String Analysis for Binaries

Mihai Christodorescu
Nicholas Kidd
Wen-Han Goh

University of Wisconsin, Madison

What is *String Analysis*?

- Recovery of values a string variable might take at a given program point.

```
void main( void )
{
  char * msg = “no msg”;
  printf( “This food has %s.\n”, msg );
}
```

Output: `This food has no msg.`

Why Do We Need String Analysis?

- We could just use the `strings` program:

```
$ strings no_msg
/lib/ld-linux.so.2
libc.so.6
...
...
no msg
This food has %s.
$
```

Why Perform String Analysis?

- Computer forensics

  Given an unknown program, we want to know
    the files it might access,

    the registry keys it might get and set,

    the commands it might execute.

- Program verification

  SQL queries, embedded scripting, …

A Complicated Example

```
void main( void )
{
  char buf[257];
  strcpy( buf, “/” );
  strcat( buf, “b” );
  strcat( buf, “i” );
  strcat( buf, “n” );
  ...
  system( buf );
}
```

A Complicated Example

```
void main( void )
{
  char buf[257];
  strcpy( buf, "/" );
  strcat( buf, "b" );
  strcat( buf, "i" );
  strcat( buf, "n" );
  ...
  system( buf );
}
```

Running `strings`:

```
/
a
b
c
d
...
```

A Complicated Example

```
void main( void )
{
  char buf[257];
  strcpy( buf, “/” );
  strcat( buf, “b” );
  strcat( buf, “i” );
  strcat( buf, “n” );
  ...
  system( buf );
}
```

Running `strings`:

```
/
a
b
c
d
...
```

Running a string analysis:

```
/bin/ifconfig -a |
     /bin/mail ...@...
```

Our Contributions

- Developed a string analysis for binaries.

- Implemented x86sa, a string analyzer for Intel IA-32 binaries.

- Evaluated on both benign and malicious binaries.

Outline

- String analysis for Java.
- String analysis for x86.
- Evaluation.
- Applications & future work.

String Analysis for Java

Christensen, Møller, Schwartzbach "Precise Analysis of String Expressions" (SAS'03)

1. Create string flowgraph.

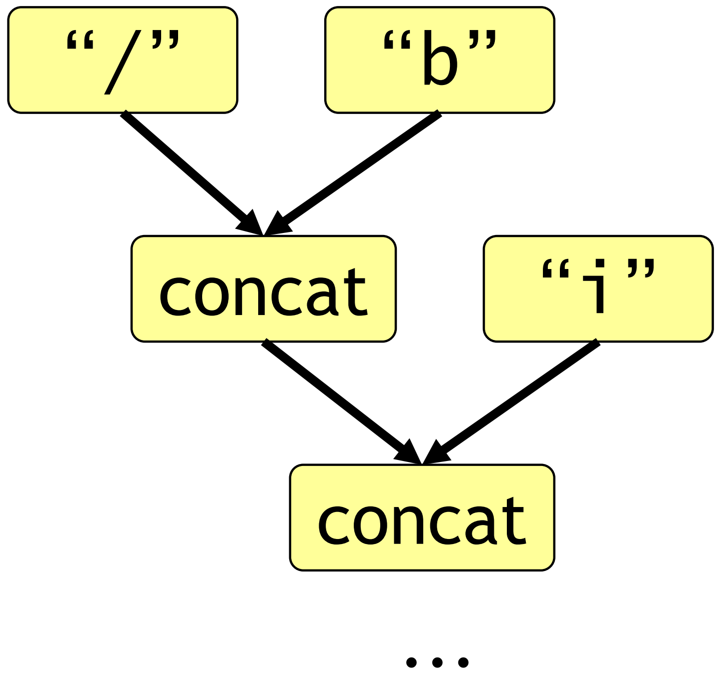
```
void main( void )
{
  String x = "/";
  x = x + "b";
  x = x + "i";
  x = x + "n";
  ...
  System.exec( x );
}
```

String Analysis for Java

Christensen, Møller, Schwartzbach "Precise Analysis of String Expressions" (SAS'03)

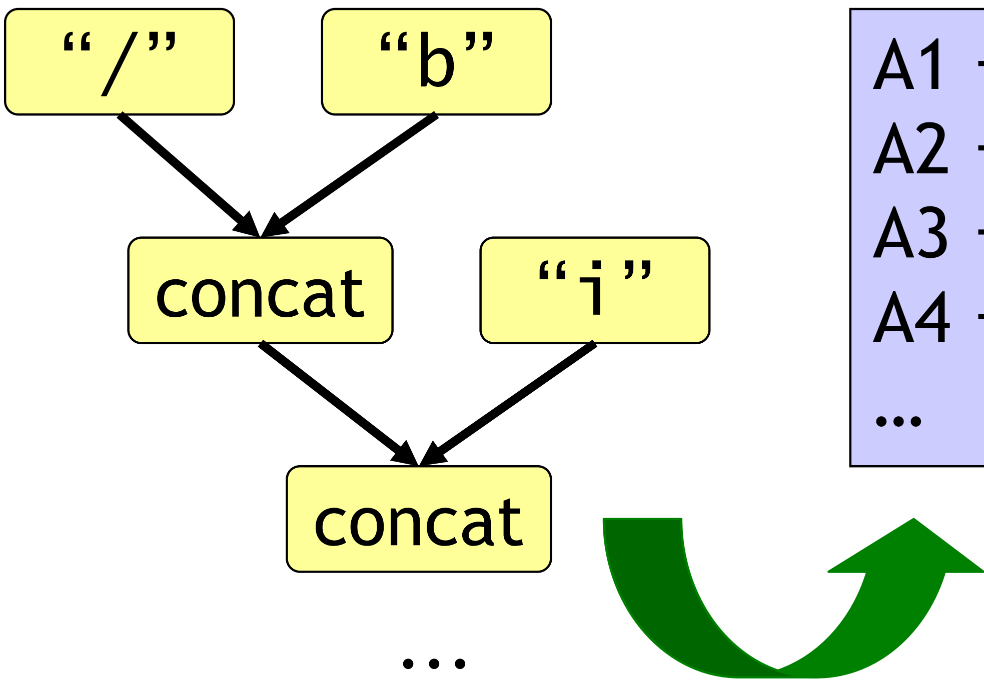
1. Create string flowgraph.

```
void main( void )
{
  String x = "/";
  x = x + "b";
  x = x + "i";
  x = x + "n";
  ...
  System.exec( x );
}
```



String Analysis for Java [2]

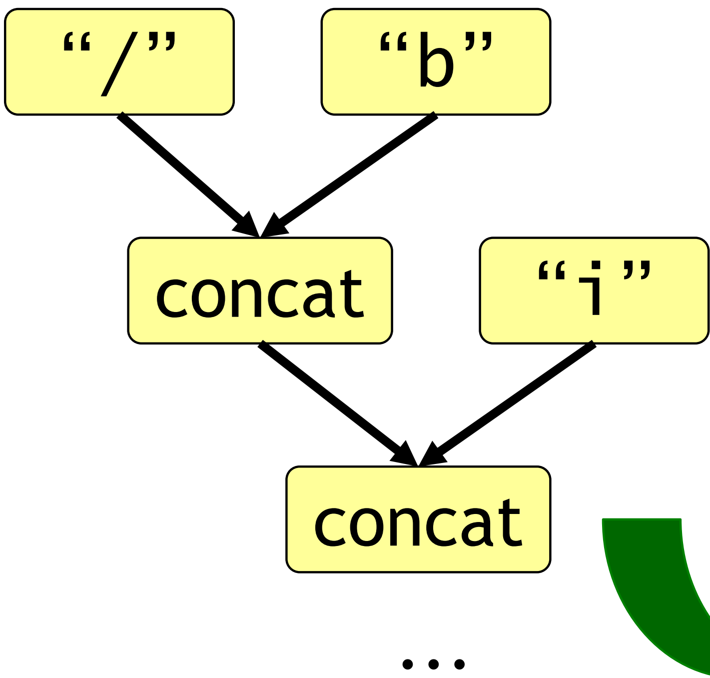
2. Create context-free grammar.



A1 → "/" "b"
A2 → A1 "i"
A3 → A2 "n"
A4 → A3 "/"
…

String Analysis for Java [2]

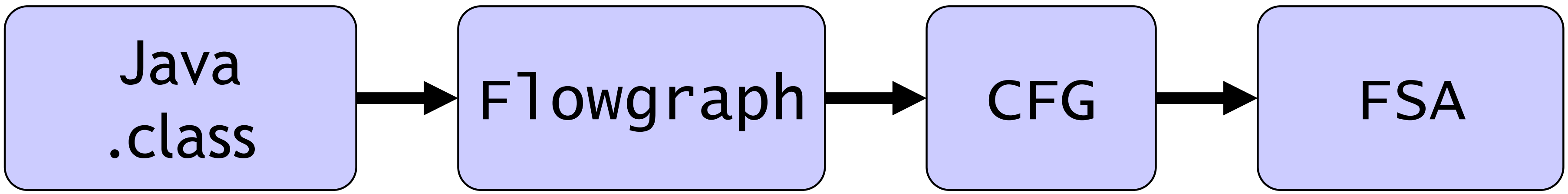
2. Create context-free grammar.
3. Approximate with finite automaton.



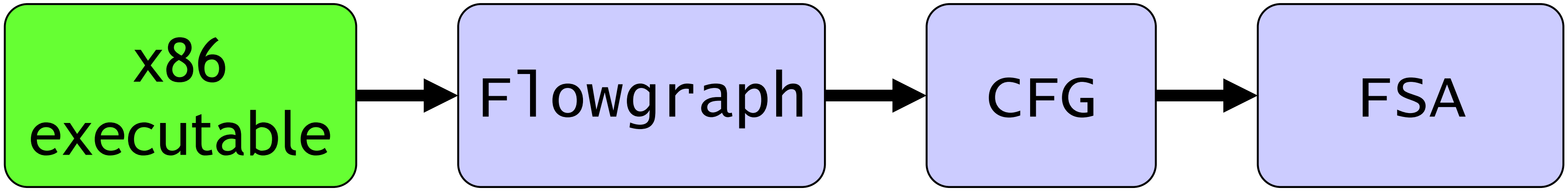
A1 → "/" "b"
A2 → A1 "i"
A3 → A2 "n"
A4 → A3 "/"
...

"/bin/ifconfig ..."

From Java to x86 executables



From Java to x86 executables



Rest of this talk:

Bridge the syntactic and semantic gaps between Java and assembly language.

Outline

- String analysis for Java.
- String analysis for x86.
- Evaluation.
- Applications & future work.

Four Problems with Assembly

1. No types.
2. No high-level constructs.
3. No argument passing convention.
4. No Java string semantics.

Problem 1: No Types

- Solution: infer types from C lib. funcs.

Assumption #1:

Strings are manipulated only using string library functions.

```
char * strcat( char * dest, char * src )
```

- After: “eax” points to a string.
- Before: “dest” and “src” point to a string.

Problem 1: No Types [cont.]

- Perform a backwards analysis to find the strings:
  - Destination registers “kill” string type information.
  - Libc string functions “gen” string type information.
  - Strings at entry to CFG are constant strings or function parameters.

Problem 1: No Types [example]

String variables:

- after the call: { eax }
- before the call: { ebx, ecx }

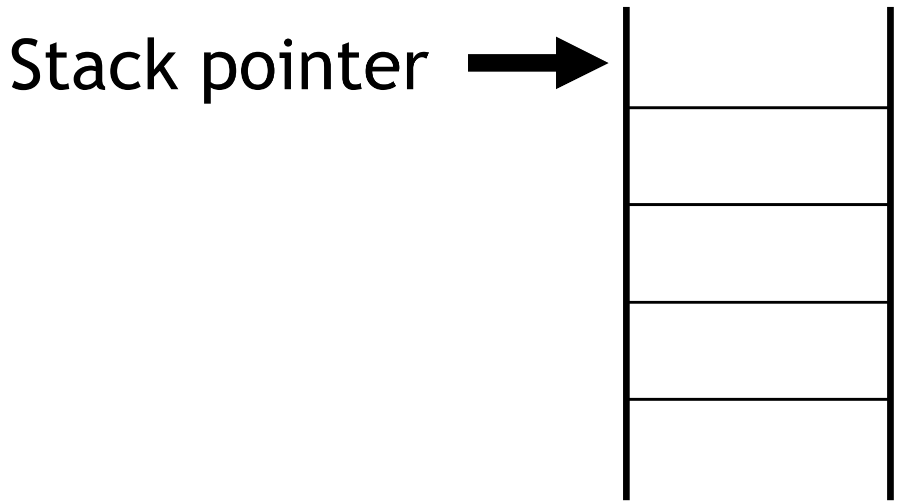
```
eax = _strcat( ebx, ecx );
```

Problem 2: Function Parameters

- Function parameters are not explicit in x86 machine code.

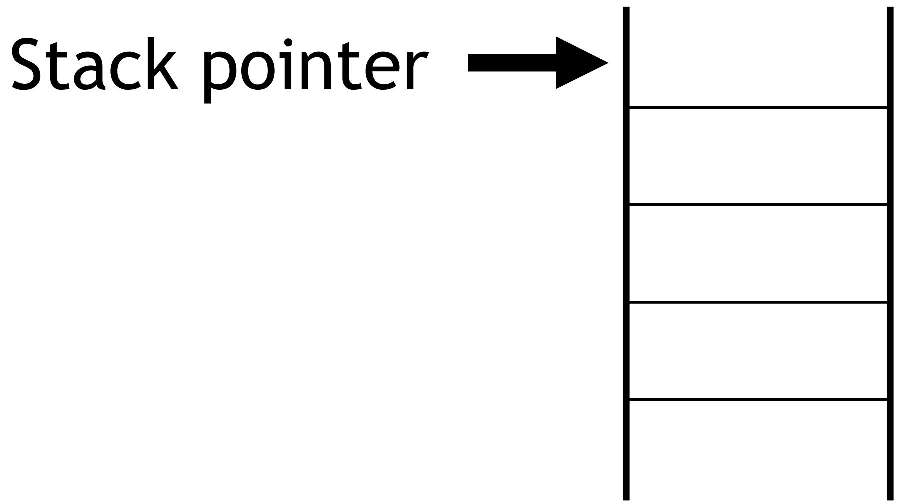
```
mov  ecx, [ebp+var1]
push ecx
mov  ebx, [ebp+var2]
push ebx
call _strcat
add esp, 8
```

Problem 2: Fn. Params [example]



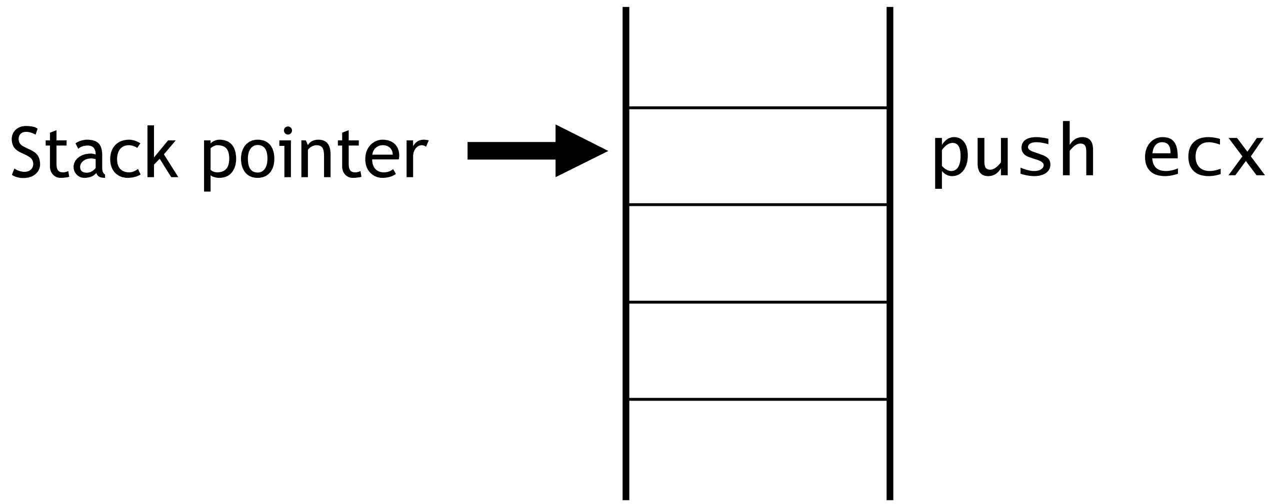

```
mov  ecx, [ebp+var1]
push ecx
mov  ebx, [ebp+var2]
push ebx
call _strcat
add esp, 8
```

Problem 2: Fn. Params [example]



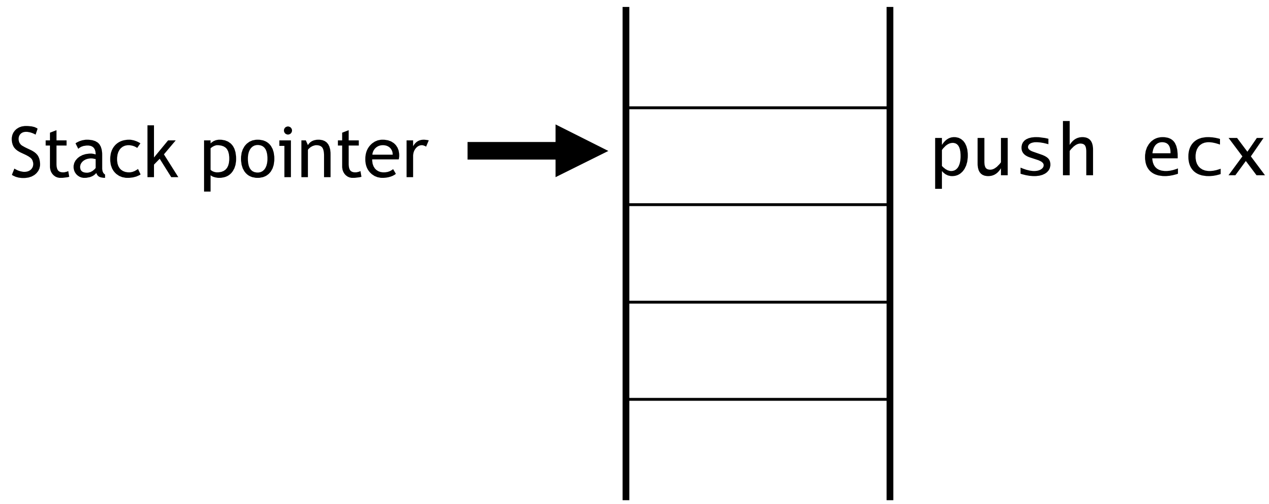

```
mov  ecx, [ebp+var1]
push ecx
mov  ebx, [ebp+var2]
push ebx
call _strcat
add esp, 8
```

Problem 2: Fn. Params [example]



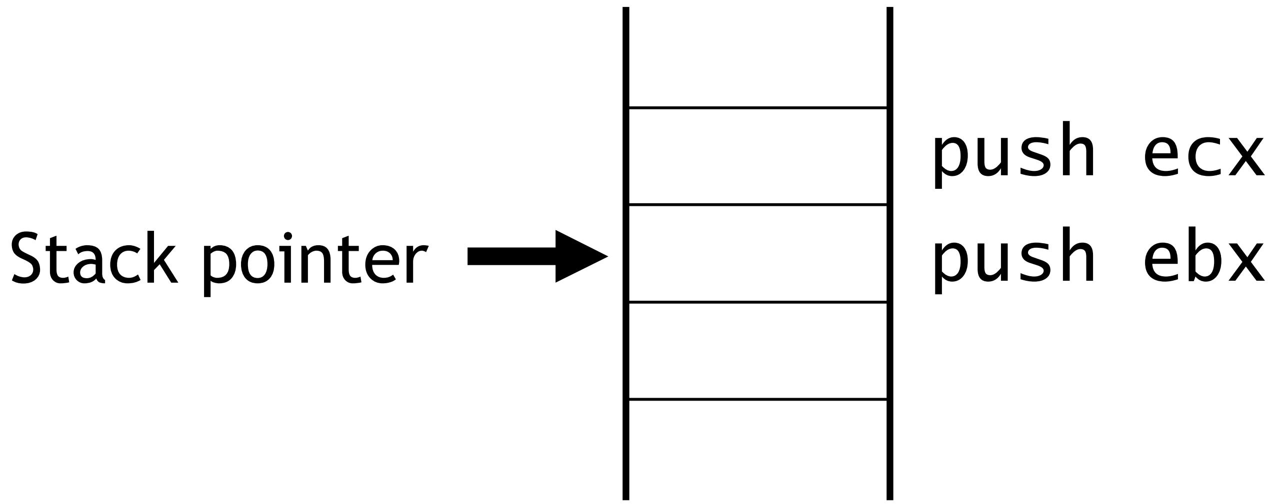

```
mov  ecx, [ebp+var1]
push ecx
mov  ebx, [ebp+var2]
push ebx
call _strcat
add esp, 8
```

Problem 2: Fn. Params [example]



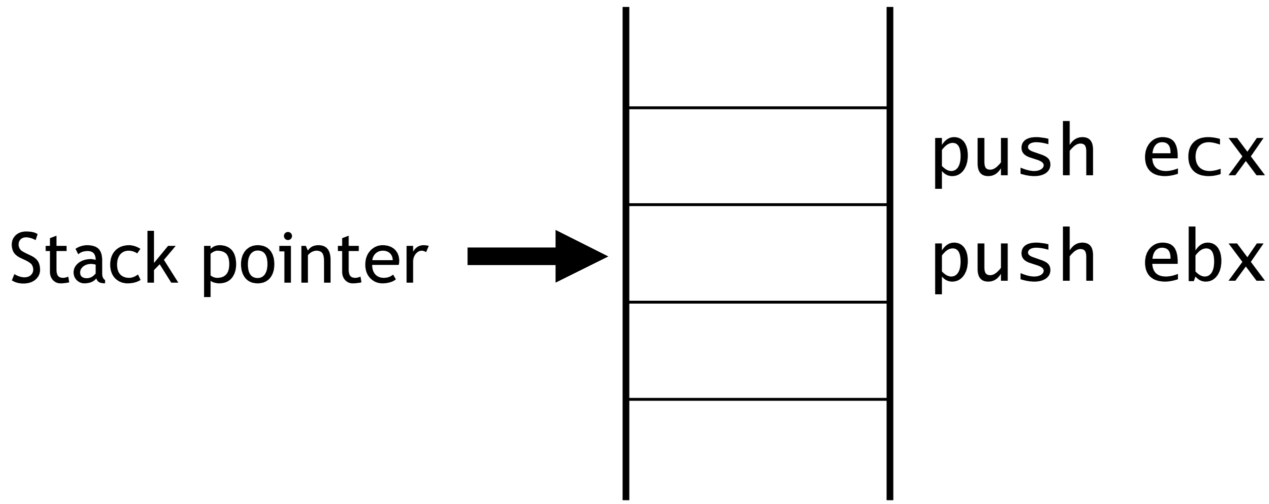

```
mov  ecx, [ebp+var1]
push ecx
mov  ebx, [ebp+var2]
push ebx
call _strcat
add esp, 8
```

Problem 2: Fn. Params [example]



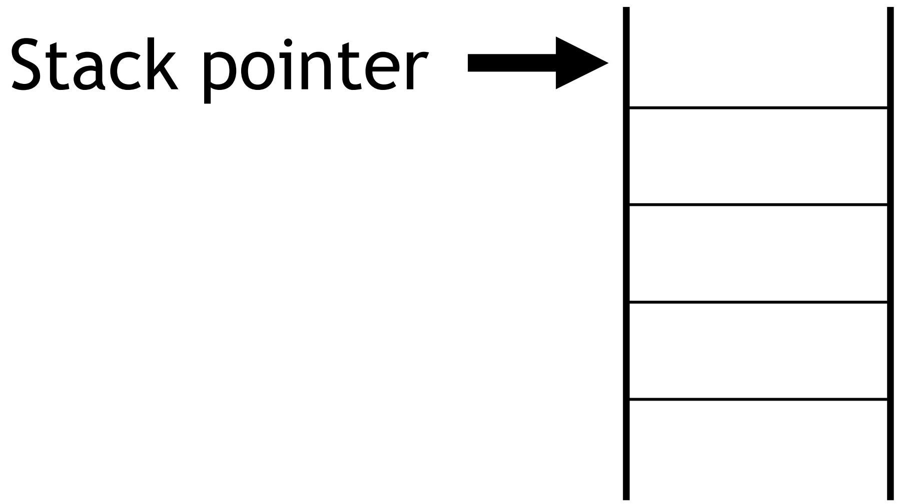

```
mov  ecx, [ebp+var1]
push ecx
mov  ebx, [ebp+var2]
push ebx
call _strcat
add esp, 8
```

Problem 2: Fn. Params [example]




```
mov  ecx, [ebp+var1]
push ecx
mov  ebx, [ebp+var2]
push ebx
call _strcat
add esp, 8
```

Problem 2: Fn. Params [example]




```
mov  ecx, [ebp+var1]
push ecx
mov  ebx, [ebp+var2]
push ebx
call _strcat
add esp, 8
```

Problem 2: Function Parameters

- Solution: Perform forwards analysis modeling x86 instructions effects on the stack.

```
mov  ecx, [ebp+var1]
push ecx
mov  ebx, [ebp+var2]
push ebx
call _strcat
add esp, 8
```

Problem 3: Unmodeled Functions

- String type information and stack model may be incorrect!

Assumption #2:

"_cdecl" calling convention and well behaved functions

- Treat all function arguments and return values as strings.

Problem 4: Java vs. x86 Semantics

- Java strings are immutable,
  x86 strings are not.

```
String y, x="x";
y = x;
y = y + "123";
System.out.println(x);
```

=> "x"

Problem 4: Java vs. x86 Semantics

- Java strings are immutable, x86 strings are not.

```
String y, x=“x”;
y = x;
y = y + “123”;
System.out.println(x);
```

```
char *y;
char x[10] = “x”;
y = x;
y = strcat(y,”123”);
printf(x);
```

=> “x”

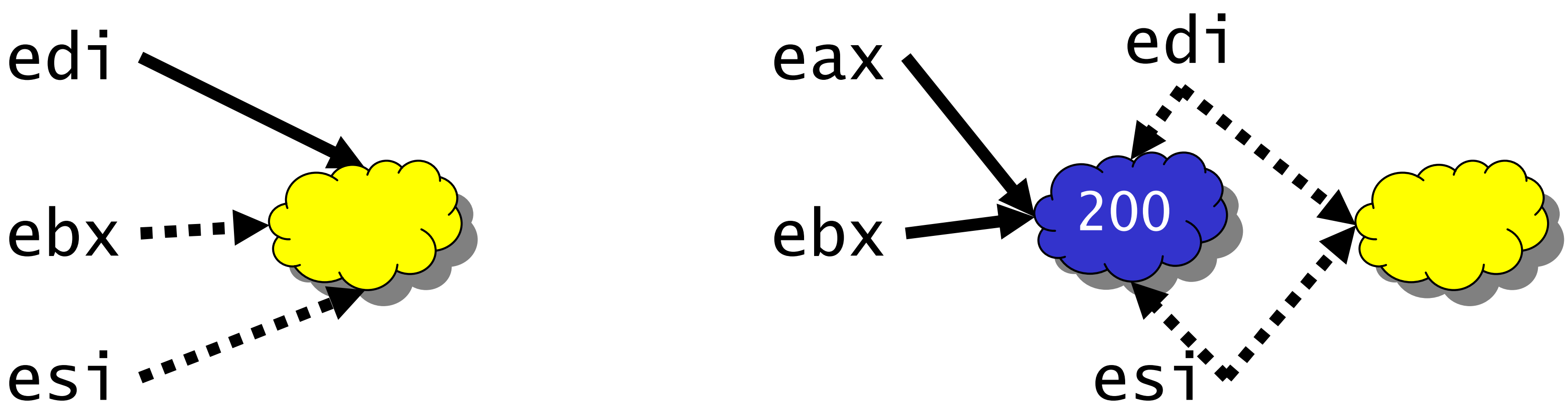
=> “x123”

Problem 4: Java vs. x86 Semantics

- Solution: May-Must alias analysis.

```
0x200: _strcat( ebx,ecx )
```

"May alias" relations:

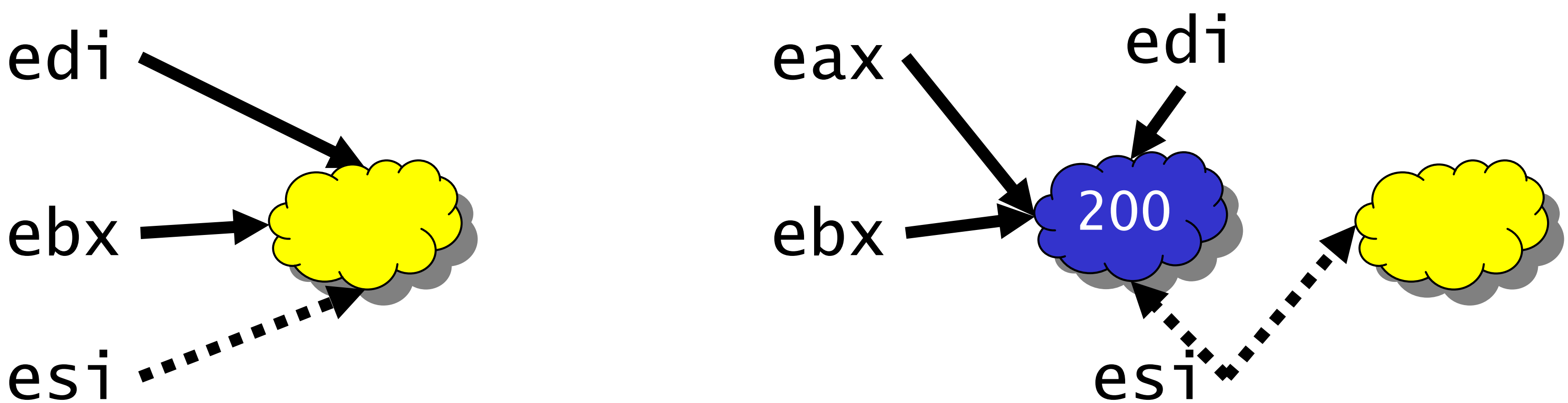


Problem 4: Java vs. x86 Semantics

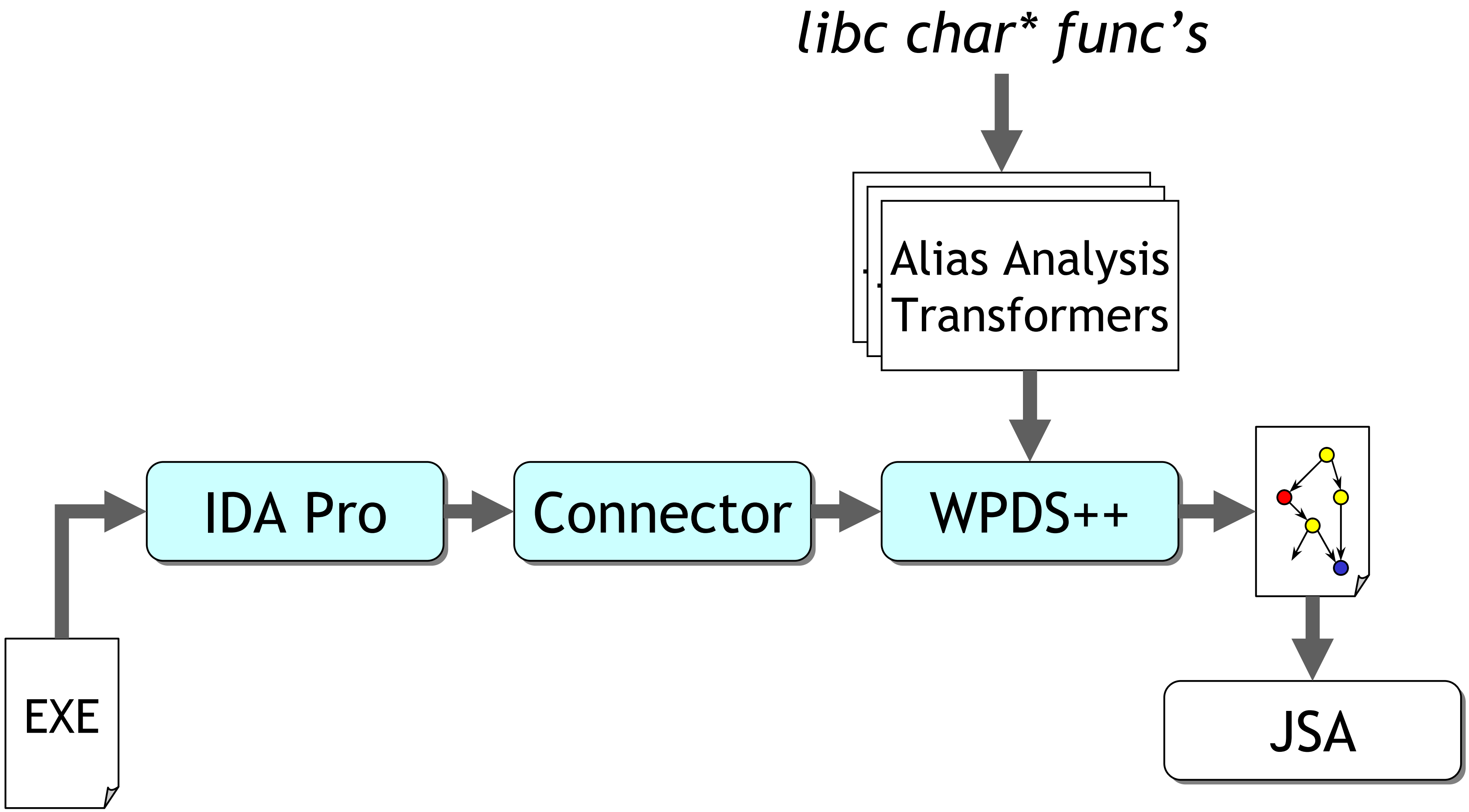
- Solution: May-Must alias analysis.

```
0x200: _strcat( ebx,ecx )
```

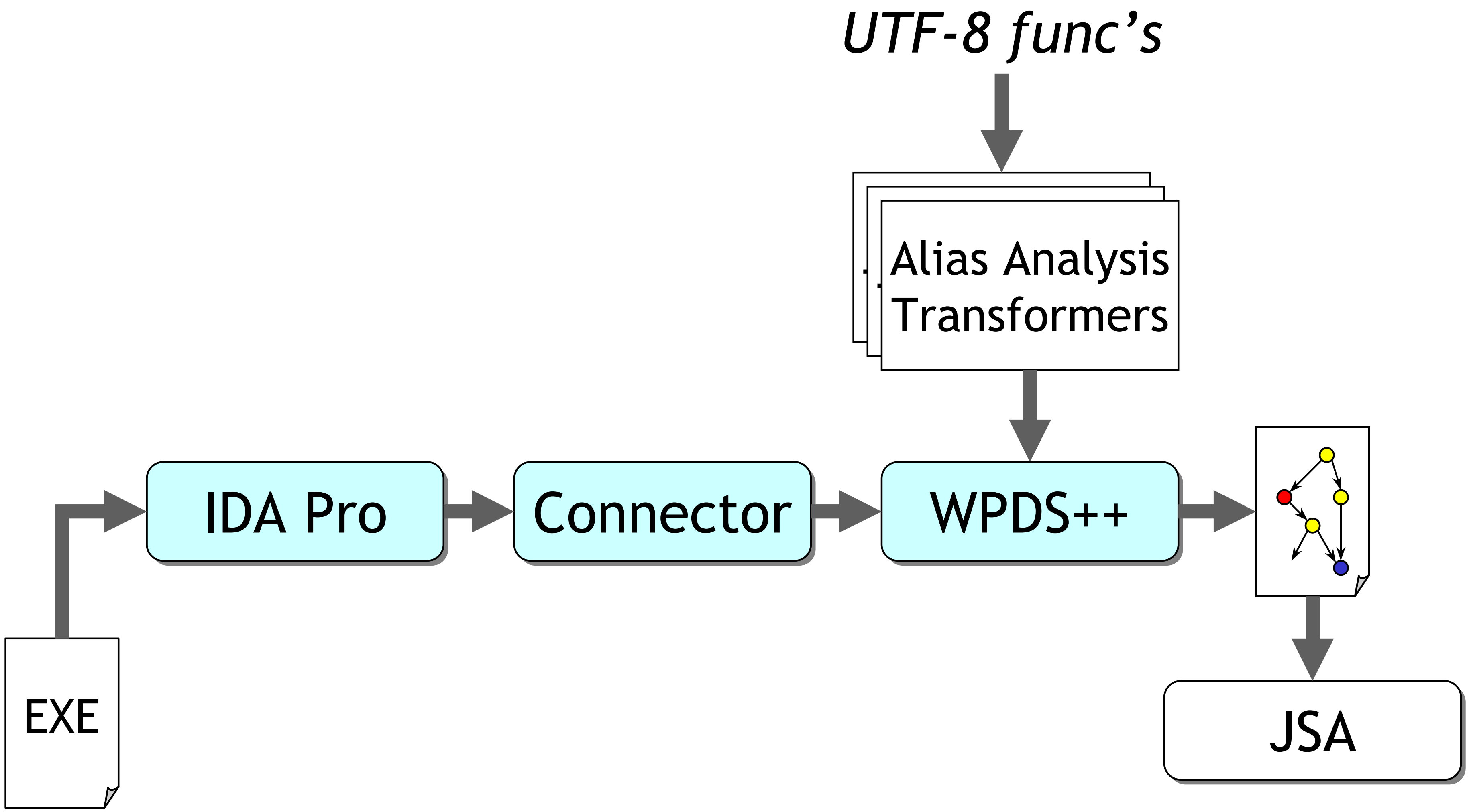
"Must alias" relations:



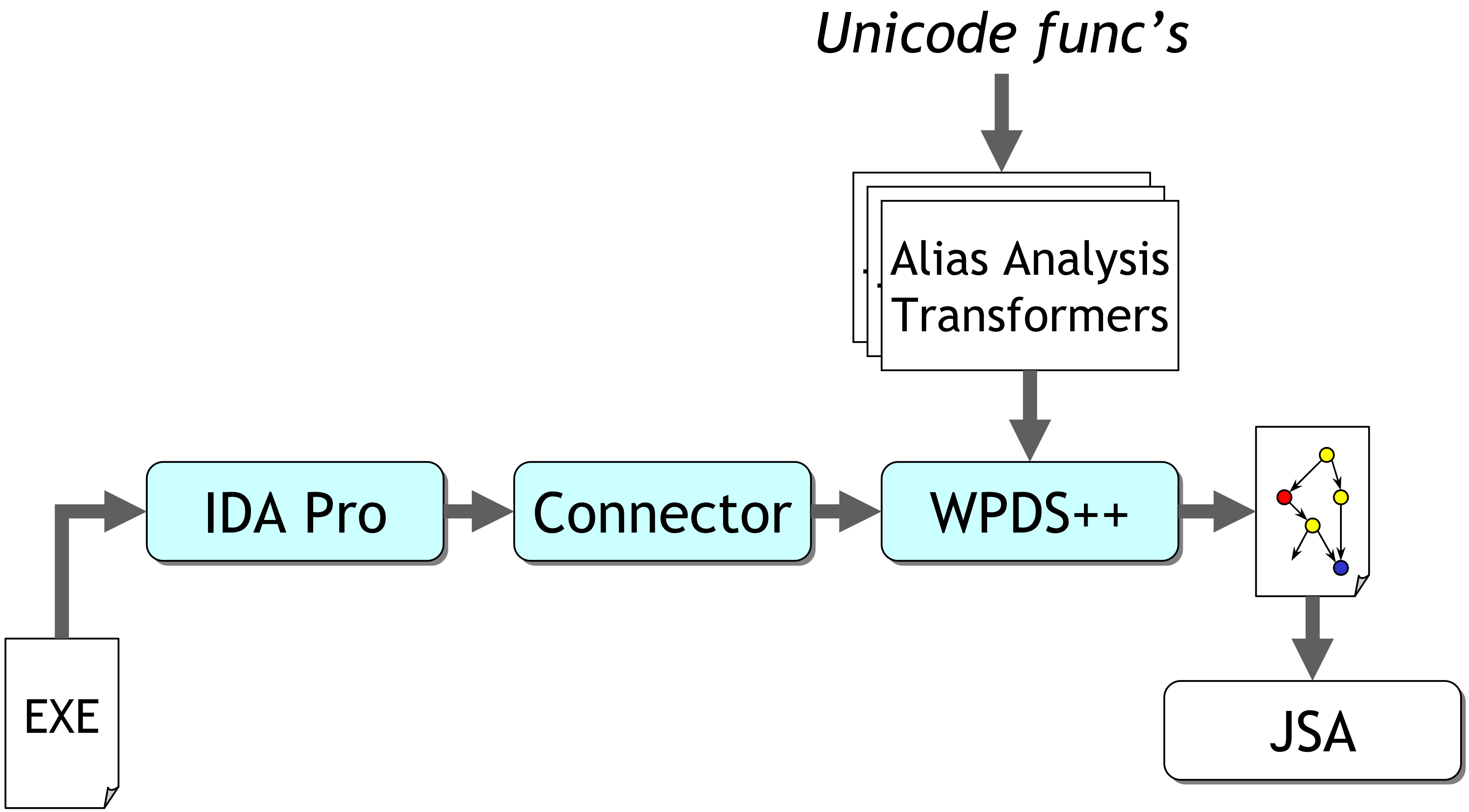
x86sa Architecture



x86sa Architecture



x86sa Architecture



Intraprocedural Analysis Summary

1. Recover callsite arguments.
   (stack-operation modeling)

2. Infer string types.
   (backward type analysis)

3. Discover aliases.
   (may-, must-alias forward analysis)

✓ Generate the String Flow Graph for the Control Flow Graph.

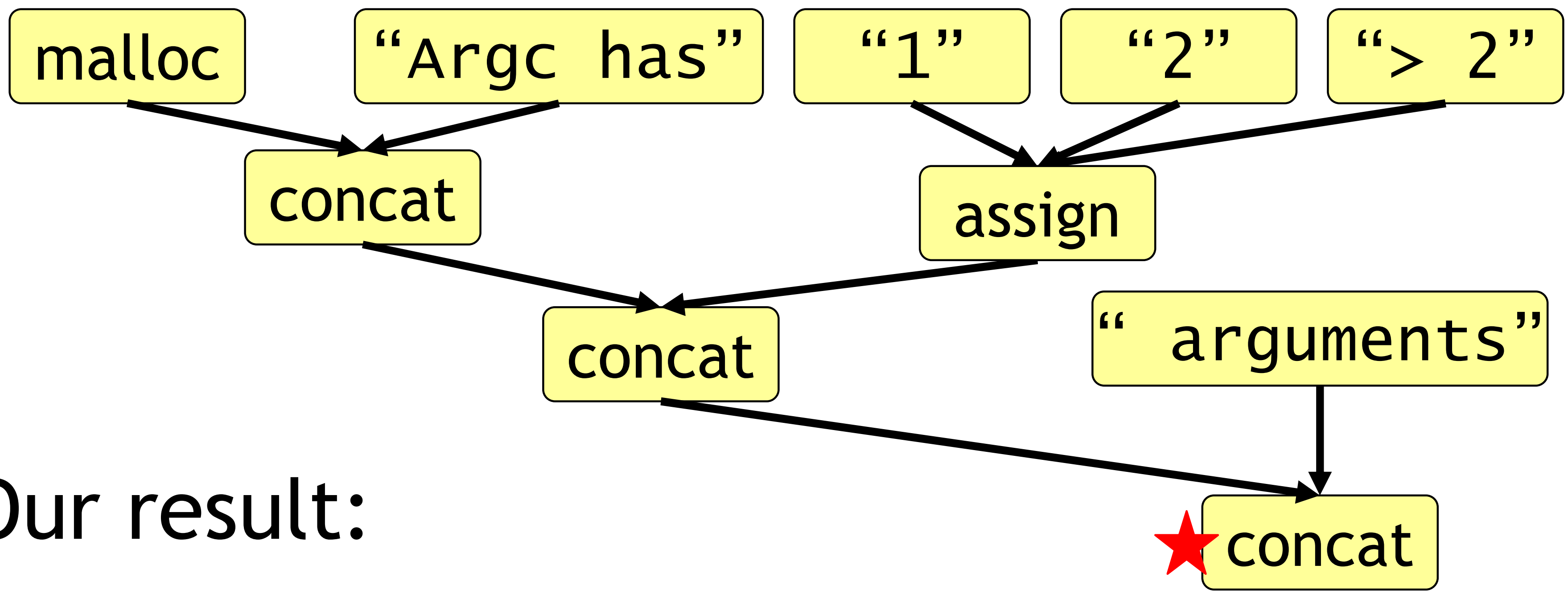
Outline

- String analysis for Java.
- String analysis for x86.
- Evaluation.
- Applications & future work.

Example 1: simple

```
char * s1 = "Argc has ";
char * s2;
char * s3 = " arguments";
char * s4;
switch( argc ) {
   case 1:    s2 = "1“  ; break;
   case 2:    s2 = "2“  ; break;
   default:   s2 = "> 2"; break;
}
s4 = malloc( strlen(s1)+strlen(s2)+strlen(s3)+1 );
s4[0] = 0;
strcat( strcat( strcat( s4, s1 ), s2), s3 );
printf( "%s\n", s4 );
```

Example 1: String Flow Graph



Our result:

"Argc has 1 arguments"

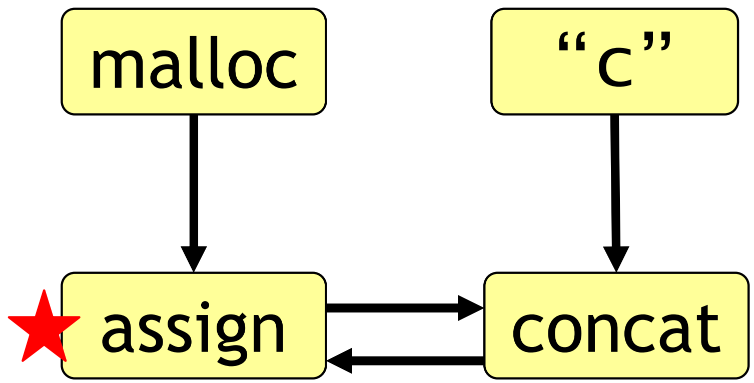
"Argc has 2 arguments"

"Argc has > 2 arguments"

Example 2: cstar

```
char * c = “c";
char * s4 = malloc(101);
for( int i=0; i < 100 ; i++ ) {
   strcat( s4, c );
}
printf( "%s\n", s4 );
```

Example 2: String Flow Graph



Our result: c*

Correct answer: c^{100}

Example 3: Lion Worm

- Code and String Flow Graph omitted.

- x86sa analysis results:

  `"/sbin/ifconfig -a|/bin/mail angelz1578@usa.net"`

Future Work: Interprocedural Analysis

1. Inline everything and apply intra-procedural analysis.
2. “Hook” intraprocedural String Flow Graphs into a “Super String Flow Graph”.
3. Polyvariant analysis over function summaries for String Flow Graphs.

Future Work: Relax Assumptions

- Relax the assumptions:
  - Strings can be manipulated in many ways.
  - Calling conventions can vary in a program.

- Value Set Analysis looks promising:
  - Identifies "variables" based on usage patterns.

Future Work: More Applications

- Malicious code analysis
- Analysis of dynamic code generators:
  - Packed programs
  - Shell code generators

String Analysis for Binaries

Mihai Christodorescu
Nicholas Kidd
Wen-Han Goh

University of Wisconsin, Madison
{ mihai, kidd, wen-han }@cs.wisc.edu