Precise Static Analysis of Binaries by Extracting Relational Information

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Introduction

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- automatically find bugs/security exploits in executables
- soundness (no missed bugs)
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What are we doing

- static analysis of executables constructed using abstract interpretation theory
- over-approximate reachability analysis by calculating fixpoints

Motivation

Why binaries

- no source code available
- compiler correctness
- security bugs can only be understood here
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Problems specific to binary analysis

- no variable boundaries/types
- many architectures
- large instruction sets

RREIL (Relational Reverse Engineering Intermediate Language)

RREIL: yet another intermediate language

- translate one x86, ARM, AVR . . . instruction into a handful of RREIL instructions $\leadsto$ architecture independent analyses
- faithful down to the bit-level but platform independent

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What is special about RREIL

- concise: has 24 instructions vs. Intel x86 ca. 600 instructions
- arithmetic expressions only over operands of same bit-size
- special translation of relational tests such as $a < b$
- precise handling of e.g. x86 registers by using *fields*

Running example

```
for (int i = -1; i > -100; i--) { /* body */ }
```

x86-64 translation:

```
01: mov eax,0xffffffff
02: sub eax,0x1
/* body */
03: cmp eax,0xffffff9c
04: jg 02
```

RREIL translation:

```
01.00: mov rax:32, −1:32
01.01: mov rax:32/32, 0:32
02.00: sub t0:32, rax:32, 1:32
02.01: cmpltu CF:1, rax:32, 1:32
02.02: cmpleu BE:1, rax:32, 1:32
02.03: cmplts LT:1, rax:32, 1:32
02.04: cmples LE:1, rax:32, 1:32
02.05: cmpeq ZF:1, rax:32, 1:32
02.06: cmplts SF:1, t0:32, 0:32
02.07: xor OF:1, LT:1, SF:1
02.08: mov rax:32, t0:32
02.09: mov rax:32/32, 0:32
/* body */
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03.06: cmplts SF:1, t0:32, 0:32
03.07: xor OF:1, LT:1, SF:1
04.00: xor t0:1, LE:1, 1:1
04.01: brc t0:1, 02.00
```

RREIL virtual flags

Consider the translation of x86 code:

```
01: cmp eax, ebx
02: jl sLess
```

RREIL code:

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01.04: cmpleu CForZF:1, eax:32, ebx:32
01.05: cmplts SFxorOF:1, eax:32, ebx:32
01.06: cmples SFxorOForZF:1, eax:32, ebx:32
01.07: xor    OF:1, SFxorOF:1, SF:1
02.00: brc    SFxorOF:1, sLess:32
```

create *virtual* flags `SFxorOF` that express numeric semantics

RREIL virtual flags with applied liveness

Consider the translation of x86 code:

```
01: cmp eax, ebx
02: jl sLess
```

RREIL code:

```
01.00: nop
01.01: nop
01.02: nop
01.03: nop
01.04: nop
01.05: cmplts SFxorOF:1, eax:32, ebx:32
01.06: nop
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02.00: brc    SFxorOF:1, sLess:32
```

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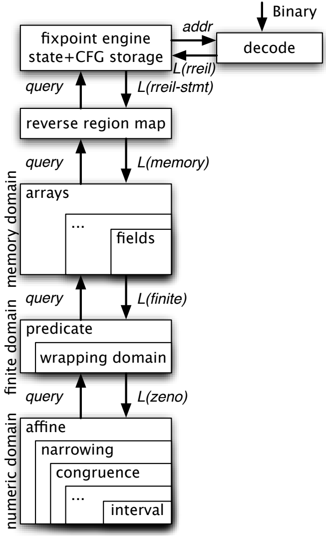
Abstract Domains Hierarchy

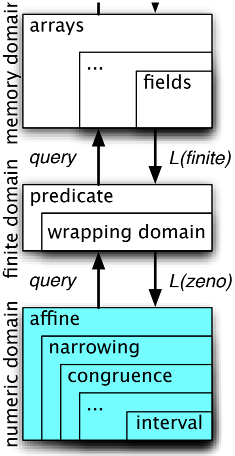


Overall Idea:

- RREIL instructions are *processed* by the domain hierarchy (down channel)
- indirect jumps are resolved by *querying* the hierarchy (up channel)

Numeric Domain

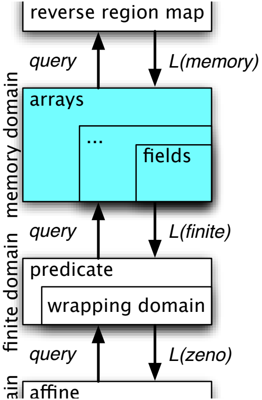
Numeric domains map variables $x \in \mathbb{X}$ to a subset of $\mathbb{Z}$.



- the affine tracks equalities $c_i x_i = \sum_j c_j x_j$ where $i < j$
- $\rightsquigarrow$ no need to store x_i in child domains; some linear assignments need not be propagated to child
- the interval domain maps x_k to $[l_k, u_k]$

Memory Domain

From operations on registers/memory $m \in \mathbb{M}$ to operations on numeric variables $x \in \mathbb{X}$:



Consider again x86-64: **`mov`** `eax,0xffffffff`

- 32-bit **`mov`** clears upper 32 bits of `rax`
- cannot store -1 in numeric domain since then `rax`=`0xffffffffffffffff`
- tracking `rax` as one numeric variable leads to precision loss

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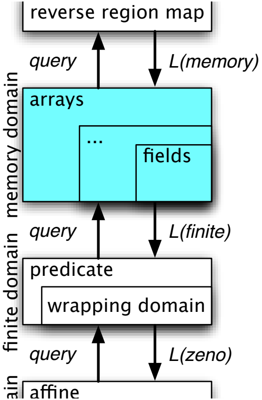

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RREIL:

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mov rax:32/0, -1:32
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```

leads to:

`rax`:32/32	`rax`:32/0
0	-1

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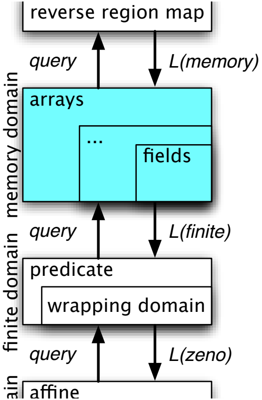

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leads to:

`rax`:32/32	`rax`:32/0
x_1	x_2

Dealing with finite integer arithmetic

We have a special view on numeric information:

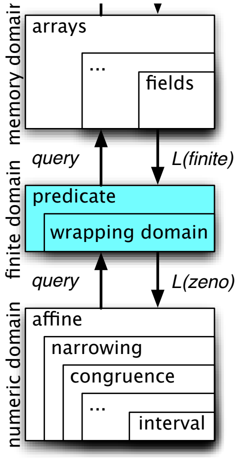
- we store e.g. `al` $\in [254, 257]$ (`al` is 8 bits big)
- this means:

$$\begin{aligned} 254 &\equiv 11111110 \\ 255 &\equiv 11111111 \\ 256 &\equiv 00000000 \\ 257 &\equiv 00000001 \end{aligned}$$

- which is also $[254, 255] \sqcup [0, 1] = [0, 255]$
- we call this conversion *wrapping*

Finite Domain

The finite domains associate a bit-size with each $x \in \mathbb{X}$.



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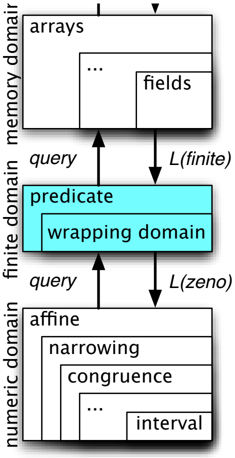

Idea:

- wrap operand `i` before each operation; wrapping is no-op if $\mathtt{i} \in [-2^{31}, 2^{31} - 1]$

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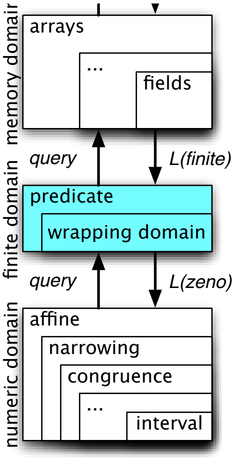

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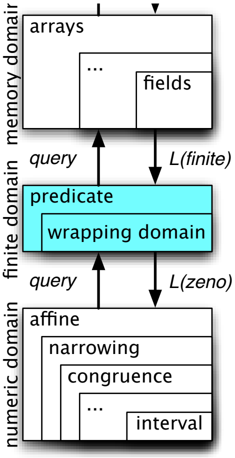

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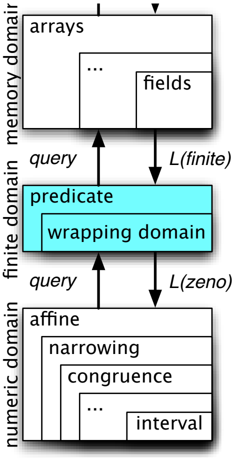

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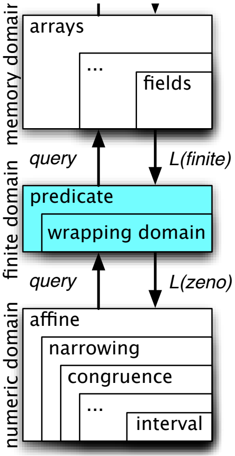

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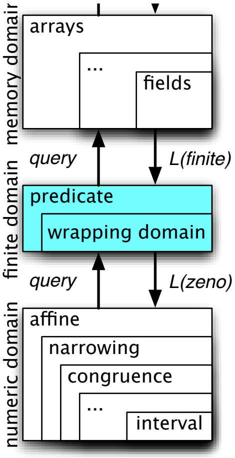

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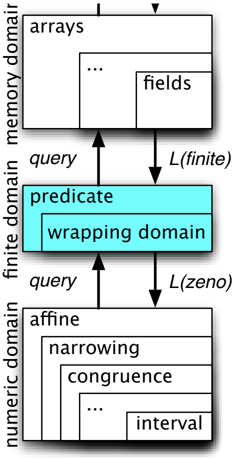

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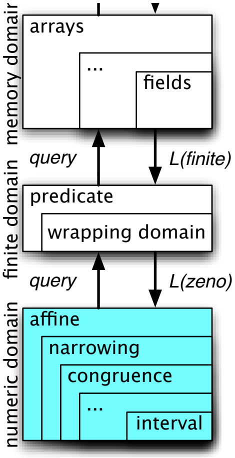
- $\rightsquigarrow$ wrapping of widened value $[-\infty, -1]$ gives $[-2^{31}, 2^{31}-1]$
- cannot infer that `i` is negative

Narrowing Domain

Avoiding precision loss incurred by widening: the *narrowing* domain



Fix wrapping + widening by:

- have a *narrowing* domain that tracks all tests that don't affect the state (redundant)
- $\leadsto$ the test `i > -100` is stored when analyzing the loop
- after widening `i` to $[-\infty, -1]$ apply all stored tests
- $\leadsto$ `i` $\in [-99, -1]$ follows
- wrapping to positive values avoided

Summary

Framework for static analysis of binaries:

- disassemblers as simple stateless decoder frontends
- memory layout, finite integer arithmetic, fixpoints, etc.
  - accesses to part of memory regions, registers
  - combined widening and wrapping
  - associate flag with test after **`cmp`**
- extensible domain hierarchy
  - four well-defined interfaces (ILs)
  - can be extended with SAT solving, shape analysis etc.
- CFG reconstruction drops out for free
  - program execution model adjustable (fixpoint computation)
  - able to disassemble (some) obfuscated code

Future work

- Additional Disassemblers
    - ARM
- Additional Domains
    - array summaries domain
    - strings domain
    - heap memory models (malloc)
- Malware and obfuscated code