Tracelet-Based Code Search in Executables

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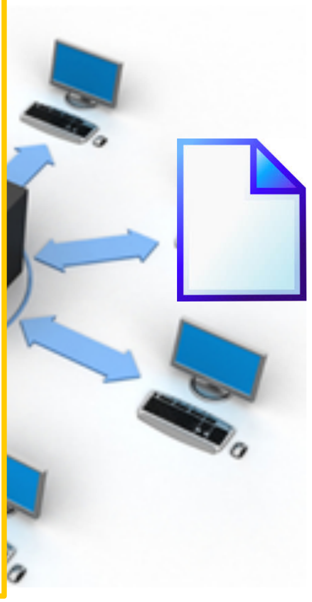
Finding vulnerable apps

We can find identical or patched code

```
int foo() {
  …
 // buffer
 // overflow
  …
  printf(…)
  …
}
```

```
int alsoFoo() {
  …
  // buffer
  // overflow
  …
  printf(…)
  …
}
```

```
int patchedFoo()
{
    …
    // buffer
    // overflow
    …
    if (…) {}
    printf(…)
    …
}
```



Where else does this vulnerable function exist?

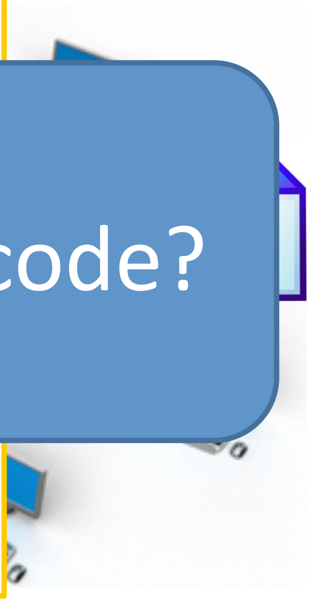
Finding vulnerable apps

We can find identical or patched code

```
int foo() {

}
```

```
int alsoFoo() {

}
```

```
int patchedFoo()

    printf(…)
    …
}
```



What if we don't have the source code?

Where else does this vulnerable function exist?

Boogle

binary functions

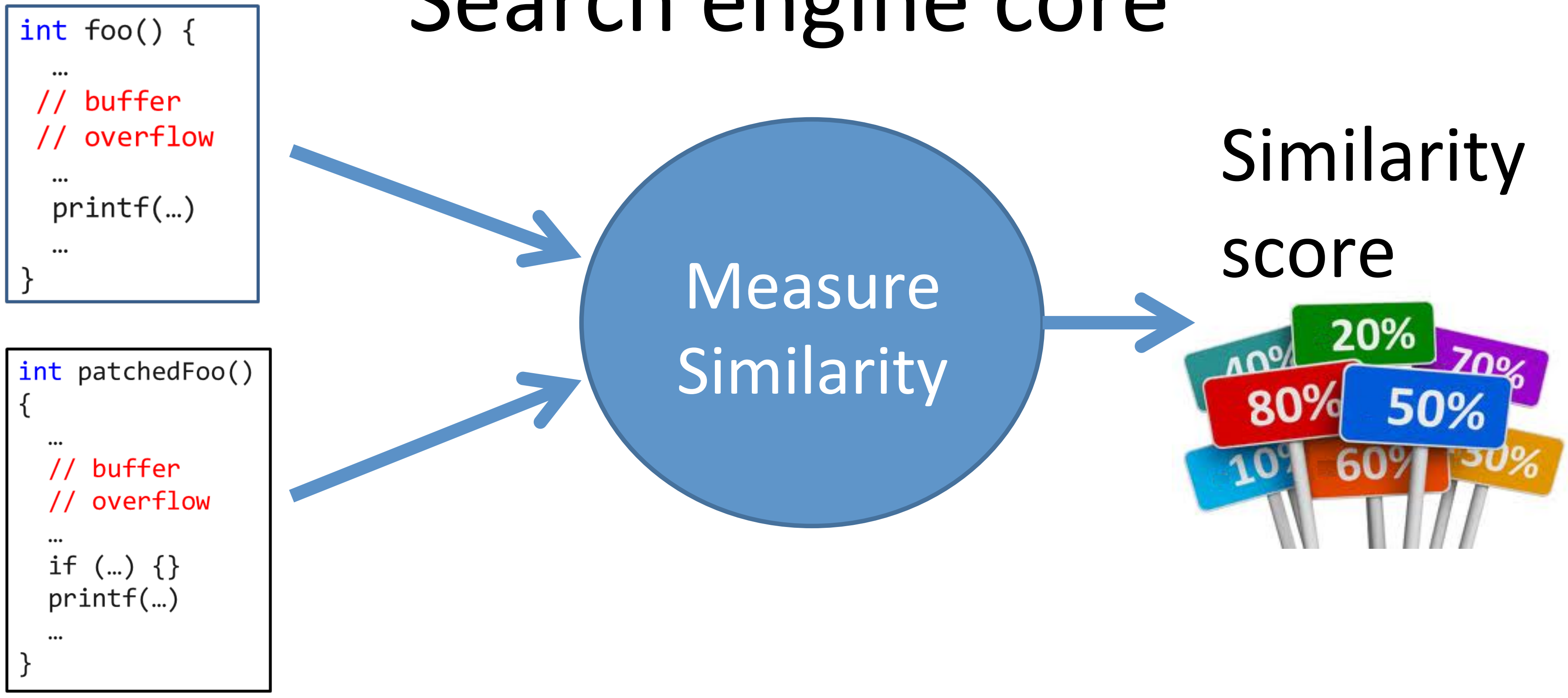
```
...
mov [esp+18h+var_18],offset aD1
mov ecx,1
mov [esp+18h+var_14], ecx
call _printf
...
```

Search in Binaries

Function 1 - wc
Coreutils 6.12

Function 2 – diff
Coreutils 7.15

Search engine core



```
int foo() {
  …
 // buffer
 // overflow
  …
  printf(…)
  …
}
```

```
int patchedFoo()
{
  …
  // buffer
  // overflow
  …
  if (…) {}
  printf(…)
  …
}
```

- Fast & Scalable
- Accurate (low false positives)

Challenge1: similarity at the binary level

printf(…)@foo():

```
int foo() {
   …
   // buffer
   // overflow
   …
   printf(…)
   …

}
```

printf(…)@patchedFoo():

```
int patchedFoo()
{
   …
   // buffer
   // overflow
   …
   if (…) {}
   printf(…)
   …
}
```

Challenge1: similarity at the binary level

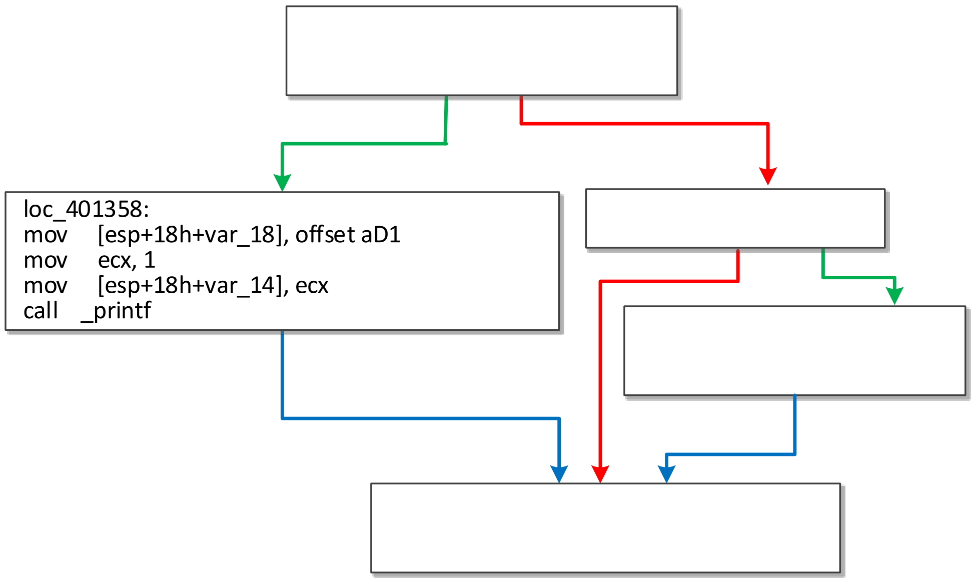
```
loc_401358:
mov [esp+18h+var_18],offset aD1
mov ecx,1
mov [esp+18h+var_14], ecx
call _printf
```

```
loc_401370:
mov [esp+28h+var_28],offset aD1
mov ebx,1
mov esi,4
mov [esp+28h+var_24], ebx
call _printf
```

- Offsets in memory
- Register allocation
- New Instruction

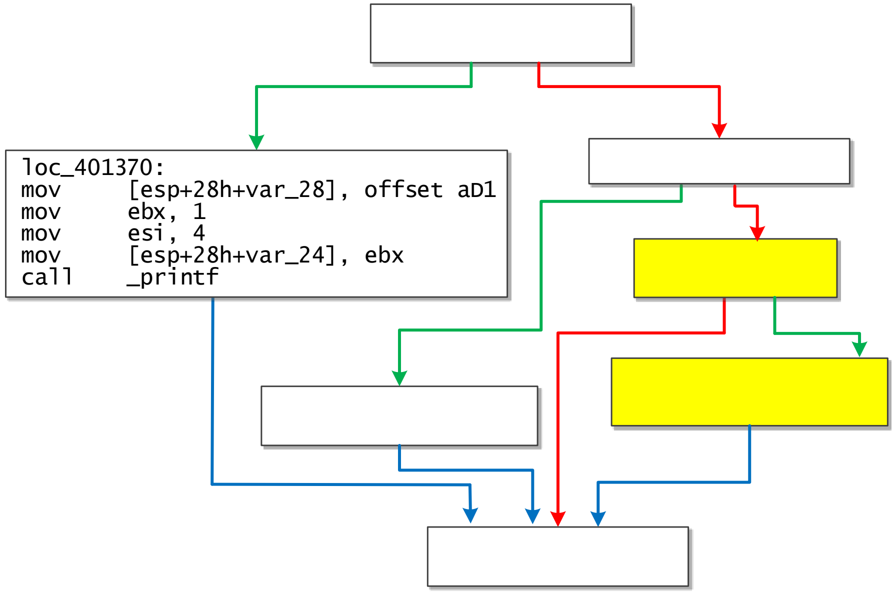
Challenge2: similarity between different structures

foo's CFG:



```
loc_401358:
mov    [esp+18h+var_18], offset aD1
mov    ecx, 1
mov    [esp+18h+var_14], ecx
call   _printf
```

patchedFoo's CFG:



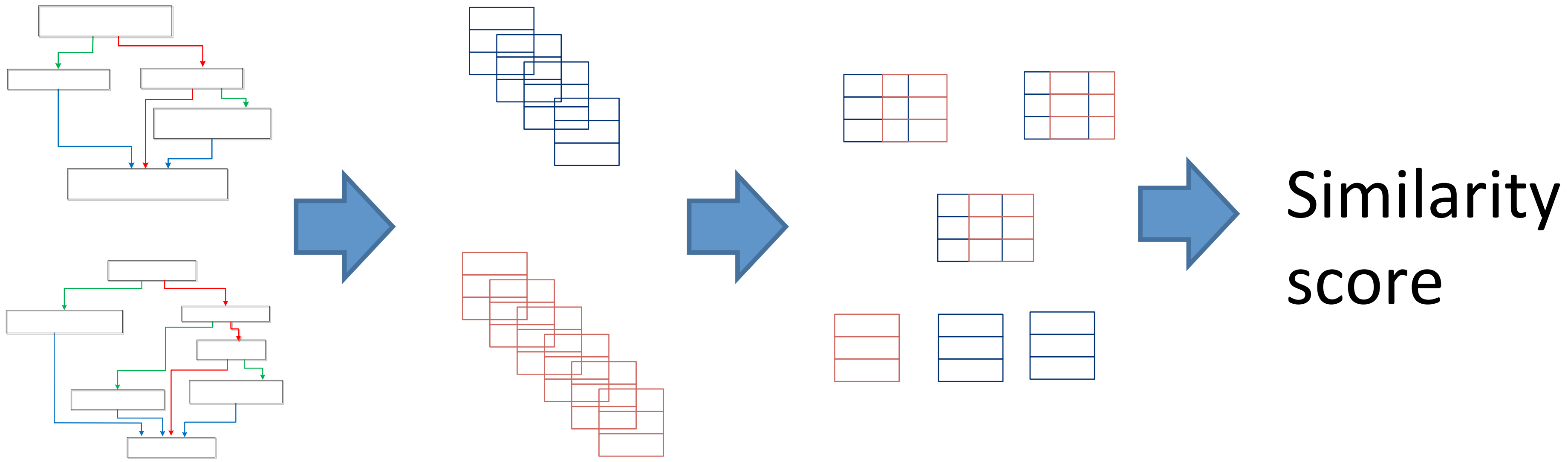
```
loc_401370:
mov     [esp+28h+var_28], offset aD1
mov     ebx, 1
mov     esi, 4
mov     [esp+28h+var_24], ebx
call    _printf
```

In this talk

- A system for searching code in executables
  - Based on tracelet decomposition of each function
  - Works by solving a set of alignment and dataflow constraints with minimal violations on tracelets

- An evaluation methodology based on tools from Information Retrieval
  - How do we know that our search engine is good?

Our Approach



Extract
tracelets

Pair tracelets
using **alignment**
and **rewrite**

Deal with structural changes

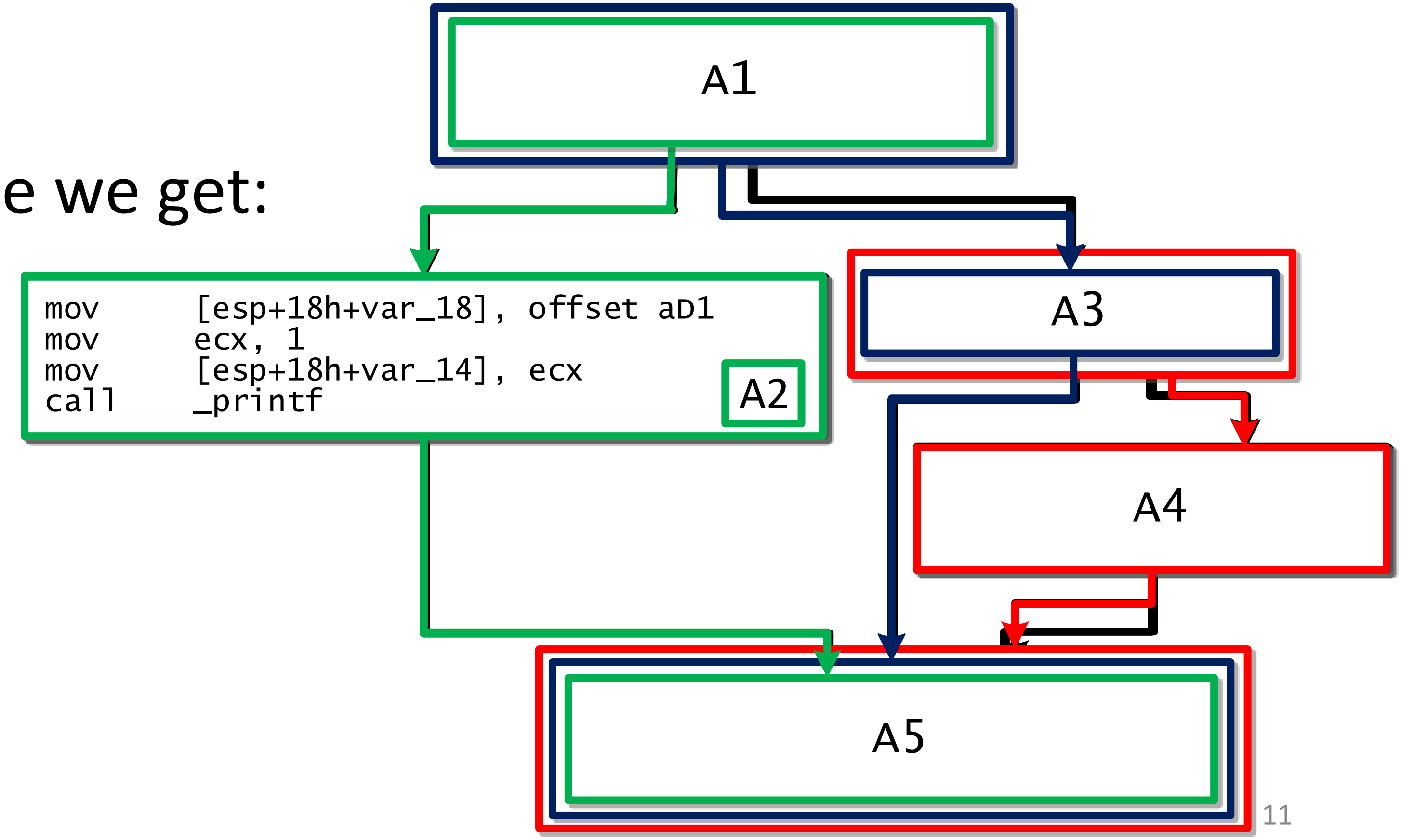
Deal with the code changes

Using tracelets to deal with CFG structural changes

A tracelet is a fixed length sub-trace

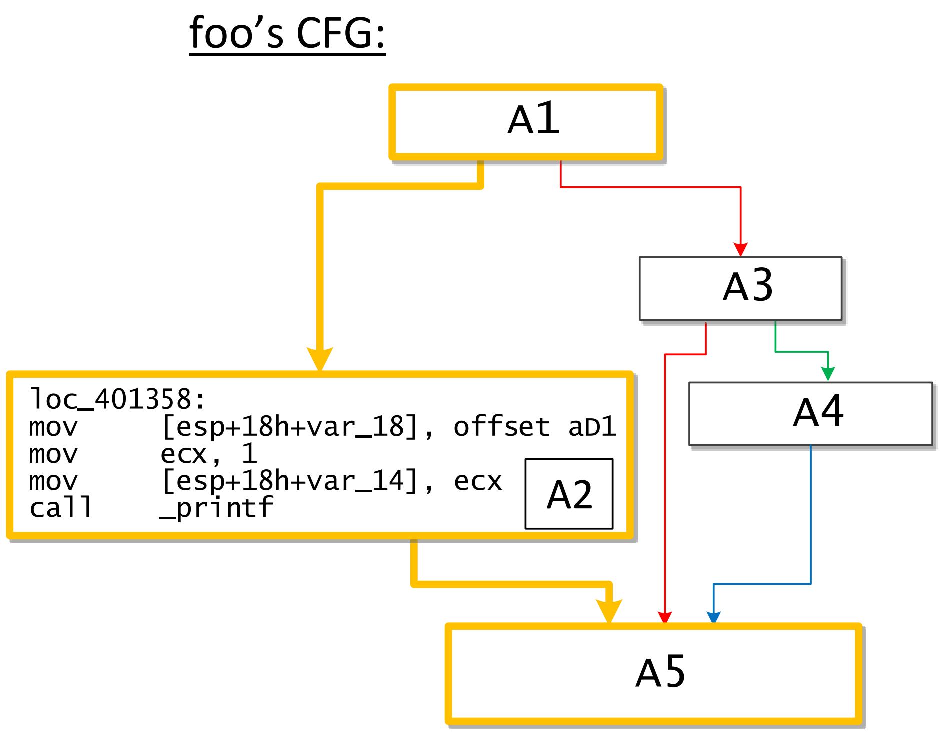
For length=3,
In this example we get:

- (A1,A2,A5)
- (A1,A3,A5)
- (A3,A4,A5)

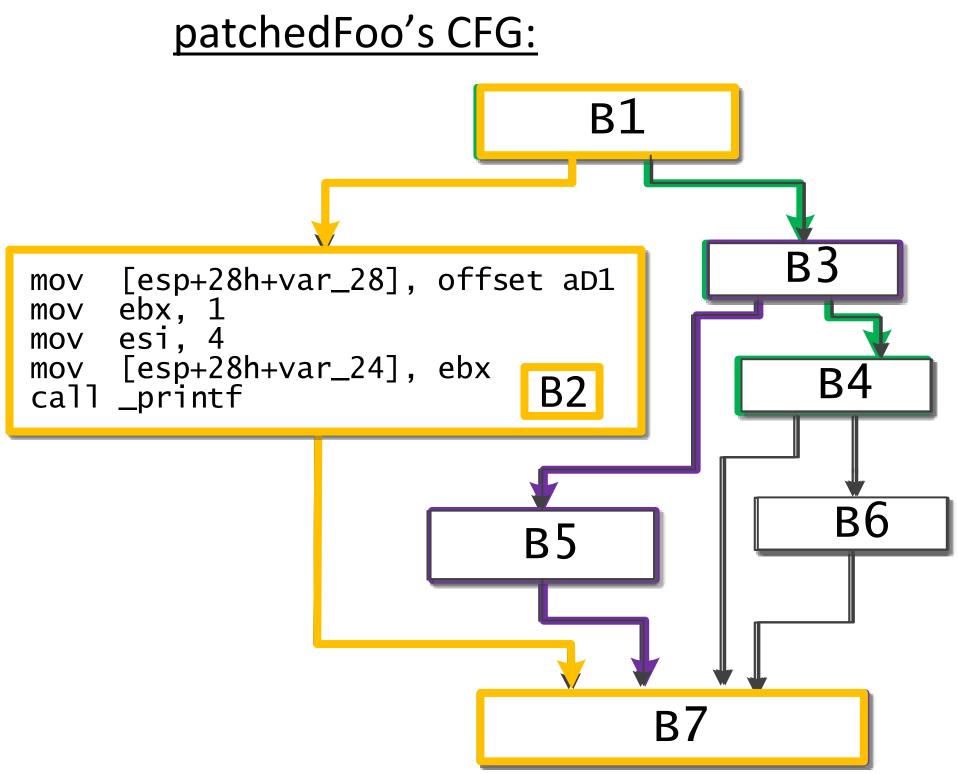


```
mov     [esp+18h+var_18], offset aD1
mov     ecx, 1
mov     [esp+18h+var_14], ecx
call    _printf
```

Using tracelets calculate similarity between different structures



```
loc_401358:
mov      [esp+18h+var_18], offset aD1
mov      ecx, 1
mov      [esp+18h+var_14], ecx
call     _printf
```

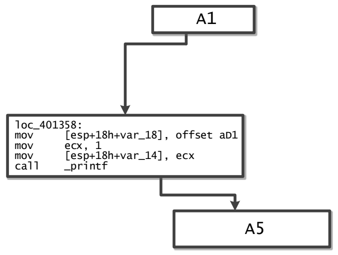


```
mov   [esp+28h+var_28], offset aD1
mov   ebx, 1
mov   esi, 4
mov   [esp+28h+var_24], ebx
call _printf
```

We need to find the corresponding tracelet

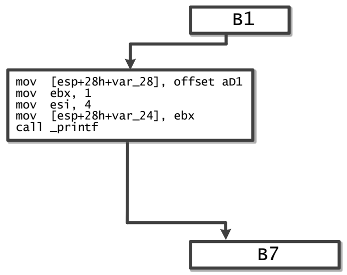
Comparing tracelets

foo’s tracelet

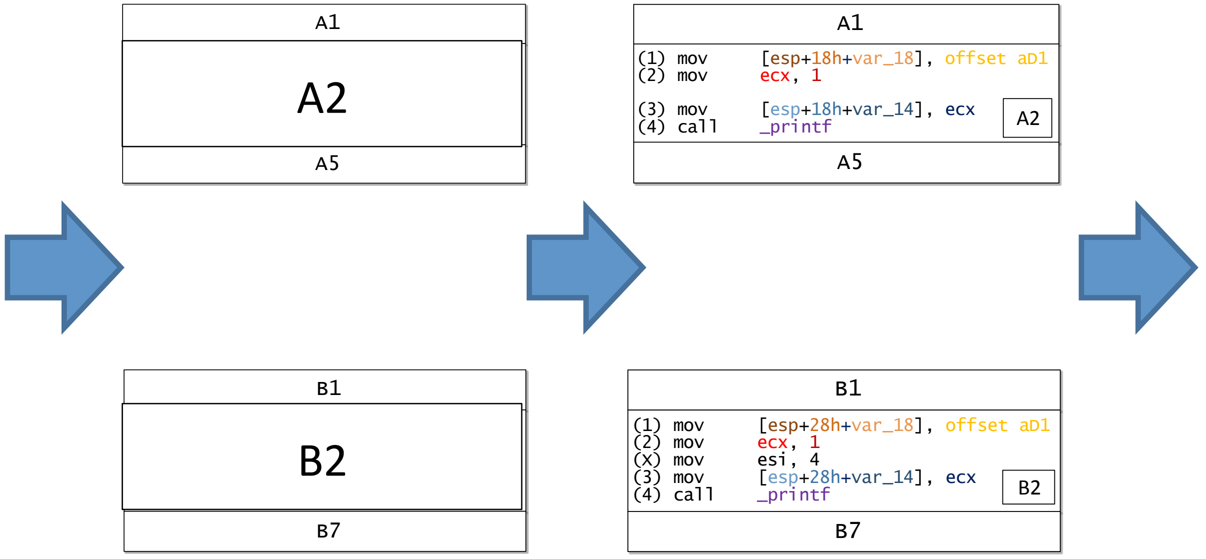


```
loc_401358:
mov     [esp+18h+var_18], offset aD1
mov     ecx, 1
mov     [esp+18h+var_14], ecx
call    _printf
```

patchedFoo’s
tracelet:



```
mov  [esp+28h+var_28], offset aD1
mov  ebx, 1
mov  esi, 4
mov  [esp+28h+var_24], ebx
call _printf
```



```
(1) mov     [esp+18h+var_18], offset aD1
(2) mov     ecx, 1

(3) mov     [esp+18h+var_14], ecx
(4) call    _printf
```

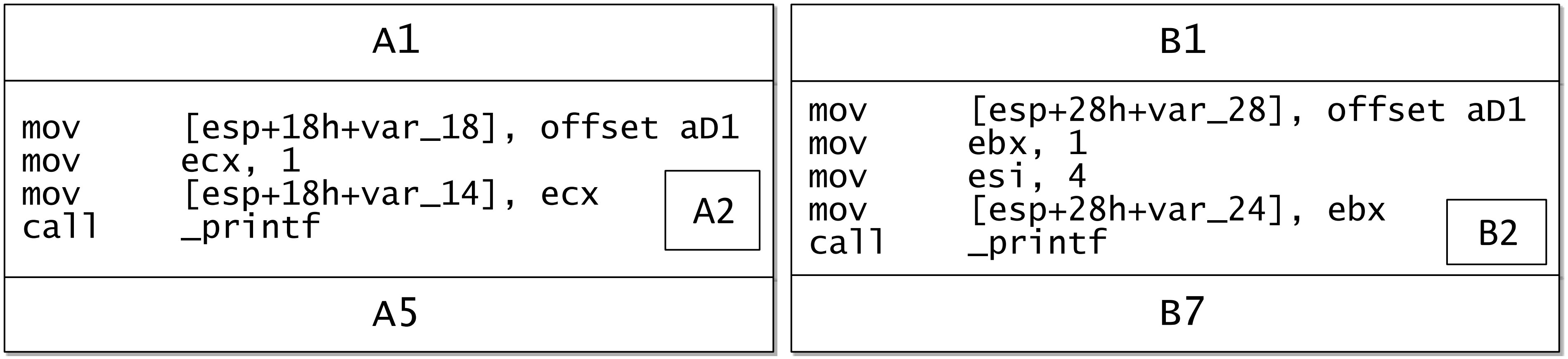
```
(1) mov     [esp+28h+var_18], offset aD1
(2) mov     ecx, 1
(X) mov     esi, 4
(3) mov     [esp+28h+var_14], ecx
(4) call    _printf
```

Edit distance

Graph -> linear code

Align & RW

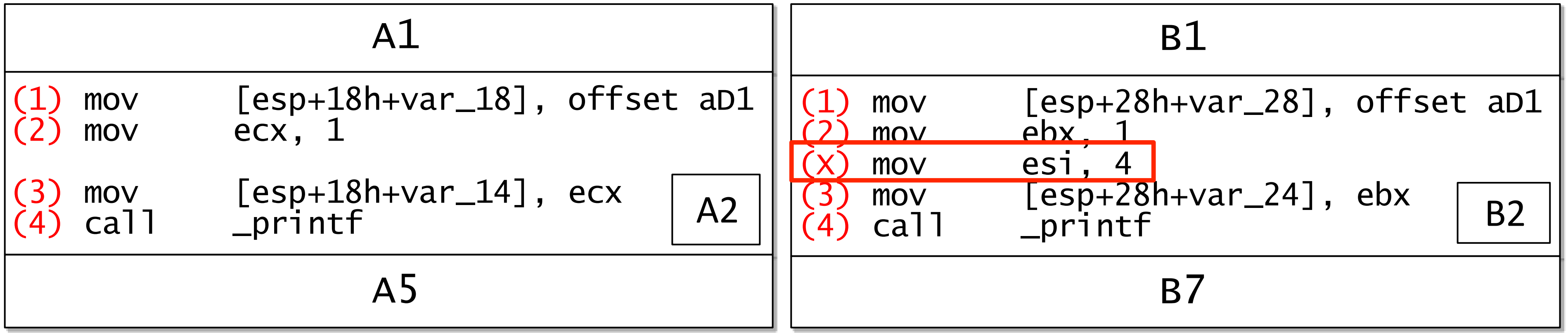
Dealing with code changes: Align



```
mov     [esp+18h+var_18], offset aD1
mov     ecx, 1
mov     [esp+18h+var_14], ecx
call    _printf
```

```
mov     [esp+28h+var_28], offset aD1
mov     ebx, 1
mov     esi, 4
mov     [esp+28h+var_24], ebx
call    _printf
```

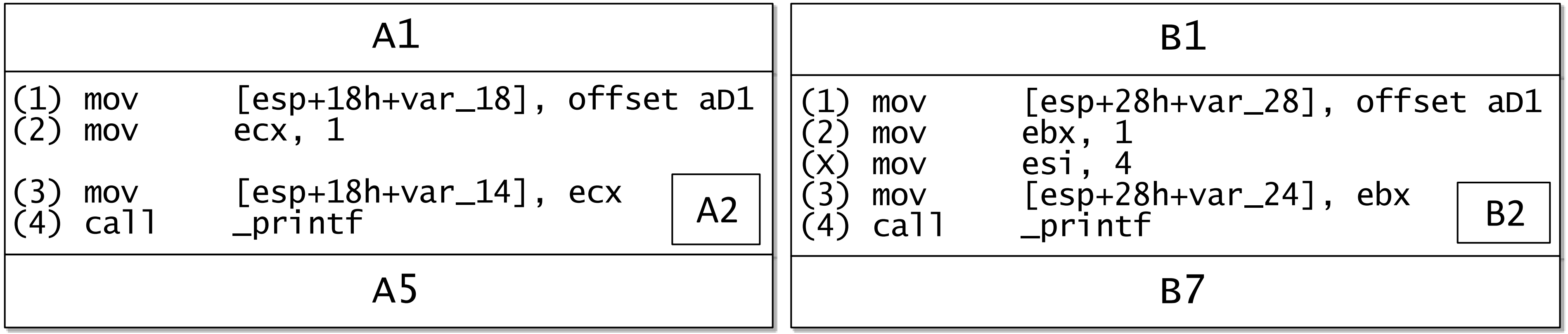
Align tracelets using specialized edit-distance



```
(1) mov     [esp+18h+var_18], offset aD1
(2) mov     ecx, 1

(3) mov     [esp+18h+var_14], ecx
(4) call    _printf
```

```
(1) mov     [esp+28h+var_28], offset aD1
(2) mov     ebx, 1
(x) mov     esi, 4
(3) mov     [esp+28h+var_24], ebx
(4) call    _printf
```

Dealing with code changes: DFA

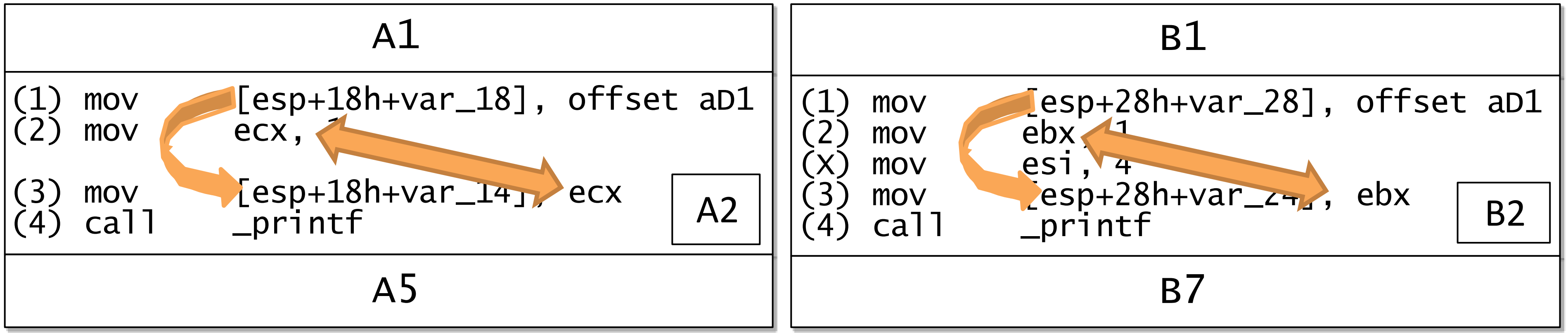


```
(1) mov     [esp+18h+var_18], offset aD1
(2) mov     ecx, 1

(3) mov     [esp+18h+var_14], ecx
(4) call    _printf
```

```
(1) mov     [esp+28h+var_28], offset aD1
(2) mov     ebx, 1
(X) mov     esi, 4
(3) mov     [esp+28h+var_24], ebx
(4) call    _printf
```

Analyze data flow

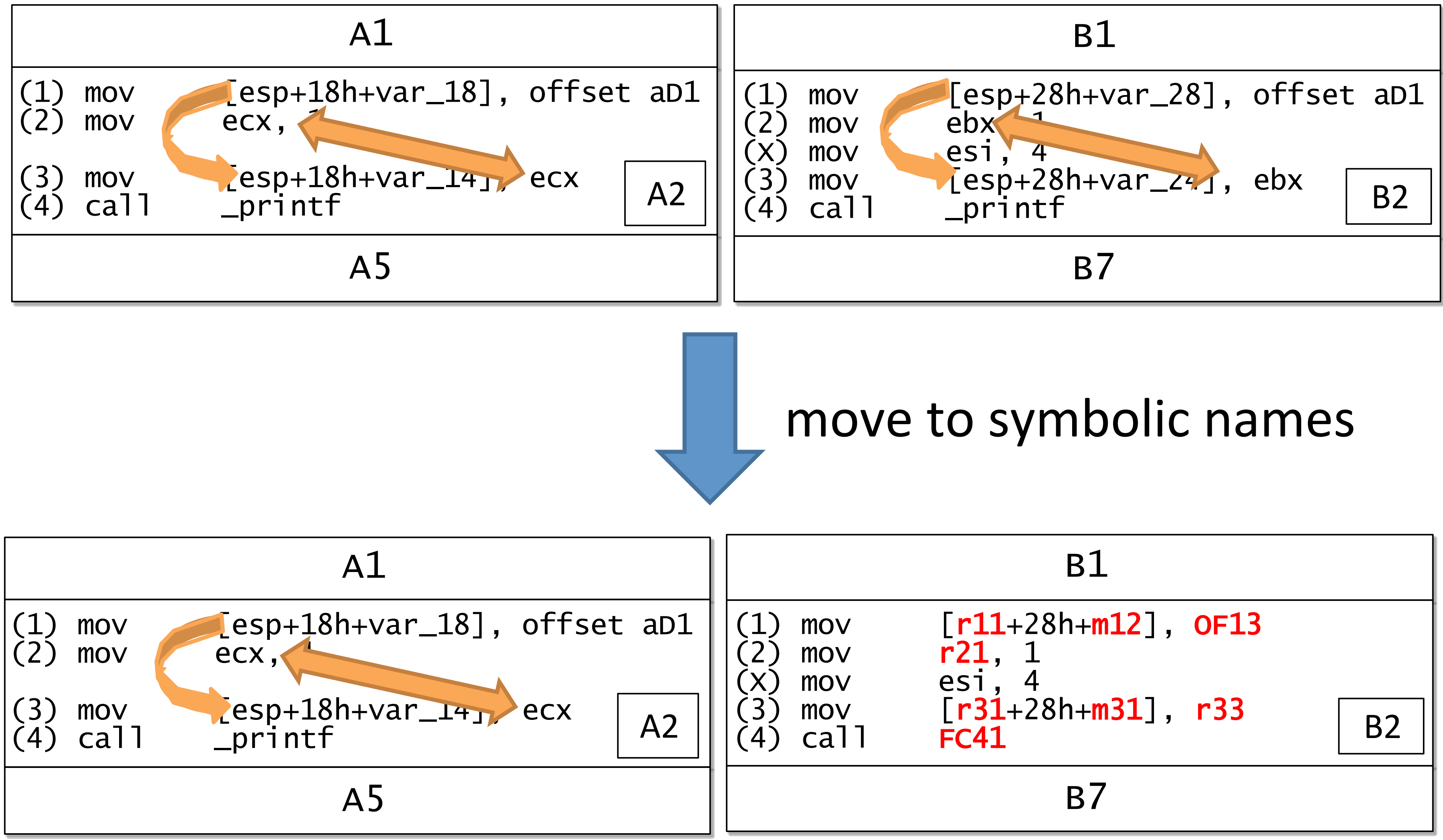
Record live registers



```
(1) mov     [esp+18h+var_18], offset aD1
(2) mov     ecx, 1

(3) mov     [esp+18h+var_14], ecx
(4) call    _printf
```

```
(1) mov     [esp+28h+var_28], offset aD1
(2) mov     ebx, 1
(X) mov     esi, 4
(3) mov     [esp+28h+var_24], ebx
(4) call    _printf
```

Dealing with code changes: Symbolize



```
A1
(1) mov     [esp+18h+var_18], offset aD1
(2) mov     ecx, 1

(3) mov     [esp+18h+var_14], ecx
(4) call    _printf
A5
```

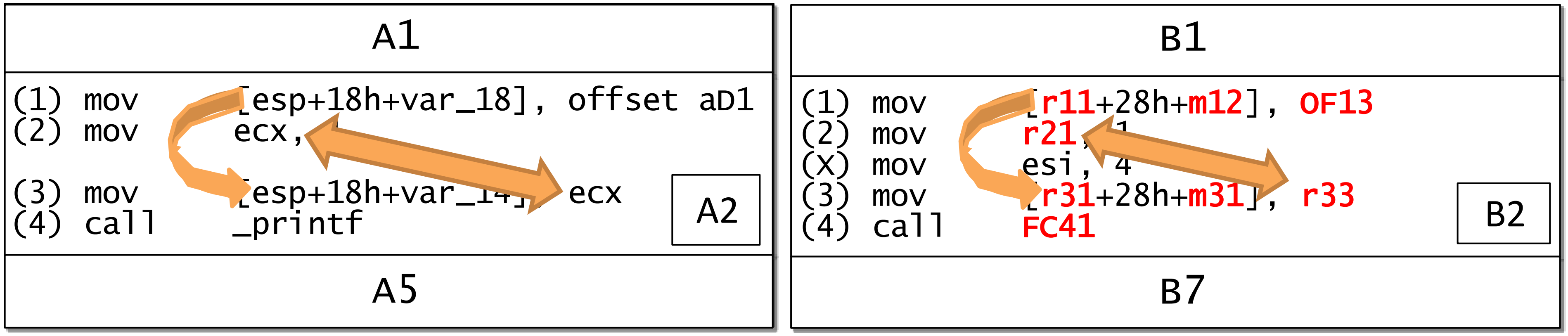
```
B1
(1) mov     [esp+28h+var_28], offset aD1
(2) mov     ebx, 1
(X) mov     esi, 4
(3) mov     [esp+28h+var_24], ebx
(4) call    _printf
B7
```

move to symbolic names

```
A1
(1) mov     [esp+18h+var_18], offset aD1
(2) mov     ecx, 1

(3) mov     [esp+18h+var_14], ecx
(4) call    _printf
A5
```

```
B1
(1) mov     [r11+28h+m12], OF13
(2) mov     r21, 1
(X) mov     esi, 4
(3) mov     [r31+28h+m31], r33
(4) call    FC41
B7
```

Dealing with code changes: Solve & Rewrite



```
(1) mov    [esp+18h+var_18], offset aD1
(2) mov    ecx, 

(3) mov    [esp+18h+var_14], ecx
(4) call   _printf
```

```
(1) mov    [r11+28h+m12], OF13
(2) mov    r21, 1
(X) mov    esi, 4
(3) mov    [r31+28h+m31], r33
(4) call   FC41
```

Use alignment & DFA to create constraints

Solve them using constraint solver with minimal conflicts

Data Flow constraints:

r21=r33;

r11=r31;

Alignment constraints:

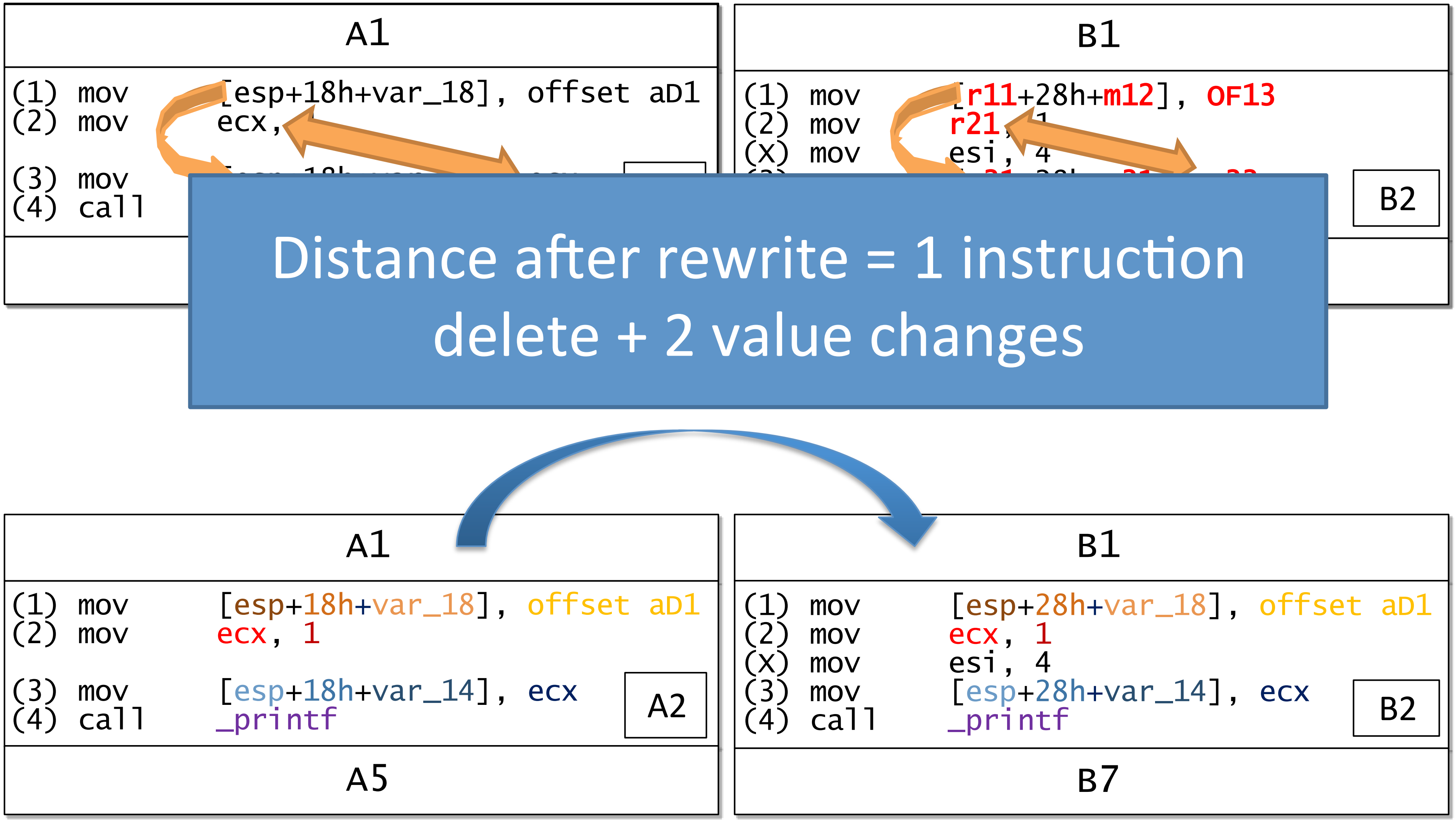
r11=esp;F13=…; m12=var_18;

r21=ecx;e31=esp;

m32=var_14; r33=ecx;

FC41=_printf;

Dealing with code changes: Solve & Rewrite



```
A1
(1) mov   [esp+18h+var_18], offset aD1
(2) mov   ecx,

(3) mov
(4) call
```

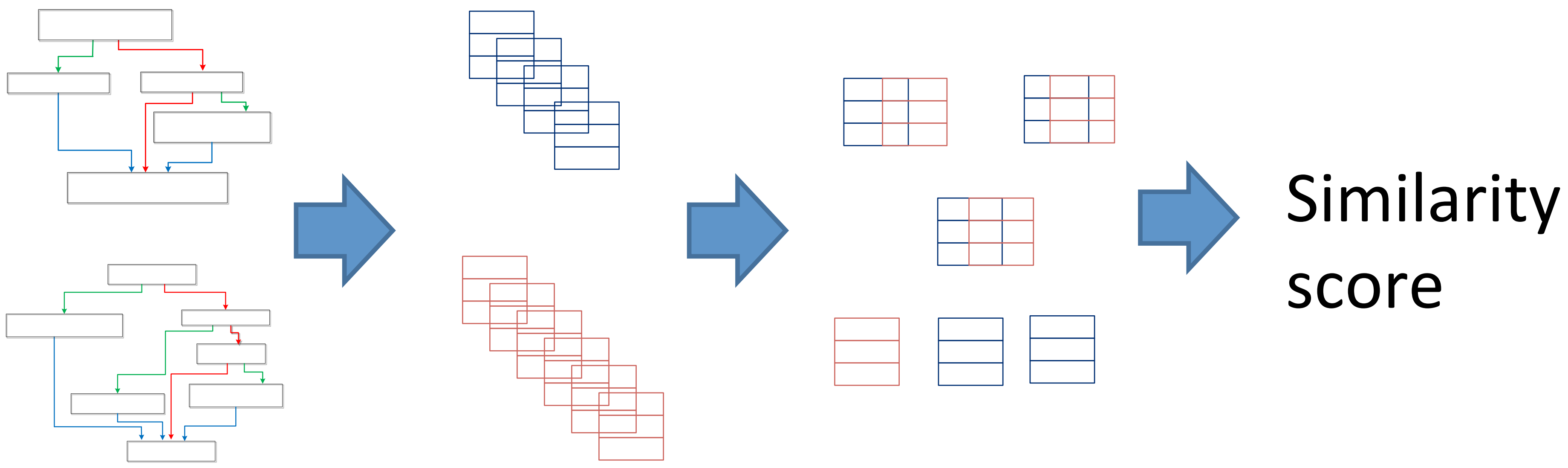
```
B1
(1) mov   [r11+28h+m12], OF13
(2) mov   r21, 1
(X) mov   esi, 4
                                      B2
```

Distance after rewrite = 1 instruction delete + 2 value changes

```
A1
(1) mov   [esp+18h+var_18], offset aD1
(2) mov   ecx, 1

(3) mov   [esp+18h+var_14], ecx        A2
(4) call  _printf
A5
```

```
B1
(1) mov   [esp+28h+var_18], offset aD1
(2) mov   ecx, 1
(X) mov   esi, 4
(3) mov   [esp+28h+var_14], ecx        B2
(4) call  _printf
B7
```

Our Approach



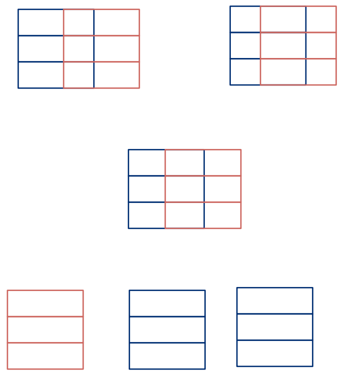
Extract tracelets

Pair tracelets using **alignment** and **rewrite**

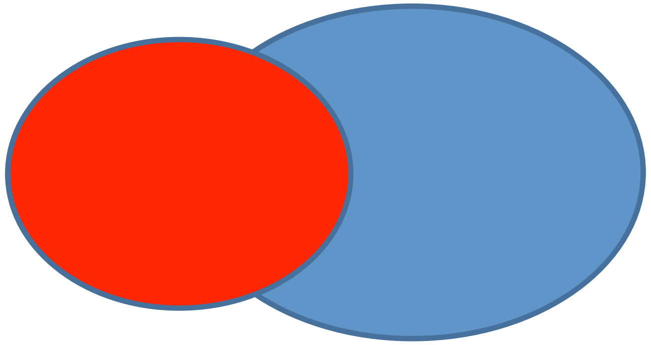
Deal with structural changes

Deal with the code changes

From paired tracelets to function similarity score

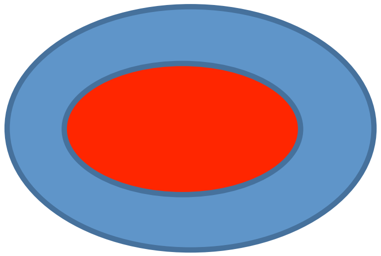


Ratio



$$\frac{2 * \#PairedTracelets(f1, f2)}{\#Tracelets(f1) + \#Tracelets(f2)}$$

Containment

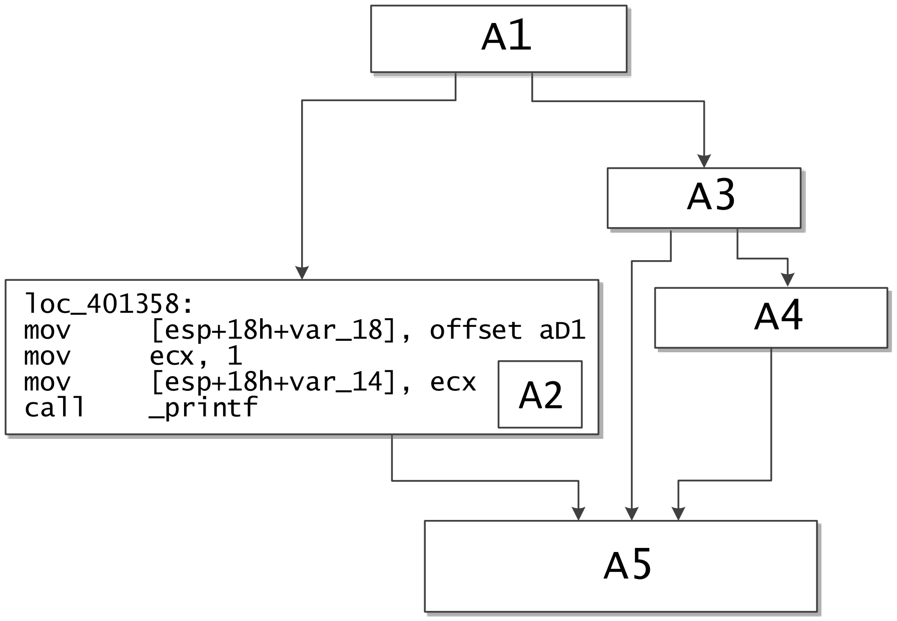


$$\frac{\#PairedTracelets(f1, f2)}{Min(\#Tracelets(f1), \#Tracelets(f2))}$$

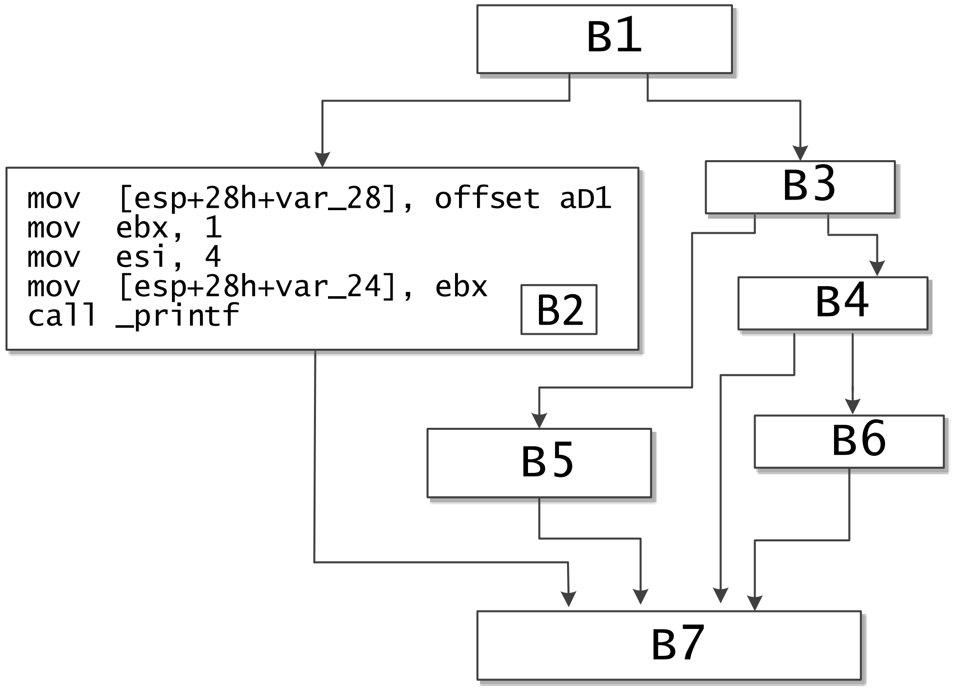
Using tracelets calculate similarity between different structures

foo's CFG:

patchedFoo's CFG:



```
loc_401358:
mov     [esp+18h+var_18], offset aD1
mov     ecx, 1
mov     [esp+18h+var_14], ecx
call    _printf
```

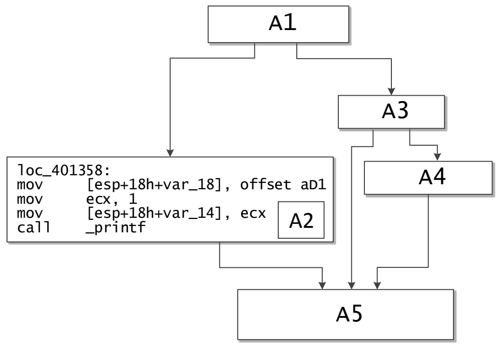


```
mov   [esp+28h+var_28], offset aD1
mov   ebx, 1
mov   esi, 4
mov   [esp+28h+var_24], ebx
call _printf
```

(A1,A2,A5)~(B1,B2,B7),(A1,A3,A4)~(B1,B3,B4),
(A3,A4,A5)~(B3,B4,B7),(A1,A3,A5) -> "lost"

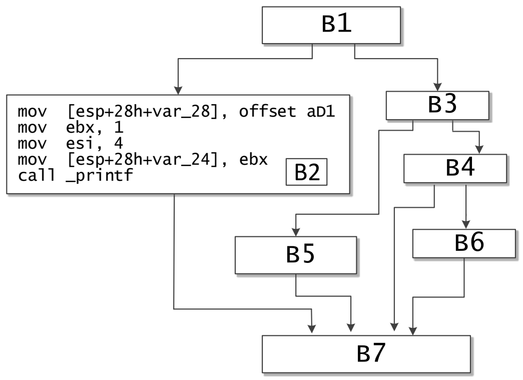
Using tracelets calculate similarity between different structures

foo's CFG:



```
loc_401358:
mov     [esp+18h+var_18], offset aD1
mov     ecx, 1
mov     [esp+18h+var_14], ecx
call    _printf
```

patchedFoo's CFG:



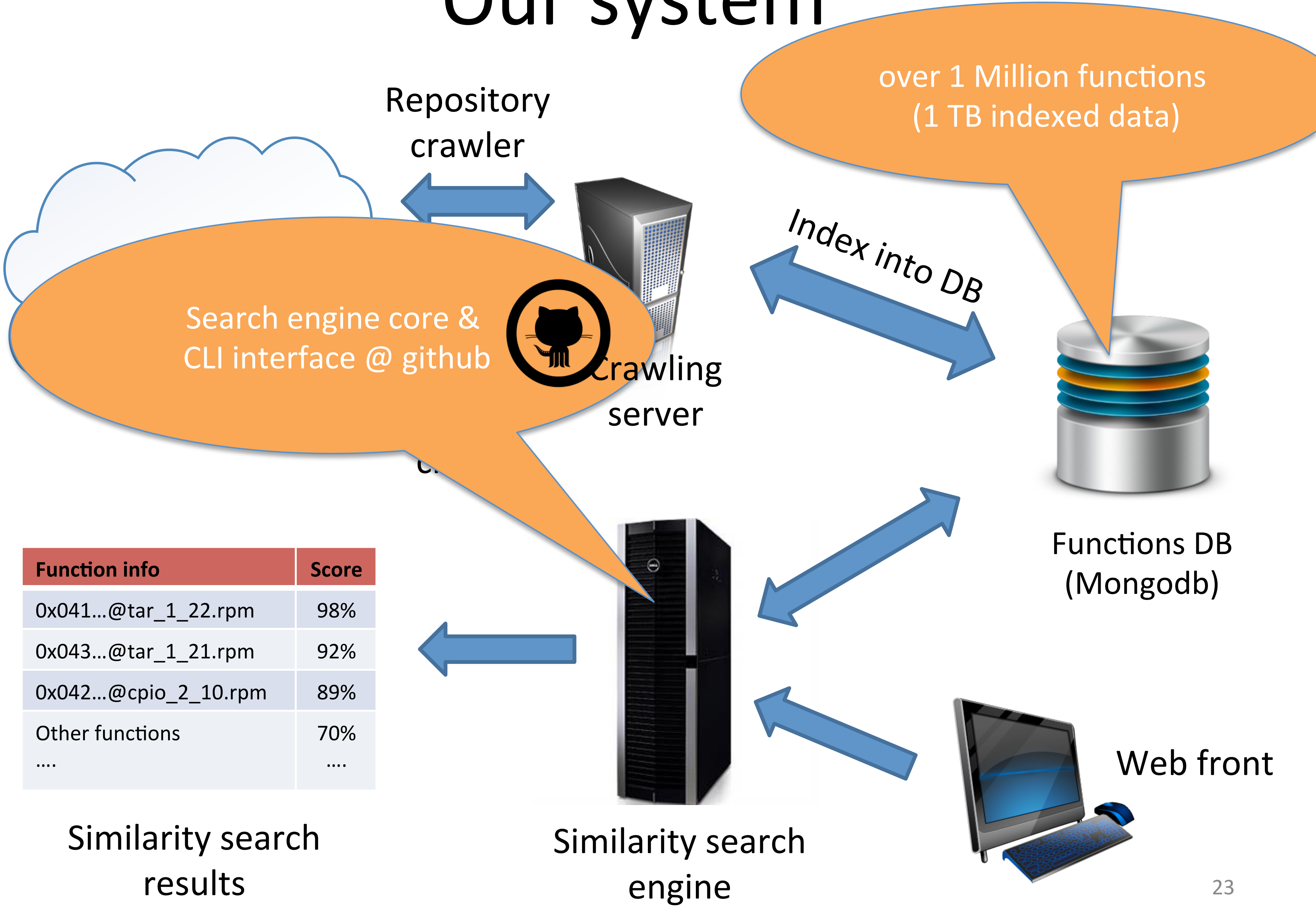
```
mov  [esp+28h+var_28], offset aD1
mov  ebx, 1
mov  esi, 4
mov  [esp+28h+var_24], ebx
call _printf
```

$$\frac{2 * \#PairedTracelets(f1, f2)}{\#Tracelets(f1) + \#Tracelets(f2)}$$

(A1,A2,A5)~(B1,B2,B7),(A1,A3,A4)~(B1,B3,B4),
(A3,A4,A5)~(B3,B4,B7),(A1,A3,A5) -> "lost"

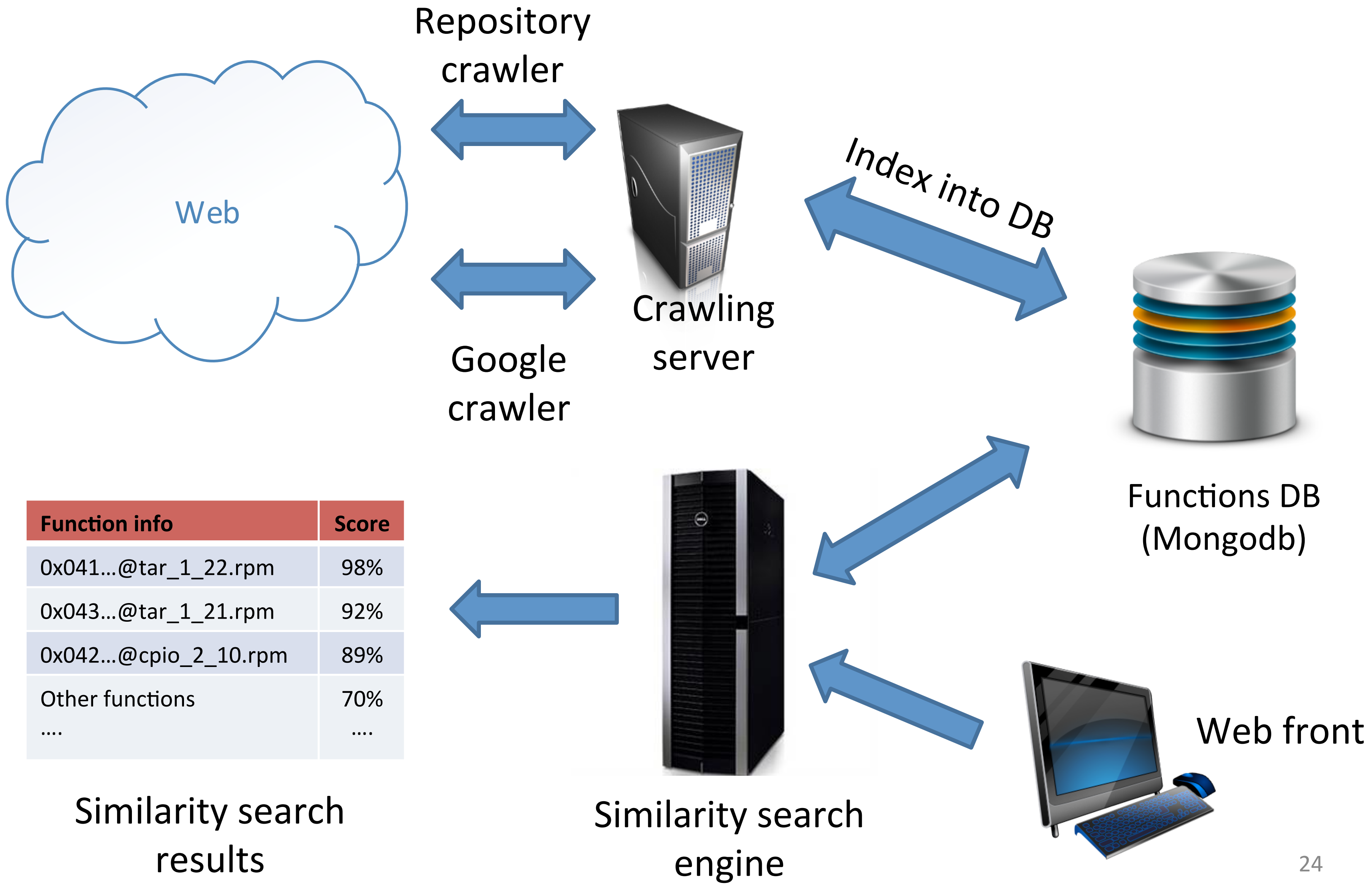
$$\frac{2 * 3}{4 + 6} = \frac{6}{10} = 60\%\ similarity\ (ratio)$$

Our system


Repository crawler
over 1 Million functions (1 TB indexed data)
Index into DB
Search engine core & CLI interface @ github
Crawling server
Functions DB (Mongodb)
Web front
Similarity search engine
Similarity search results

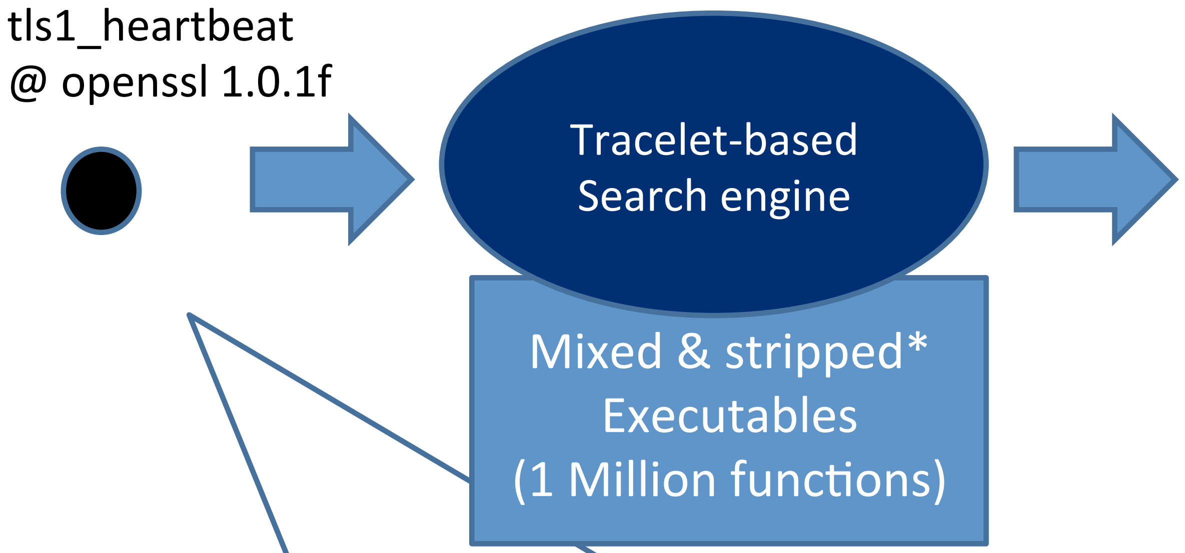
Function info	Score
0x041…@tar_1_22.rpm	98%
0x043…@tar_1_21.rpm	92%
0x042…@cpio_2_10.rpm	89%
Other functions ….	70% ….

Our system



Function info	Score
0x041…@tar_1_22.rpm	98%
0x043…@tar_1_21.rpm	92%
0x042…@cpio_2_10.rpm	89%
Other functions ….	70% ….

One experiment – find my Heartbleed (CVE-2014-0160)



Function info	Score
tls1_heartbeat @openssl_1_0_1f.rpm	98%
dtls1_process_heartbeat @openssl_1_0_1f.rpm	96%
…@openssl_1_0_1e.rpm	89%
more vulnerable functions ….	….

TLS implementation does not properly handle Heartbeat Extension packets causes information disclosure

Using a single threshold

90% similarity score is…good?
Can we really choose one threshold?

Function info	Score
tls1_heartbeat @openssl_1_0_1f.rpm	98%
dtls1_process_heartbeat @openssl_1_0_1f.rpm	96%
…@openssl_1_0_1e.rpm	89%
other functions ….	….

Function info	Score
0x041…@tar_1_22.rpm	88%
0x043…@tar_1_21.rpm	83%
0x042…@cpio_2_10.rpm	89%
Other functions ….	70% ….

Function info	Score
0x042…@wget_1_12.rpm	94%
0x045…@wget_1_14.rpm	91%
Other functions ….	60% ….

Using a single threshold

90% similarity score is…good?
Can we really choose one threshold?

Function info	Score
tls1_heartbeat @openssl_1_0_1f.rpm	98%
dtls1_process_heartbeat @openssl_1_0_1f.rpm	96%
other functions ….	….

Function info	Score
0x041…@tar_1_22.rpm	88%
0x043…@tar_1_21.rpm	83%
Other functions ….	70% ….

Function info	Score
0x042…@wget_1_12.rpm	94%
0x045…@wget_1_14.rpm	91%
….	….

Threshold

There should be a more accurate way

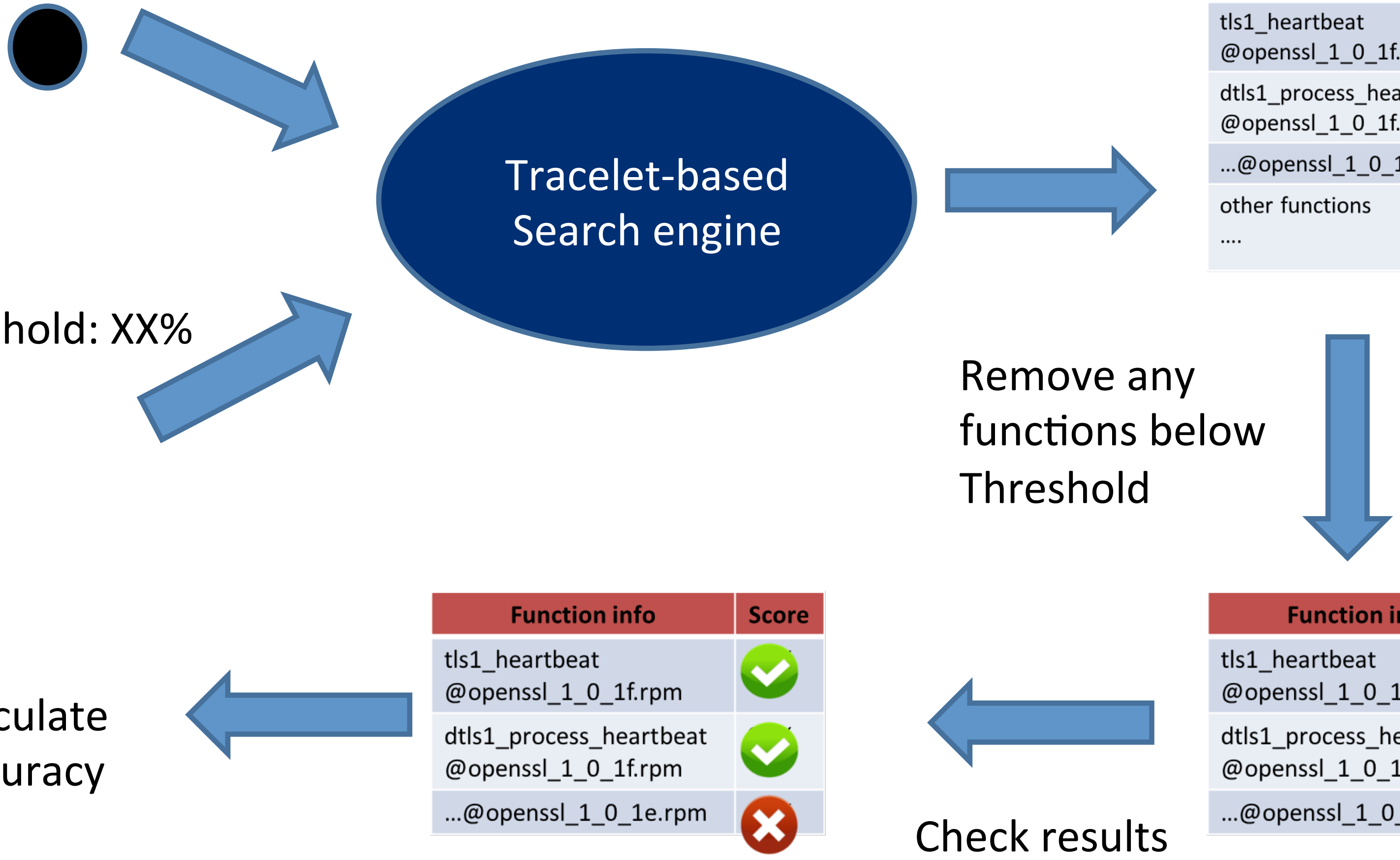
ROC – trying all thresholds

- Receiver operating characteristic
- Try every threshold (=>binary classifier)
- Get a number representing the method's accuracy

Experiment example

The function we are searching for

Threshold: XX%



Function info	Score
tls1_heartbeat @openssl_1_0_1f.rpm	98%
dtls1_process_heartbeat @openssl_1_0_1f.rpm	96%
…@openssl_1_0_1e.rpm	89%
other functions ….	….

Remove any functions below Threshold

Function info	Score
tls1_heartbeat @openssl_1_0_1f.rpm	98%
dtls1_process_heartbeat @openssl_1_0_1f.rpm	96%
…@openssl_1_0_1e.rpm	89%

Check results (manually)

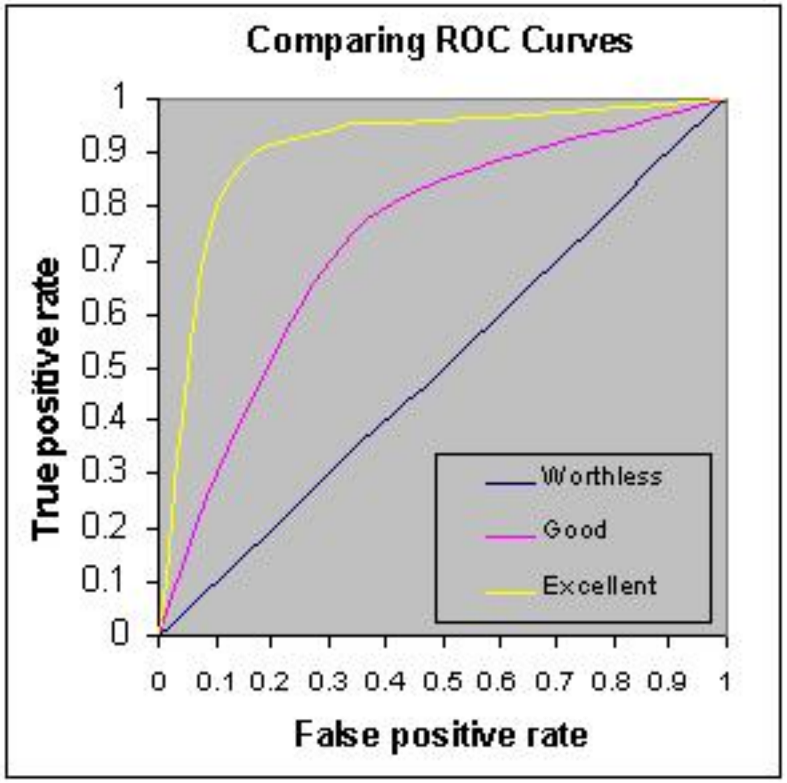
Function info	Score
tls1_heartbeat @openssl_1_0_1f.rpm	✓
dtls1_process_heartbeat @openssl_1_0_1f.rpm	✓
…@openssl_1_0_1e.rpm	✗

Calculate Accuracy

$$Accuracy = (TP + TN)/(P + N)$$

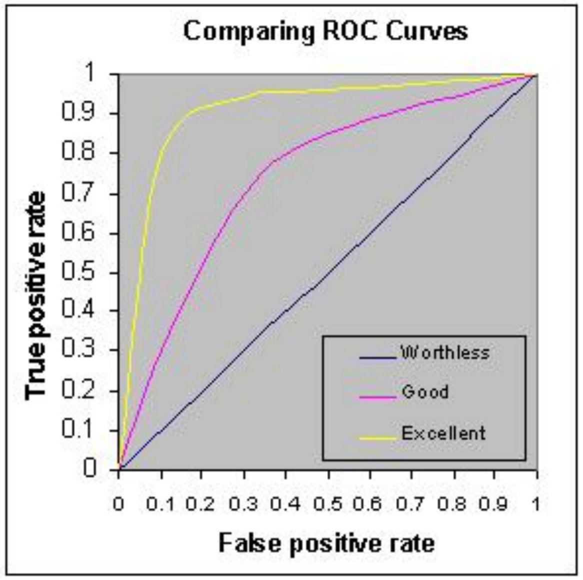
ROC – trying all thresholds

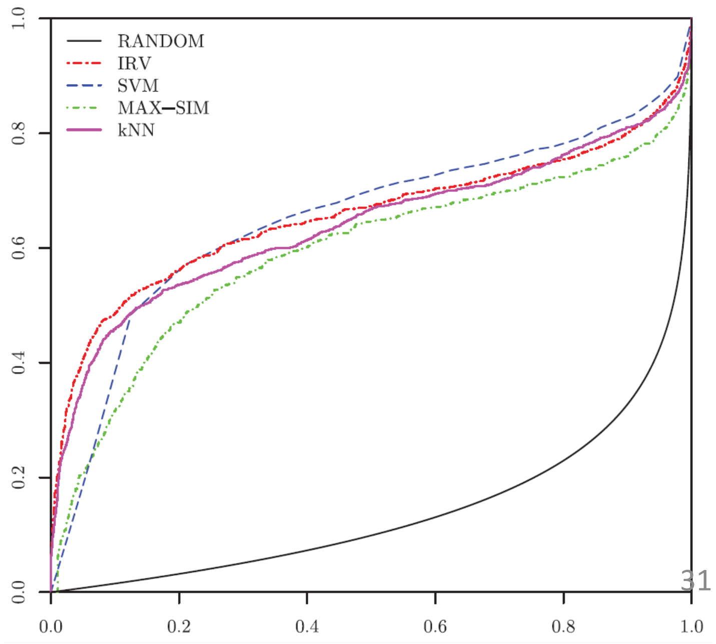
- Method's accuracy is Area Under Curve (AUC) determines precision



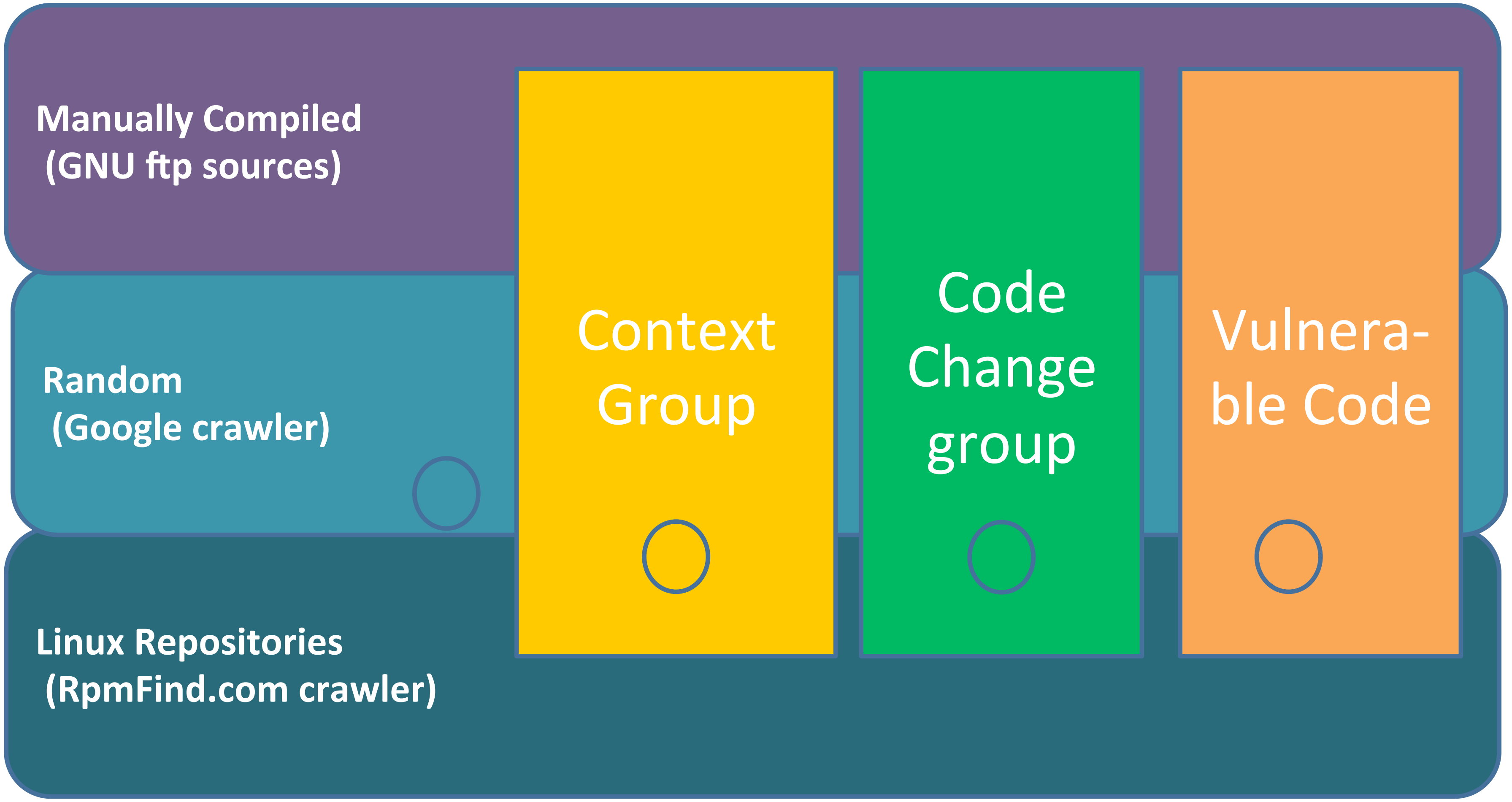
CROC is better then ROC

- The matches we expect are **very sparse**
- We need to "punish" false positives – they have a high cost
- CROC does exactly that

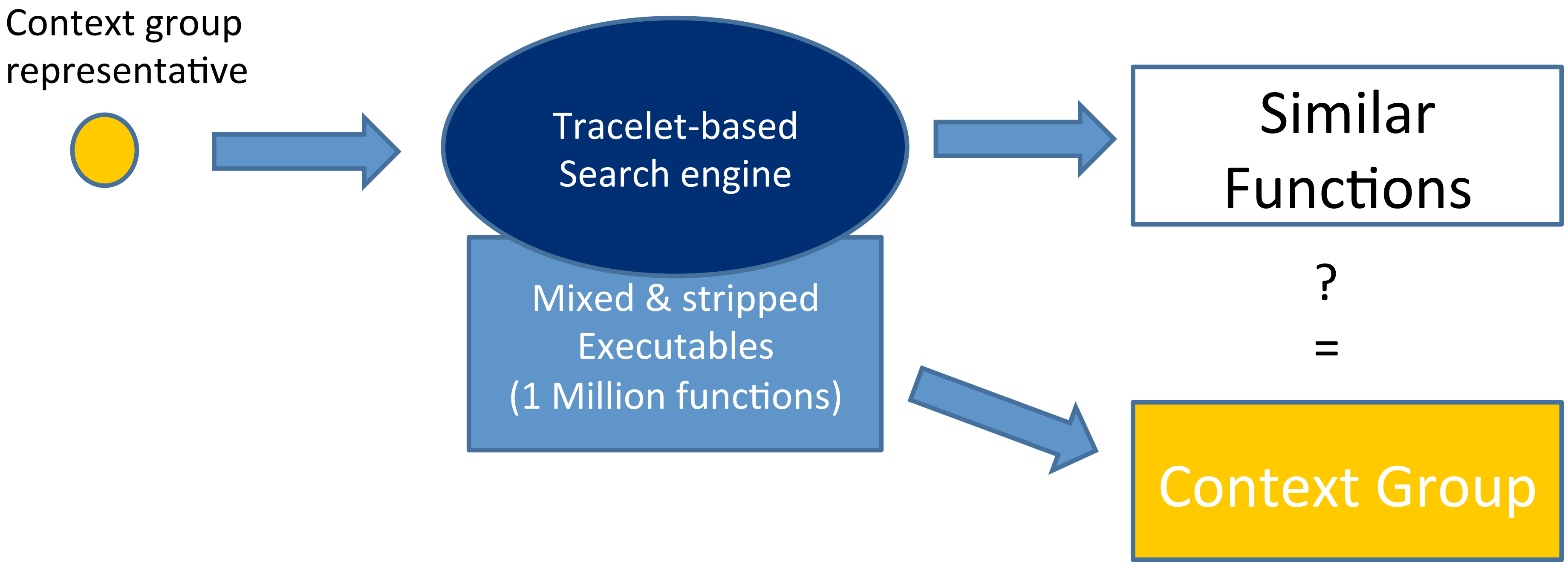




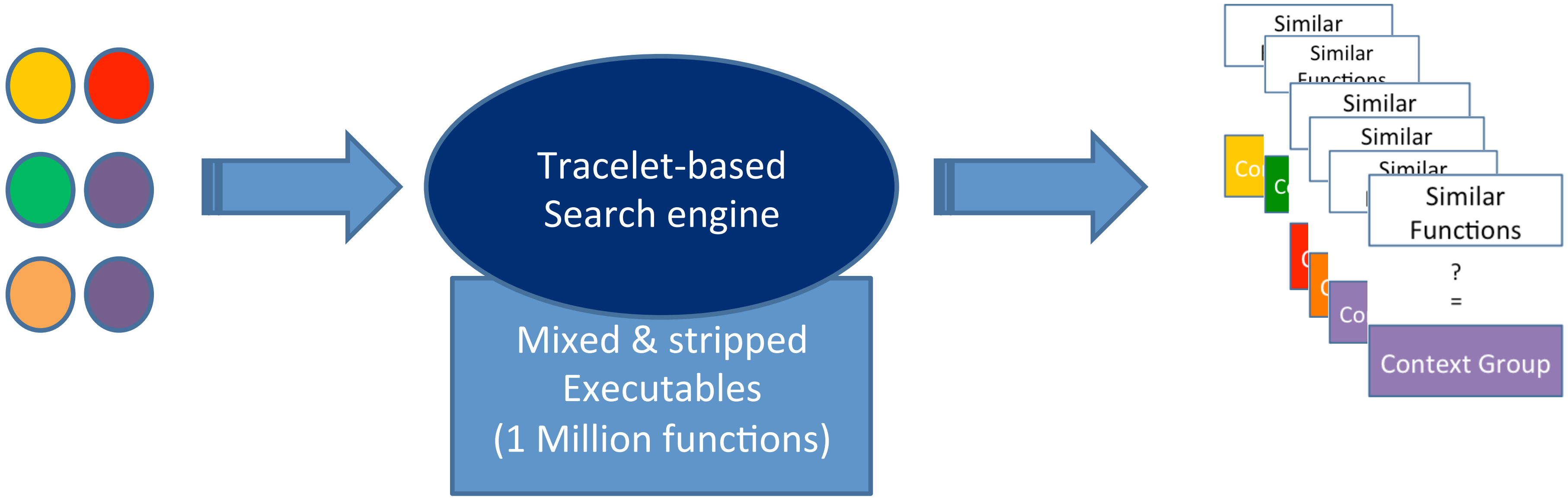
Experiment Structure



Experiment goal


Context group representative
Tracelet-based Search engine
Mixed & stripped Executables (1 Million functions)
Similar Functions
?
=
Context Group

Experiment Setup & Results


Tracelet-based Search engine
Mixed & stripped Executables (1 Million functions)
Similar Functions
?
=
Context Group

	N-grams Size 5,Delta 1	Graphlets K=5	Tracelets K=3
AUC[ROC]	72%	60%	99%
AUC[CROC]	25%	12%	99%

Conclusions

- Tracelets based code search system
  - Effective in finding exact and near matches
  - Provides a quantitative similarity score

- Evaluated using Information Retrieval tools
  - Achieves good precision and recall
  - Tested against other leading methods