Native x86 Decompilation Using Semantics-Preserving Structural Analysis and Iterative Control-Flow Structuring

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Which would you rather analyze?

```
push    %ebp
mov     %esp,%ebp
sub     $0x10,%esp
movl    $0x1,-0x4(%ebp)
jmp     1d <f+0x1d>
mov     -0x4(%ebp),%eax
imul    0x8(%ebp),%eax
mov     %eax,-0x4(%ebp)
subl    $0x1,0x8(%ebp)
cmpl    $0x1,0x8(%ebp)
jg      f <f+0xf>
mov     -0x4(%ebp),%eax
leave
ret
```

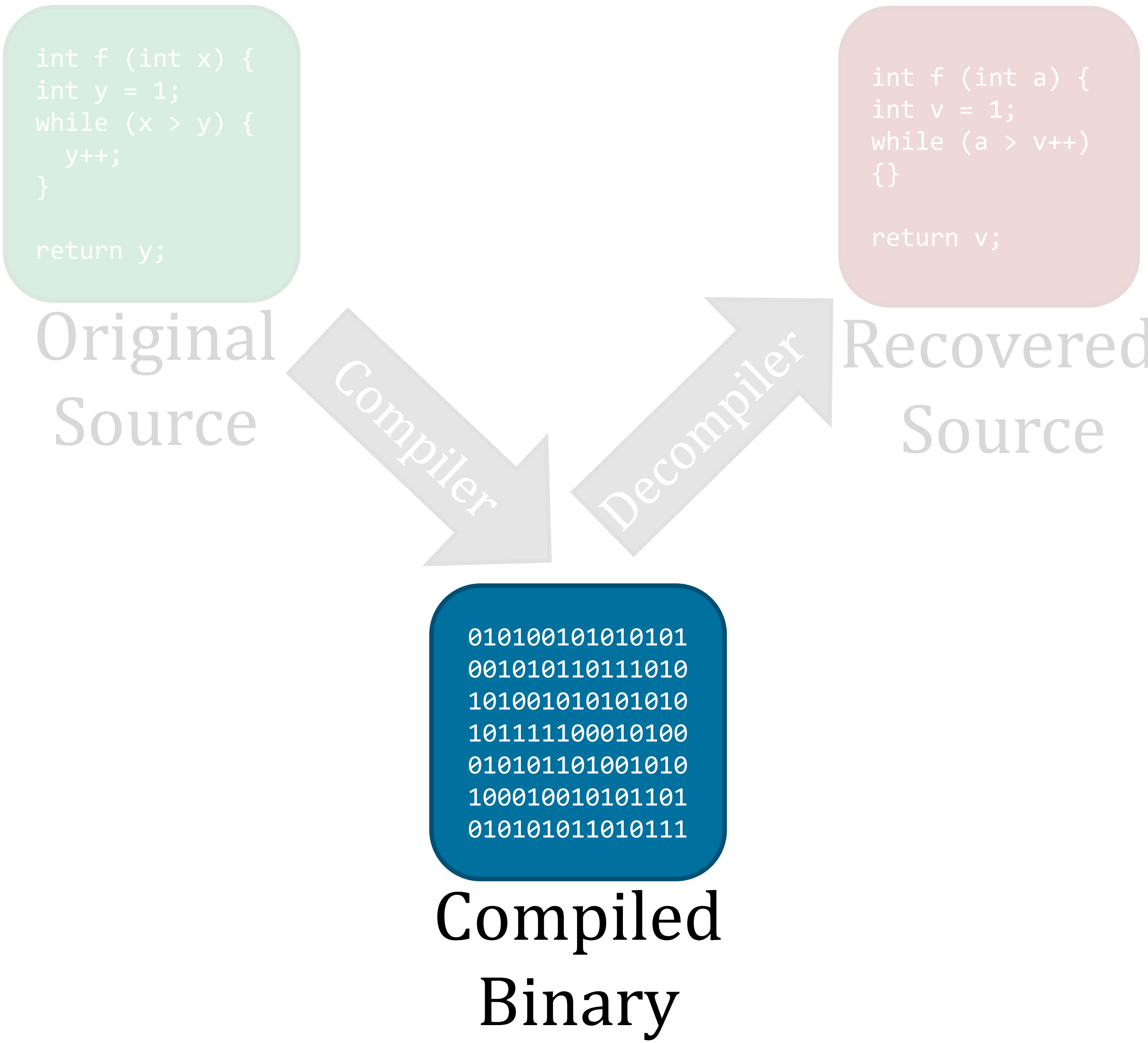
Functions

Types

Variables

Control Flow

```
int f(int c) {
  int accum = 1;
  for (; c > 1; c--) {
    accum = accum * c;
  }
  return accum;
}
```


int f (int x) {
int y = 1;
while (x > y) {
y++;
}
return y;
Original Source
Compiler
Decompiler
int f (int a) {
int v = 1;
while (a > v++)
{}
return v;
Recovered Source
0101001010101010
0010101101111010
1010010101010100
1011111000101000
0101011010010100
1000100101011010
0101010110101110
Compiled Binary

Decompilers for Software Security

- **Manual reverse-engineering**
  – Traditional decompiler application
- **Apply wealth of existing source-code techniques to compiled programs** [Chang06]
  – Find bugs, vulnerabilities
- **Heard at Usenix Security 2013, during Dowsing for Overflows**
  – "We need source code to access the high-level control flow structure and types"

Desired Properties for Security

1. Effective abstraction recovery
   – Abstractions improve comprehension

Effective Abstraction Recovery

```
s1;
while (e1) {
  if (e2) { break; }
  s2;
}
s3;
```

More Abstract

```
s1;
L1: if (e1) { goto L2; }
    else { goto L4; }
L2: if (e2) { goto L4; }
L3: s2; goto L1;
L4: s3;
```

Less Abstract

Desired Properties for Security

1. Effective abstraction recovery
   – Abstractions improve comprehension

2. Correctness
   – Buggy(Decompiled) ➔ Buggy(Original)

Correctness

```
int f (int x) {
int y = 1;
while (x > y) {
  y++;
}

return y;
```

Original Source

```
int f (int a) {
int v = 1;
while (a > v++)
{}

return v;
```

Recovered Source

Are these two programs semantically equivalent?

Compiled Binary

Prior Work on Decompilation

- Over 60 years of decompilation research
- Emphasis on manual reverse engineering
  - Readability metrics
    - Compression ratio: $1 - \frac{LOC\ decompiled}{LOC\ assembly}$
    - Smaller is better
- Little emphasis on other applications
  - Correctness is rarely explicitly tested

The Phoenix C Decompiler

How to build a better decompiler?

- Recover missing abstractions one at a time
  - <u>Semantics preserving</u> abstraction recovery
    - Rewrite program to use abstraction
    - Don’t change behavior of program
    - Similar to compiler optimization passes

Semantics Preservation

Abstraction Recovery

```
s1;
L1: if (e1) { goto L2; }
    else { goto L4; }
L2: if (e2) { goto L4; }
L3: s2; goto L1;
L4: s3;
```

=

```
s1;
while (e1) {
  if (e2) { break; }
  s2;
}
s3;
```

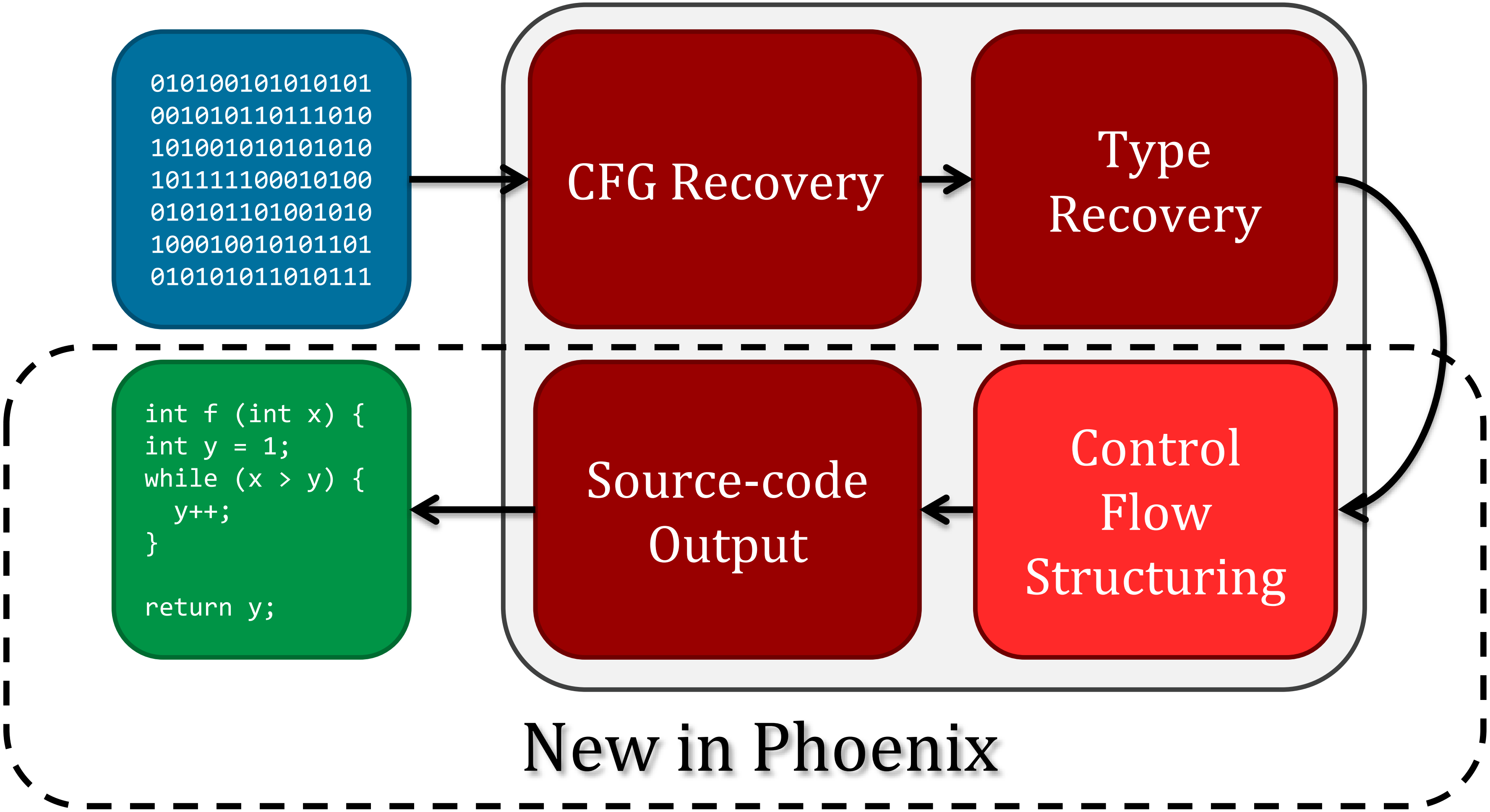
Are these two programs semantically equivalent?

How to build a better decompiler?

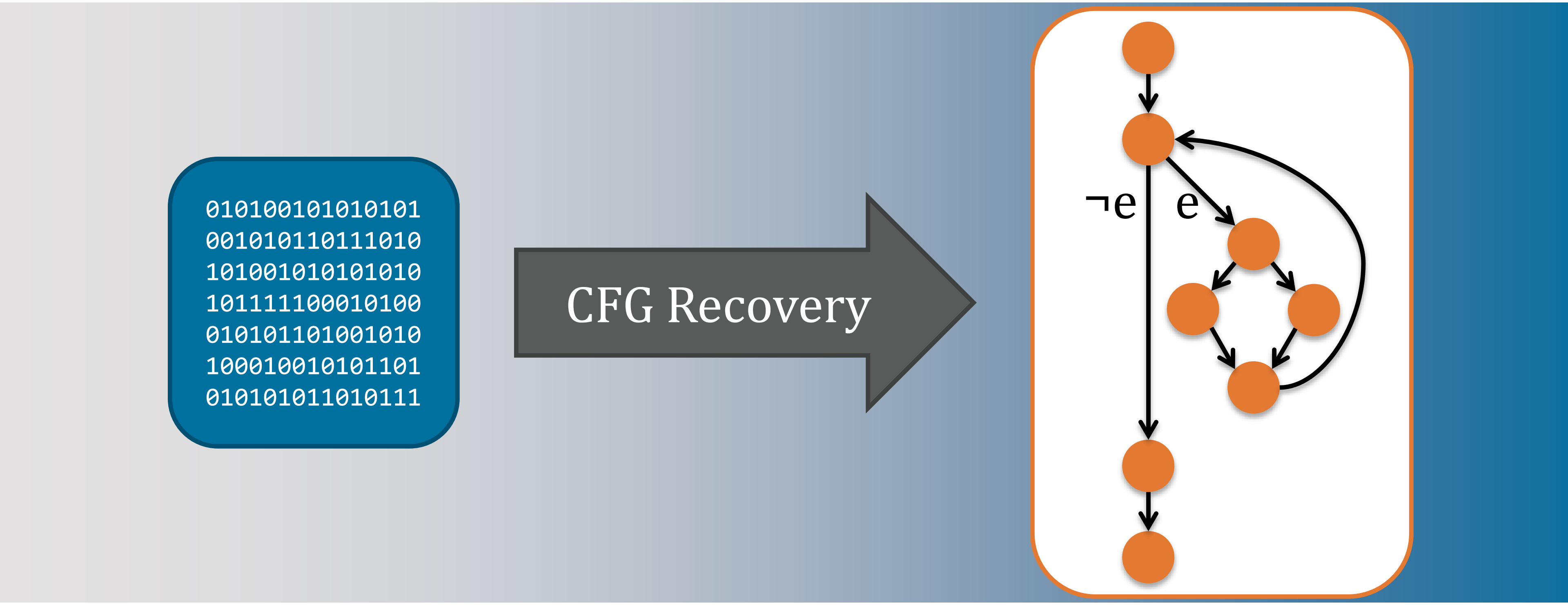
- Recover missing abstractions one at a time
  - Semantics preserving abstraction recovery
    - Rewrite program to use abstraction
    - Don't change behavior of program
    - Similar to compiler optimization passes

- Challenge: building semantics preserving recovery algorithms
  - This talk
    - Focus on control flow structuring
    - Empirical demonstration

Phoenix Overview



Control Flow Graph Recovery



- Vertex represents straight-line binary code
- Edges represents possible control-flow transitions
- **Challenge:** Where does `jmp %eax` go?
- Phoenix uses Value Set Analysis [Balakrishnan10]

Type Inference on Executables (TIE) [Lee11]

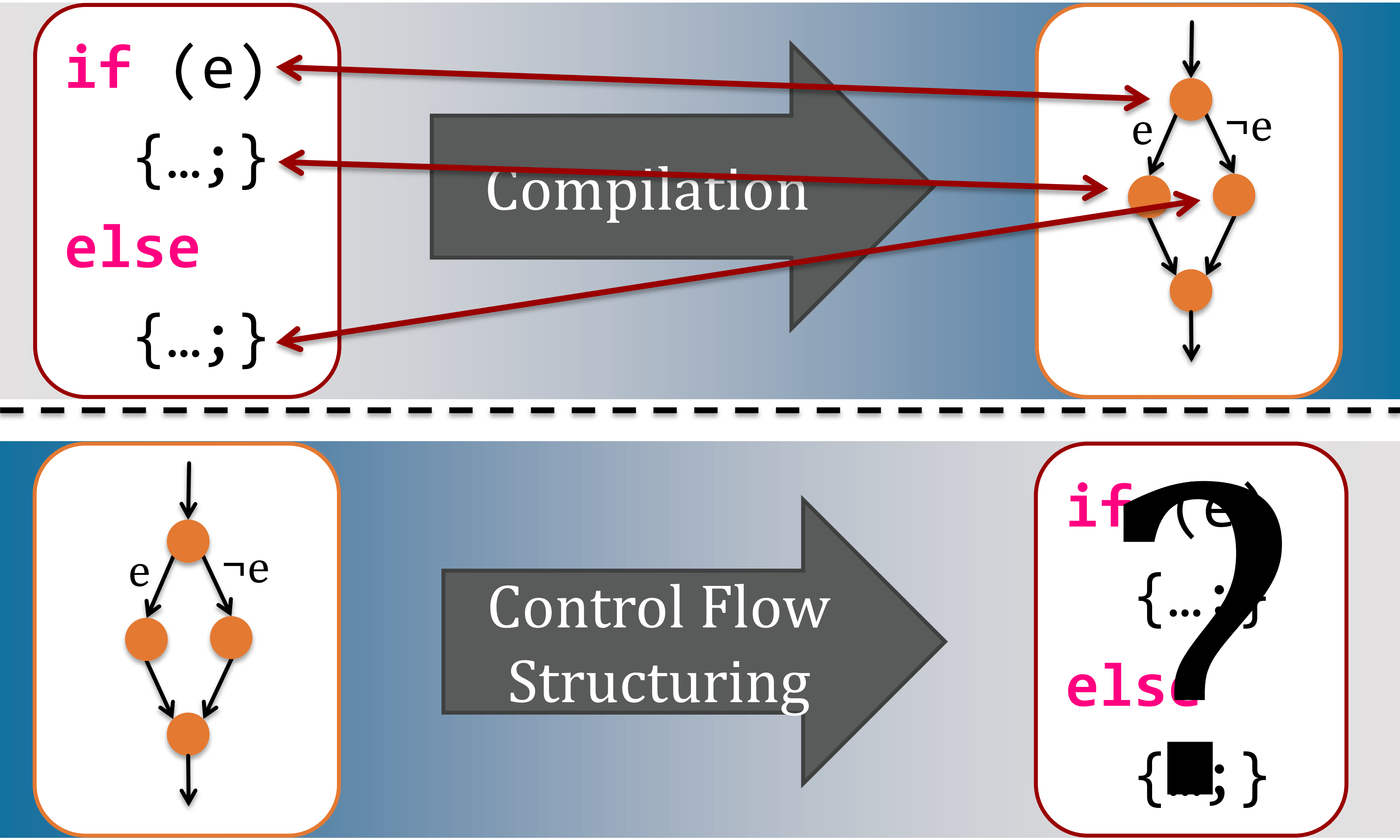
How does each instruction constrain the types?

```
movl (%eax), %ebx
```

- Constraint 1: `%eax` is a pointer to type `<a>`
- Constraint 2: `%ebx` has type `<a>`
- Solve all constraints to find `<a>`

Control Flow Structuring

Control Flow Structuring

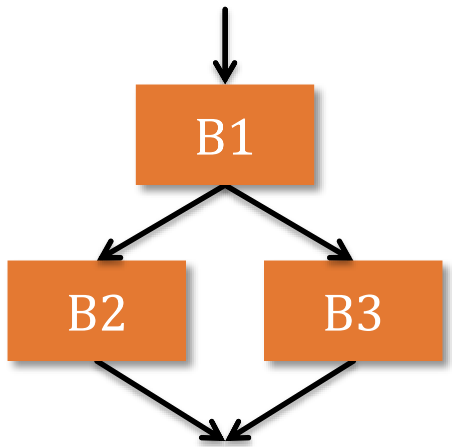


Control Flow Structuring: Don't Reinvent the Wheel

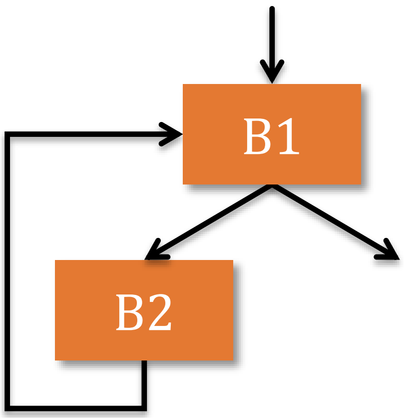
- Existing algorithms
  - Interval analysis [Allen70]
    - Identifies intervals or regions
  - Structural analysis [Sharir80]
    - Classifies regions into more specific types
- Both have been used in decompilers
- Phoenix based on structural analysis

Structural Analysis

- Iteratively match patterns to CFG
  - Collapse matching regions



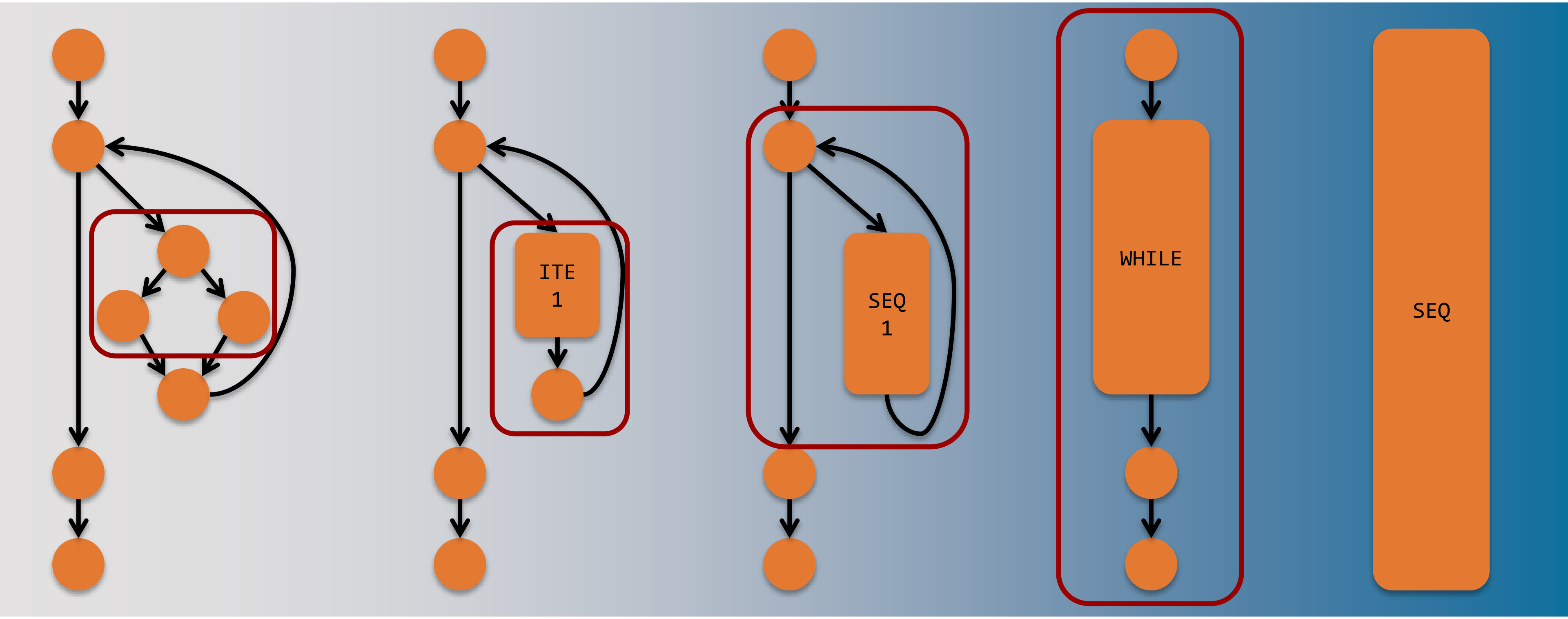
if-then-else



while

- Returns a skeleton: while (e) { if (e') {...} }

Structural Analysis Example




```
...;
while (...) { if (...) {...} else {...} };
...; ...;
```

Structural Analysis Property Checklist

1. Effective abstraction recovery

Structural Analysis Property Checklist

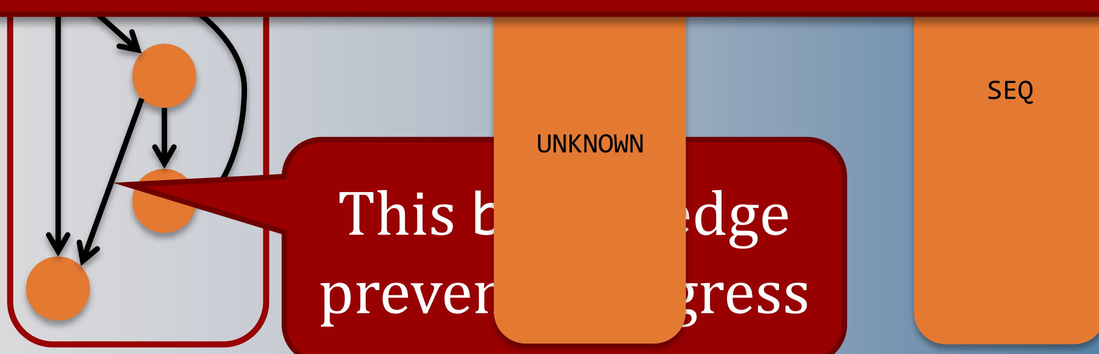
1. ~~Effective abstraction recovery~~
   - Grace<u>less</u> failures for unstructured programs
     - `break`, `continue`, and `goto` statements
     - Failures cascade to large subgraphs

Unrecovered Structure

```
s1;
while (e1) {
  if (e2) { break; }
  s
}
s3
```

```
s1;
L1: if (e1) { goto L2; }
    else { goto L4; }
                         }
```

Fix: New structuring algorithm featuring <u>Iterative Refinement</u>



Iterative Refinement

- Remove edges that are preventing a match
  - Represent in decompiled source as `break`, `goto`, `continue`

- Allows structuring algorithm to make more progress

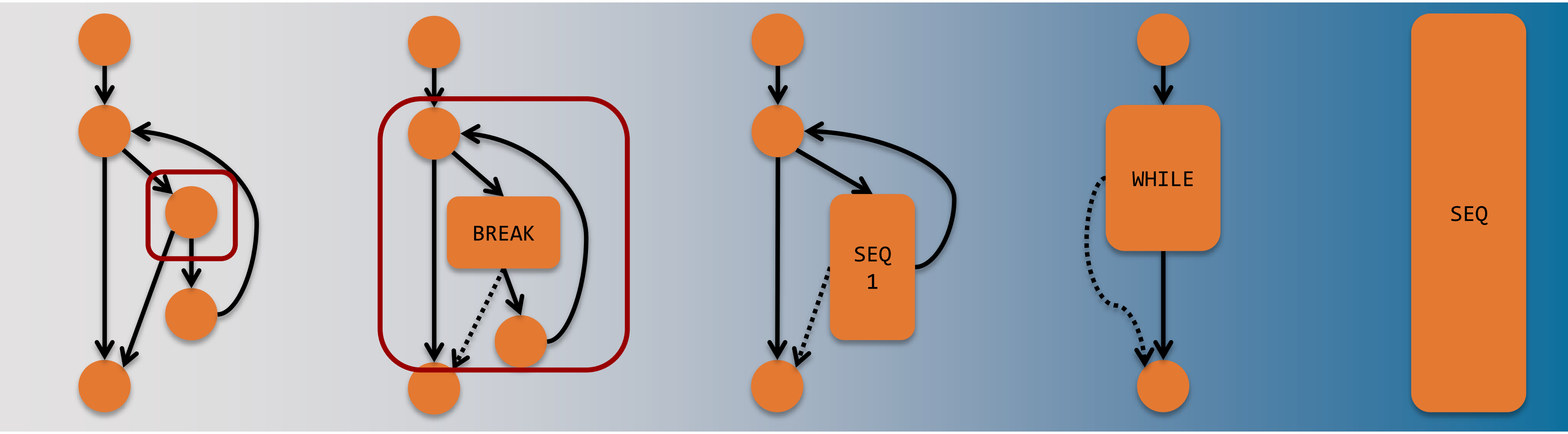
Iterative Refinement

```
s1;
while (e1) {
  if (e2) { break; }
  s2;
}
s3;
```

Original

```
s1;
while (e1) {
  if (e2) { break; }
  s2;
}
s3;
```

Decompiled



Structural Analysis Property Checklist

1. ~~Effective abstraction recovery~~
   - Grace*less* failures for unstructured programs
     - `break`, `continue`, and `goto`s
     - Failures cascade to large subgraphs

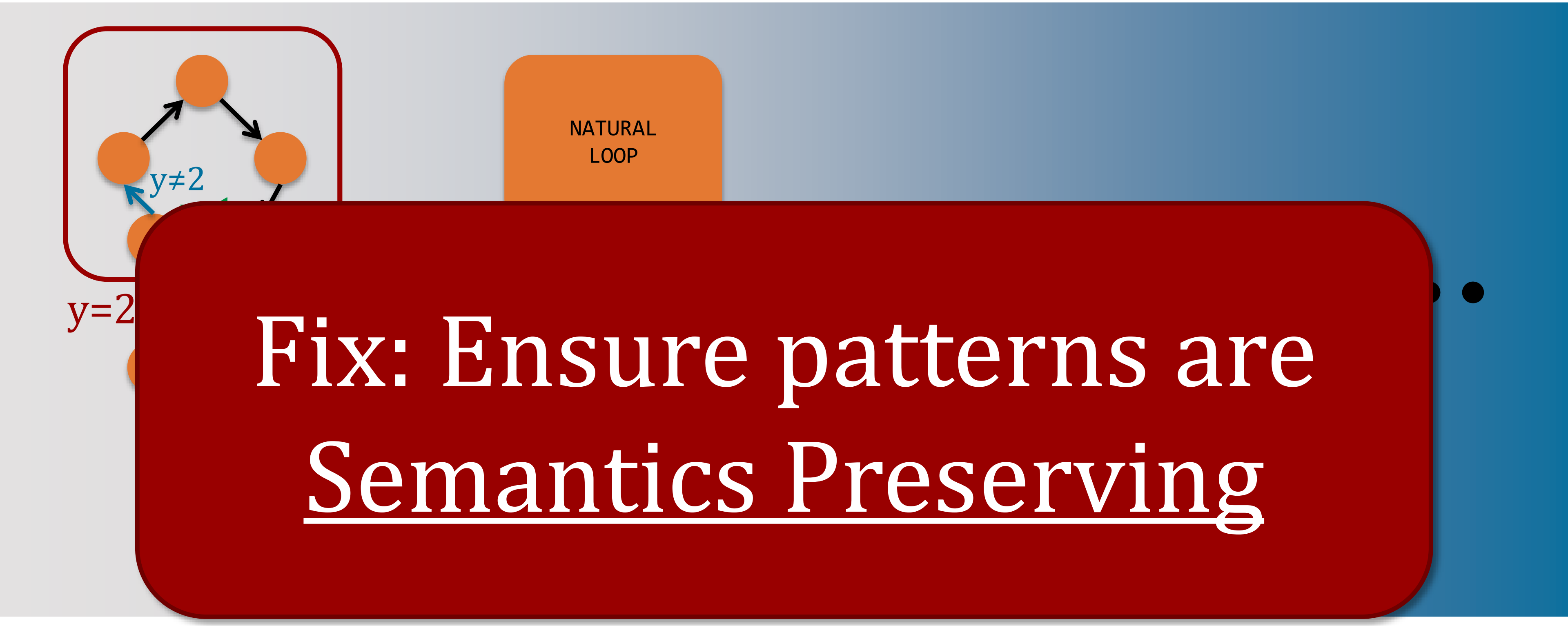
2. Correctness

Structural Analysis Property Checklist

1. ~~Effective abstraction recovery~~
   - Graceless failures for unstructured programs
     - `break`, `continue`, and `gotos`
     - Failures cascade to large subgraphs

2. ~~Correctness~~
   - Not originally intended for decompilation
   - Structure can be incorrect for decompilation

Natural Loop Correctness Problem

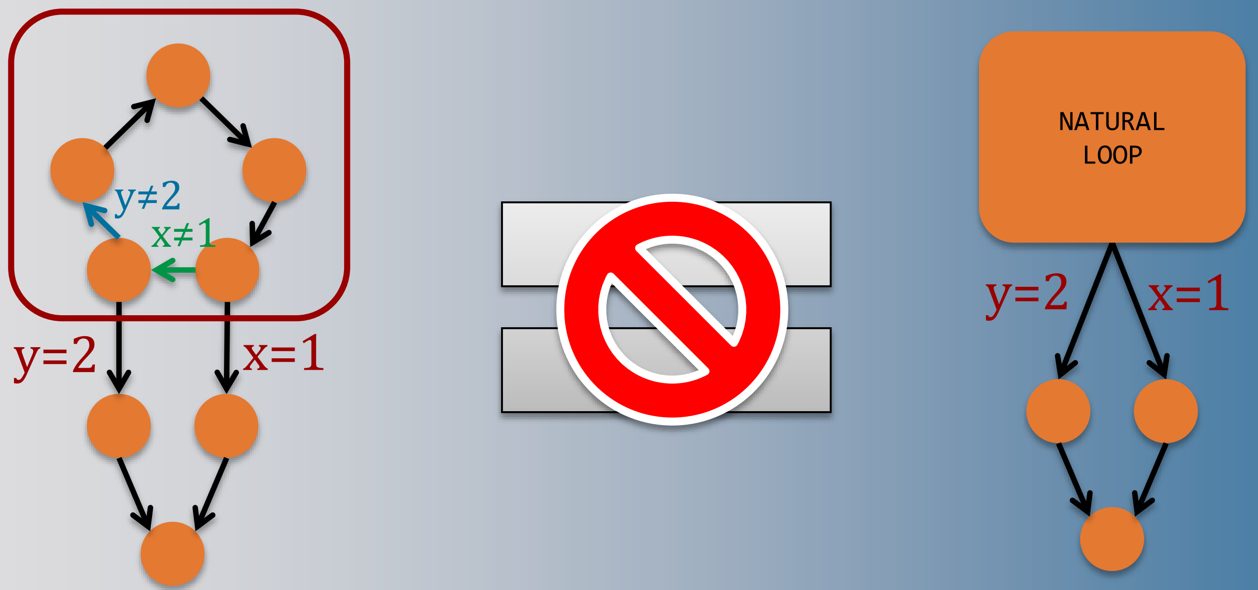


Fix: Ensure patterns are Semantics Preserving

```
while (true) {
  s1; if (x==1) goto L2;
  if (y==2) goto L1;
}
```

Semantics Preservation

- Applies inside of control flow structuring too



Phoenix Implementation and Evaluation

Readability: Phoenix Output

```
int f (void) {
  int a = 42;
  int b = 0;
  while (a) {
    if (b) {
      puts("c");
      break;
    } else {
      puts("d");
    }
    a--;
    b++;
  }
  puts ("e");
  return 0;
}
```

Original

```
t_reg32 f (void) {
  t_reg32 v20 = 42;
  t_reg32 v24;
  for (v24 = 0; v20 != 0;
       v24 = v24 + 1) {
    if (v24 != 0) {
      puts ("c");
      break;
    }
    puts ("d");
    v20 = v20 - 1;
  }
  puts ("e");
  return 0;
}
```

Decompiled

Large Scale Experiment Details

- Decompilers tested
  - Phoenix
  - Hex-Rays (industry state of the art)
  - Boomerang (academic state of the art)

- ~~Boomerang~~
  - Did not terminate in <1 hour for most programs

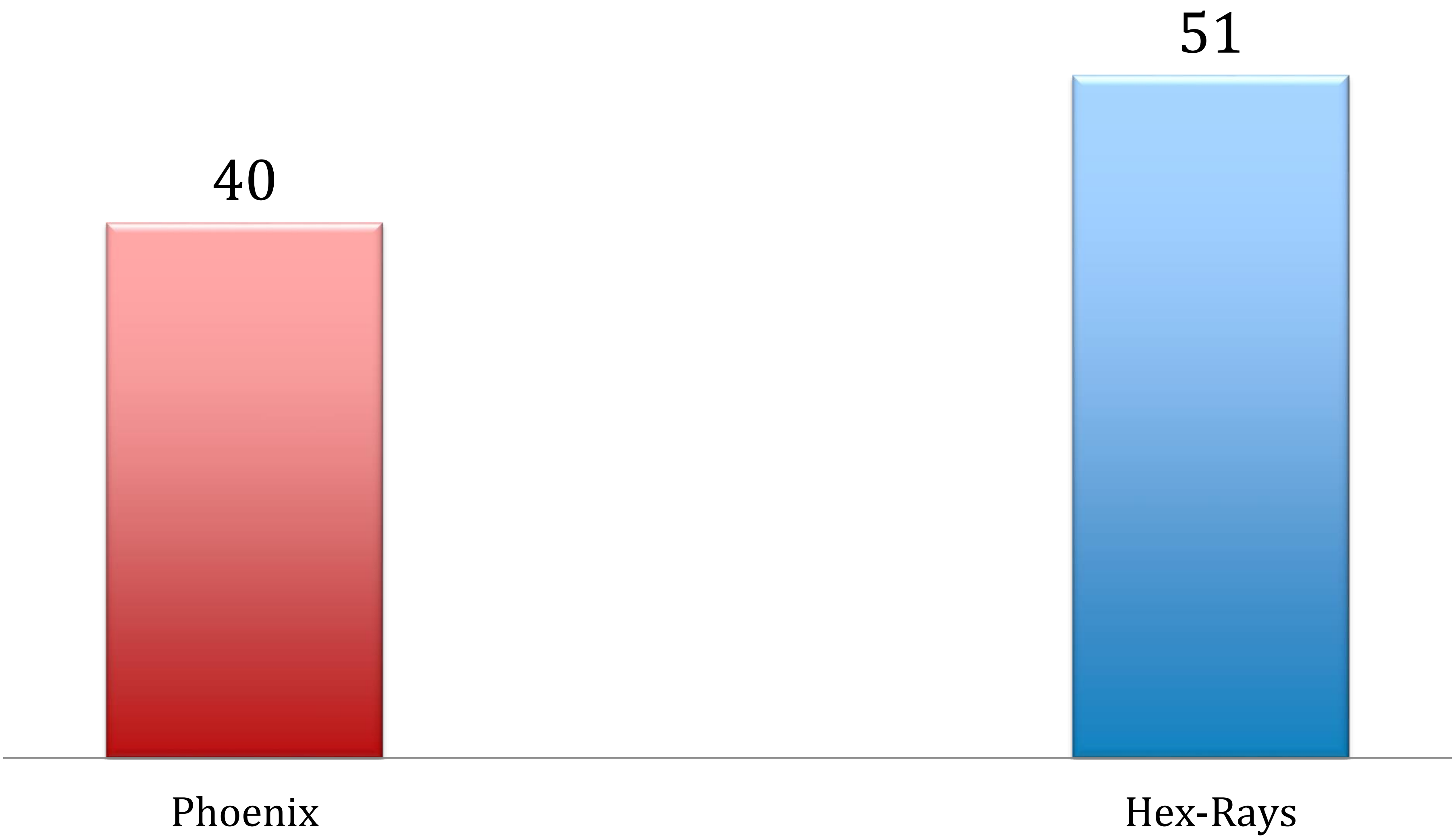
- GNU `coreutils` 8.17, compiled with `gcc`
  - Programs of varying complexity
  - Test suite

Metrics (end-to-end decompiler)

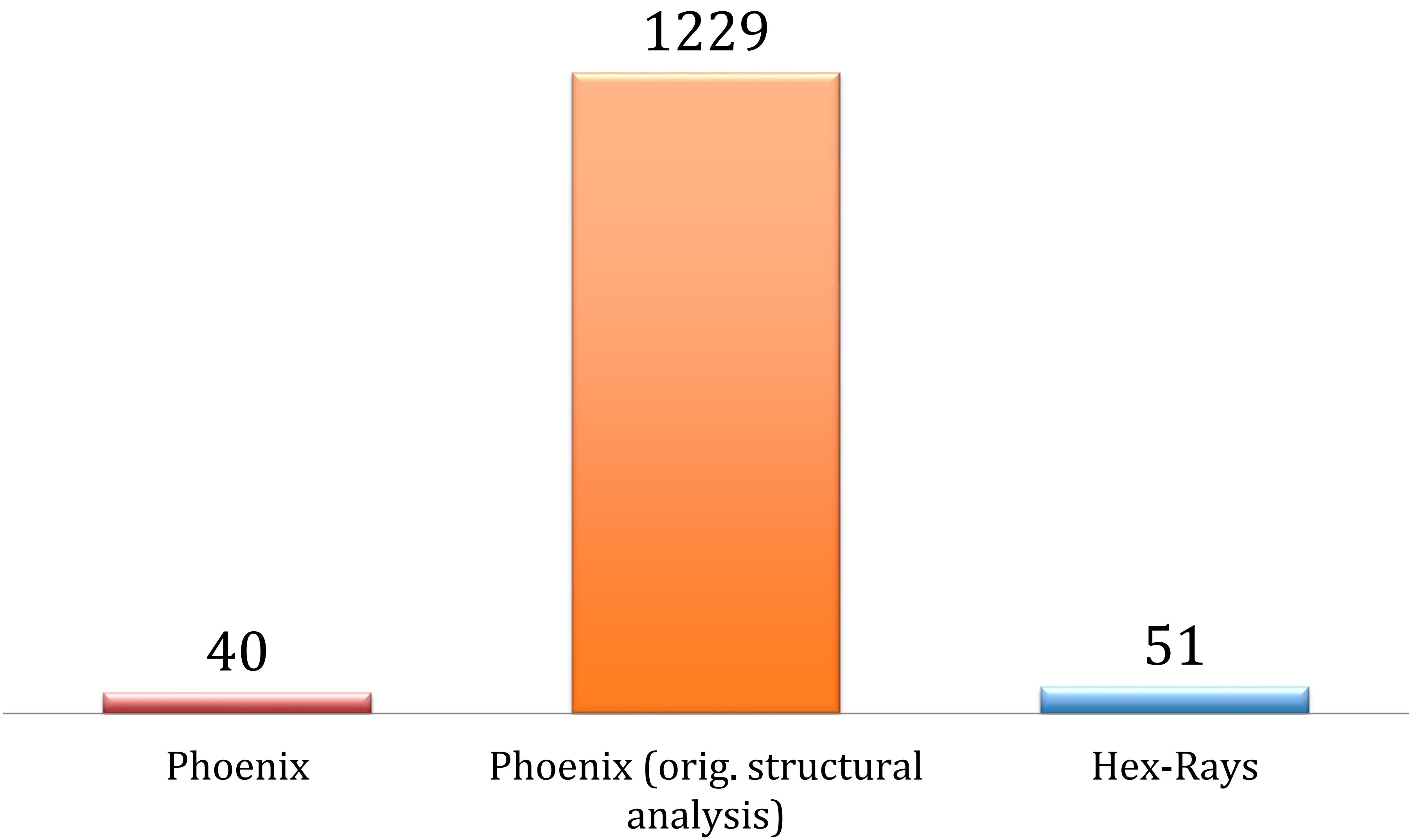
1. Effective abstraction recovery
   – Control flow structuring

2. Correctness

Control Flow Structure: Gotos Emitted (Fewer Better)



Control Flow Structure: Gotos Emitted (Fewer is Better)



Ideal: Correctness

```
int f (int x) {
int y = 1;
while (x > y) {
  y++;
}

return y;
```

Original Source

```
int f (int a) {
int v = 1;
while (a > v++)
{}

return v;
```

Recovered Source

Are these two programs semantically equivalent?

Compiled Binary

Scalable: Testing

```
int f (int x) {
int y = 1;
while (x > y) {
  y++;
}

return y;
```

Passes tests

Original Source

```
int f (int a) {
int v = 1;
while (a > v++)
{}

return v;
```

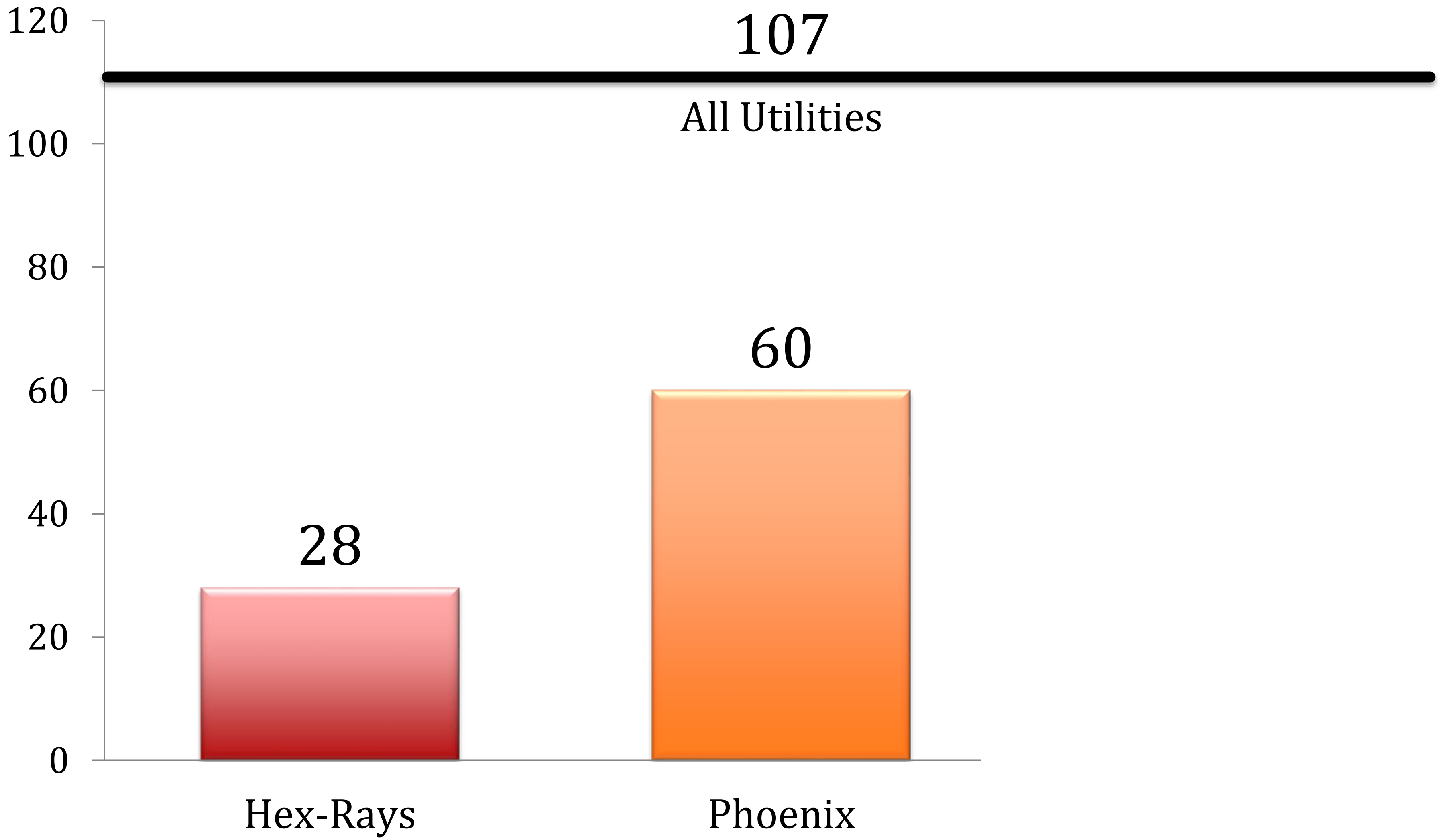
Passes tests

Recovered Source

Is the decompiled program consistent with test requirements?

Compiled Binary

Number of Correct Utilities



Correctness

- All known correctness errors attributed to type recovery
  - No known problems in control flow structuring

- Rare issues in TIE revealed by Phoenix stress testing
  - Even one type error can cause incorrectness
  - Undiscovered variables
  - Overly general type information

Conclusion

- Phoenix decompiler
  - Ultimate goal: Correct, abstract decompilation
  - Control-flow structuring algorithm
    - Iterative refinement
    - Semantics preserving schemas
- End-to-end correctness and abstraction recovery experiments on <u>>100</u> programs
  - Phoenix
    - Control flow structuring: ☺
    - Correctness: 50% ☹
- Correct, abstract decompilation of real programs is within reach
  - This paper: improving control flow structuring
  - Next direction: improved static type recovery

Thanks! ☺

- Questions?

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END