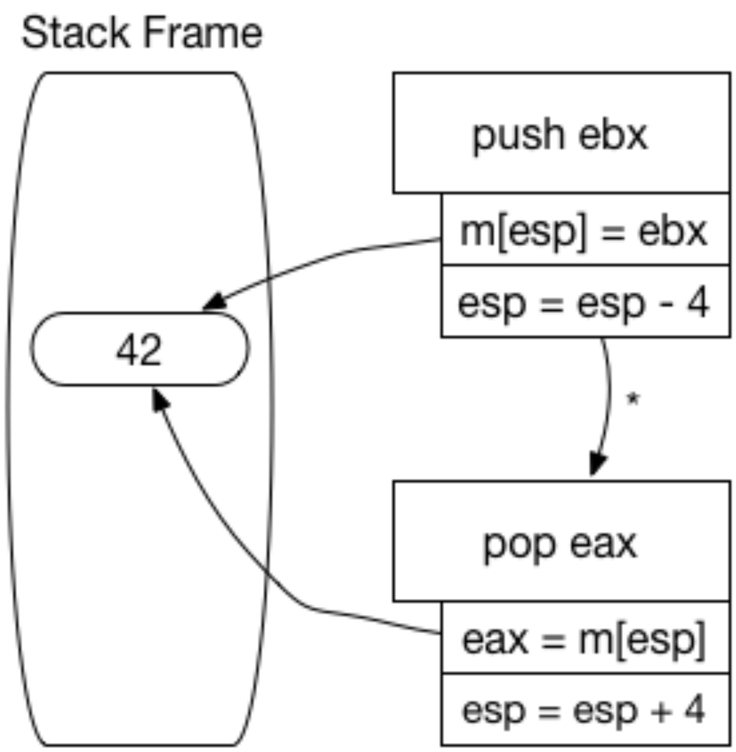
Function specification

- We only really need one function
- The specification of the CFG also specifies the functions
- This is cheating

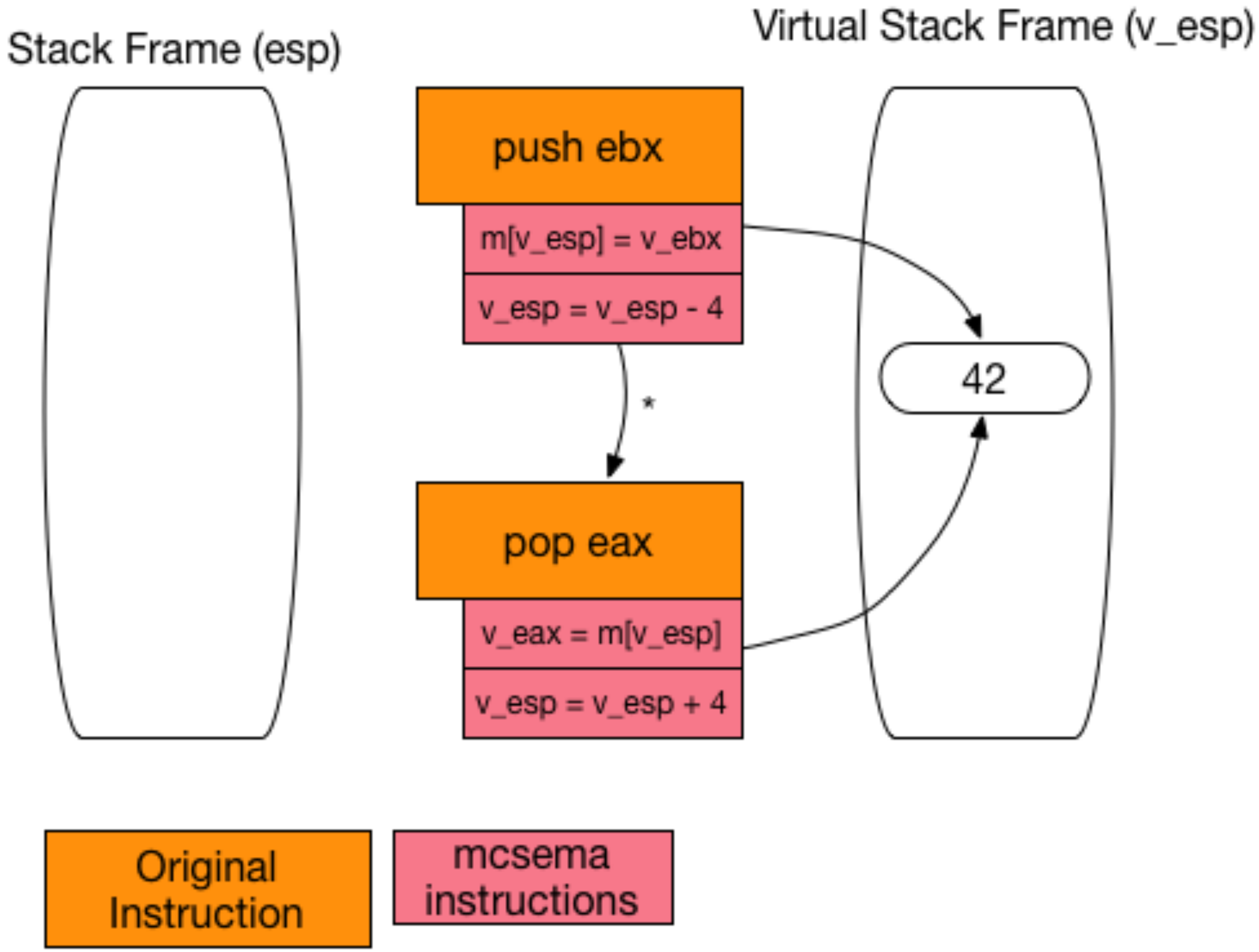
- The further away you get from compiler output the less meaning “function” has

Virtual Stacks

Before



After



Stack Frame (esp)
Virtual Stack Frame (v_esp)
push ebx
m[v_esp] = v_ebx
v_esp = v_esp - 4
*
42
pop eax
v_eax = m[v_esp]
v_esp = v_esp + 4
Original Instruction
mcsema instructions

Advantages / disadvantages

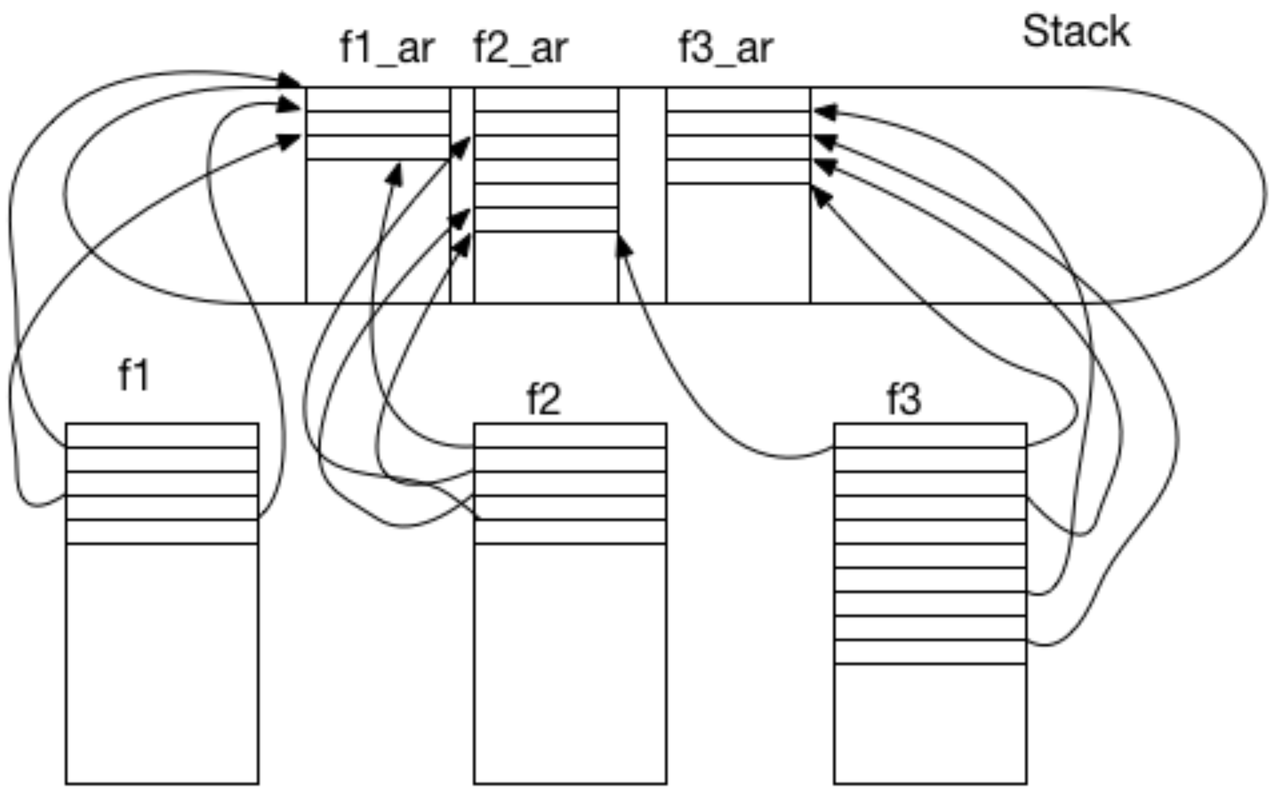
- Sound model of the stack
- No abstraction of variables
  - Kills optimizations, symbolic execution
- Large running time cost

- Fix: every variable identified and moved off of the virtual stack is space saved and maybe code optimized

Tangent: Infer Functions?

- Observation: compilers produce one activation record per function, and functions are generally related to data values stored in this activation record
- Hypothesis: compilers emit instructions such that instructions with *code locality* cluster with values on the stack with *data locality*
- This seems true for C and the C compilers we know about
  - Is it true for all HLLs?
  - Must it be true for all C compilers?

Tangent: Infer Functions?



Platform specific special cases

- What about threads?
  - New threads are basically the creation of a new machine state
- What about exceptions? Like SEH?
  - Ugh

Enough to run KLEE on binaries

```
+-+---+---+
|X|     |#|
|X| --+ | |
| |   | | |
| +-- | | |
|     |   |
+-----+---+
```

```
+-+---+---+
|X|XXXXX|#|
|X|X--+X|X|
|X|XXX|X|X|
|X+--X|X|X|
|XXXXX|XXX|
+-----+---+
```

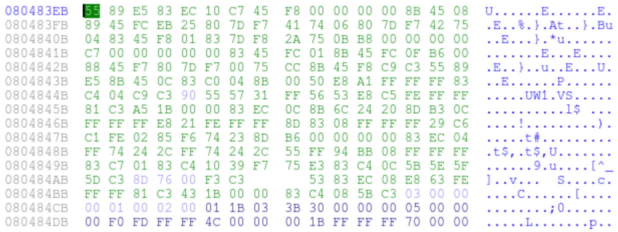
Abstraction recovery

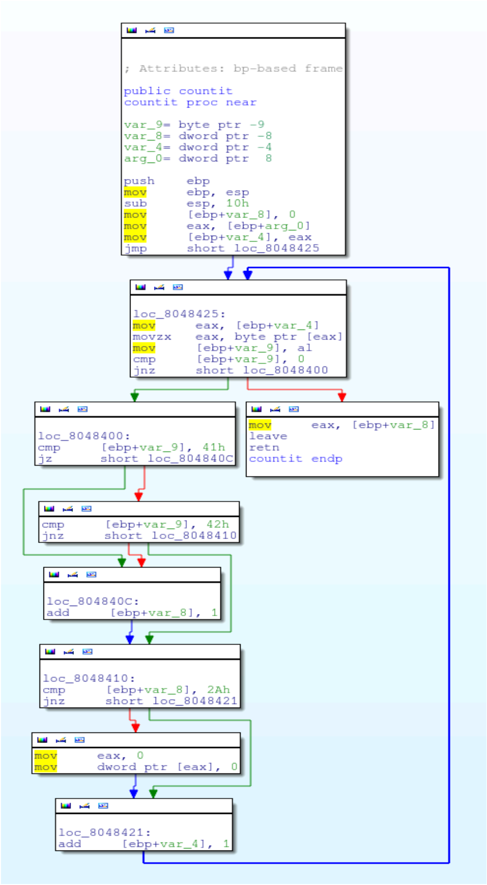
Abstractions

- Control Flow Analysis
- Memory and the heap
- Type recovery

Control Flow Analysis

- Any errors during CFA corrupt all subsequent analyses
- Overall: convert instruction stream into a control flow graph
- In general, quite hard





Control Flow Analysis

- Some possibilities
  - Use symbolic execution
    - INSIGHT
  - Use abstract interpretation and value set / value range analysis
    - Jakstab, bindead, BAP
  - Use lots of distinct traces and merge them

- All with their advantages and disadvantages

CFA in mcsema

- Control flow specified externally
- Default: specify control flow of application using IDA, export to mcsema
  - Advantages: empirically good results for compiler output analysis
  - Disadvantages: theoretically unfulfilling
- In the future: some form of value range analysis on indirect branches

Memory and the heap

- A sound abstraction: all of memory is a key / value store
  - aka a big flat array

- Some big downsides: optimizer doesn’t know that stack variables are variables

- Would like to be able to allow mscema to try and register allocate stack variables

Memory and the heap

- Heap objects are manipulated via integer pointers and offsets to those pointers
- Downside: analyses can't do a semantics or type driven analysis of record uses
  - Because there are no records to speak of!
- This is edging us closer and closer towards…

Type Recovery

- Assign some type information to values in the (partially) recovered program
- Assists human analysts understand the program
- Assists automated analyses to be more precise and perform better
  - Optimizations can know what variables are now
  - Symbolic executors can know what regions of memory are disjoint and have different widths

An advantage of LLVM

- The same type infrastructure used to represent the original program (*) is available to represent the recovered programs types!

- Saves you from having to define your own type system

* MANY LARGE CAVEATS

Primitive types

- Partition the type of values into
  - Pointer vs not?
  - Integer widths?

Typing a stack frame

- Some problems addressed by very recent work (Noonan et al PLDI16)
  - What if a stack slot is re-used between a signed and unsigned type?
  - What about polymorphic functions?
- Some remain:
  - How do you type a stack frame that contains an alloca?
  - How do you type malloc in general?

Present status, future,conclusion

What translates now

- Modestly sized (1-40 KLOC) C/C++ programs for Linux and Windows
- Web servers
- CGC challenge binaries

Currently cooking

- A better variable specification scheme as input to mcsema
- A dependent type system for machine code
- Using C as a DSL to specify instruction semantics

Wish list

- Implementation of a better control flow analysis scheme
    - Iterated refinements of recursive descent using value range analysis would be a start
- A better symbolic execution system for LLVM

Thanks!