Platform-independent static binary code analysis using a meta-assembly language

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CanSecWest 2009

Overview

- The REIL Language
- Abstract Interpretation
- MonoREIL
- Results

Motivation

- Bugs are getting harder to find
- Defensive side (most notably Microsoft) has invested a lot of money in a „bugocide“
- Concerted effort: Lots of manual code auditing aided by static analysis tools
- Phoenix RDK: Includes „lattice based“ analysis framework to allow pluggable abstract interpretation in the compiler

Motivation

- Offense needs automated tools if they want to avoid being sidelined
- Offensive static analysis: Depth vs. Breadth
- Offense has no source code, no Phoenix RDK, and should not depend on Microsoft
- We want a static analysis framework for offensive purposes

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REIL

- Reverse Engineering Intermediate Language
- Platform-Independent meta-assembly language
- Specifically made for static code analysis of binary files
- Can be recovered from arbitrary native assembly code
  - Supported so far: x86, PowerPC, ARM

Advantages of REIL

- Very small instruction set (17 instructions)
- Instructions are very simple
- Operands are very simple
- Free of side-effects
- Analysis algorithms can be written in a platform-independent way
  - Great for security researchers working on more than one platform

Creation of REIL code

- Input: Disassembled Function
  - x86, ARM, PowerPC, potentially others
- Each native assembly instruction is translated to one or more REIL instructions
- Output: The original function in REIL code

Example

```
597DA51B    netapi32.xpsp3.dll::sub_597DA51B
597DA53E    cmp         word ax, word si
597DA541    jz          cs:loc_597DD83D
```

```
597DA53E00: and eax, 65535, t1
597DA53E01: and esi, 65535, t3
597DA53E02: and t1, 32768, t4
597DA53E03: and t3, 32768, t5
597DA53E04: sub t1, t3, t6
597DA53E05: and t6, 32768, t7
597DA53E06: bsh t7, -15, SF
597DA53E07: xor t4, t5, t8
597DA53E08: xor t4, t7, t9
597DA53E09: and t8, t9, t10
597DA53E0A: bsh t10, -15, OF
597DA53E0B: and t6, 65536, t11
597DA53E0C: bsh t11, -16, CF
597DA53E0D: and t6, 65535, t12
597DA53E0E: bisz t12, , ZF
597DA54100: jcc ZF, , 1501419581
```

Design Criteria

- Simplicity
- Small number of instructions
  - Simplifies abstract interpretation (more later)
- Explicit flag modeling
  - Simplifies reasoning about control-flow
- Explicit load and store instructions
- No side-effects

REIL Instructions

- One Address
  - Source Address * 0x100 + n
  - Easy to map REIL instructions back to input code
- One Mnemonic
- Three Operands
  - Always
- An arbitrary amount of meta-data
  - Nearly unused at this point

REIL Operands

- All operands are typed
  - Can be either registers, literals, or sub-addresses
  - No complex expressions
- All operands have a size
  - 1 byte, 2 bytes, 4 bytes, ...

The REIL Instruction Set

- Arithmetic Instructions
  – ADD, SUB, MUL, DIV, MOD, BSH
- Bitwise Instructions
  – AND, OR, XOR
- Data Transfer Instructions
  – LDM, STM, STR

The REIL Instruction Set

- Conditional Instructions
  - BISZ, JCC
- Other Instructions
  - NOP, UNDEF, UNKN
- Instruction set is easily extensible

REIL Architecture

- Register Machine
  - Unlimited number of registers t_0, t_1, ...
  - No explicit stack
- Simulated Memory
  - Infinite storage
  - Automatically assumes endianness of the source platform

Limitations of REIL

- Does not support certain instructions (FPU, MMX, Ring-0, ...) yet
- Can not handle exceptions in a platform-independent way
- Can not handle self-modifying code
- Does not correctly deal with memory selectors

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Abstract Interpretation

- Theoretical background for most code analysis
- Developed by Patrick and Rhadia Cousot around 1975-1977
- Formalizes „static abstract reasoning about dynamic properties“
- Huh ?
- A lot of the literature is a bit dense for many security practitioners

Abstract Interpretation

- We want to make statements about programs
- Example: Possible set of values for variable x at a given program point p
- In essence: For each point p, we want to find $K_p \in P(States)$
- Problem: $P(States)$ is a bit unwieldly
- Problem: Many questions are undecidable (where is the w*nker that yells „halting problem“) ?

Dealing with unwieldy stuff

- Reason about something simpler:

$$\mathcal{P}(States) \xrightarrow{\text{Abstraction}} D$$

$$\mathcal{P}(States) \xleftarrow{\text{Concretisation}} D$$

- Example: Values vs. Intervals

Lattices

- In order for this to work, D must be structurally similar to $P(States)$
- $P(States)$ supports intersection and union
- You can check for inclusion (contains, does not contain)
- You have an empty set (bottom) and „everything“ (top)

Lattices

- A lattice is something like a generalized powerset
- Example lattices: Intervals, Signs, $P(\text{Registers})$, mod p

Dealing with halting

- Original program consists of p_1 ... p_n program points
- Each instruction transforms a set of states into a different set of states
- p_1 ... p_n are mappings $P(States) \rightarrow P(States)$
- Specify $p'_1 \ldots p'_n : D \rightarrow D$
- This yields us $\tilde{p} : D^n \rightarrow D^n$

Dealing with halting

- We cheat: Let D be finite ➔ D^n is finite
- Make sure that $\tilde{p}$ is monotonous (like this talk)
- Begin with initial state I
- Calculate $\tilde{p}(l)$
- Calculate $\tilde{p}(\tilde{p}(l))$
- Eventually, you reach $\tilde{p}^n(l) = \tilde{p}^{n-1}(l)$
- You are done – read off the results and see if your question is answered

Theory vs. practice

- A lot of the academic focus is on proving correctness of the transforms

$$P(States) \xrightarrow{\;p_i\;} P(States)$$

$$\downarrow$$

$$D \xrightarrow{\;p_i'\;} D$$

- As practitioner we know that p_i is probably not fully correctly specified
- We care much more about choosing and constructing a D so that we get the results we need

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MonoREIL

- You want to do static analysis
- You do not want to write a full abstract interpretation framework
- We provide one: MonoREIL
- A simple-to-use abstract interpretation framework based on REIL

What does it do ?

- You give it
  - The control flow graph of a function (2 LOC)
  - A way to walk through the CFG (1 + n LOC)
  - The lattice D (15 + n LOC)
    - Lattice Elements
    - A way to combine lattice elements
  - The initial state (12 + n LOC)
  - Effects of REIL instructions on D (50 + n LOC)

How does it work?

- Fixed-point iteration until final state is found
- Interpretation of result
  - Map results back to original assembly code
- Implementation of MonoREIL already exists
- Usable from Java, ECMAScript, Python, Ruby

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- **Results**

Register Tracking

- First Example: Simple
- Question: What are the effects of a register on other instructions?
- Useful for following register values

Register Tracking

- Demo

Register Tracking

- Lattice: For each instruction, set of influenced registers, combine with union
- Initial State
  - Empty (nearly) everywhere
  - Start instruction: { tracked register }
- Transformations for MNEM op1, op2, op3
  - If op1 or op2 are tracked ➔ op3 is tracked too
  - Otherwise: op3 is removed from set

Negative indexing

- Second Example: More complicated
- Question: Is this function indexing into an array with a negative value ?
- This gets a bit more involved

Negative indexing

- Simple intervals alone do not help us much
- How would you model a situation where
  - A function gets a structure pointer as argument
  - The function retrieves a pointer to an array from an array of pointers in the structure
  - The function then indexes negatively into this array
- Uh. Ok.

Abstract locations

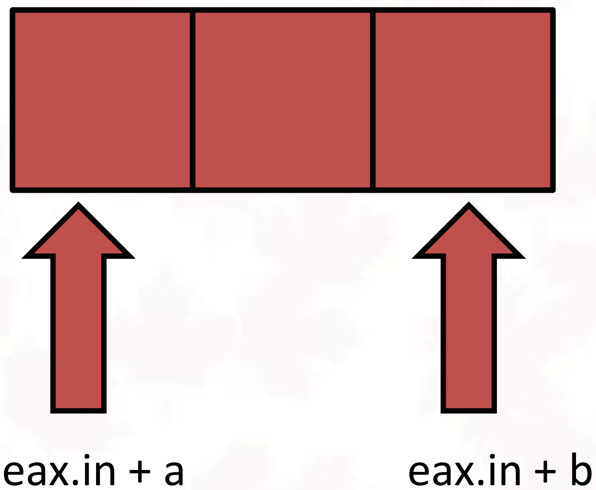
- For each instruction, what are the contents of the registers ? Let‘s slowly build complexity:
- If eax contains arg_4, how could this be modelled ?
  - eax = *(esp.in + 8)
- If eax contains arg_4 + 4 ?
  - eax = *(esp.in + 8) + 4
- If eax can contain arg_4+4, arg_4+8, arg_4+16, arg_4 + 20 ?
  - eax = *(esp.in + 8) + [4, 20]

Abstract locations

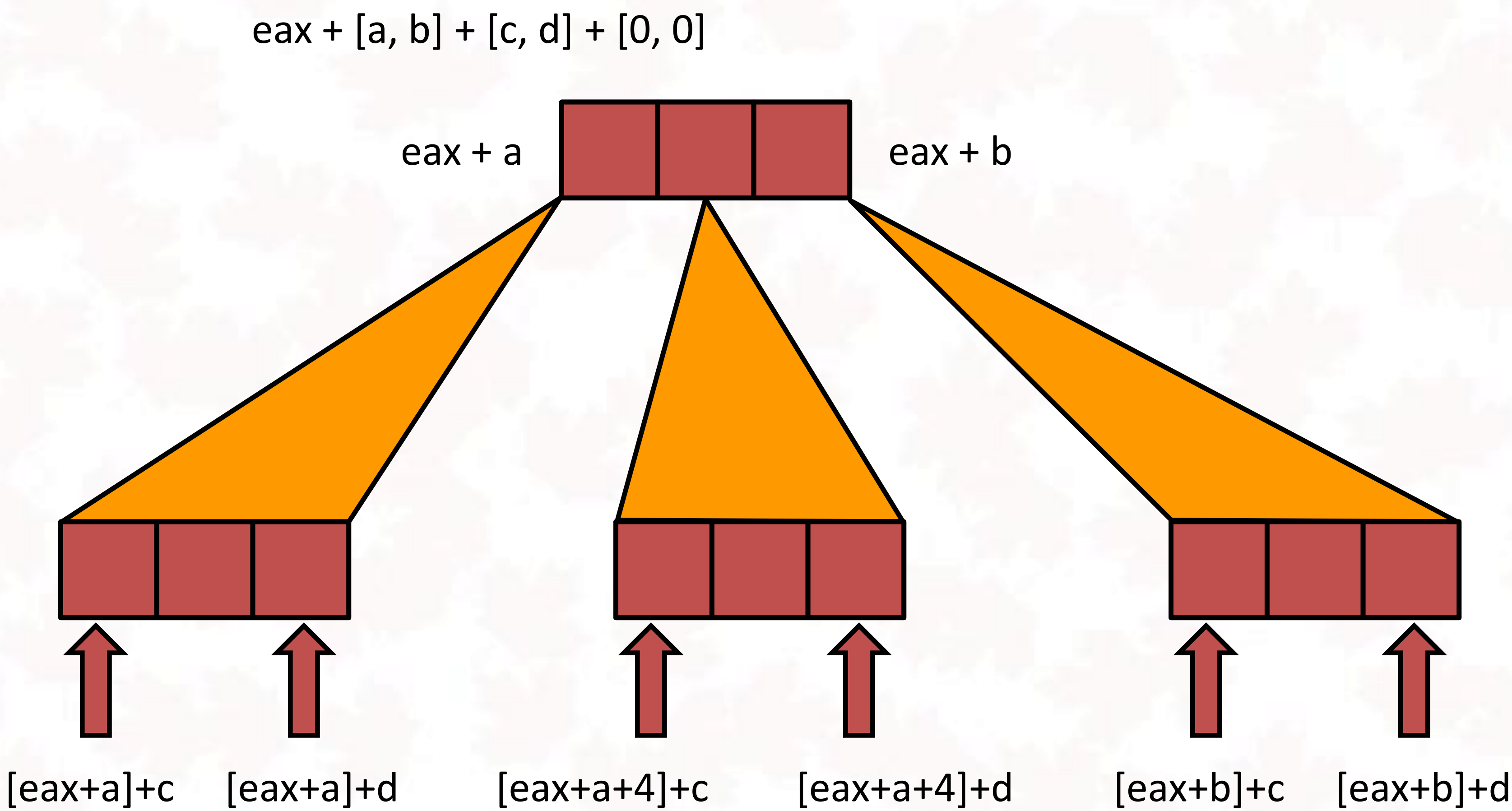
- If eax can contain arg_4+4, arg_8+16 ?
  - eax = *(esp.in + [8,12]) + [4,16]
- If eax can contain any element from
  - arg_4→mem[0] to arg_4→mem[10], incremented once, how do we model this ?
  - eax = *(*(esp.in + [8,8]) + [4, 44]) + [1,1]
- OK. An abstract location is a base value and a list of intervals, each denoting memory dereferences (except the last)

Range Tracking

eax.in + [a, b] + [0, 0]



Range Tracking



Range Tracking

- Lattice: For each instruction, a map:

$$Register \bigcup Aloc \rightarrow Aloc$$

- Initial State
  – Empty (nearly) everywhere
  – Start instruction: { reg -> reg.in + [0,0] }
- Transformations
  – Complicated. Next slide.

Range Tracking

- Transformations
  - ADD/SUB are simple: Operate on last intervals
  - STM op_1, , op_3
    - If op_1 or op_3 not in our input map M skip
    - Otherwise, M[M[op_3]] = op_1
  - LDM op_1, , op_3
    - If op_1 or op_3 is not in our input map M skip
    - M[op_3] = M[op_1]
  - Others: Case-specific hacks

Range Tracking

- Where is the meat ?
- Real world example: Find negative array indexing

MS08-67

- Function takes in argument to a buffer
- Function performs complex pointer arithmetic
- Attacker can make this pointer arithmetic go bad
- The pointer to the target buffer of a wcscpy will be decremented beyond the beginning of the buffer

MS08-67

- Michael Howard's Blog:
  - "In my opinion, hand reviewing this code and successfully finding this bug would require a great deal of skill and luck. So what about tools? It's very difficult to design an algorithm which can analyze C or C++ code for these sorts of errors. The possible variable states grows very, very quickly. It's even more difficult to take such algorithms and scale them to non-trivial code bases. This is made more complex as the function accepts a highly variable argument, it's not like the argument is the value 1, 2 or 3! Our present toolset does not catch this bug."

MS08-67

- Michael is correct
  - He has to defend all of Windows
  - His „regular“ developers have to live with the results of the automated tools
  - His computational costs for an analysis are gigantic
  - His developers have low tolerance for false positives

MS08-67

- Attackers might have it easier
  - They usually have a much smaller target
  - They are highly motivated: I will tolerate 100 false positives for each „real“ bug
    - I can work through 20-50 a day
    - A week for a bug is still worth it
  - False positive reduction is nice, but if I have to read 100 functions instead of 20000, I have already gained something

MS08-67

- Demo

Limitations and assumptions

- Limitations and assumptions
  - The presented analysis does not deal with aliasing
  - We make no claims about soundness
  - We do not use conditional control-flow information
  - We are still wrestling with calling convention issues
  - The important bit is not our analysis itself – the important part is MonoREIL
  - Analysis algorithms will improve over time – laying the foundations was the boring part

Status

- Abstract interpretation framework available in BinNavi
- Currently x86
- In April (two weeks !): PPC and ARM
  - Was only a matter of adding REIL translators
- Some example analyses:
  - Register tracking (lame, but useful !)
  - Negative array indexing (less lame, also useful !)

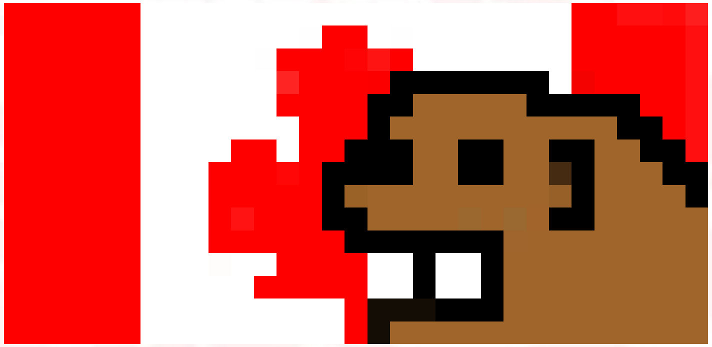
Outlook

- Deobfuscation through optimizing REIL
- More precise and better static analysis
- Register tracking etc. release in April (two weeks !)
- Negative array indexing etc. release in October
- Attempting to encourage others to build their own lattices

Related work ?

- Julien Vanegue / ERESI team (EKOPARTY)
- Tyler Durden‘s Phrack 64 article
- Principles of Program Analysis (Nielson/Nielson/Hankin)
- University of Wisconsin WISA project
- Possibly related: GrammaTech CodeSurfer x86

Questions ?



(Good Bye, Canada)