ByteWeight:
Learning to Recognize Functions in Binary Code

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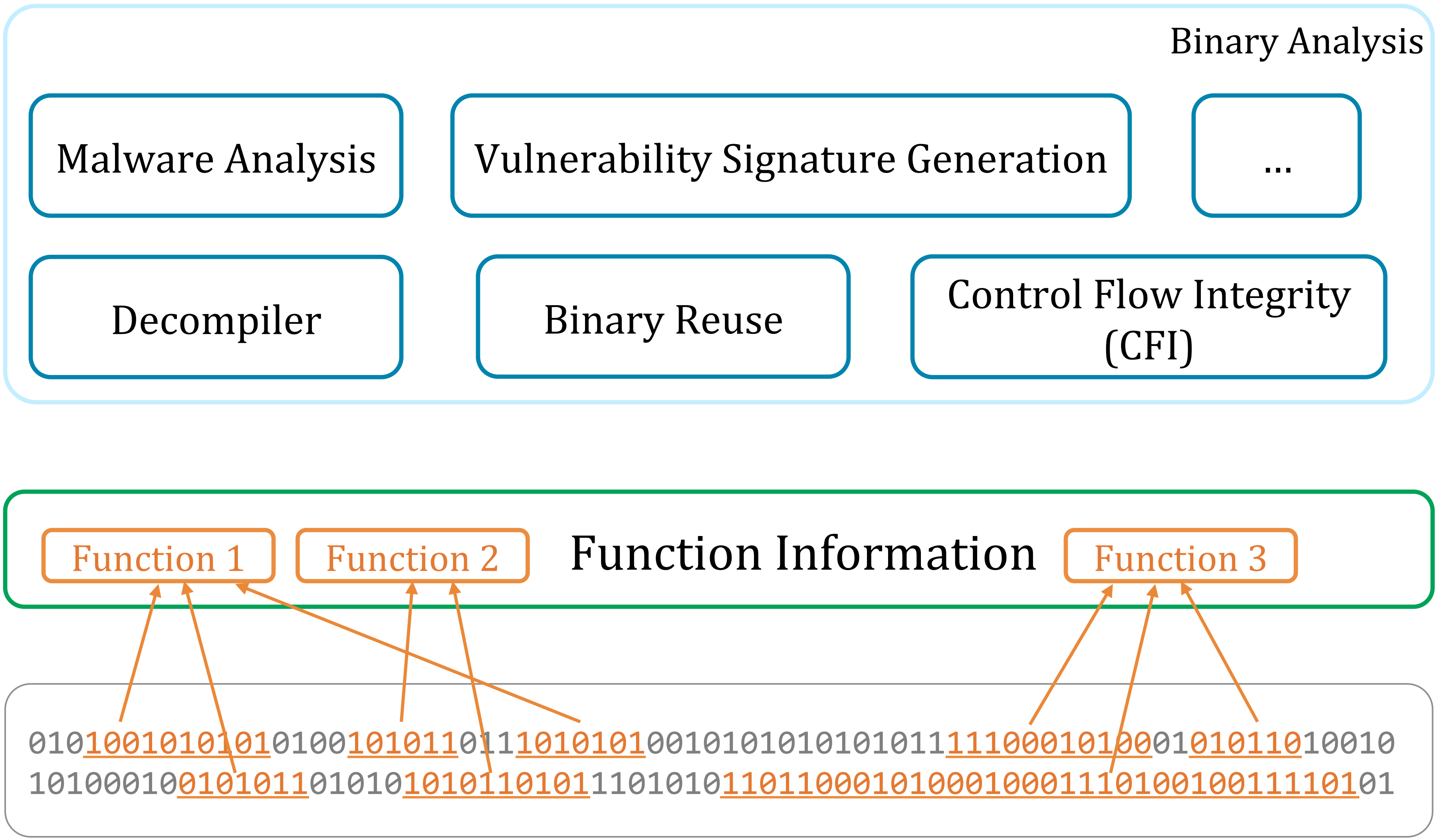
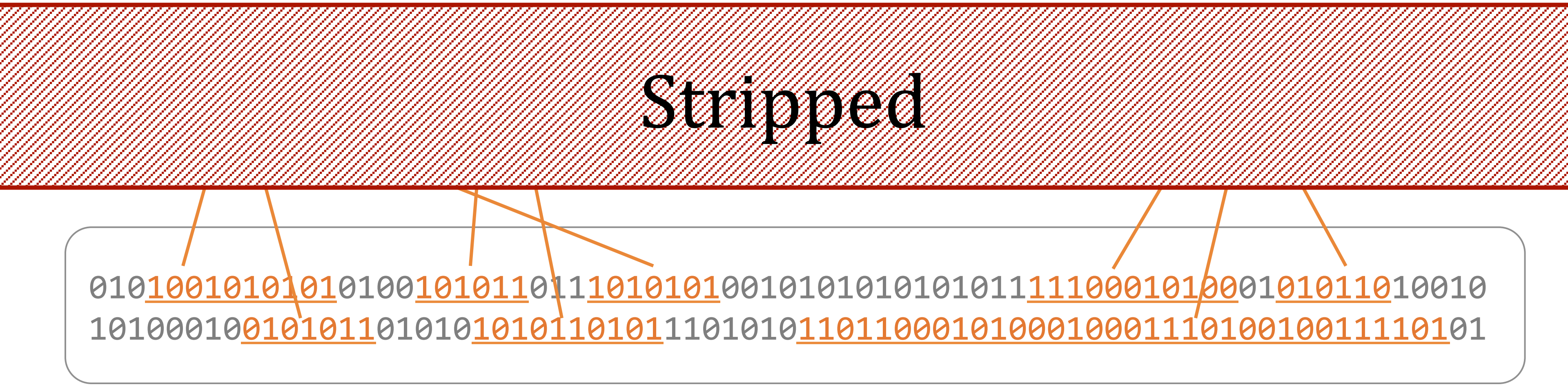

Binary Analysis
Malware Analysis
Vulnerability Signature Generation
...
Decompiler
Binary Reuse
Control Flow Integrity (CFI)
Function 1
Function 2
Function Information
Function 3
010100101010101001010110111010101001010101010101111100010100010101101010010
1010001001010110101010101101011101010110110001010001000111010010011110101

Can we *automatically* and *accurately* recover function information from stripped binaries?



Example: GCC

```
#include <stdio.h>
int fac(int x){
    if (x == 1)
        return 1;
    else
        return x * fac(x - 1);
}

void main(int argc, char **argv){
    printf("%d", fac(10));
}
```

Source Code

Example: GCC

```
08048443 <main>:
push    %ebp
mov     %esp,%ebp
and     $0xfffffff0,%esp
sub     $0x10,%esp
…

0804841c <fac>:
push    %ebp
mov     %esp,%ebp
sub     $0x18,%esp
cmpl    $0x1,0x8(%ebp)
jne     804842f <fac+0x13>
mov     $0x1,%eax
…
```

–O0: Default

Example: GCC

```
0804841c <fac>:
push     %ebx
sub      $0x18,%esp
mov      0x20(%esp),%ebx
mov      $0x1,%eax
cmp      $0x1,%ebx
…
```

–O1: Optimize

```
08048330 <main>:
mov      $0x1,%edx
mov      $0xa,%eax
lea      0x0(%esi),%esi
…
push     %ebp
mov      %esp,%ebp
and      $0xfffffff0,%esp
sub      $0x10,%esp
…
```

–O2: Optimize Even More

Current Industry Solution: IDA

IDA Misses

IDA Misses

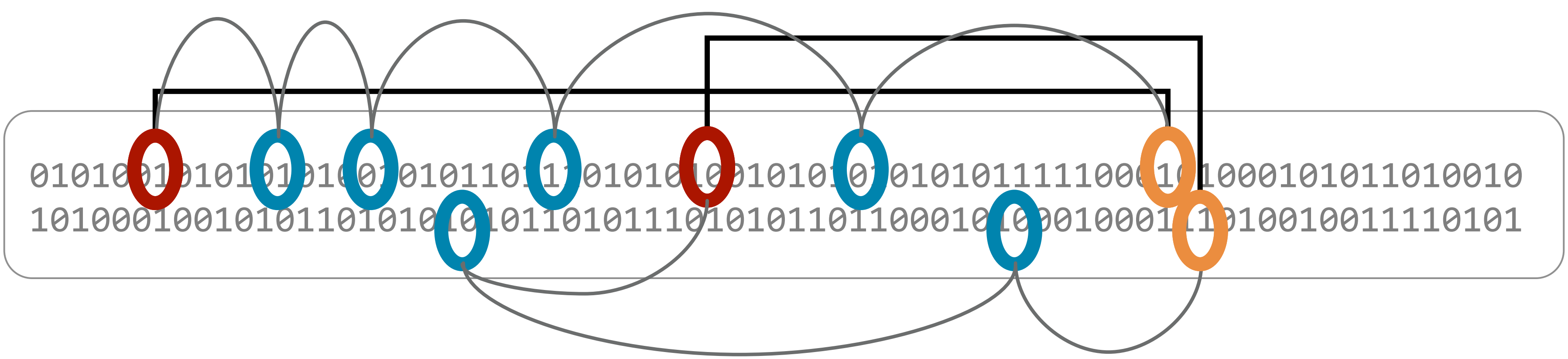
IDA Misses

```
#include<stdio.h>
#include<string.h>
#define MAX 128

void sum(char a[MAX], char b[MAX]){
    printf("%s + %s = %d\n", a, b, atoi(a) + atoi(b));
}

void sub(char a[MAX], char b[MAX]){
    printf("%s - %s = %d\n", a, b, atoi(a) - atoi(b));
}

void assign(char a[MAX], char b[MAX]){
    char pre_b[MAX];
    strcpy(pre_b, b);
    strcpy(b, a);
    printf("b is changed from %s to %s\n", pre_b, b);
}

int main(){
    void (*funcs[3]) (char x[MAX], char y[MAX]);
    int f;
    char a[MAX], b[MAX];
    funcs[0] = sum;
    funcs[1] = sub;
    funcs[2] = assign;
    scanf("%d %s %s", &f, &a, &b);
    (*funcs[f])(a, b);
    return 0;
}
```

Function Identification Problems

Given a ***stripped*** binary, return

1. A list of function start addresses
   - *“Function Start Identification (FSI) Problem”*
2. A list of function (start, end) pairs
   - *“Function Boundary Identification (FBI) Problem”*
3. A list of functions as sets of instruction address
   - *“Function Identification (FI) Problem”*



ByteWeight

A *machine learning* + *program analysis* approach
to function identification

Training:

- 1. Creates a model of function start patterns using supervised machine learning

Usage:

- 1. Use trained models to match function start on stripped binaries — Function Start Identification
- 2. Use program analysis to identify all bytes associated with a function — Function Identification
- 3. Calculate the minimum and maximum addresses of each function — Function Boundary Identification

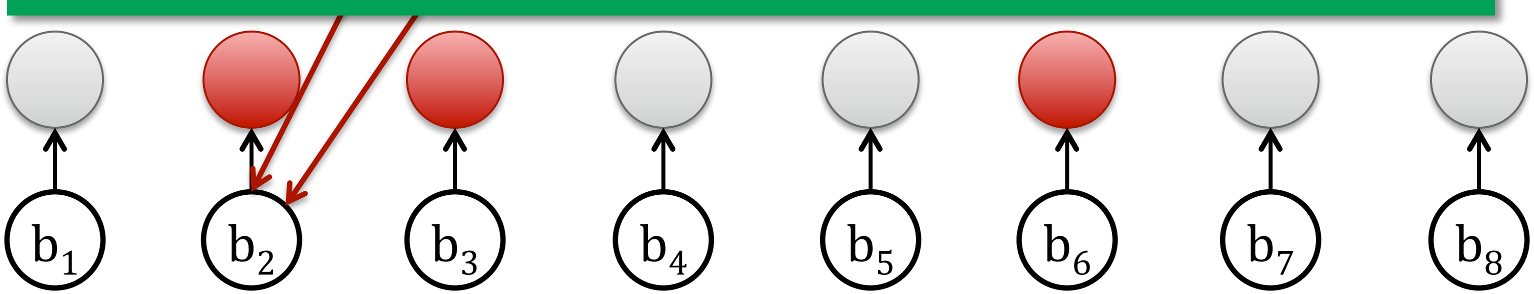
Function Start Identification

1. Previous approaches
2. Our approach

Previous Work: Rosenblum et al.[1]

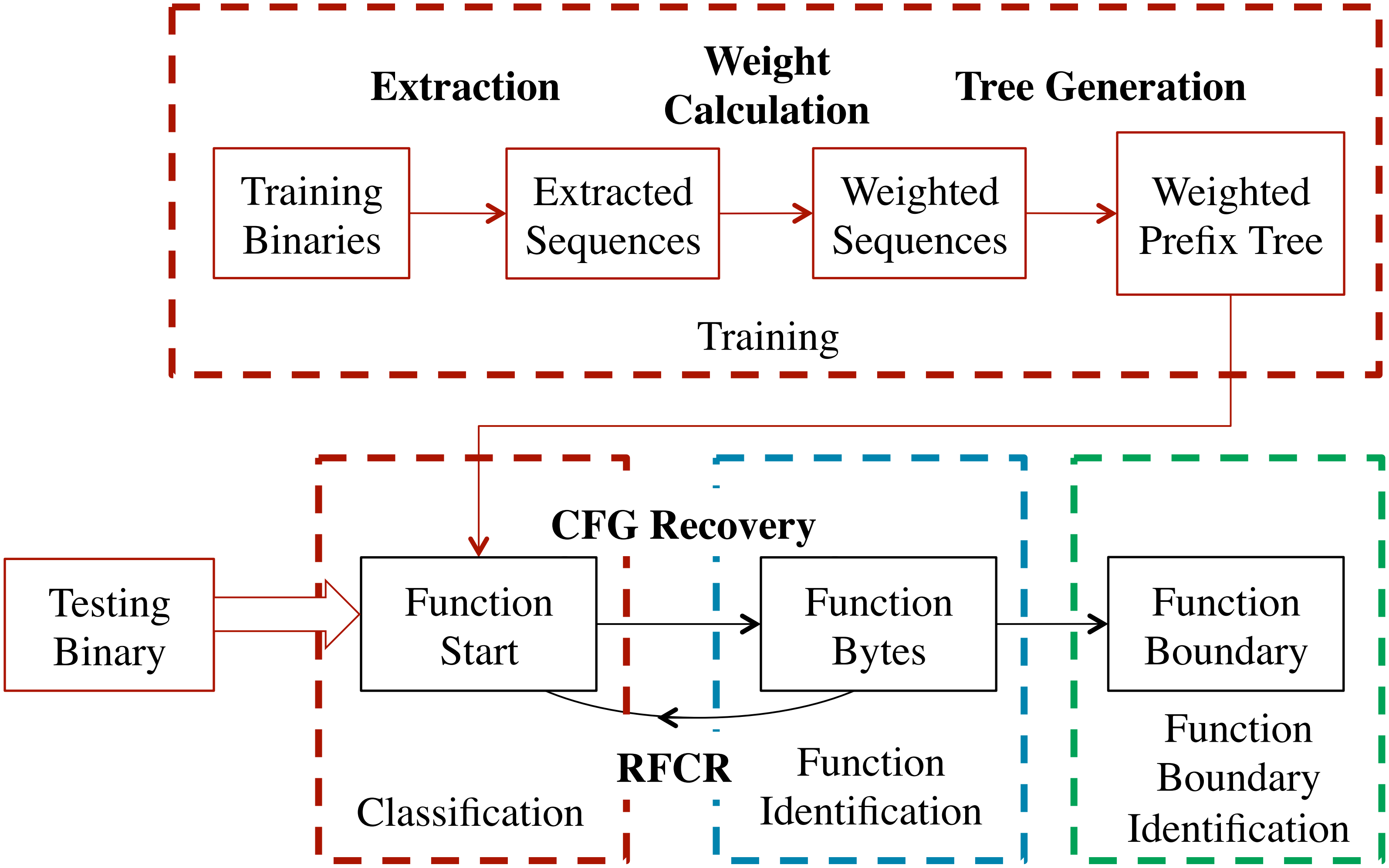
Method: Select instruction idioms up to length 4; learn idiom parameters; label test binaries

"Feature (idiom) selection for all three data sets (1,171 binaries) consumed over <u>150</u> compute-days of machine computation"



[1] N. E. Rosenblum, X. Zhu, B. P. Miller, and K. Hunt. Learning to Analyze Binary Computer Code. In Proceedings of the 23rd National Conference on Artificial Intelligence (2008), AAAI, pp. 798–804.

ByteWeight: Lighter (Linear) Method



Step 1: Extract All ≤ K-length Sequences

Bytes

- 55
- 55 48
- 55 48 89
- 55 48 89 e5
- …

```
0000000100000e3b <_func_1>:
push   %rbp
mov    %rsp,%rbp
sub    $0x10,%rsp
mov    %edi,-0x4(%rbp)
mov    %esi,-0x8(%rbp)
mov    -0x8(%rbp),%edx
mov    -0x4(%rbp),%eax
mov    %eax,%esi
lea    0xc0(%rip),%rdi
mov    $0x0,%eax
callq  100000ee8
leaveq
retq
```

Instructions

- `push %rbp`
- `push %rbp; mov %rsp,%rbp`
- `push %rbp; mov %rsp,%rbp; sub $0x10,%rsp`
- `push %rbp; mov %rsp,%rbp; sub $0x10,%rsp; mov %edi,-0x4(%rbp)`
- …

Step 2: Weight Sequences

push %rbp → 55

score:

2 / (2 + 2) = 0.5

```
0000000100000e3b <_func_1>:
55                          push    %rbp
48 89 e5                    mov     %rsp,%rbp
48 83 ec 10                 sub     $0x10,%rsp
89 7d fc                    mov     %edi,-0x4(%rbp)
89 75 f8                    mov     %esi,-0x8(%rbp)
8b 55 f8                    mov     -0x8(%rbp),%edx
8b 45 fc                    mov     -0x4(%rbp),%eax
89 c6                       mov     %eax,%esi
48 8d 3d c0 00 00 00        lea     0xc0(%rip),%rdi
b8 00 00 00 00              mov     $0x0,%eax
e8 86 00 00 00              callq   100000ee8
c9                          leaveq
c3                          retq

0000000100000e64 <_func_2>:
55                          push    %rbp
48 89 e5                    mov     %rsp,%rbp
48 83 ec 16                 sub     $0x16,%rsp
89 7d fc                    mov     %edi,-0x4(%rbp)
89 75 f8                    mov     %esi,-0x8(%rbp)
8b 55 f8                    mov     -0x8(%rbp),%edx
8b 45 fc                    mov     -0x4(%rbp),%eax
89 c6                       mov     %eax,%esi
48 8d 3d a6 00 00 00        lea     0xa6(%rip),%rdi
b8 00 00 00 00              mov     $0x0,%eax
e8 5d 00 00 00              callq   100000ee8
c9                          leaveq
c3                          retq
```

Step 2: Weight Sequences

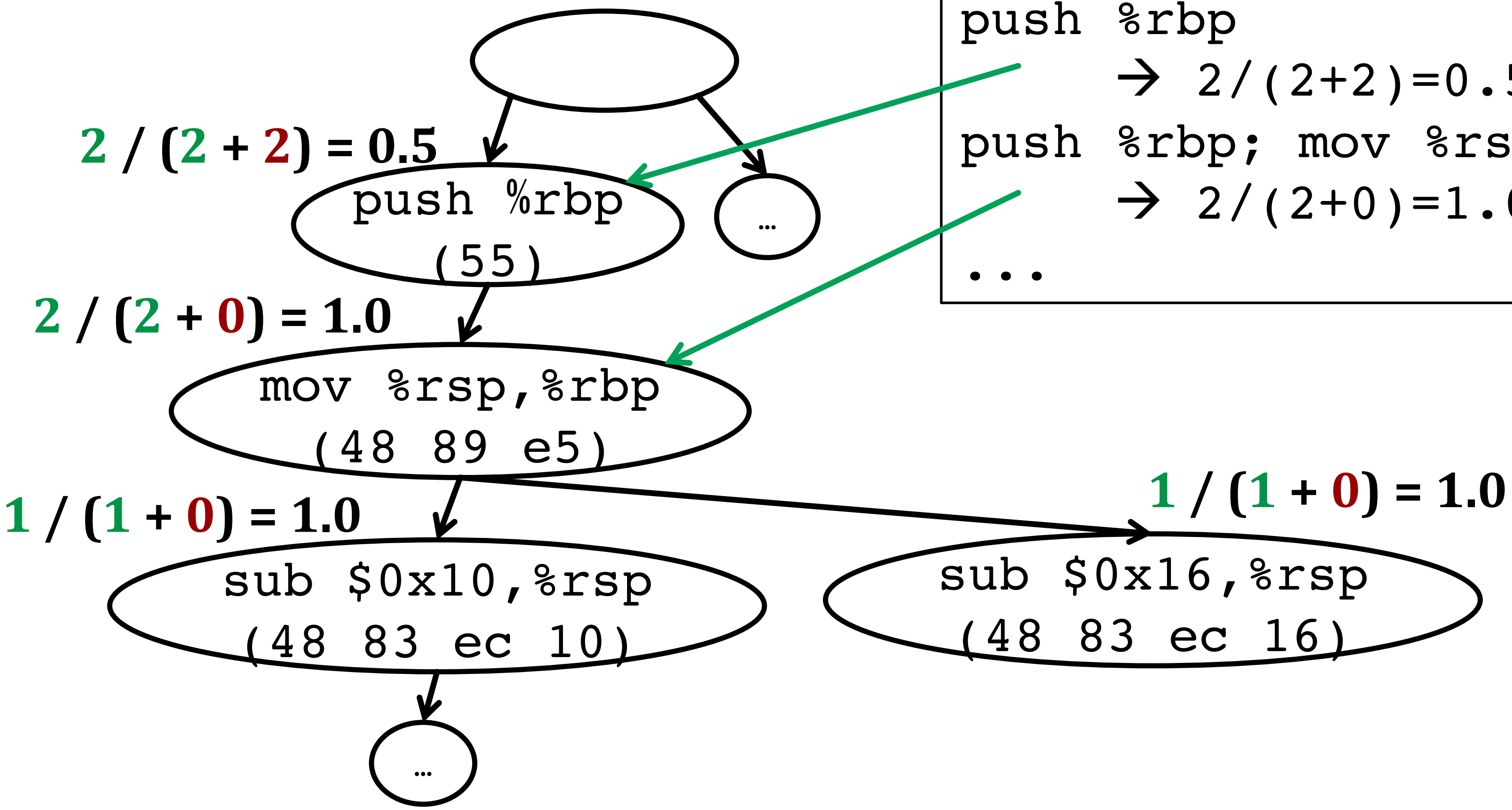
```
push %rbp; mov %rsp,%rbp
→ 55 48 89 e5
```

score:

2 / (2 + 0) = 1.0

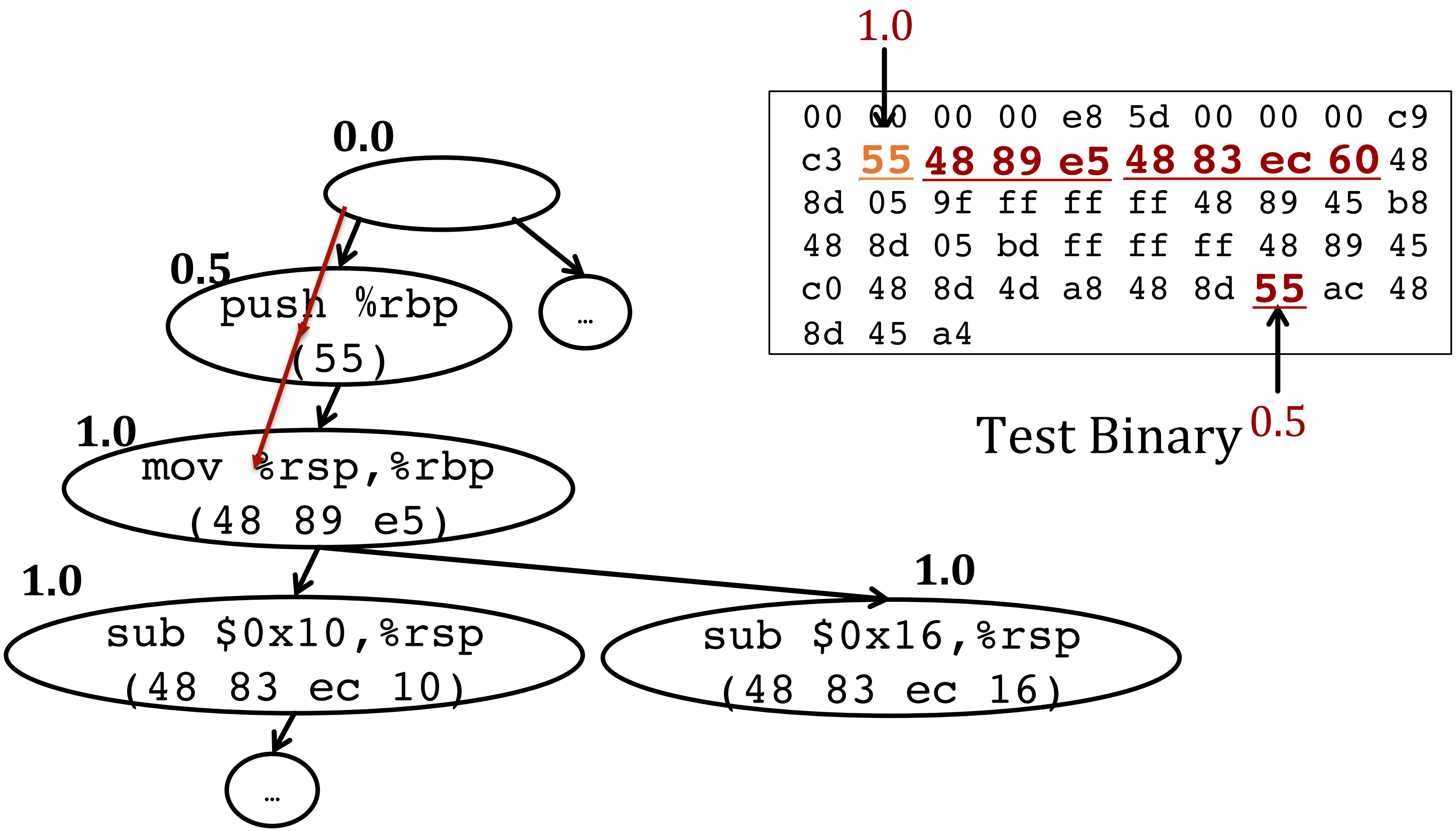
```
0000000100000e3b <_func_1>:
55                          push    %rbp
48 89 e5                    mov     %rsp,%rbp
48 83 ec 10                 sub     $0x10,%rsp
89 7d fc                    mov     %edi,-0x4(%rbp)
89 75 f8                    mov     %esi,-0x8(%rbp)
8b 55 f8                    mov     -0x8(%rbp),%edx
8b 45 fc                    mov     -0x4(%rbp),%eax
89 c6                       mov     %eax,%esi
48 8d 3d c0 00 00 00        lea     0xc0(%rip),%rdi
b8 00 00 00 00              mov     $0x0,%eax
e8 86 00 00 00              callq   100000ee8
c9                          leaveq
c3                          retq

0000000100000e64 <_func_2>:
55                          push    %rbp
48 89 e5                    mov     %rsp,%rbp
48 83 ec 16                 sub     $0x16,%rsp
89 7d fc                    mov     %edi,-0x4(%rbp)
89 75 f8                    mov     %esi,-0x8(%rbp)
8b 55 f8                    mov     -0x8(%rbp),%edx
8b 45 fc                    mov     -0x4(%rbp),%eax
89 c6                       mov     %eax,%esi
48 8d 3d a6 00 00 00        lea     0xa6(%rip),%rdi
b8 00 00 00 00              mov     $0x0,%eax
e8 5d 00 00 00              callq   100000ee8
c9                          leaveq
c3                          retq
```

Step 3: Generate Weighted Prefix Tree

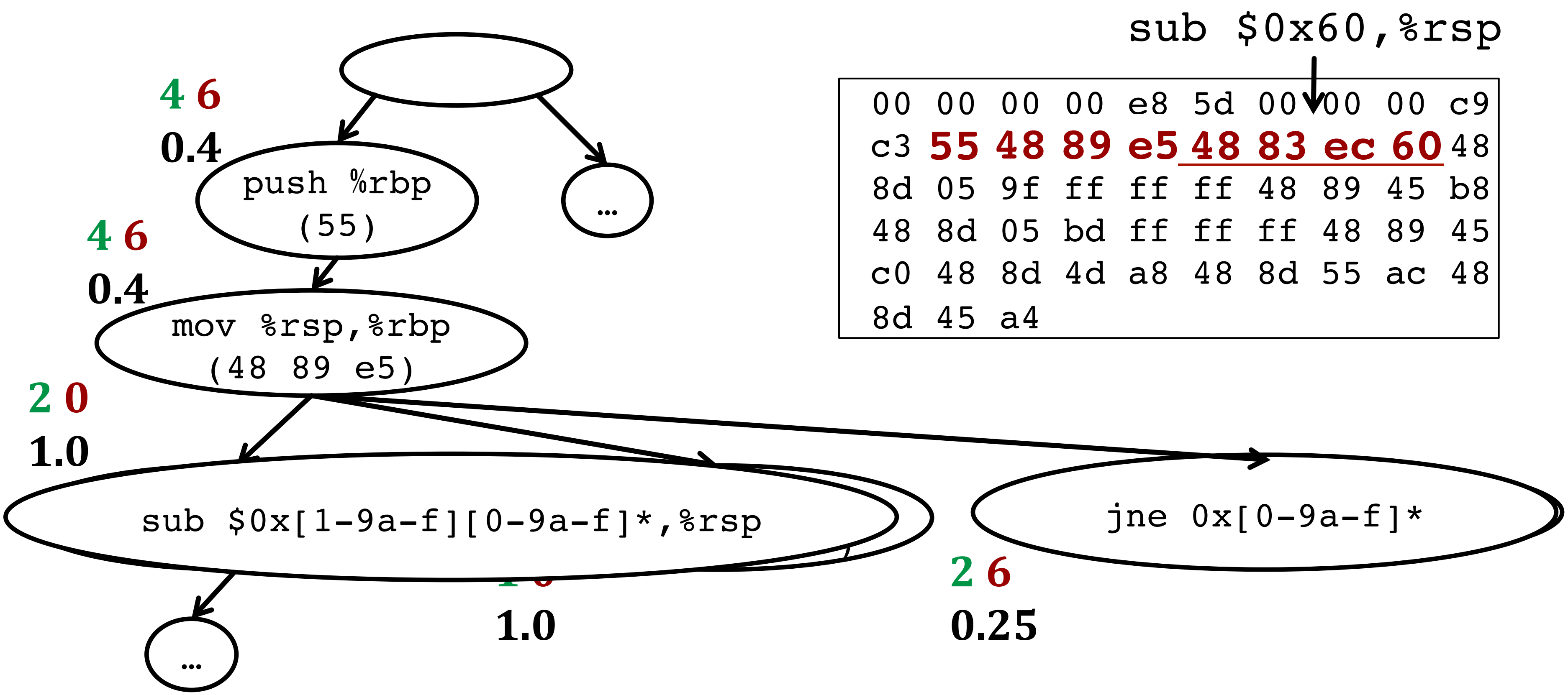



```
push %rbp
    → 2/(2+2)=0.5
push %rbp; mov %rsp,%rbp
    → 2/(2+0)=1.0
...
```

Classification



Normalization (Optional)



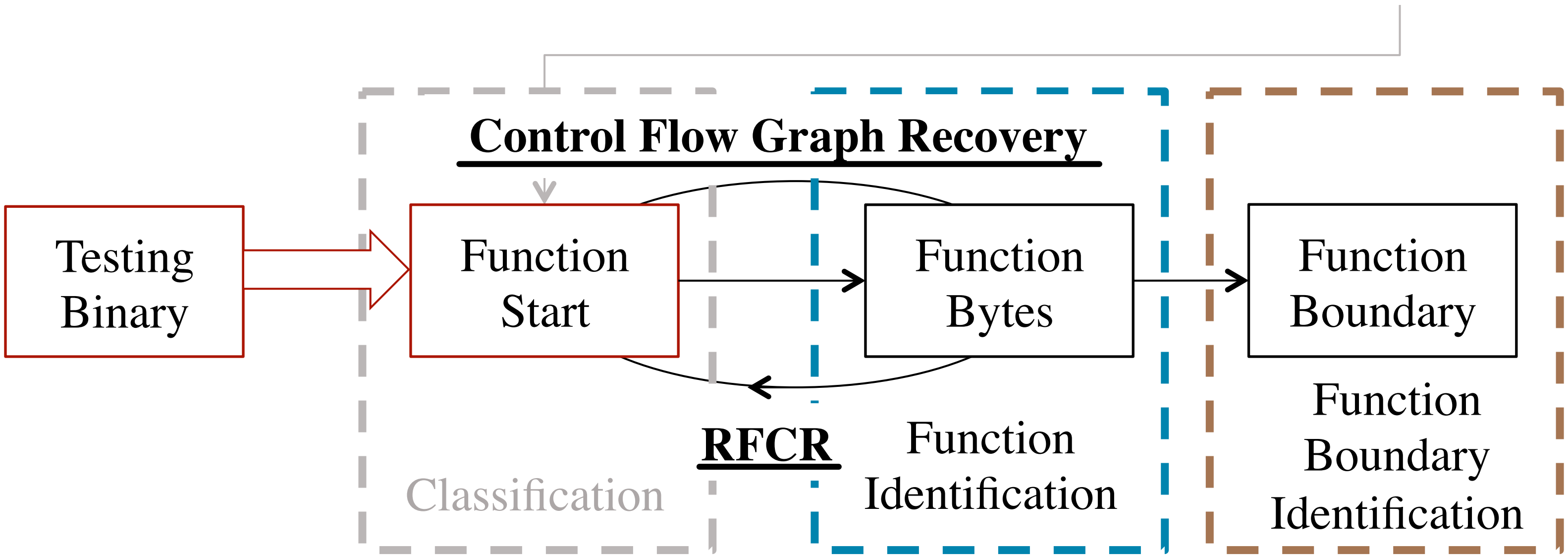
Function (Boundary) Identification

Identify all bytes associated with a function, and extract the lowest and highest addresses

ByteWeight: Function (Boundary) Identification

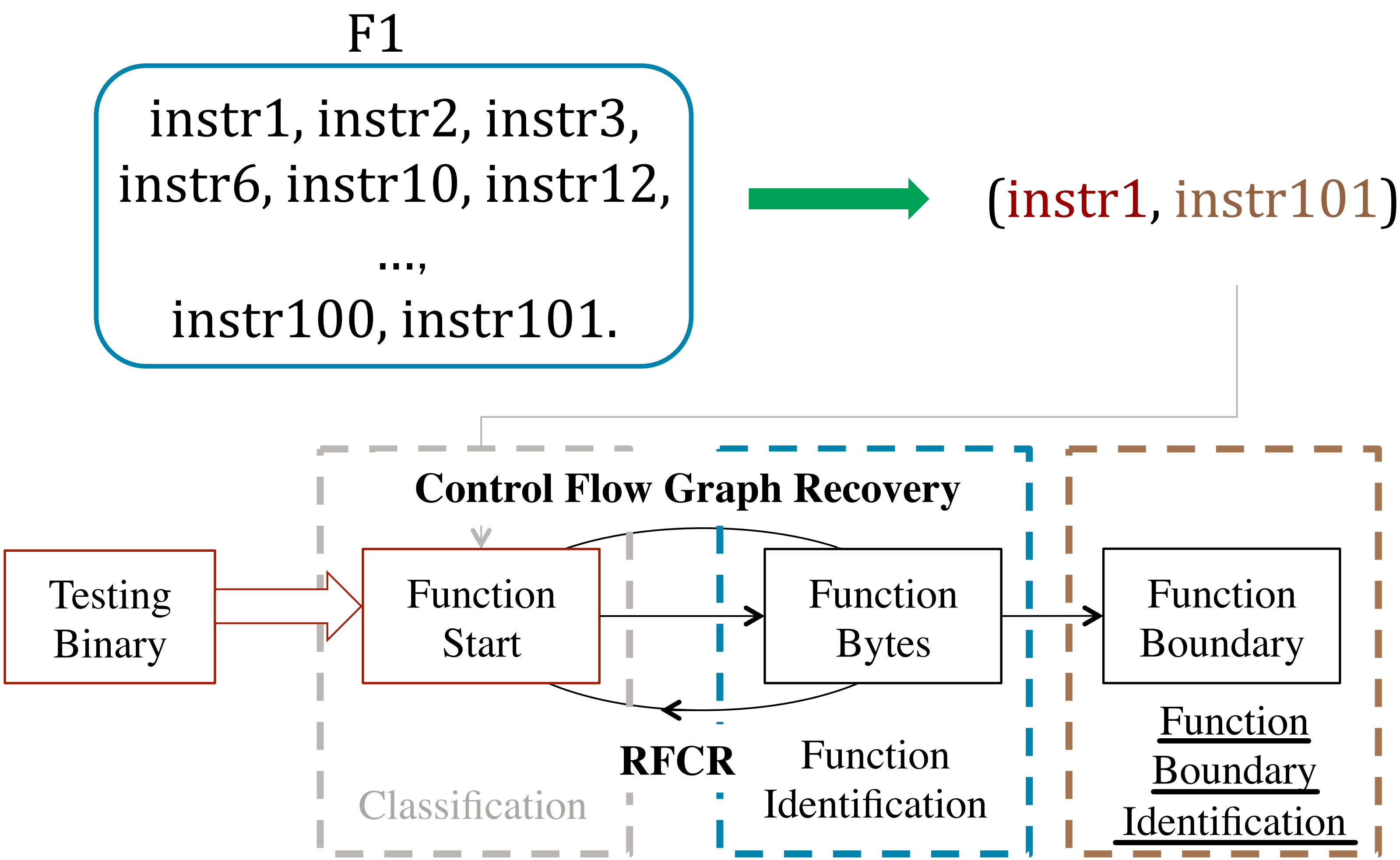
1. Recursive disassembly, using Value Set Analysis[2] to resolve indirect jumps.

2. Recursive Function Call Resolution—add any call target as a function start.



[2] G. Balakrishan. WYSINWYX: What You See Is Not What You Execute. PhD thesis, University of Wisconsin-Madison, 2007.

ByteWeight: Function (Boundary) Identification



[2] G. Balakrishan. WYSINWYX: What You See Is Not What You Execute. PhD thesis, University of Wisconsin-Madison, 2007.

Experiment Results

Compilers: GCC , ICC, and MSVS

Platforms: Linux and Windows

Optimizations: O0(Od), O1, O2, and O3(Ox)

Training Performance

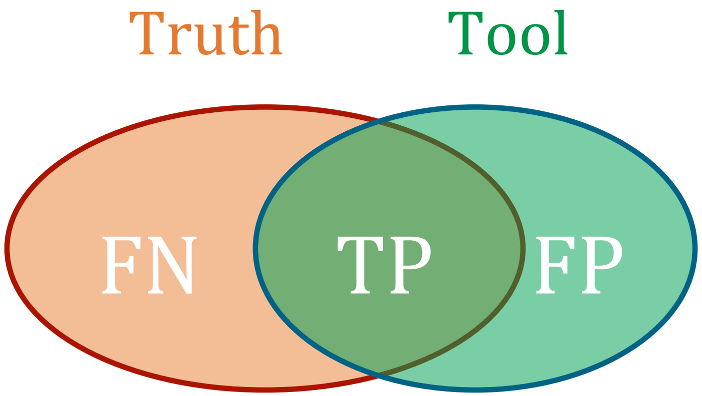
ByteWeight:

– 10-fold cross-validation, 2200 binaries
– 6.1 days to train from all platforms and all compilers including logging

Rosenblum et al.:

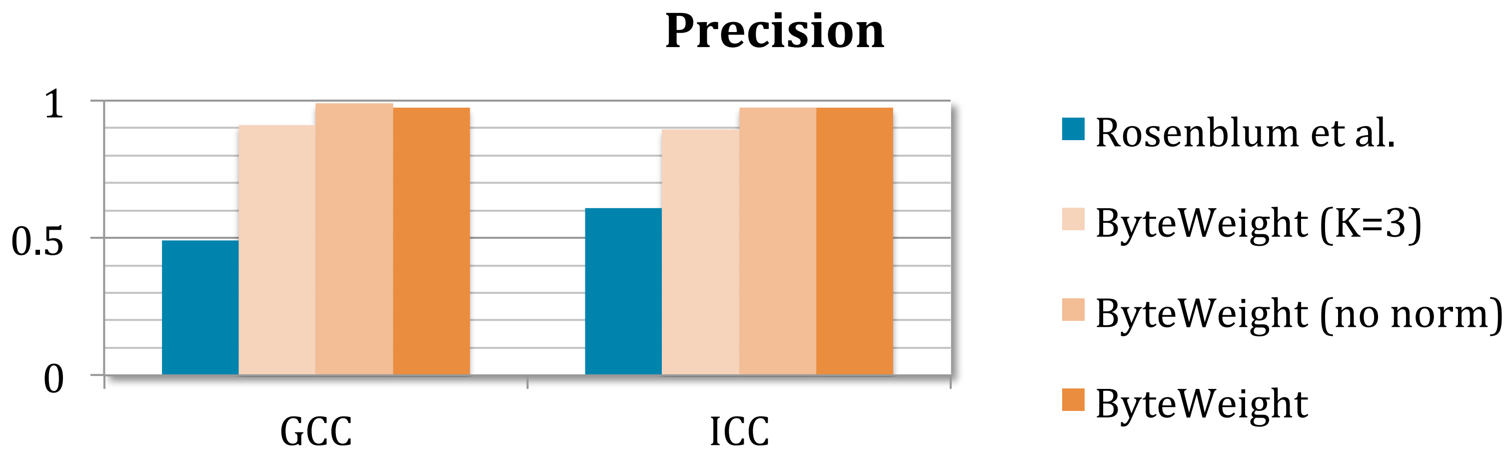
– ??? (They reported 150 compute days for one step of training, but did not report total time, or make their training implementation available.)
    - training data and code both unavailable

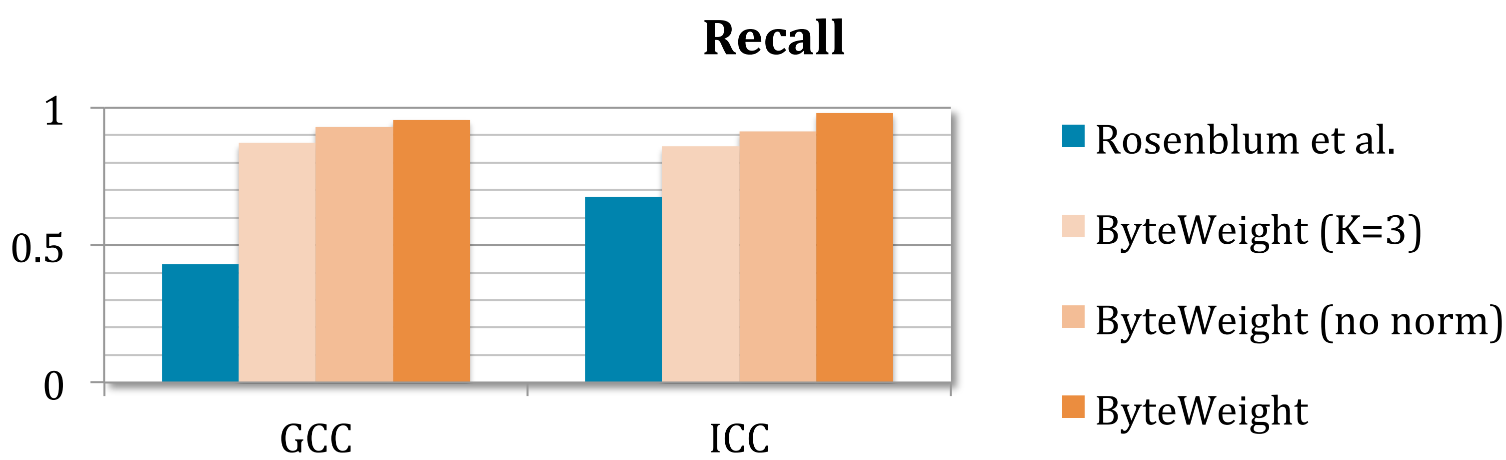
Precision and Recall



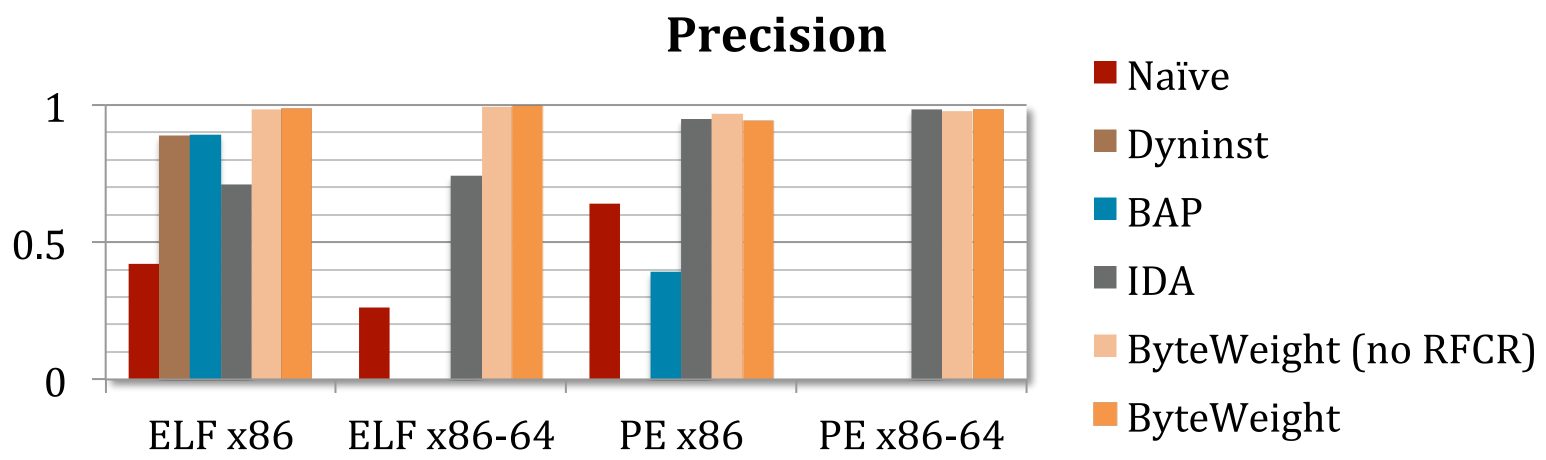
$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}} \qquad \text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}}$$

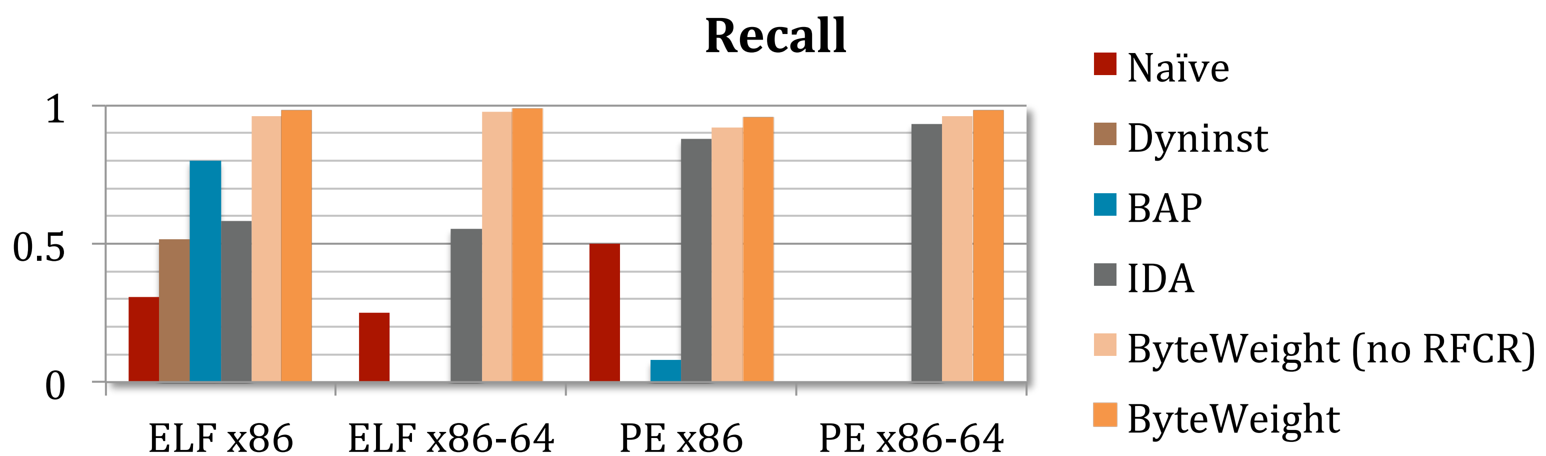
Function Start Identification: Comparison with Rosenblum et al.



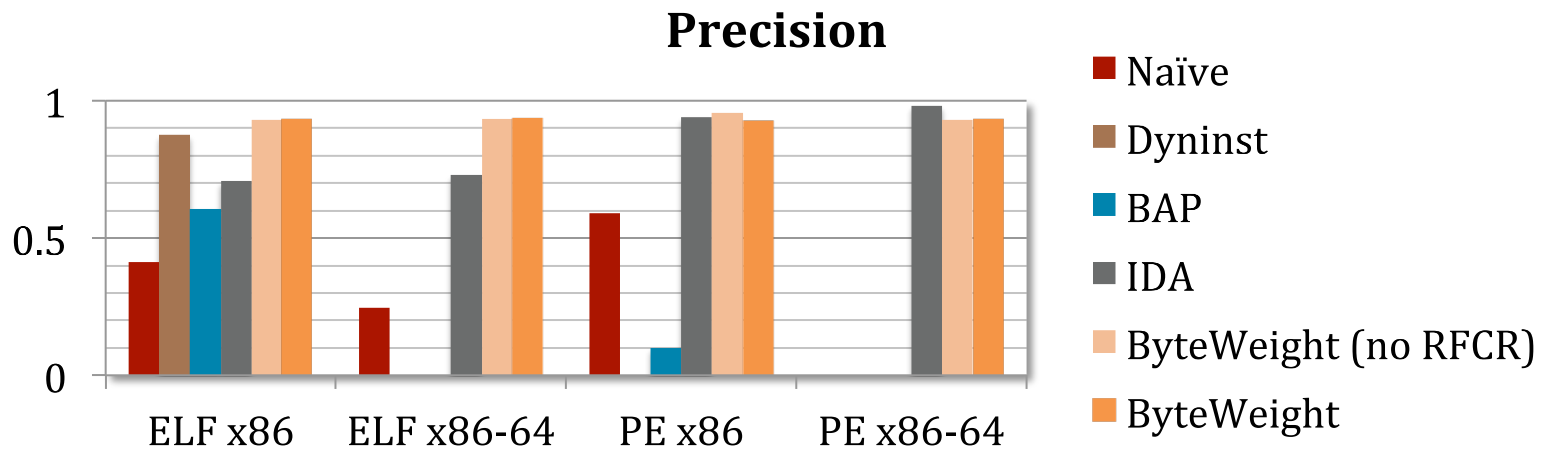


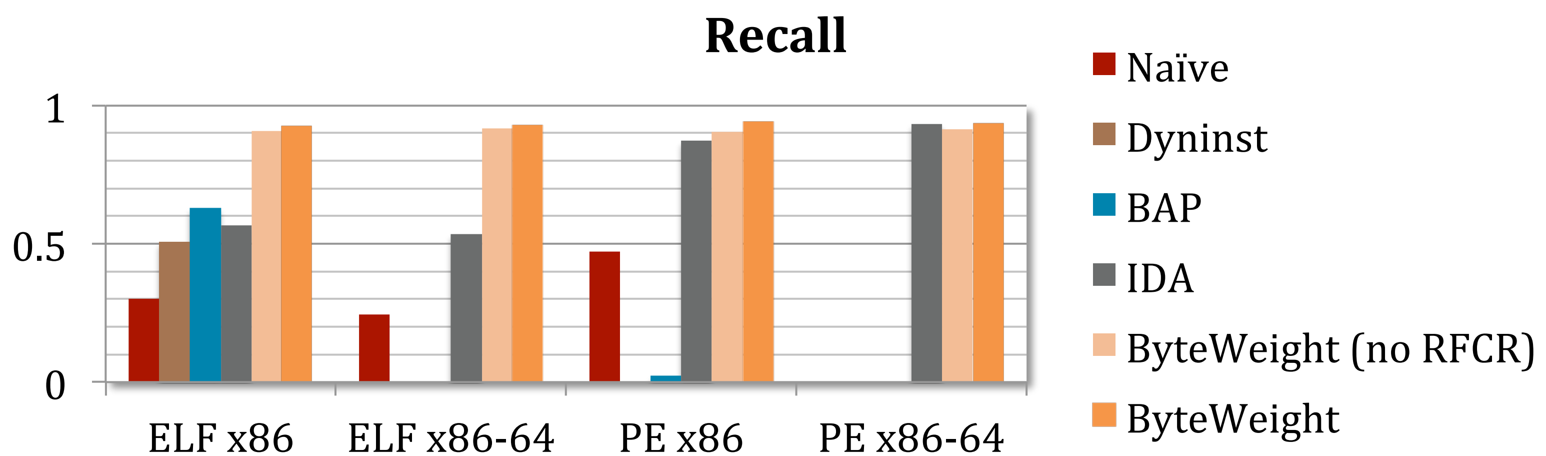
Function Start Identification: Existing Binary Analysis Tools





Function Boundary Identification: Existing Binary Analysis Tools





Summary: ByteWeight

Machine-learning based approach

- Creates a model of function start patterns using supervised machine learning
- Matches model on new samples
- Uses program analysis to identify all bytes associated with a function
- Faster and more accurate than previous work

Thank You

Our experiment VM is available at:

http://security.ece.cmu.edu/byteweight/

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