Securing Cryptographic Software via Typed Assembly Language

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Andres Erbsen, Adam Chlipala, Mengjia Yan

Cryptographic Software

Timing Side Channels

Cryptographic Software

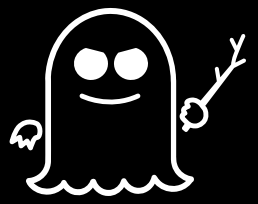
Timing Side Channels

Constant-time Coding Guidelines

```
e.g., a = array[secret]
```

Cryptographic Software

Timing Side Channels



Spectre-like Attacks

Constant-time Coding Guidelines

`e.g., a = array[secret]` 

Speculative Execution violates 

Software

Hardware

[1] Lesly-Ann Daniel, Marton Bognar, Job Noorman, Sébastien Bardin, Tamara Rezk, and Frank Piessens. 2023. ProSpeCT: Provably Secure Speculation for the Constant-Time Policy. In 32nd USENIX Security Symposium (USENIX Security 23). 7161–7178.

Software

Hardware

```
movq (%rsi),%rax
```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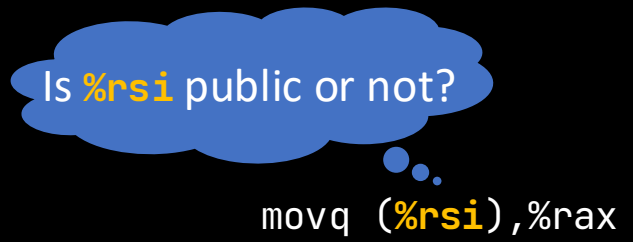
Software

Hardware



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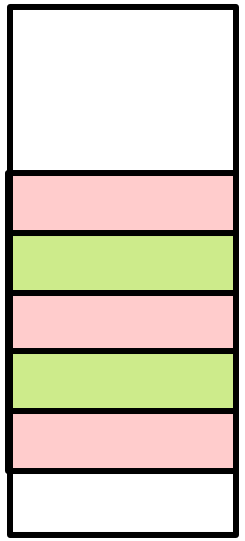

Hardware


```
movq (%rdi),%rsi; movq (%rsi),%rax
```


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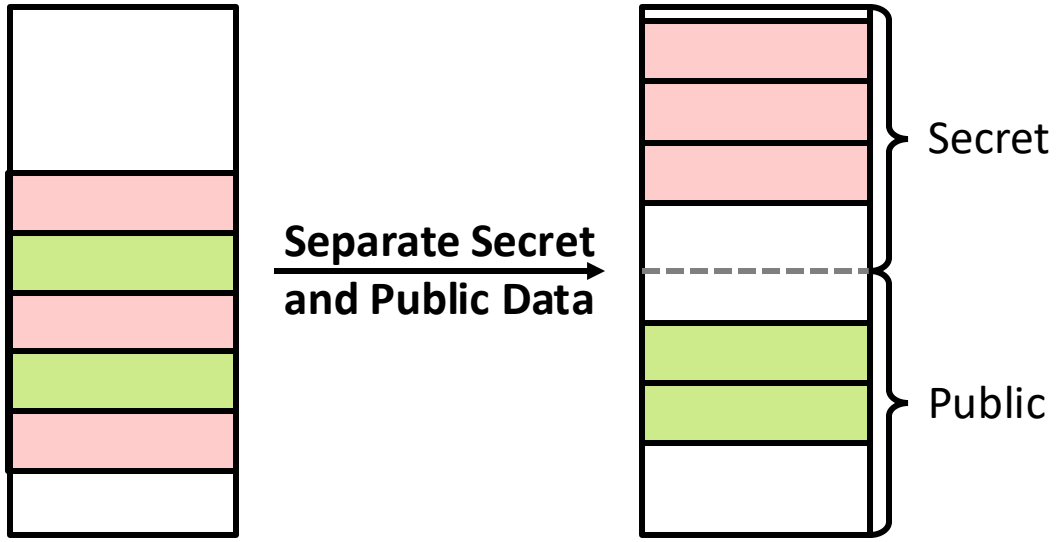

Hardware

Is %rsi public or not?

```
movq (%rdi),%rsi; movq (%rsi),%rax
```


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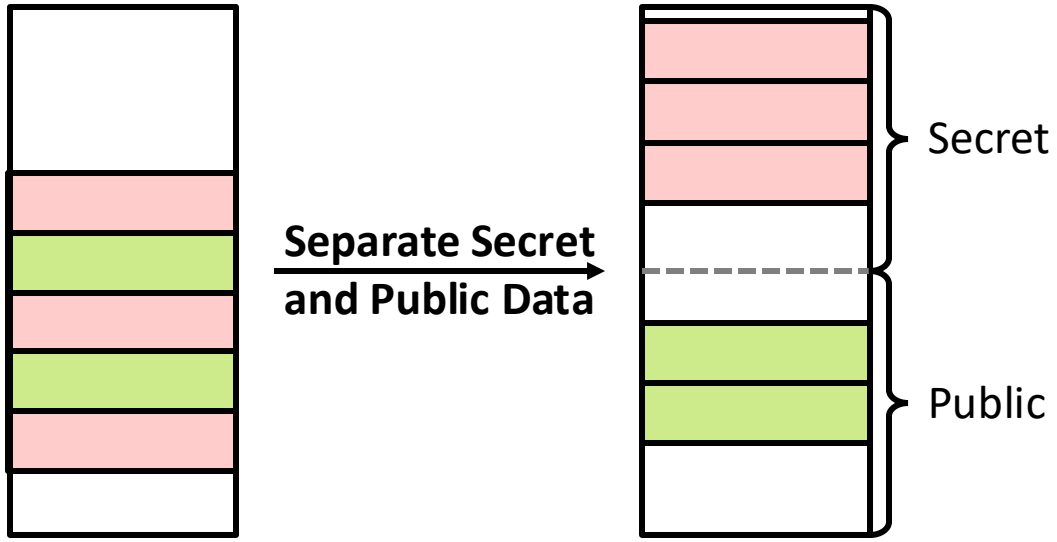

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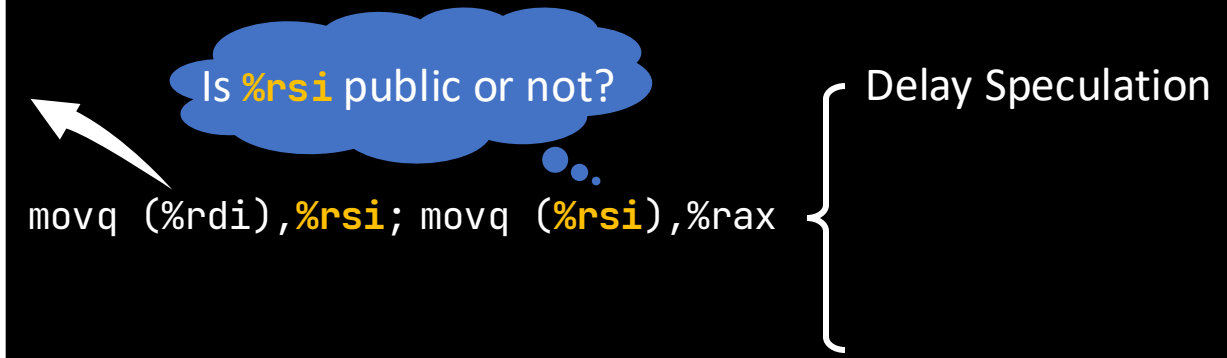

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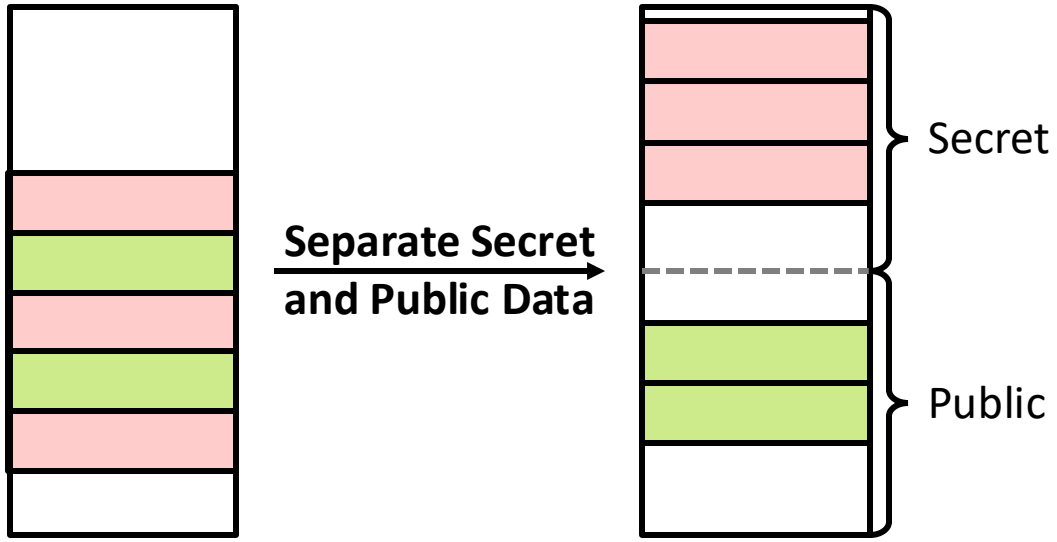

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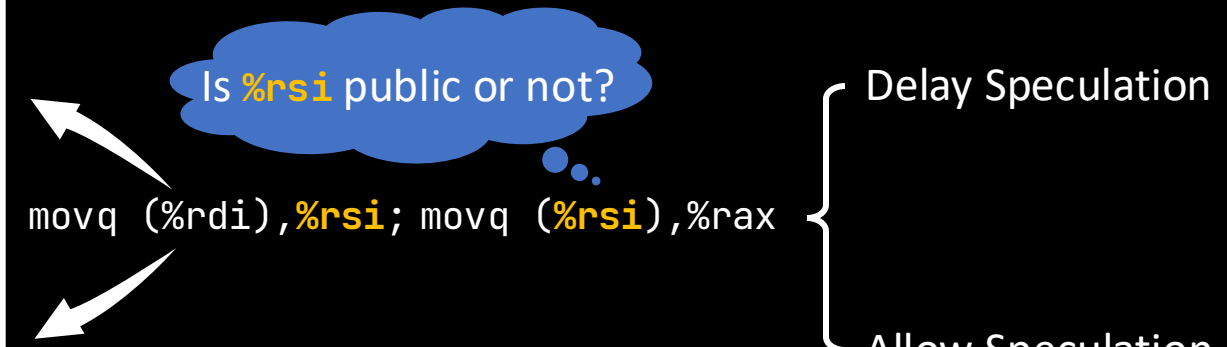

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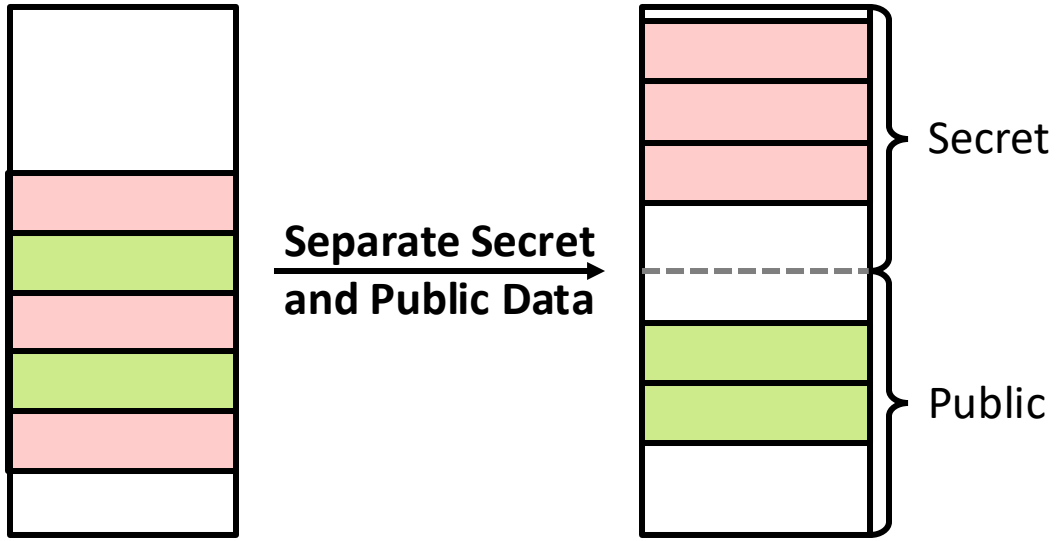

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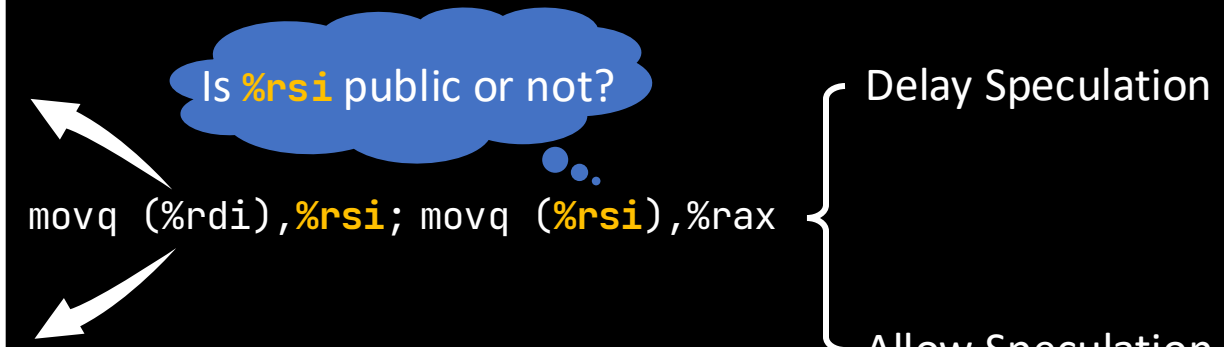

Existing Solution: ProSpeCT[1]

Low hardware cost

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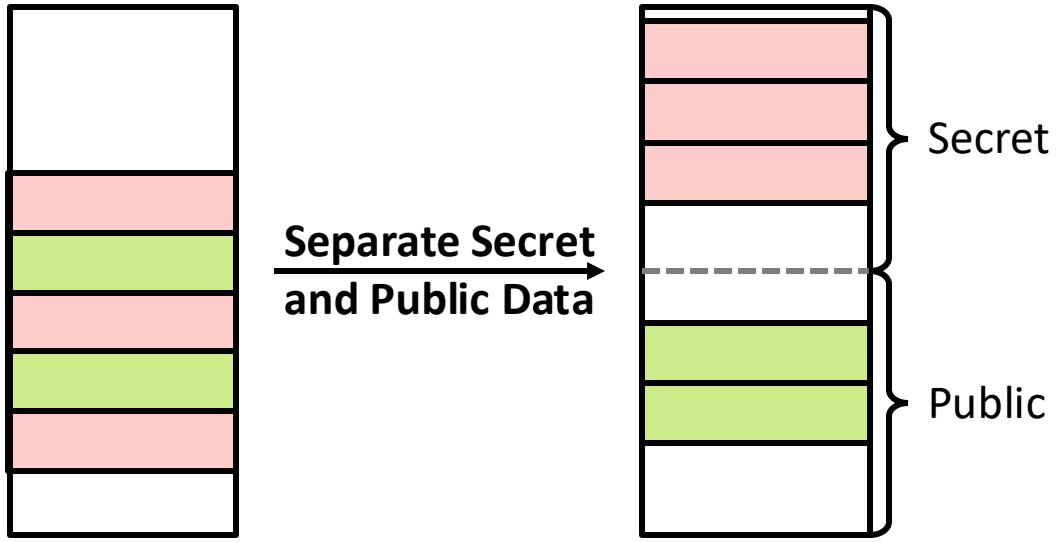
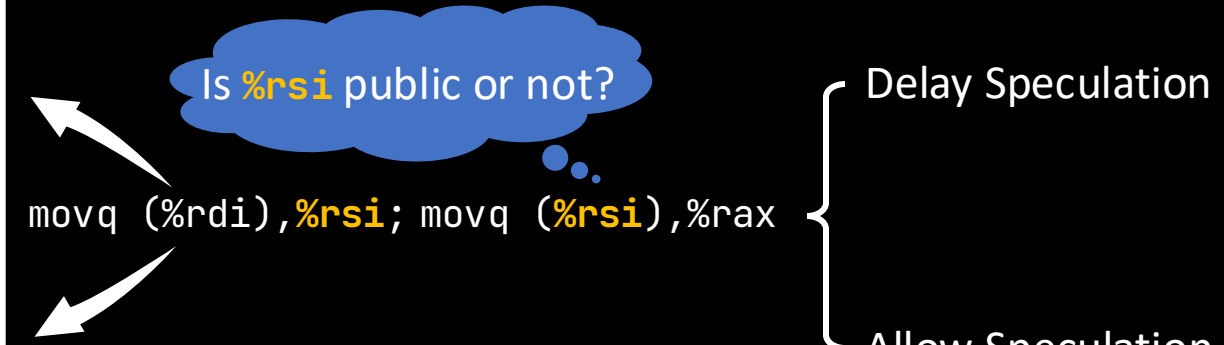


Existing solutions **cannot** separate secret and public **stack** data **accurately**

Hardware



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Separating Secret and Public Stack Data

```
void salsa20_words
  (uint32_t *d, uint32_t s[16]) {

  uint32_t x[4][4];
  int i;
  for (i=0; i<16; ++i)
    x[i/4][i%4] = s[i];
  // ...
}
```

Separating Secret and Public Stack Data

```
void salsa20_words
  (uint32_t *d, uint32_t s[16]) {
__attribute__((section("sec"))) static
  uint32_t x[4][4];
  int i;
  for (i=0; i<16; ++i)
    x[i/4][i%4] = s[i];
  // ...
}
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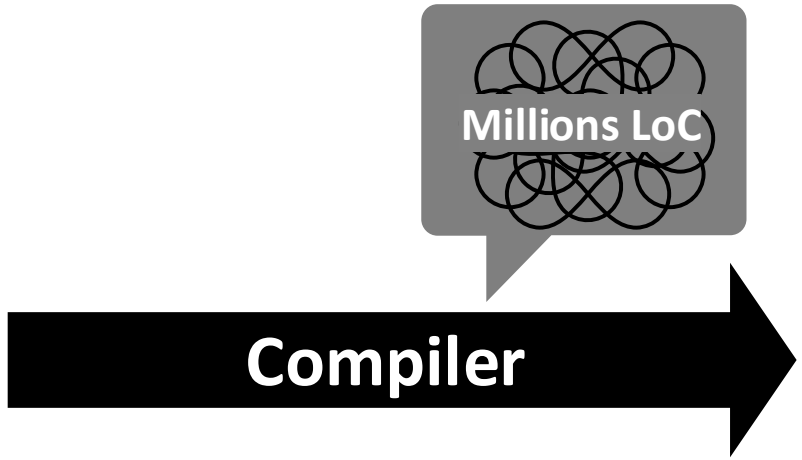


```
salsa20_words:
  movq %rdi, -64(%rsp)
  movl (%rsi), %r12d
  movl 4(%rsi), %r11d
  movl 8(%rsi), %r9d
  ...
  // Secret Stack Spill
  movq %rax, -88(%rsp)
  ...
```

Separating Secret and Public Stack Data

```
void salsa20_words
  (uint32_t *d, uint32_t s[16]) {
__attribute__((section("sec"))) static
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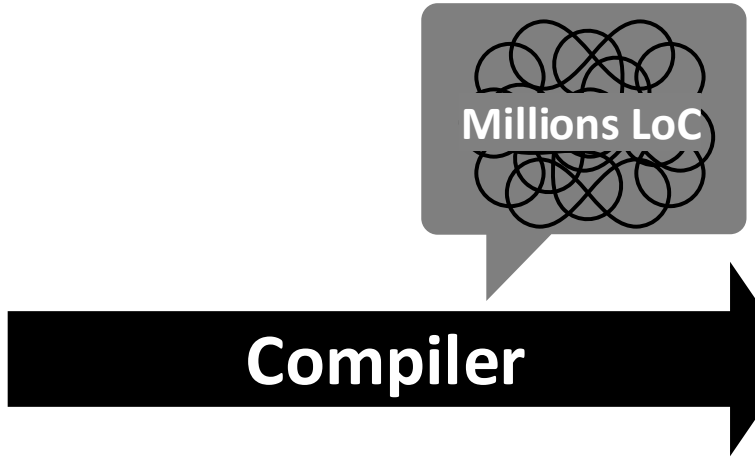
    x[i/4][i%4] = s[i];
  // ...
}
```

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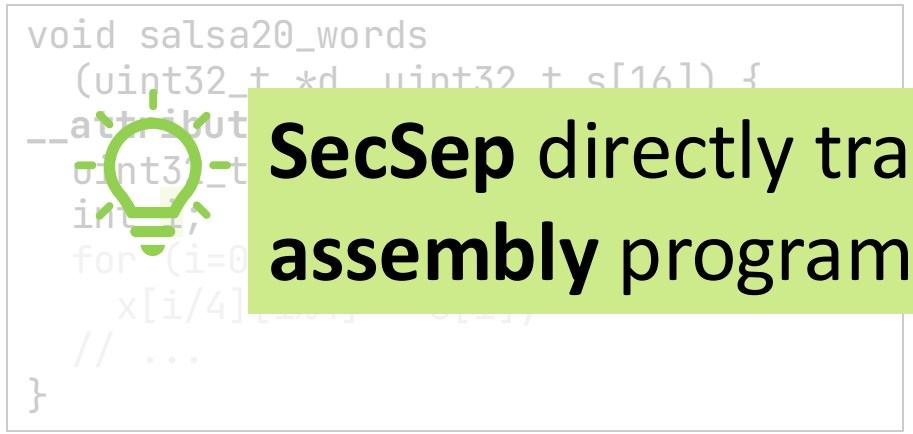
  movq %rdi, -64(%rsp)
  movl (%rsi), %r12d
  movl 4(%rsi), %r11d
  movl 8(%rsi), %r9d
  ...
  // Secret Stack Spill
  movq %rax, -88(%rsp)
  ...
```

Source code annotation cannot separate secret and public **stack** data accurately.

Separating Secret and Public Stack Data



SecSep directly transforms the compiled **assembly** program.

```
salsa20_words:
  movq %rdi, -64(%rsp)
  movl (%rsi), %r12d
  movl 4(%rsi), %r11d
  movl 8(%rsi), %r9d
  ...
  // Secret Stack Spill
  movq %rax, -88(%rsp)
  ...
```

- Accurate stack separation
- Smaller TCB

SecSep: Overview

Compiler-generated assembly

```
foo:
  ...
  movq %rdi, (%rsp)
  ...
  movq (%rsp), %rdi
  movq (%rdi), %rax
```

Challenge: Track memory access to secret and public data at the **assembly level**.

SecSep: Overview

Compiler-generated assembly

```
foo:
  ...
  movq %rdi, (%rsp)
  ...
  movq (%rsp), %rdi
  movq (%rdi), %rax
```

Typed assembly: Octal

```
foo:
  ...
  movq %rdi, (%rsp)
  ...
  movq (%rsp), %rdi
  movq (%rdi), %rax
```

Challenge: Track memory access to secret and public data at the **assembly level**.

Solution: Octal type system + type inference + transformation

SecSep: Overview

Compiler-generated assembly

```
foo:
  ...
  movq %rdi, (%rsp)
  ...
  movq (%rsp), %rdi
  movq (%rdi), %rax
```

Type inference

Typed assembly: Octal

```
foo:
  ...
  movq %rdi, (%rsp)
  ...
  movq (%rsp), %rdi
  movq (%rdi), %rax
```

Challenge: Track memory access to secret and public data at the **assembly level**.

Solution: Octal type system + type inference + transformation

SecSep: Overview

Compiler-generated assembly

```
foo:
  ...
  movq %rdi, (%rsp)
  ...
  movq (%rsp), %rdi
  movq (%rdi), %rax
```

Type inference

Typed assembly: Octal

```
foo:
  ...
  movq %rdi, (%rsp)
  ...
  movq (%rsp), %rdi
  movq (%rdi), %rax
```

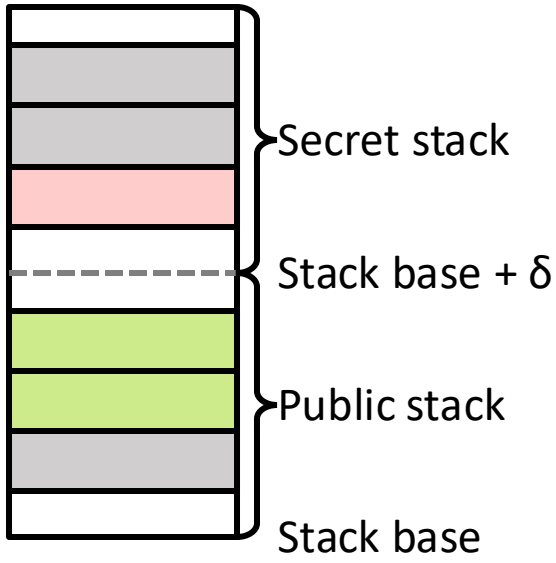
Transformation

Transformed assembly

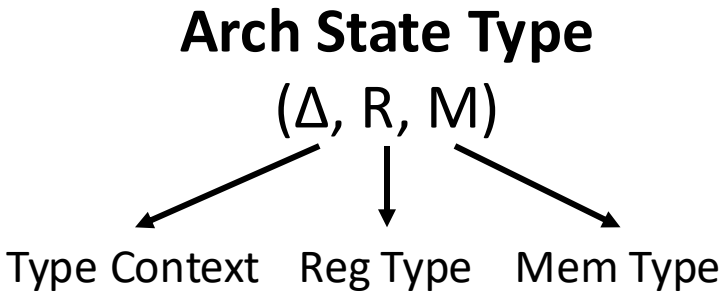
```
foo:
  ...
  movq %rdi, (%rsp)
  ...
  movq (%rsp), %rdi
  movq δ(%rdi), %rax
```

Challenge: Track memory access to secret and public data at the **assembly level**.

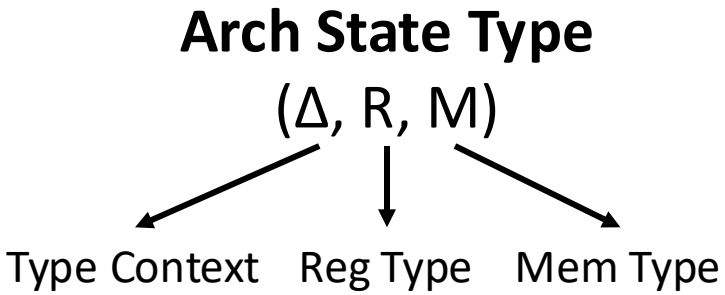
Solution: Octal type system + type inference + transformation

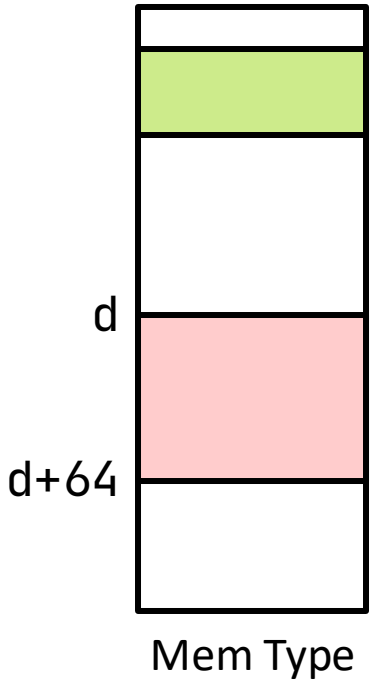


Octal: Typed Assembly Language

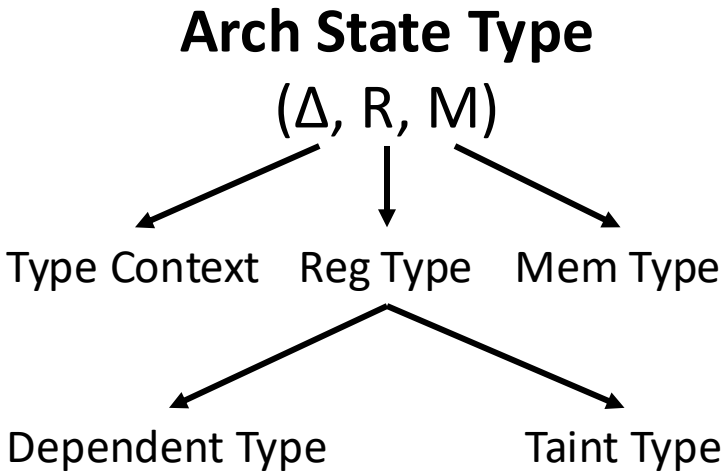


Octal: Typed Assembly Language

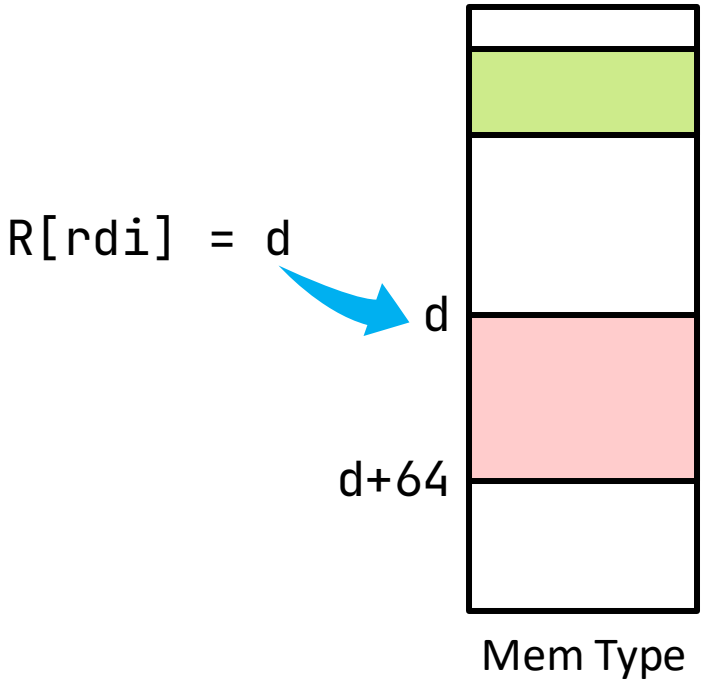




Octal: Typed Assembly Language




```
.L0:
movq (%rdi), %rsi
...
```



Octal: Typed Assembly Language

Arch State Type

(Δ, R, M)

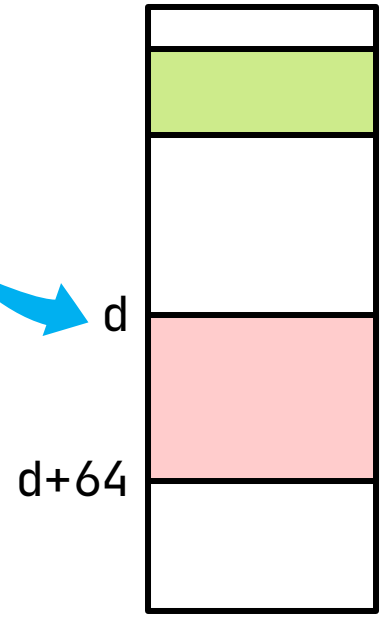
Is subtype of …
(type soundness)

(Δ’, R’, M’)

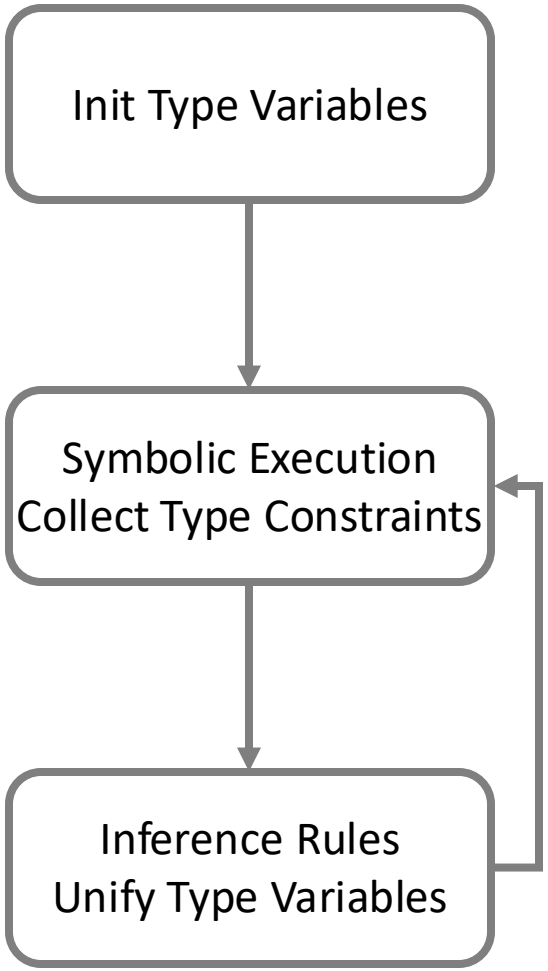
```
.L0:
movq (%rdi), %rsi
...
```

```
.L1:
...
```

R[rdi] = d



Infer Octal Types for Cryptographic Assembly



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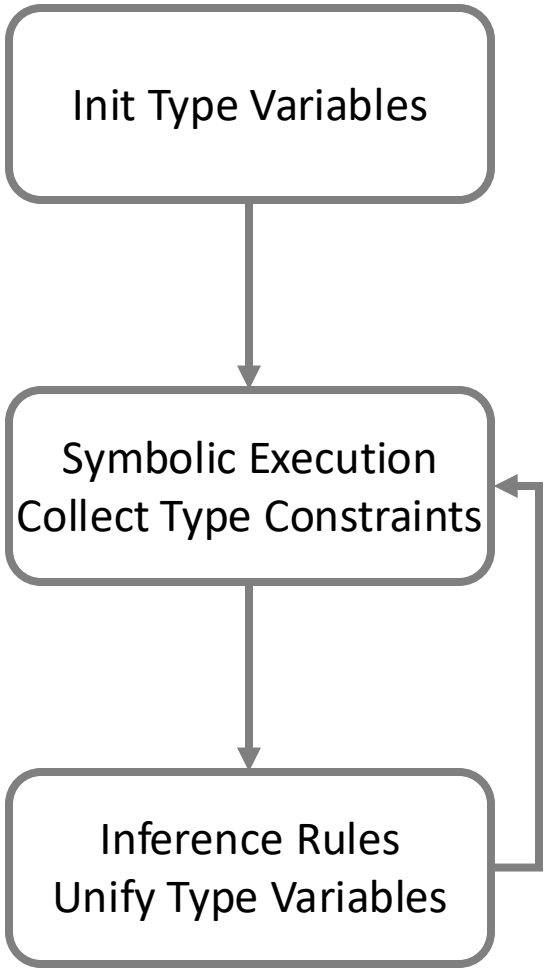


```
.foo:
  movq  (❓)    → ❓
  addq   ❓, $1 → ❓
  cmpq   ❓, $8
  addq   ❓, ❓ → ❓
  jne    .foo
  ...
```

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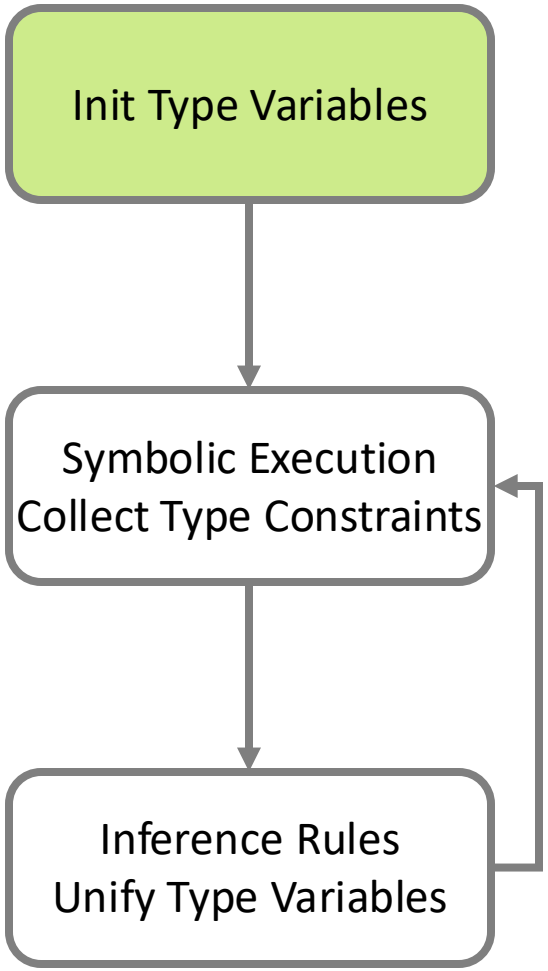
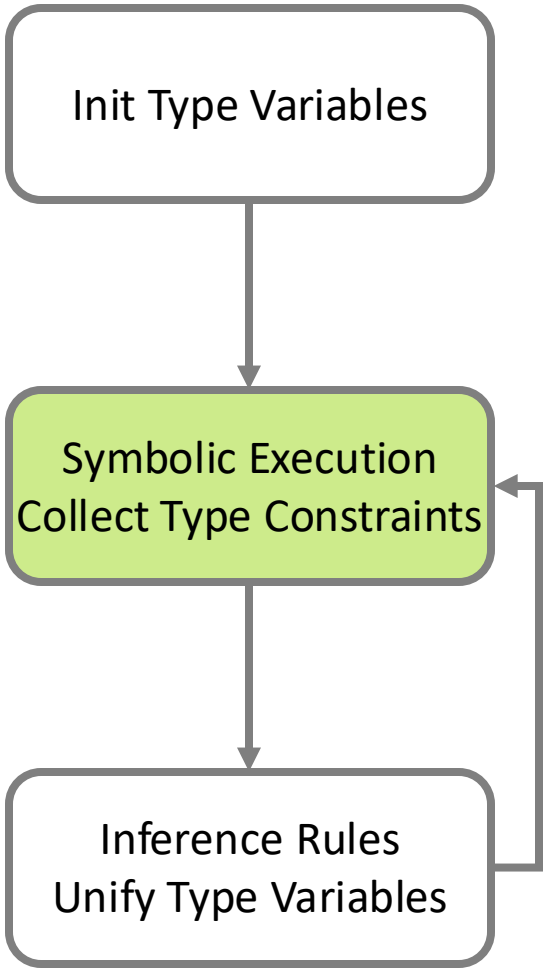



```
.foo:
  movq  (?)    → ?
  addq   ?, $1 → ?
  cmpq   ?, $8
  addq   ?, ? → ?
  jne    .foo
  ...
```

Infer Octal Types for Cryptographic Assembly

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  jne    .foo
  ...
```

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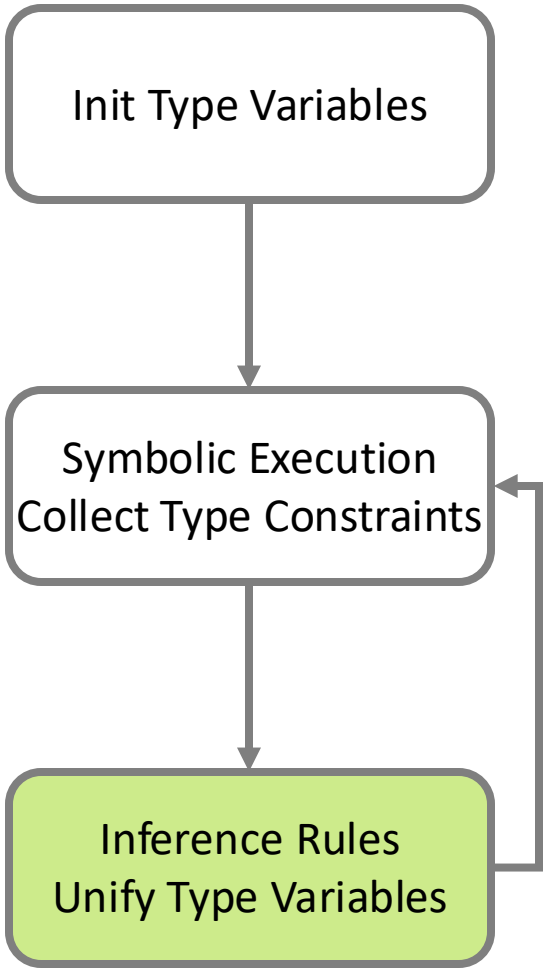

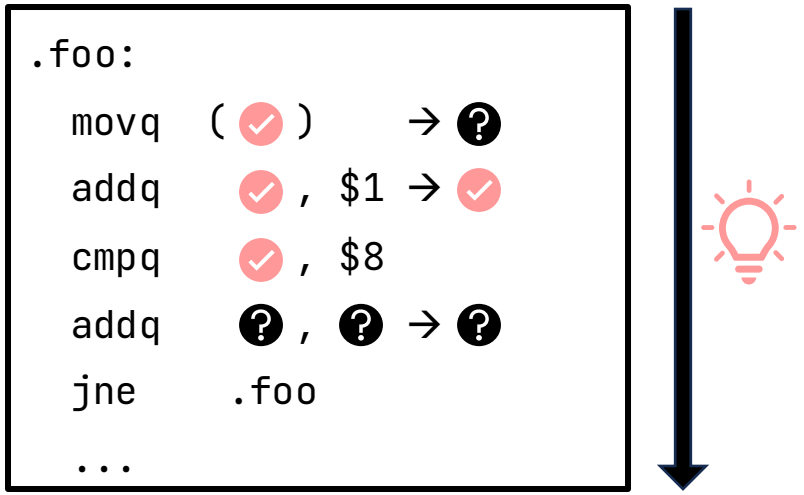

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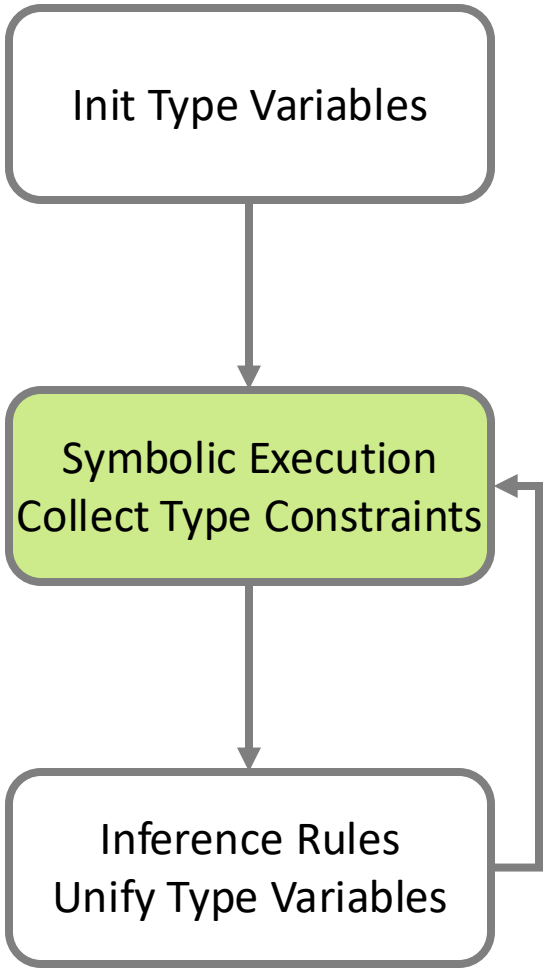

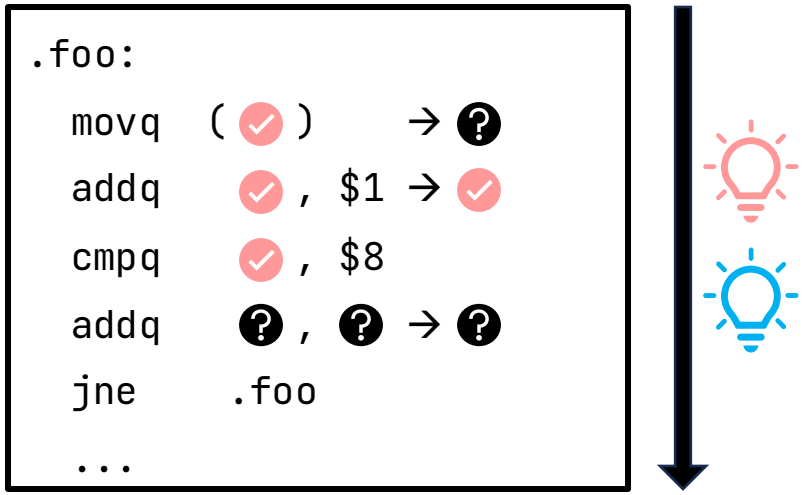

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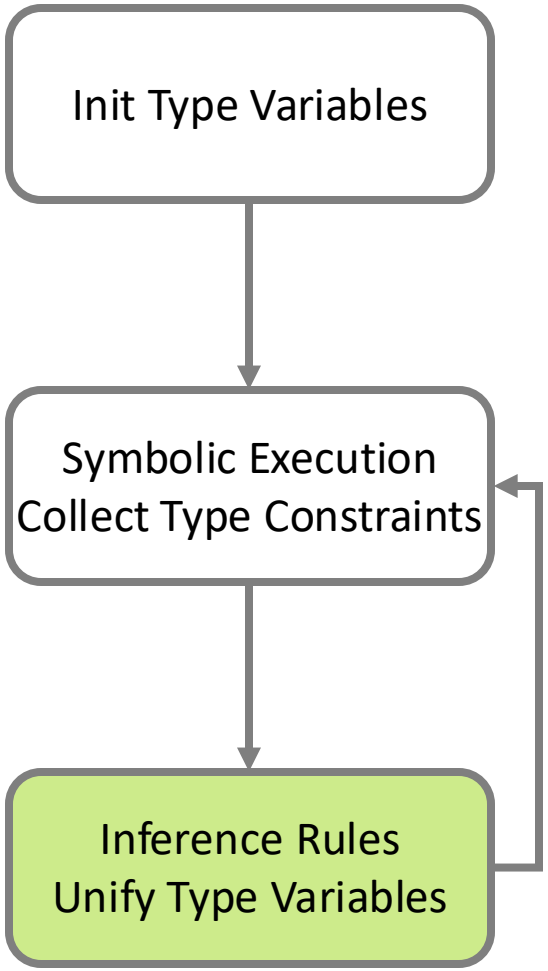

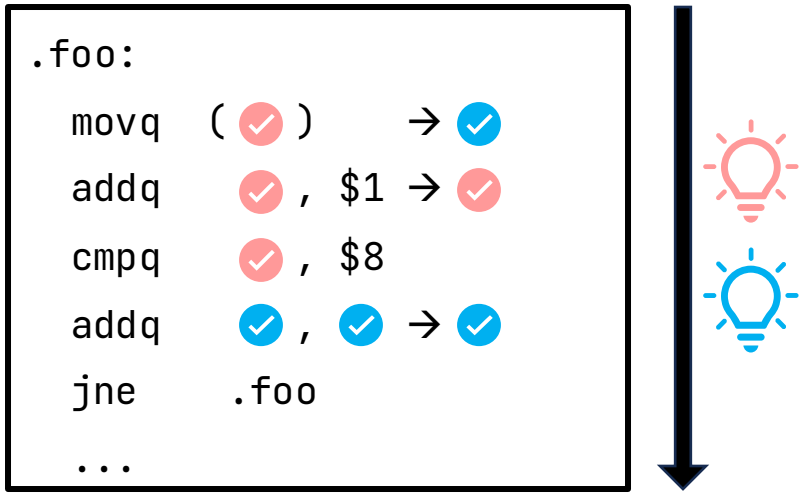

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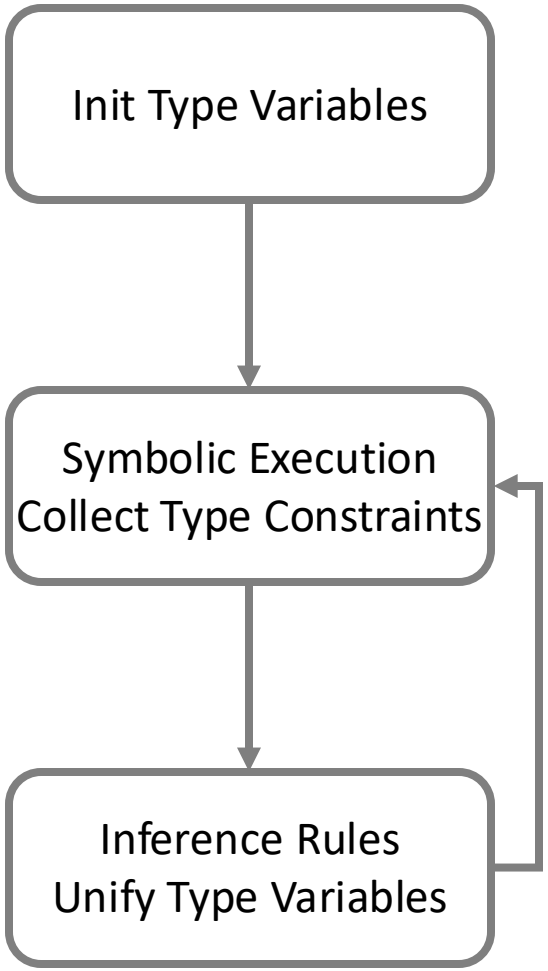

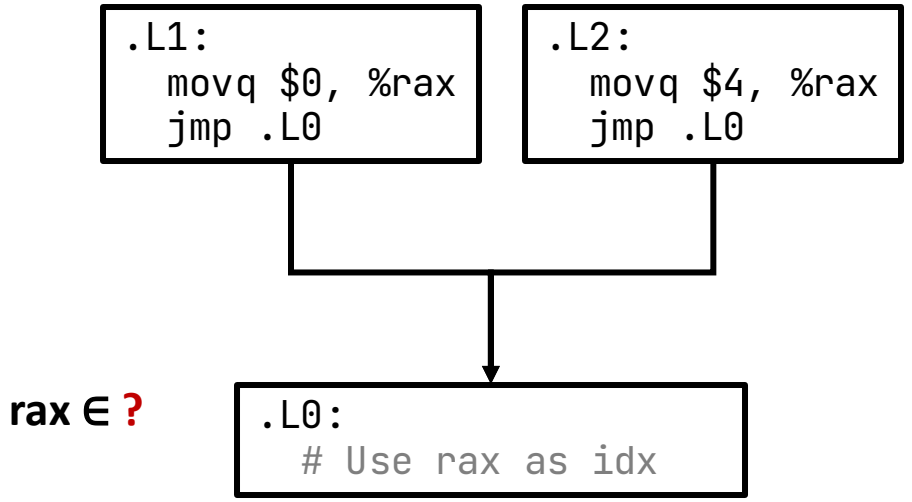

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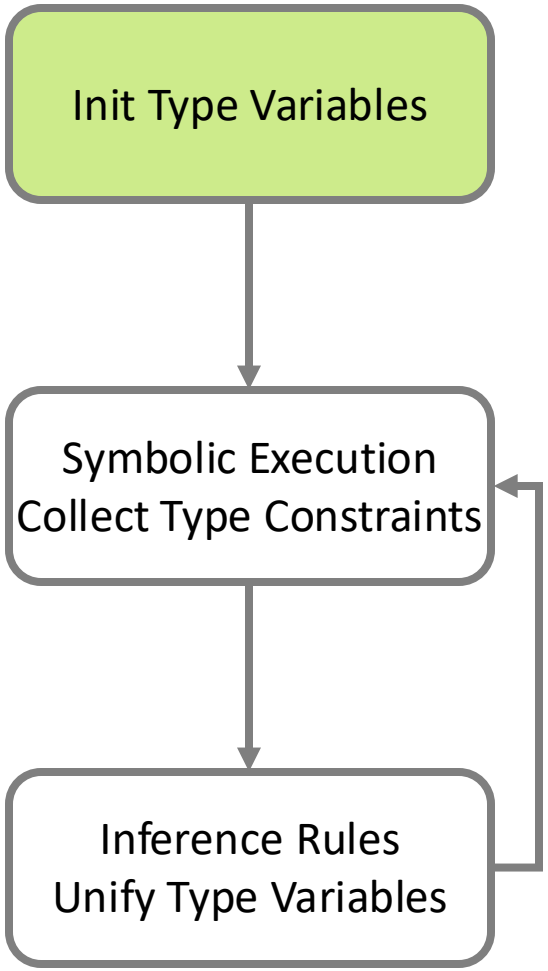

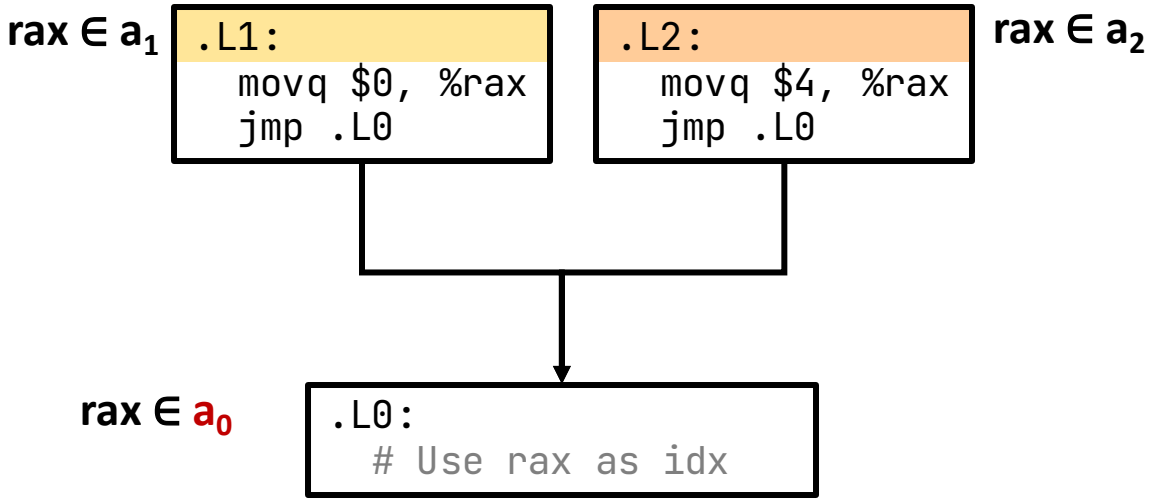

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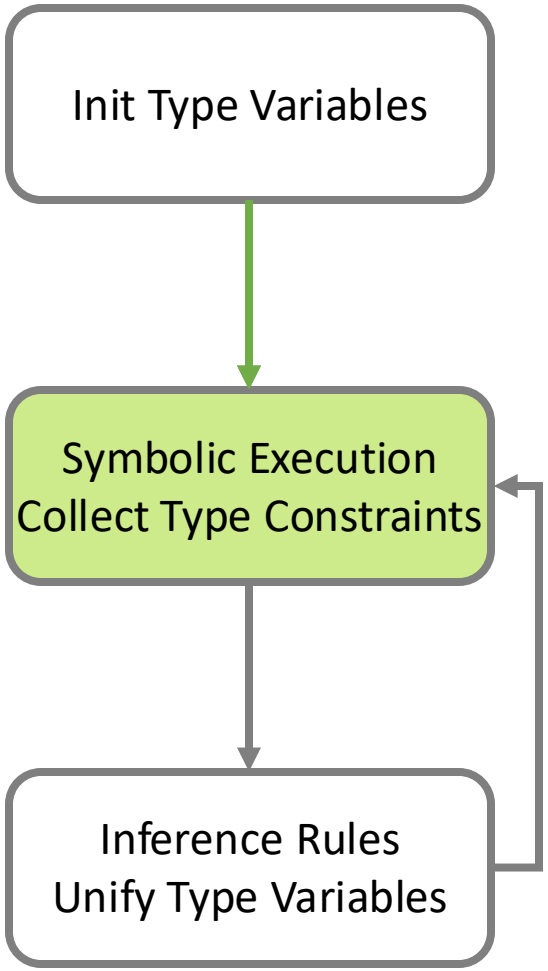

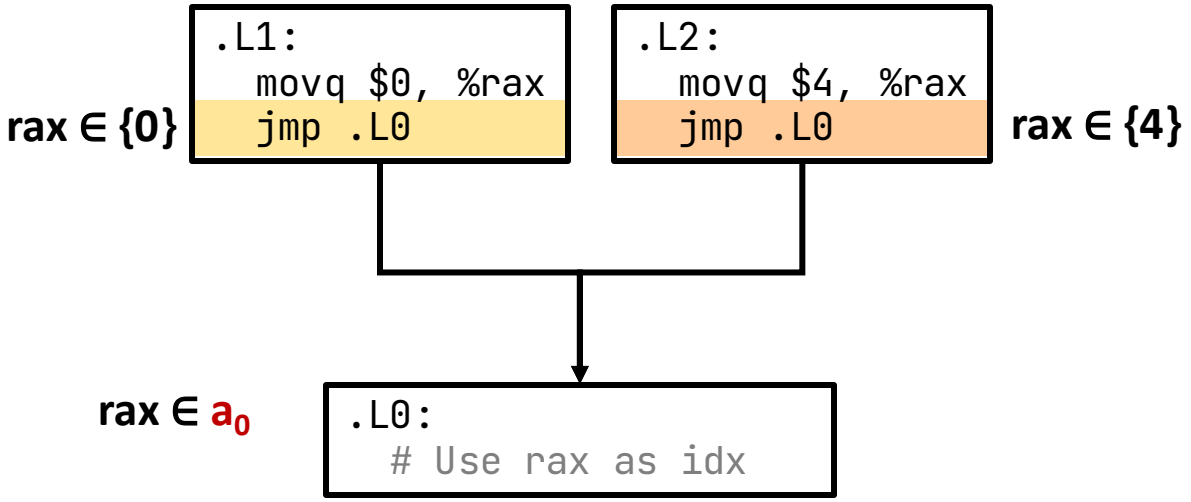

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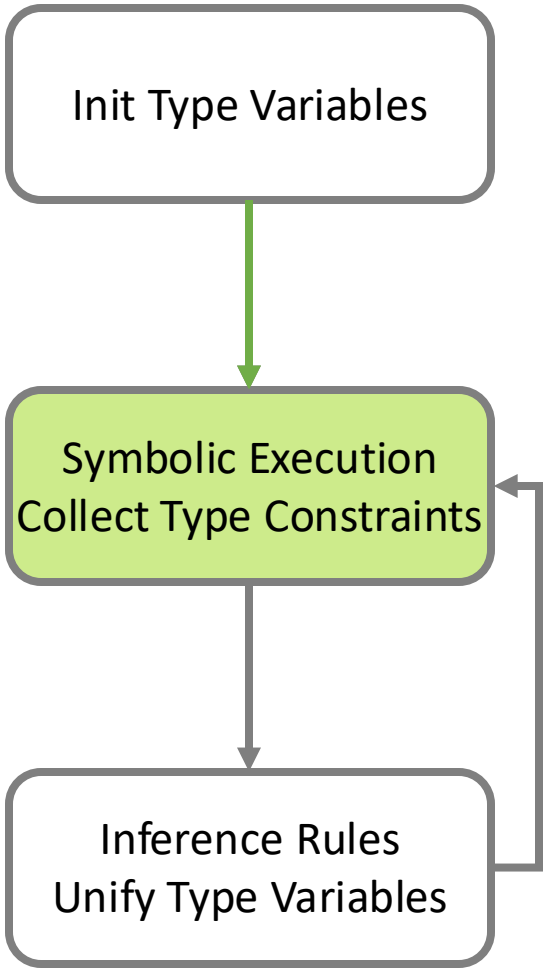
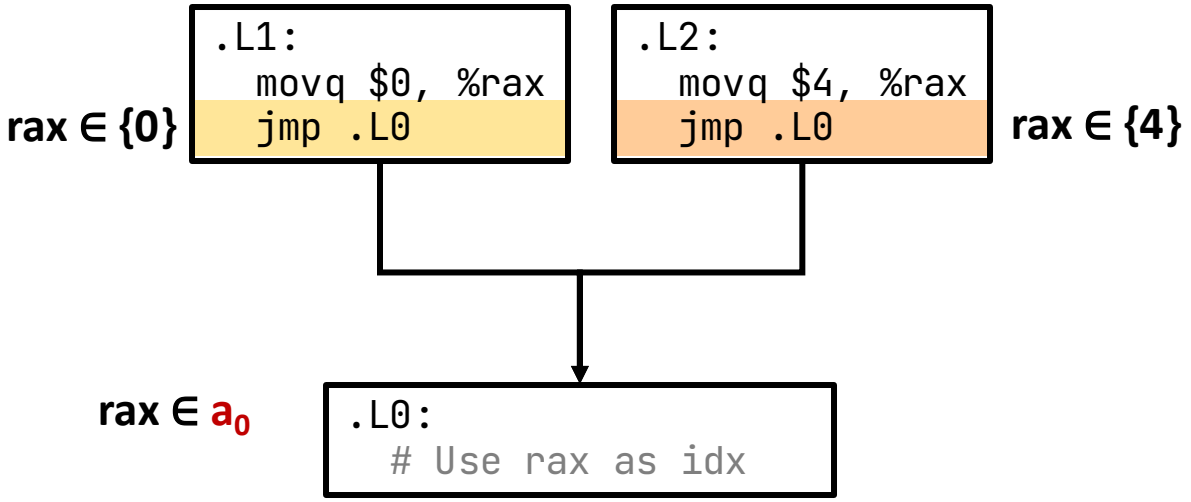
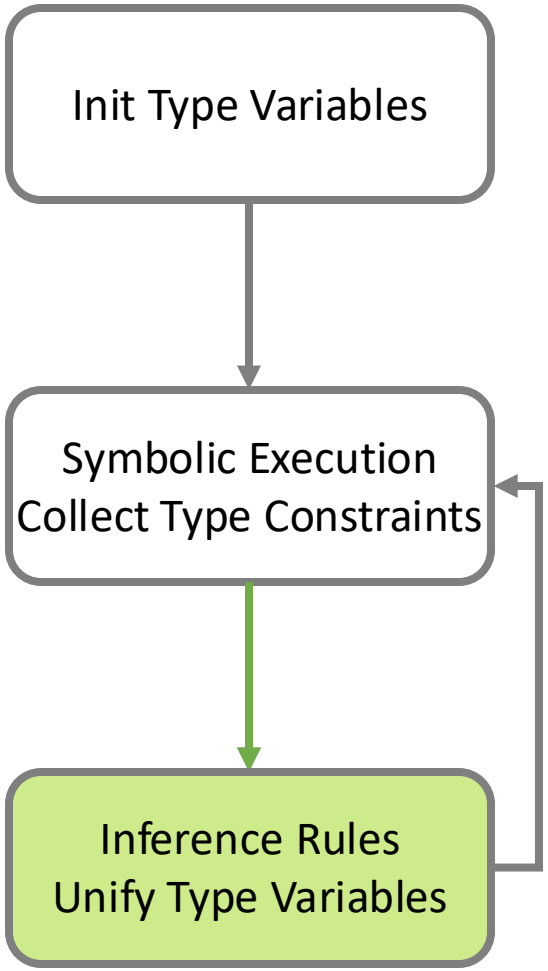


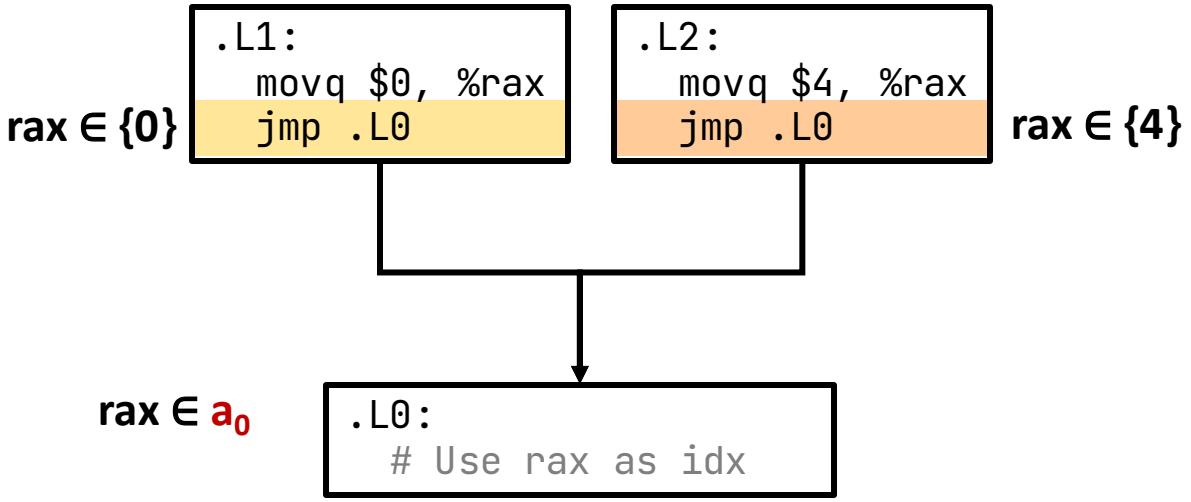


Type constraints to satisfy the tying rules

$\{0\} \subseteq a_0$
$\{4\} \subseteq a_0$

Infer Octal Types for Cryptographic Assembly





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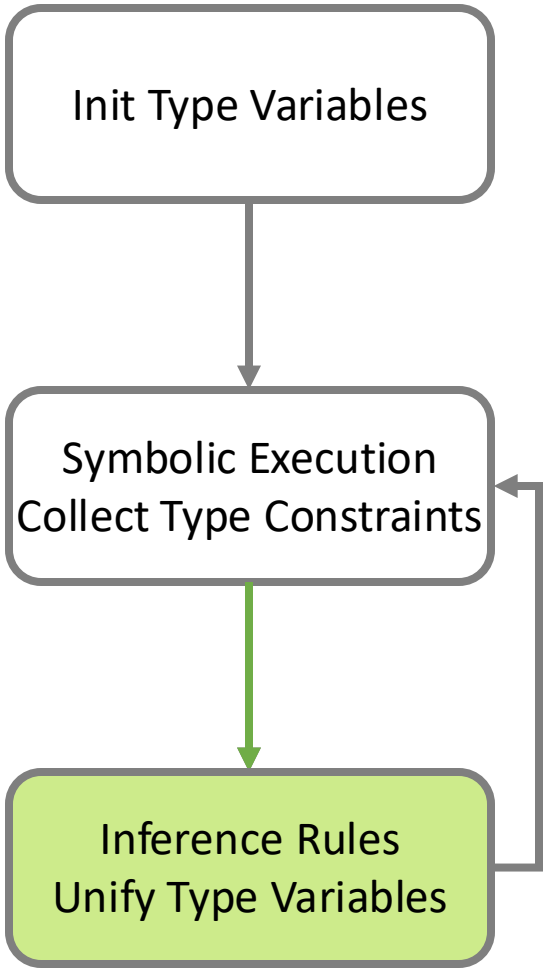
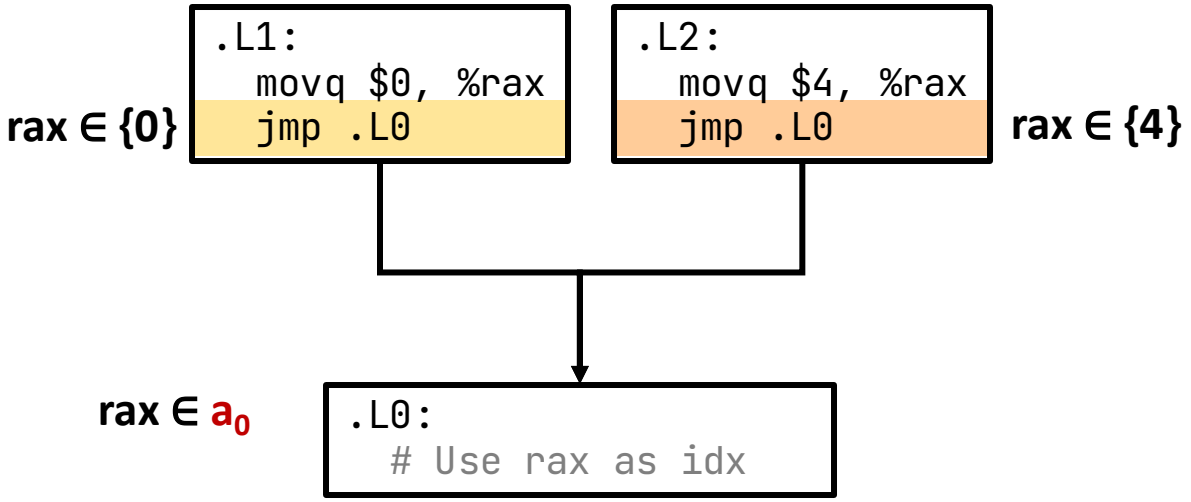




Type constraints to satisfy the tying rules

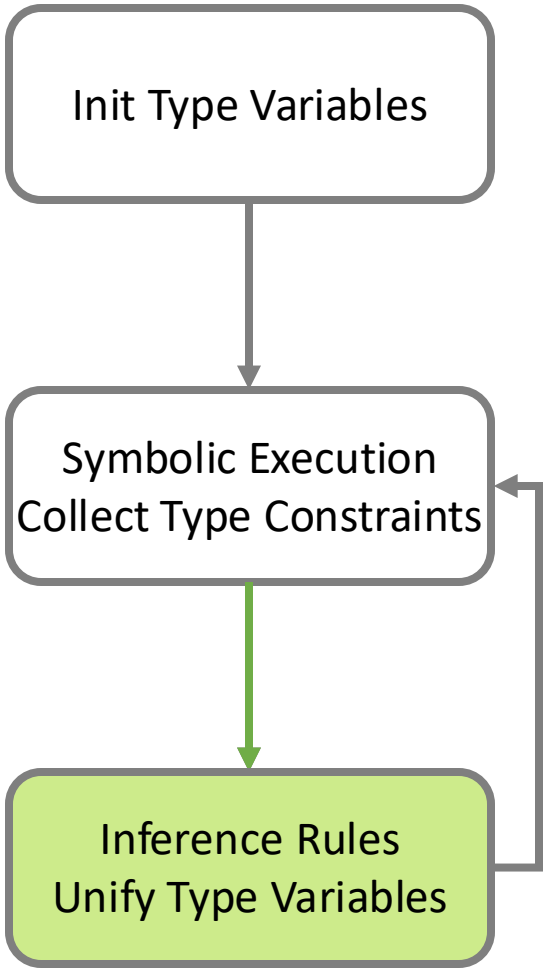
Inferred type

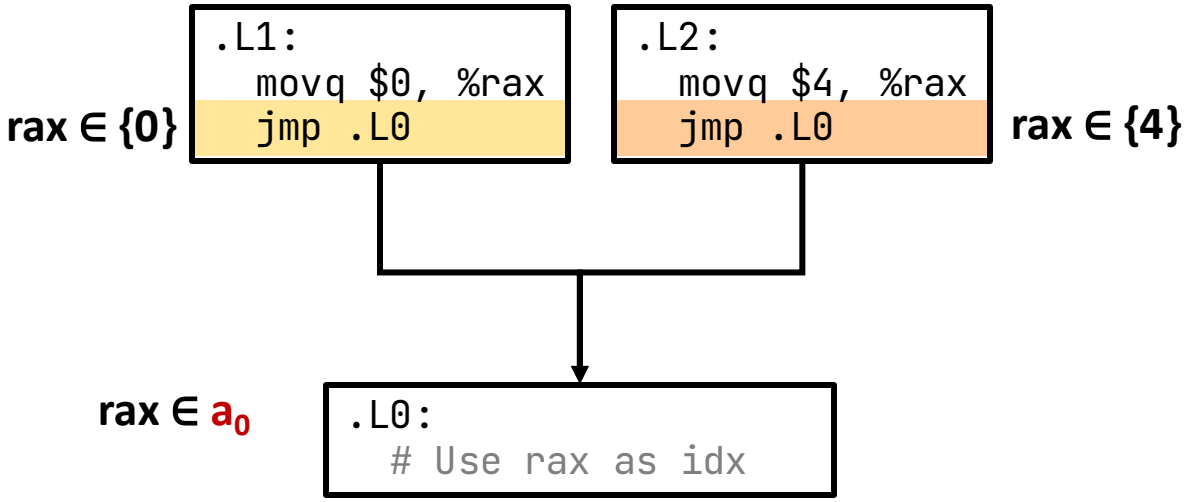
$\{0\} \subseteq a_0$
$\{4\} \subseteq a_0$
→ $a_0 = \{0, 4\}$

$\{0\} \subseteq b_0$
$\{b_0+4\} \subseteq b_0$
$b_0 < 64$
→ $b_0 = \text{range}(0, 64, \text{step}=4)$

And more inference rules…

Infer Octal Types for Cryptographic Assembly





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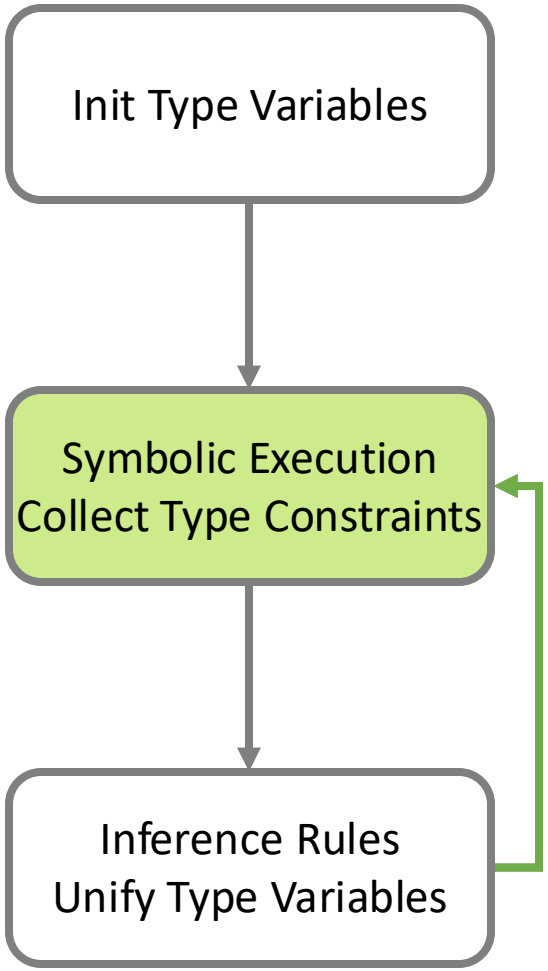
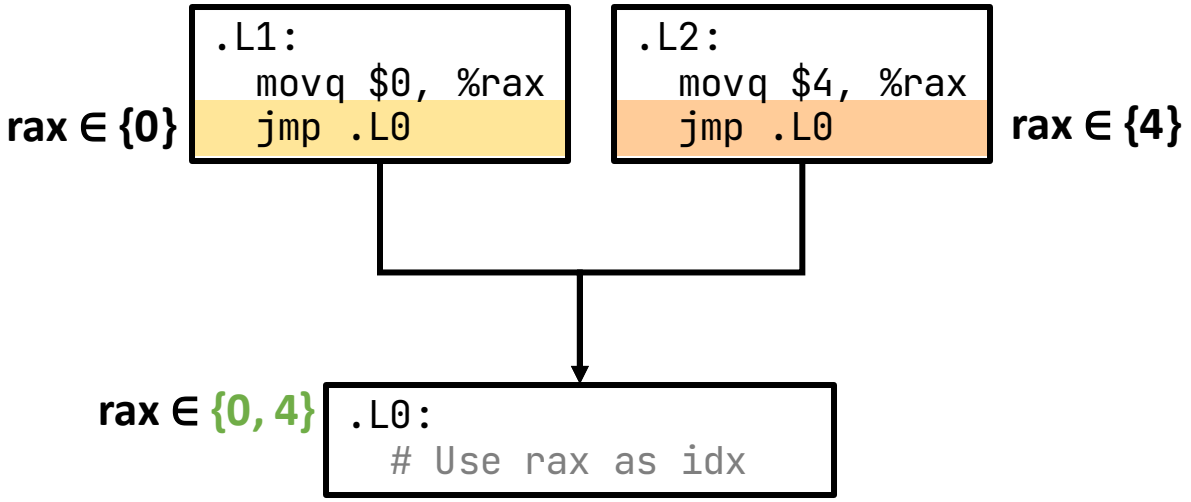
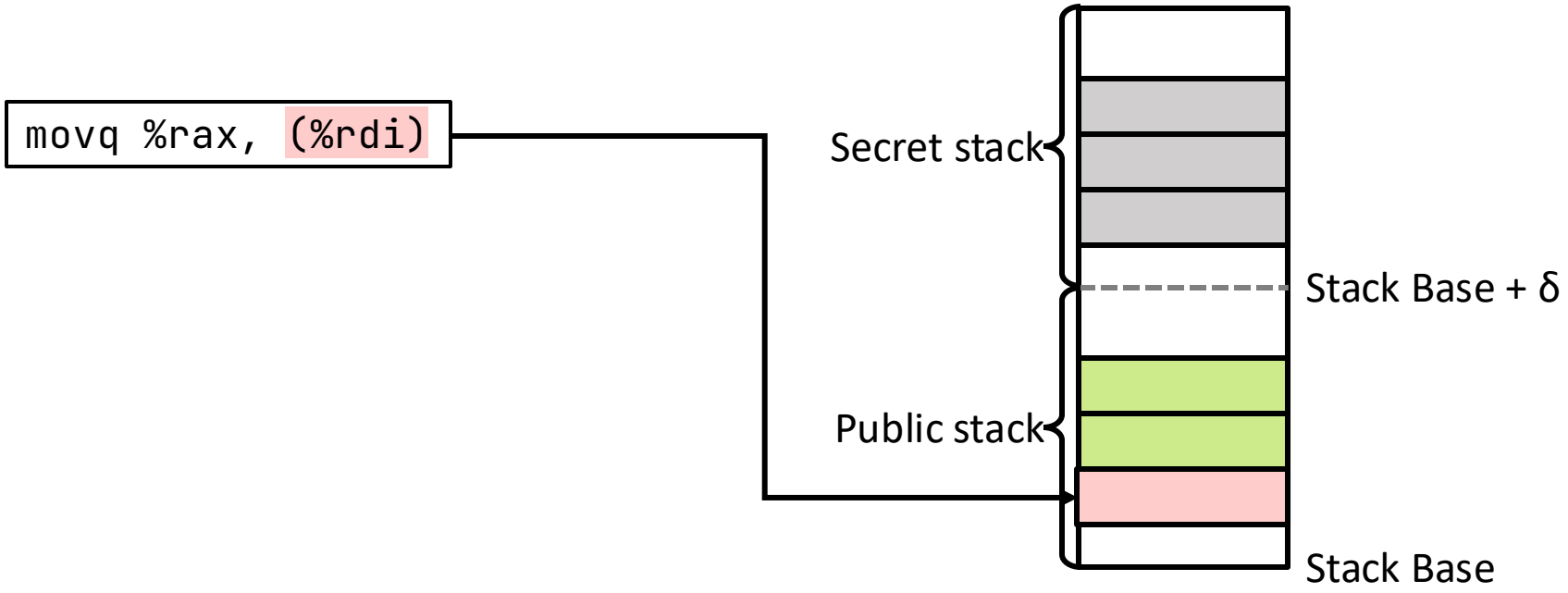


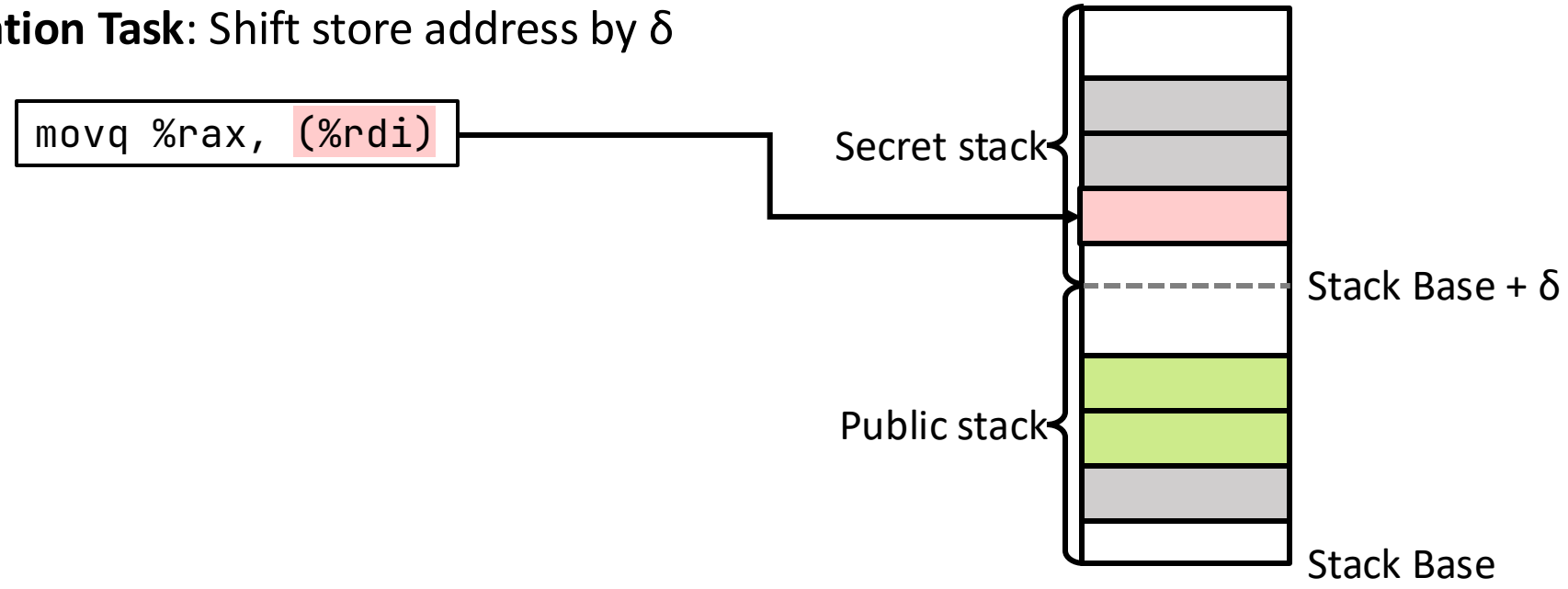


Two Transformation Strategies

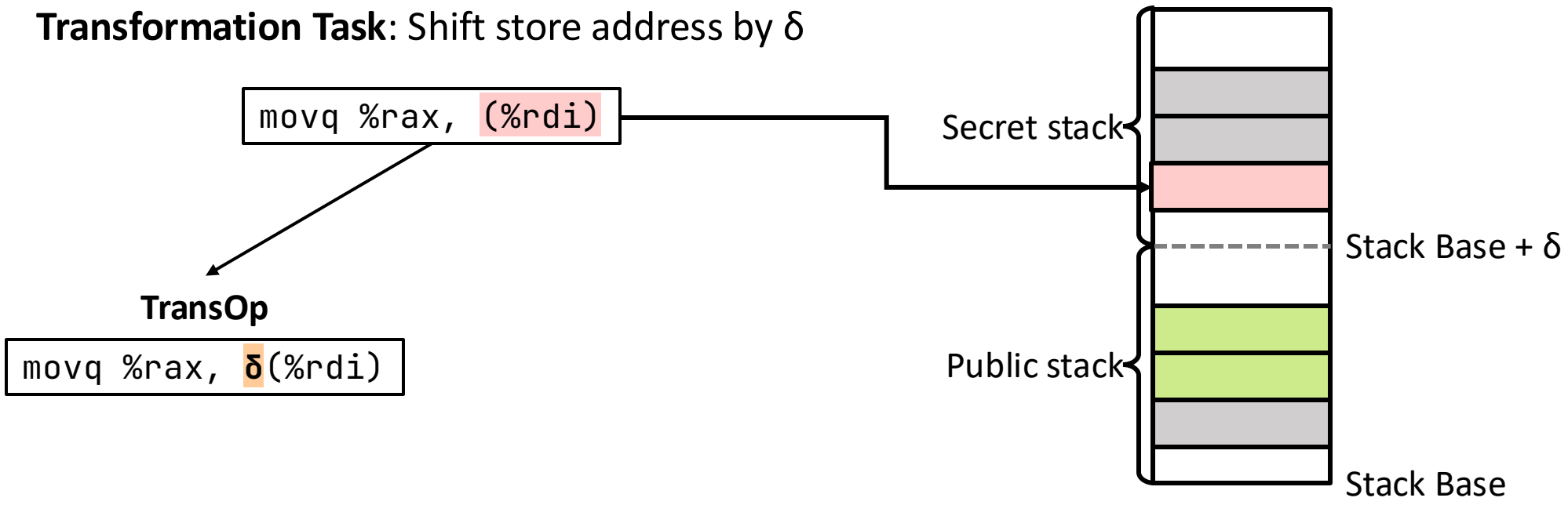


Two Transformation Strategies

Transformation Task: Shift store address by δ



Two Transformation Strategies



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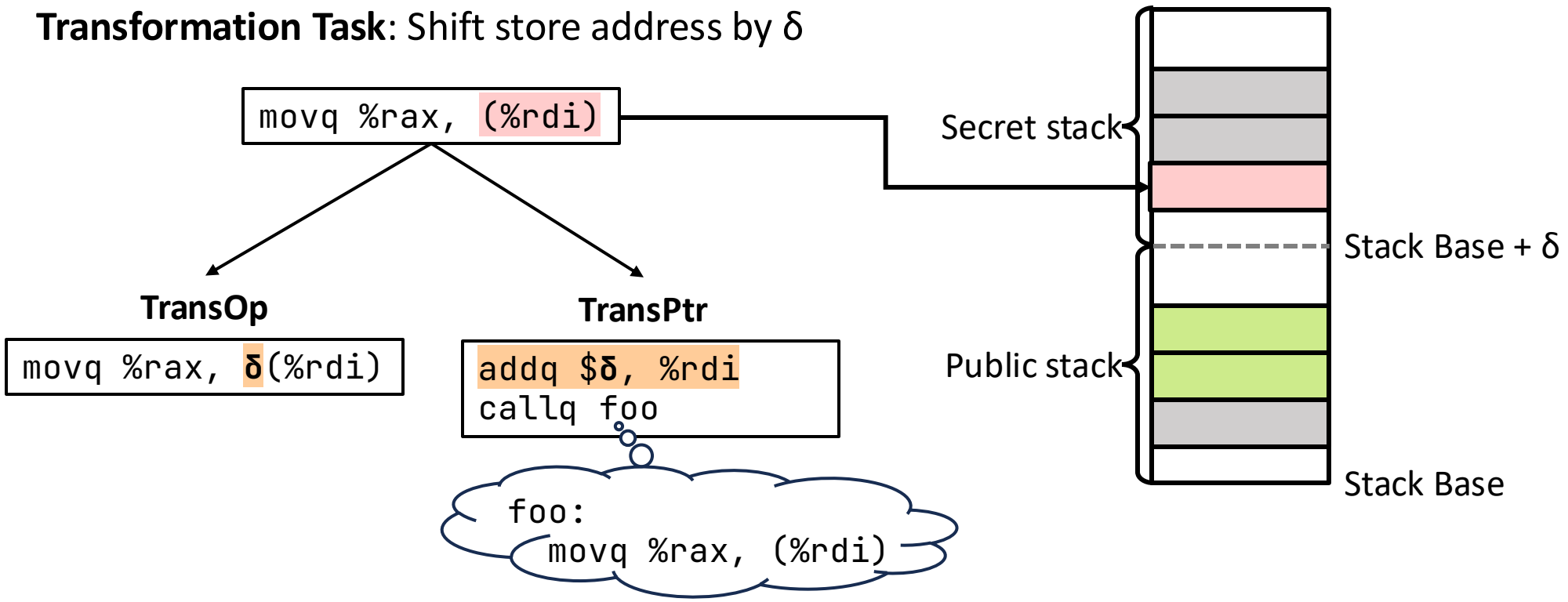

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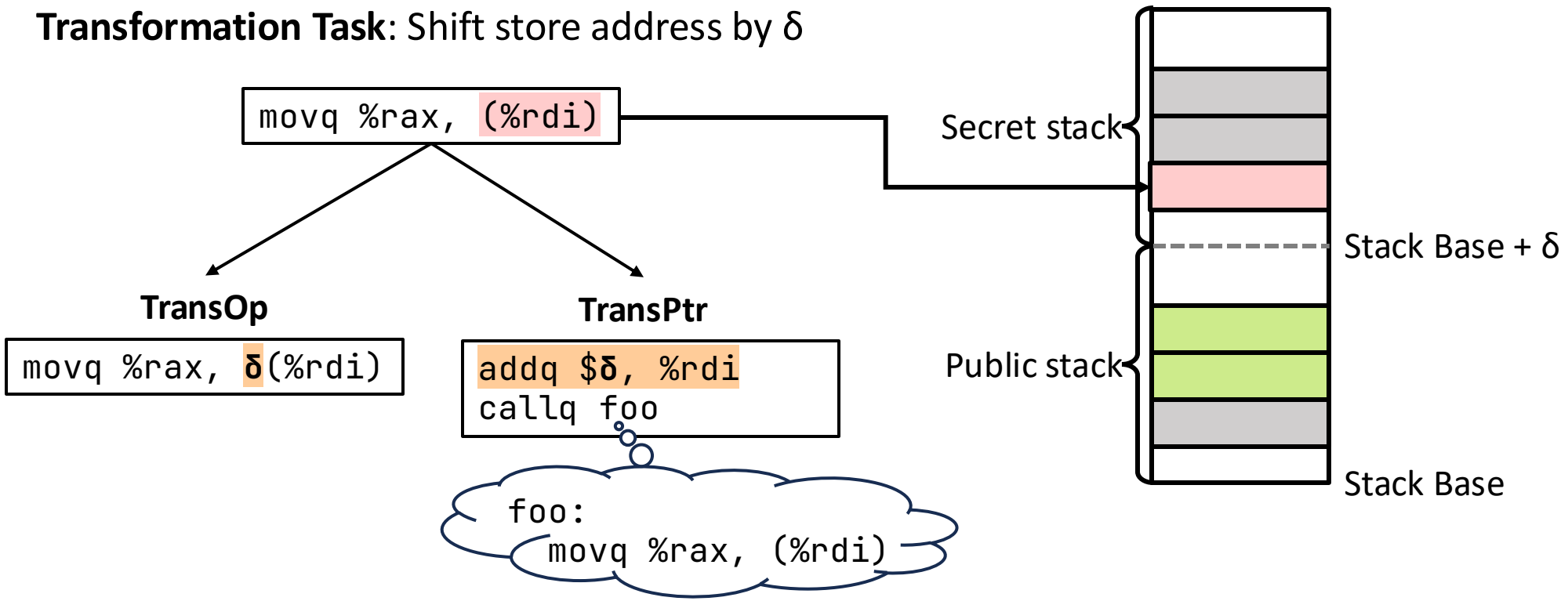

? Which transformation strategy should we use?

Two Transformation Strategies

Example 1: Pointer is a function argument

Example 2: Base pointer references secret and public data (e.g., struct)

Two Transformation Strategies

Example 1: Pointer is a function argument

`rdi`: sometimes points to **secret**, sometimes **public**

```
// memset(rdi, rsi, size)
memset:
  movb %rsi, (%rdi)
```

Example 2: Base pointer references secret and public data (e.g., struct)

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✗ **TransOp**

✓ **TransPtr** at call site

```
// At call site
  addq $δ, %rdi
  callq memset
```

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TransOp

TransPtr

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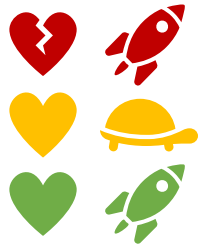
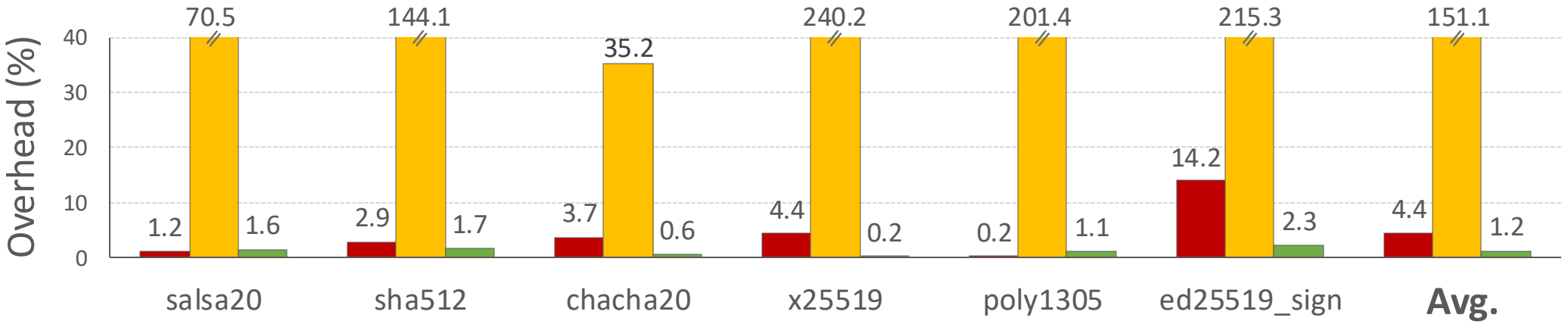
Performance Evaluation Results[1]

ProSpeCT (public stack): Compiler can spill secret data to the public stack

ProSpeCT (secret stack): Conservatively mark public stack data as secret

SecSep: Accurately separate public and secret stack data

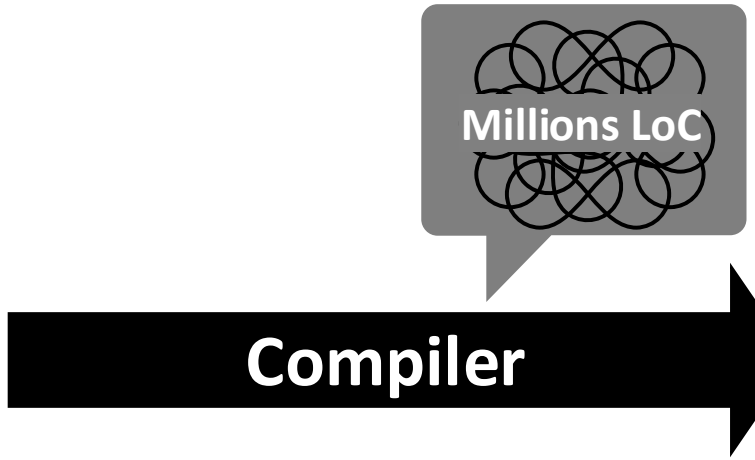




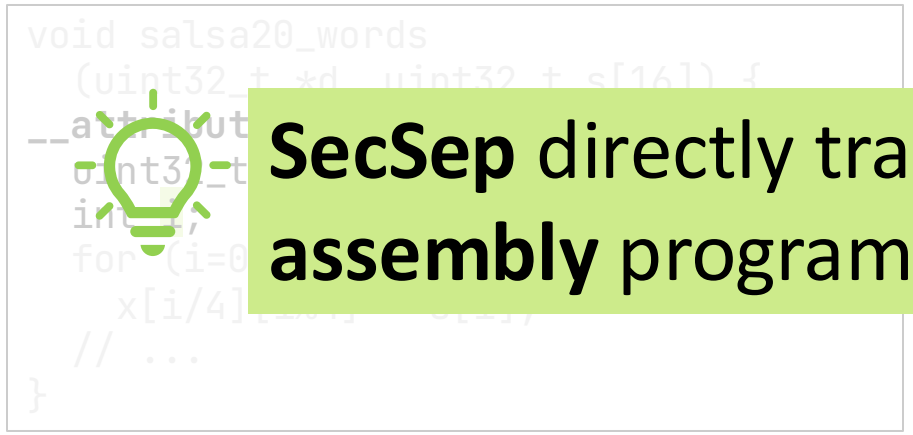
SecSep introduces a low overhead of **1.2%.**

[1] Gem5 is used to implement the CPU with defense and perform evaluation.

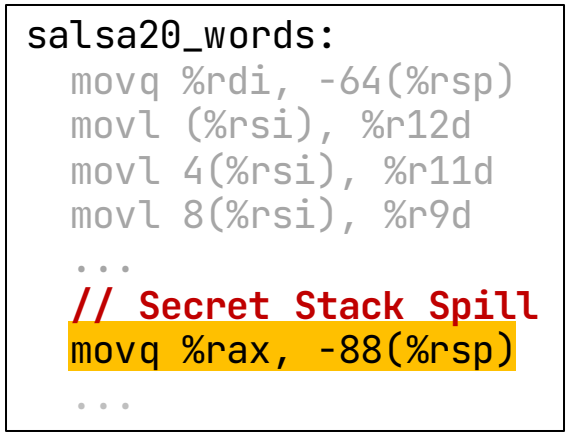
```
void salsa20_words
  (uint32_t *d, uint32_t s[16]) {
__attribute__((section("sec"))) static
  uint32_t x[4][4];
  int i;
  for (i=0; i<16; ++i)
    x[i/4][i%4] = s[i];
  // ...
}
```




```
salsa20_words:
  movq %rdi, -64(%rsp)
  movl (%rsi), %r12d
  movl 4(%rsi), %r11d
  movl 8(%rsi), %r9d
  ...
  // Secret Stack Spill
  movq %rax, -88(%rsp)
  ...
```



Millions LoC



SecSep directly transforms the compiled **assembly** program.

Accurate stack separation

Smaller TCB