Static Single Assignment Form in the COINS Compiler Infrastructure

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Background

Static single assignment (SSA) form facilitates compiler optimizations
Compiler infrastructure facilitates compiler development.

Outline

0. COINS infrastructure and the SSA form
1. Current status of optimization using SSA form in COINS infrastructure
2. A comparison of two major algorithms for translating from normal form into SSA form
3. A comparison of two major algorithms for translating back from SSA form into normal form
0. COINS infrastructure and Static Single Assignment Form (SSA Form)
COINS compiler infrastructure

- Multiple source languages
- Retargetable
- Two intermediate form, HIR and LIR
- Optimizations
- Parallelization
- C generation, source-to-source translation
- Written in Java
- 2000~ developed by Japanese institutions under Grant of the Ministry
Static Single Assignment (SSA) Form

(a) Normal (conventional) form (source program or internal form)

1: \( a = x + y \)
2: \( a = a + 3 \)
3: \( b = x + y \)

(b) SSA form

1: \( a_1 = x_0 + y_0 \)
2: \( a_2 = a_1 + 3 \)
3: \( b_1 = x_0 + y_0 \)

SSA form is a recently proposed internal representation where each use of a variable has a single definition point.

Indices are attached to variables so that their definitions become unique.
Optimization in Static Single Assignment (SSA) Form

(a) Normal form
1: \(a = x + y\)
2: \(a = a + 3\)
3: \(b = x + y\)

(b) SSA form
1: \(a_1 = x_0 + y_0\)
2: \(a_2 = a_1 + 3\)
3: \(b_1 = x_0 + y_0\)

Optimization in SSA form (common subexpression elimination)

(c) After SSA form optimization
1: \(a_1 = x_0 + y_0\)
2: \(a_2 = a_1 + 3\)
3: \(b_1 = a_1\)

(d) Optimized normal form
1: \(a_1 = x_0 + y_0\)
2: \(a_2 = a_1 + 3\)
3: \(b_1 = a_1\)

SSA form is becoming increasingly popular in compilers, since it is suited for clear handling of dataflow analysis and optimization.
Translating into SSA form (SSA translation)

(a) Normal form

L1 \( x = 1 \)

L2 \( x = 2 \)

L3 \( ... = x \)

(b) SSA form

L1 \( x1 = 1 \)

L2 \( x2 = 2 \)

L3 \( x3 = \phi (x1; L1, x2; L2) \)

\( ... = x3 \)
Translating into SSA form (SSA translation)

Minimal SSA form
- $x_1 = ...$
- $y_1 = ...$
- $z_1 = ...
- $x_3 = \phi(x_1, x_2)$
- $y_3 = \phi(y_1, y_2)$
- $z_3 = \phi(z_1, z_2)$
- $z_3 = z_3$

Semi-pruned SSA form
- $x_2 = ...$
- $y_2 = ...$
- $z_2 = ...
- $y_3 = \phi(y_1, y_2)$
- $z_3 = \phi(z_1, z_2)$
- $z_3 = z_3$

Pruned SSA form
- $x_2 = ...$
- $y_2 = ...$
- $z_2 = ...
- $z_3 = \phi(z_1, z_2)$
- $z_3 = z_3$

Normal form
- $x = ...
- $y = ...
- $z = ...
- $y = y_1$
- $z = z_3$
Translating back from SSA form
(SSA back translation)

(a) SSA form

(b) Normal form
1. SSA form module in the COINS compiler infrastructure
SSA optimization module in COINS

Source program

Low level Intermediate Representation (LIR)

LIR to SSA translation (3 variations)

LIR in SSA

SSA basic optimization
- com subexp elimination
- copy propagation
- cond const propagation
- dead code elimination

Optimized LIR in SSA

SSA to LIR back translation (2 variations) + 2 coalescing

transformation on SSA
- copy folding
- dead phi elimination
- edge splitting

12,000 lines
Outline of SSA module in COINS

- Translation into and back from SSA form on Low Level Intermediate Representation (LIR)
  - SSA translation: Use dominance frontier [Cytron et al. 91]
  - SSA back translation: [Sreedhar et al. 99]
  - Basic optimization on SSA form: dead code elimination, copy propagation, common subexpression elimination, conditional constant propagation

- Useful transformation as an infrastructure for SSA form optimization
  - Copy folding at SSA translation time, critical edge removal on control flow graph …
  - Each variation and transformation can be made selectively

- Preliminary result
  - 1.43 times faster than COINS w/o optimization
  - 1.25 times faster than gcc w/o optimization
2. A comparison of two major algorithms for SSA translation

- Algorithm by Cytron [1991] Dominance frontier
- Algorithm by Sreedhar [1995] DJ-graph

Comparison made to decide the algorithm to be included in COINS
Translating into SSA form (SSA translation)

(a) Normal form

L3

... = x

L1

x = 1

L2

x = 2

(b) SSA form

L3

x3 = \phi (x1:L1, x2:L2)

... = x3

L1

x1 = 1

L2

x2 = 2
Usual programs

The gap is due to the garbage collection.
Peculiar programs

(a) nested loop

(b) ladder graph
Nested loop programs

![Graph showing translation time (milli sec) vs. No. of nodes of control flow graph for Cytron and Sreedhar. The graph indicates a linear relationship between the number of nodes and translation time for both programs. The Cytron data is represented by blue diamonds, and the Sreedhar data is represented by purple squares.](image-url)
Ladder graph programs

Translation time (milli sec)

No. of nodes of control flow graph

Cytron
Sreedhar
3. A comparison of two major algorithms for SSA back translation

- Algorithm by Briggs [1998]
  Insert copy statements
- Algorithm by Sreedhar [1999]
  Eliminate interference

There have been no studies of comparison
Comparison made on COINS
Translating back from SSA form
(SSA back translation)

(a) SSA form

L1: \( x_1 = 1 \)
L2: \( x_2 = 2 \)
L3: \( x_3 = \phi (x_1; L_1, x_2; L_2) \)
\( \ldots = x_3 \)

(b) Normal form

L1: \( x_1 = 1 \)
L2: \( x_3 = x_1 \)
L3: \( x_2 = 2 \)
\( x_3 = x_2 \)

L3: \( \ldots = x_3 \)
Problems of naïve SSA back translation
(lost copy problem)

Copy propagation
Back translation by naïve method

not correct
To remedy these problems...
(i) SSA back translation algorithm by Briggs

(a) SSA form

(b) normal form after back translation
(ii) SSA back translation algorithm by Sreedhar

(a) SSA form

```
block1
  x0 = 1

block2
  x1 = \phi (x0, x2)
  x2 = 2

block3
  return x1
```

(b) eliminating interference

```
block1
  x0 = 1

block2
  x1' = \phi (x0, x2)
  x1 = x1'
  x2 = 2

block3
  return x1
```

(c) normal form after back translation

```
A = 1

{x0, x1', x2} \rightarrow A
```

live range of \(x_0 \ x_1 \ x_2\)

live range of \(x_0 \ x_1' \ x_2\)

live range of \(x_0 \ x_1' \ x_2\)

{\{x0, x1', x2\} \rightarrow A}
## Empirical comparison of SSA back translation

No. of copies (no. of copies in loops)

<table>
<thead>
<tr>
<th></th>
<th>SSA form</th>
<th>Briggs</th>
<th>Briggs + Coalescing</th>
<th>Sreedhar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lost copy</td>
<td>0</td>
<td>3</td>
<td>1 (1)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>Simple ordering</td>
<td>0</td>
<td>5</td>
<td>2 (2)</td>
<td>2 (2)</td>
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<tr>
<td>Swap</td>
<td>0</td>
<td>7</td>
<td>5 (5)</td>
<td>3 (3)</td>
</tr>
<tr>
<td>Swap-lost</td>
<td>0</td>
<td>10</td>
<td>7 (7)</td>
<td>4 (4)</td>
</tr>
<tr>
<td>do</td>
<td>0</td>
<td>9</td>
<td>6 (4)</td>
<td>4 (2)</td>
</tr>
<tr>
<td>fib</td>
<td>0</td>
<td>4</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>GCD</td>
<td>0</td>
<td>9</td>
<td>5 (2)</td>
<td>5 (2)</td>
</tr>
<tr>
<td>Selection Sort</td>
<td>0</td>
<td>9</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Hige Swap</td>
<td>0</td>
<td>8</td>
<td>3 (3)</td>
<td>4 (4)</td>
</tr>
</tbody>
</table>
Previous work:

SSA form in compiler infrastructure

- SUIF (Stanford Univ.): no SSA form
- machine SUIF (Harvard Univ.): only one optimization in SSA form
- Scale (Univ. Massachusetts): a couple of SSA form optimizations. But it generates only C programs, and cannot generate machine code like in COINS.
- GCC: some attempts but experimental

Only COINS will have full support of SSA form as a compiler infrastructure
Summary

• SSA form module of the COINS infrastructure
• Empirical comparison of algorithms for SSA translation gave criterion to make a good choice
• Empirical comparison of algorithms for SSA back translation clarified there is no single algorithm which gives optimal result

Hope COINS and its SSA module help the compiler writer to compare/evaluate/add optimization methods