Strict Sequential Constructiveness

Alexander Schulz-Rosengarten
Reinhard von Hanxleden, Michael Mendler

Why restricting sequential constructiveness?

Motivation: Program P10

```
1  module P10
2  int x, y;
3  {
4    y = 0;                  //S1
5    fork
6      x = 1;                //S2
7      y = x                 //S3
8    par
9      if y == 0 then        //S4
10       x = 0               //S5
11     end
12   join
13 }
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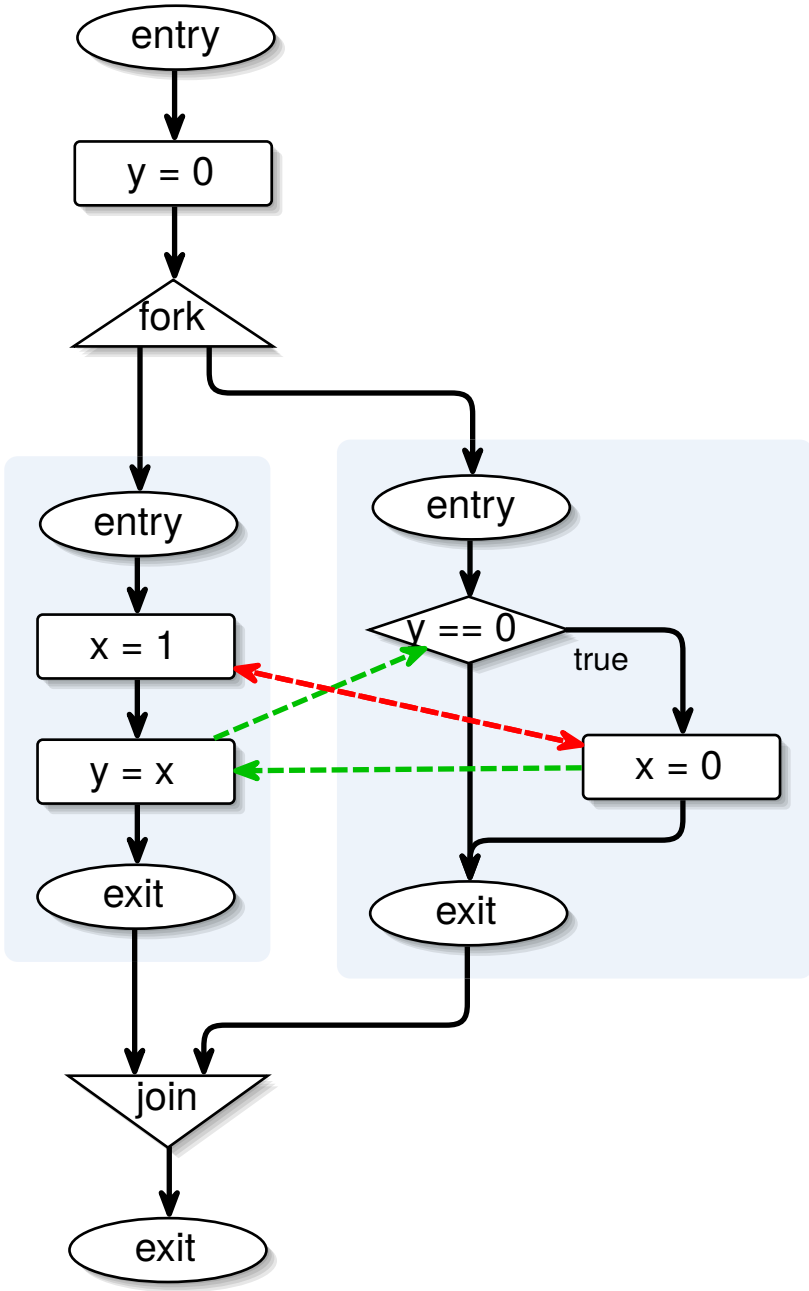

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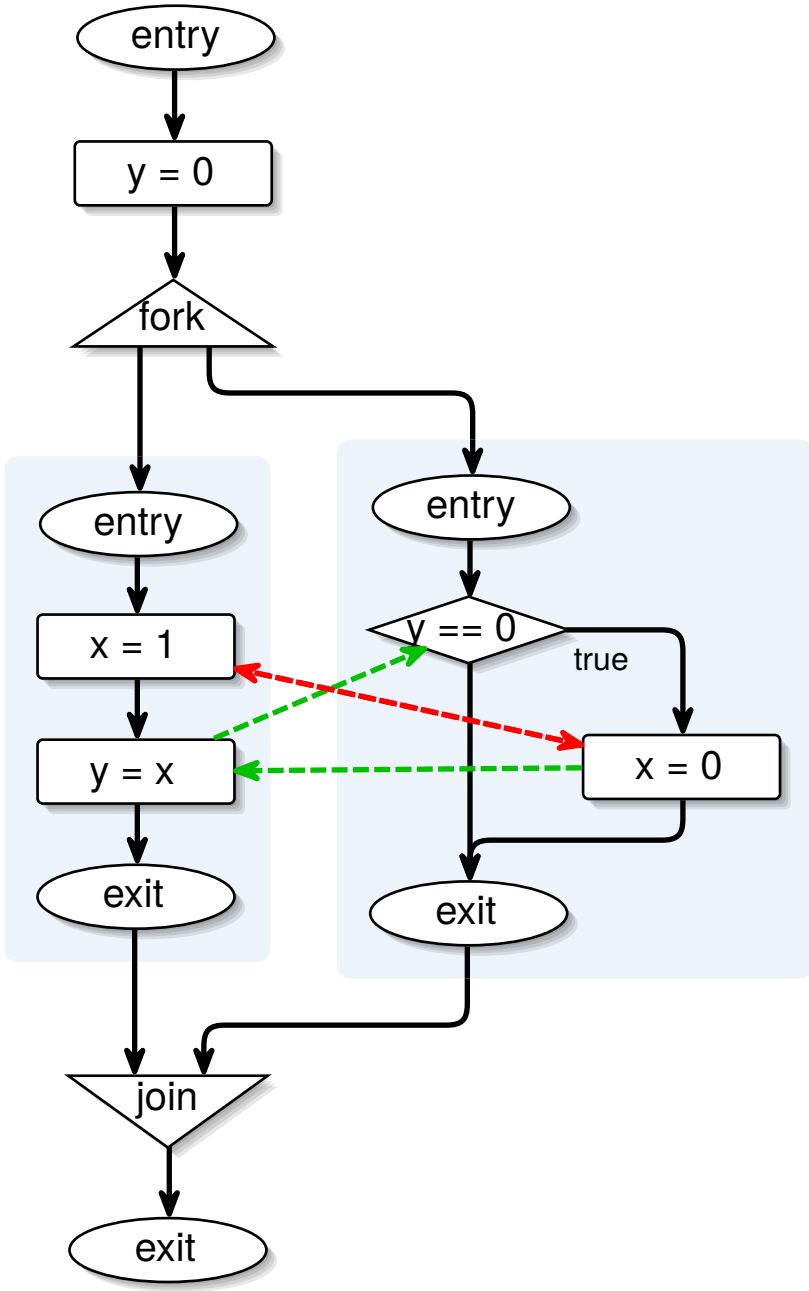
SC-admissible Schedule

S1 — S2 — S3 — S4



Problem

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- is reactive ($\exists$ SC-admissible Run)

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- but is executed in a speculative manner

YOU SHALL NOT

SPECULATE!

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Problem

The SC MoC allows speculation
$\Rightarrow$ SC programs may form non-constructive (delay sensitive) circuits

Restricting Sequential Constructiveness

Strict Sequential Constructiveness
is
Sequential Constructiveness without speculation

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How can we eliminate speculation?

Restricting Sequential Constructiveness

Idea

Ground SC in constructiveness in the spirit of Esterel

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Constructive Esterel:

- has no speculation

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- requires globally consistent signal states

Restricting Sequential Constructiveness

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Ground SC in constructiveness in the spirit of Esterel

Constructive Esterel:

- has no speculation
- always transforms into delay-insensitive (constructive) circuits

but

- requires globally consistent signal states
- has no shared variables (write & read)

Concept

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1. Transformation into SSA form

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   - sequential variable behavior

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   - iur protocol

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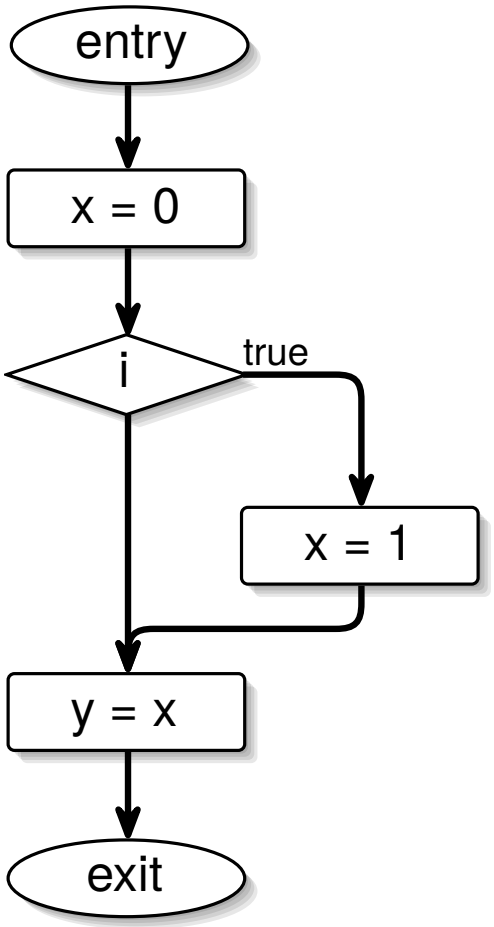
3. Esterel constructiveness check

Static Single Assignment Form



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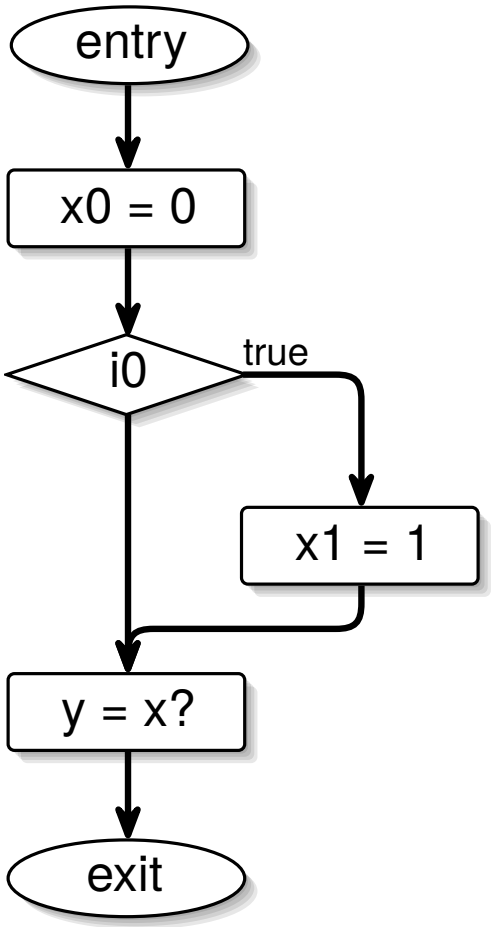

Procedure

1. Split up variables into versions

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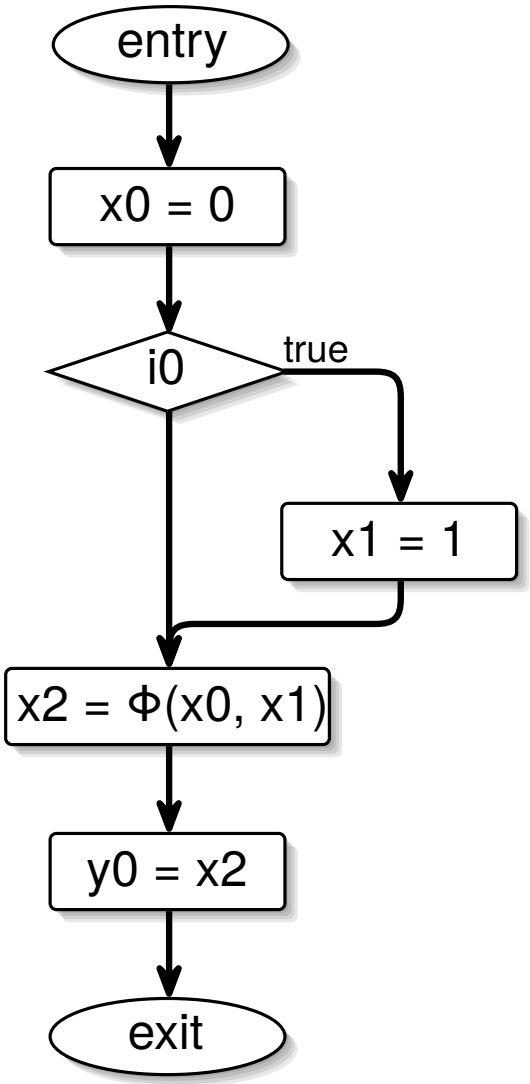

Procedure

1. Split up variables into versions
2. Introduce ϕ-functions to merge variable versions

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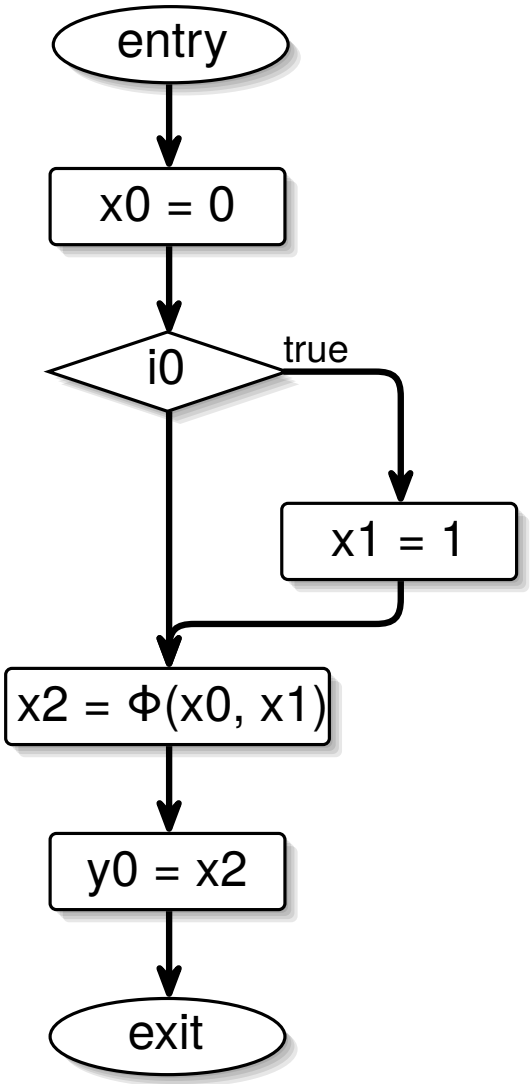

- Each variable is assigned only once (statically)

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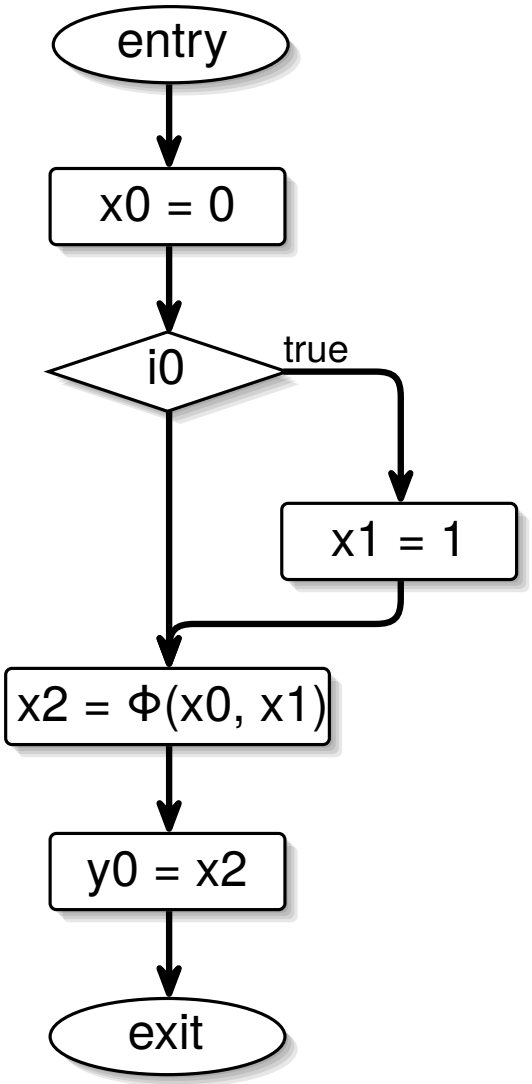

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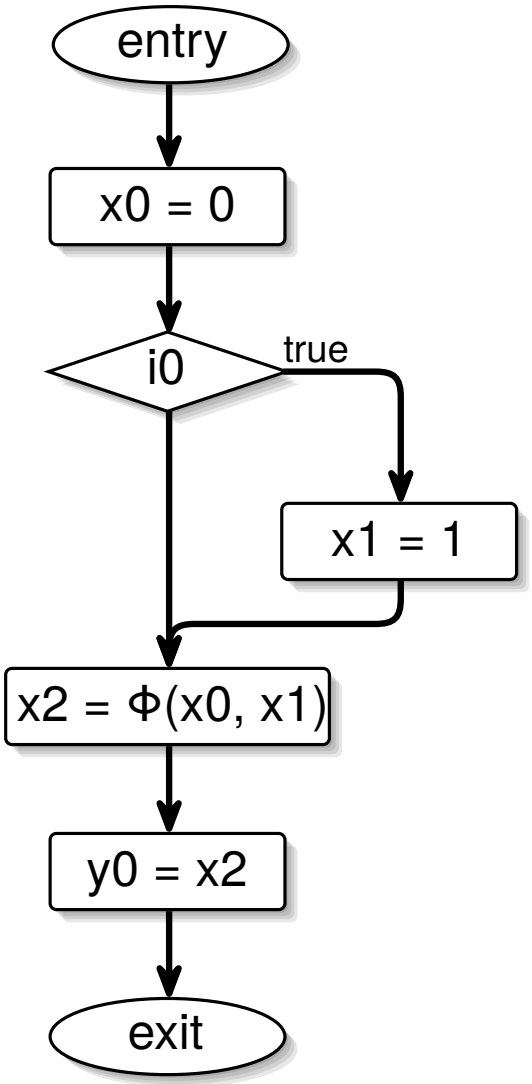

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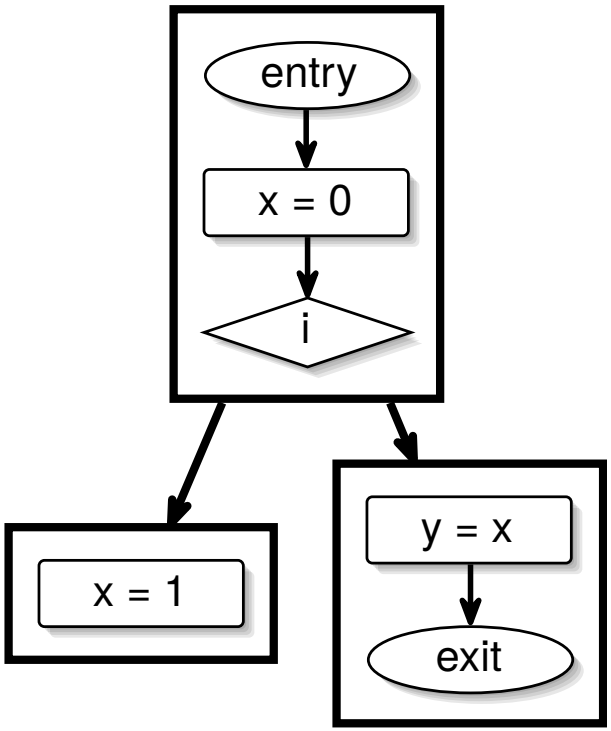

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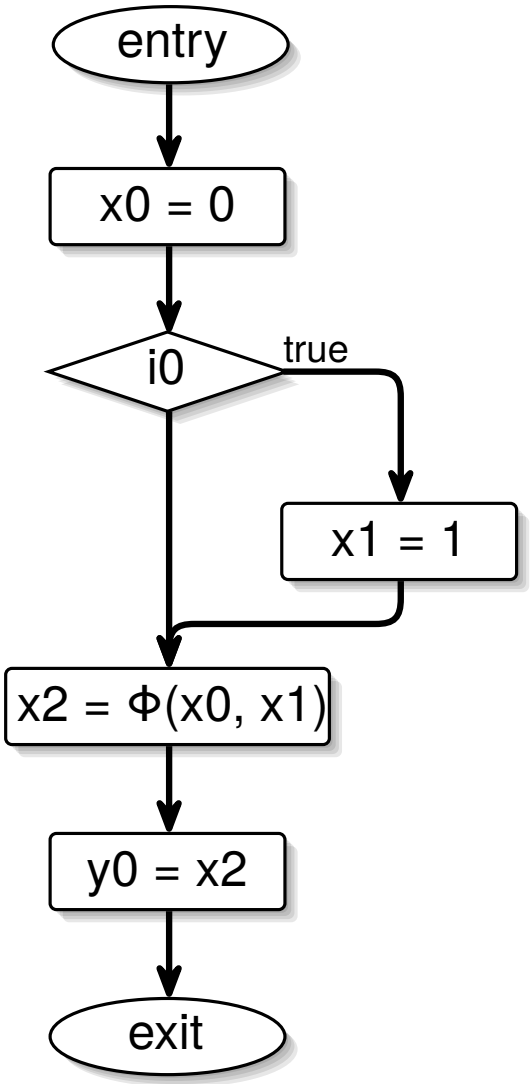

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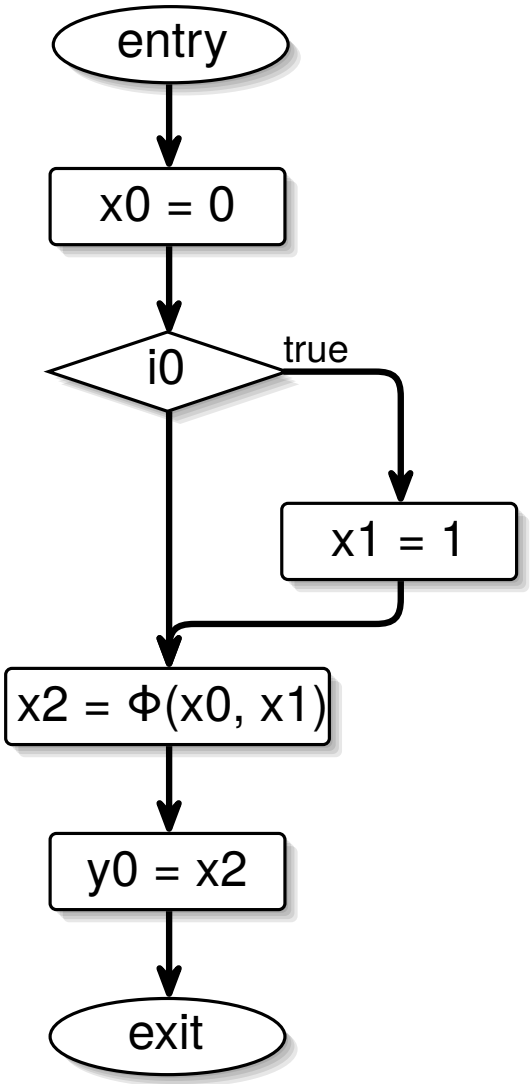

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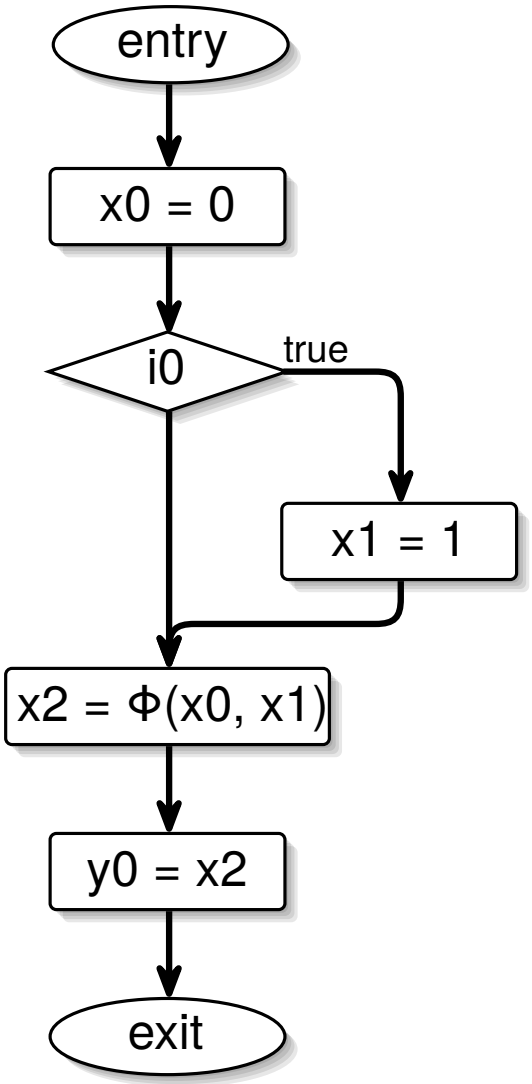

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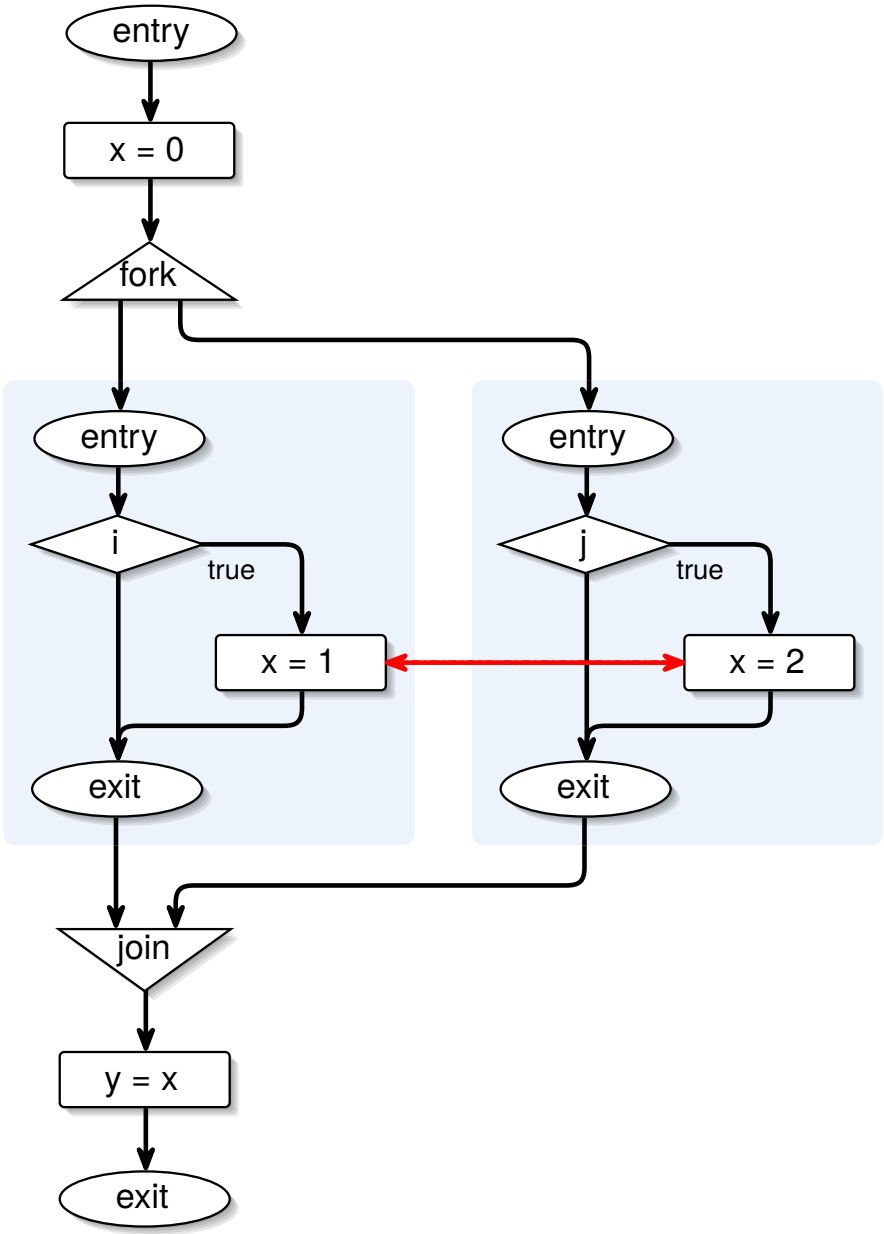
What about SCGs with concurrency?

Static Single Assignment Form with Concurrency



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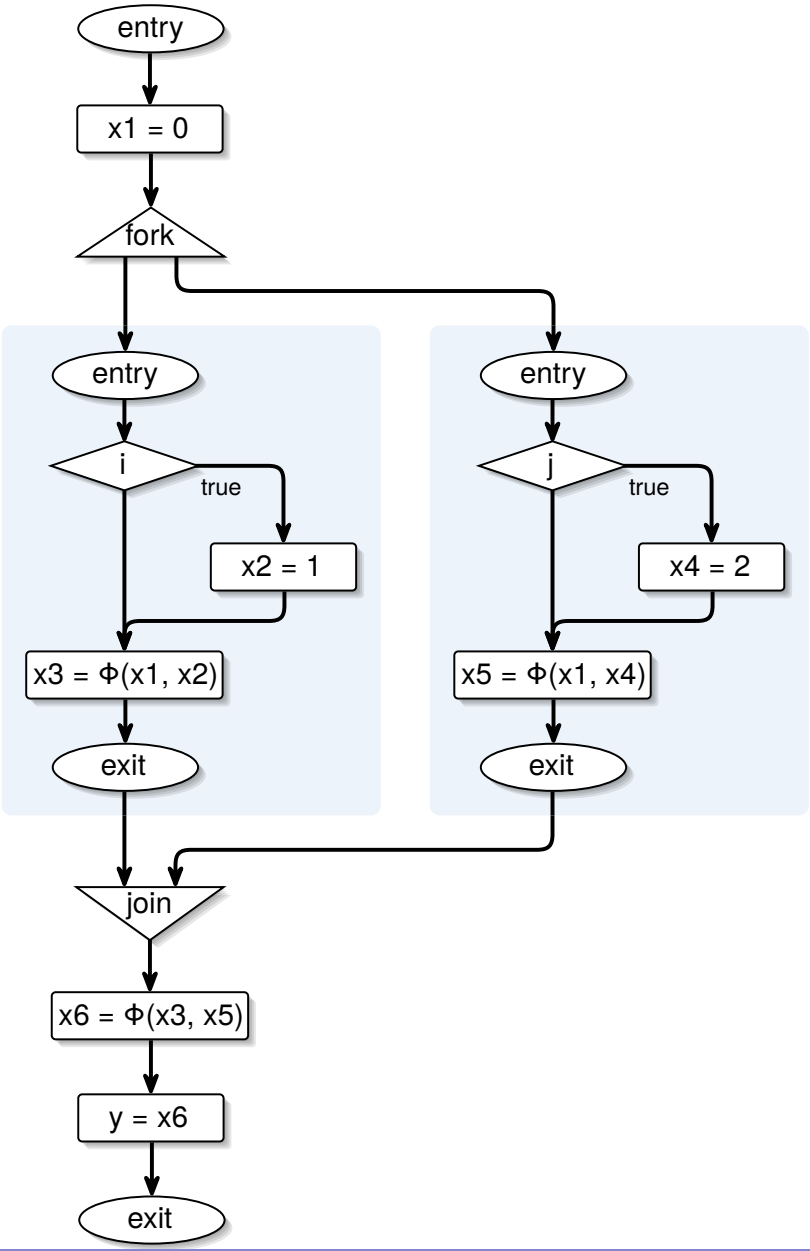

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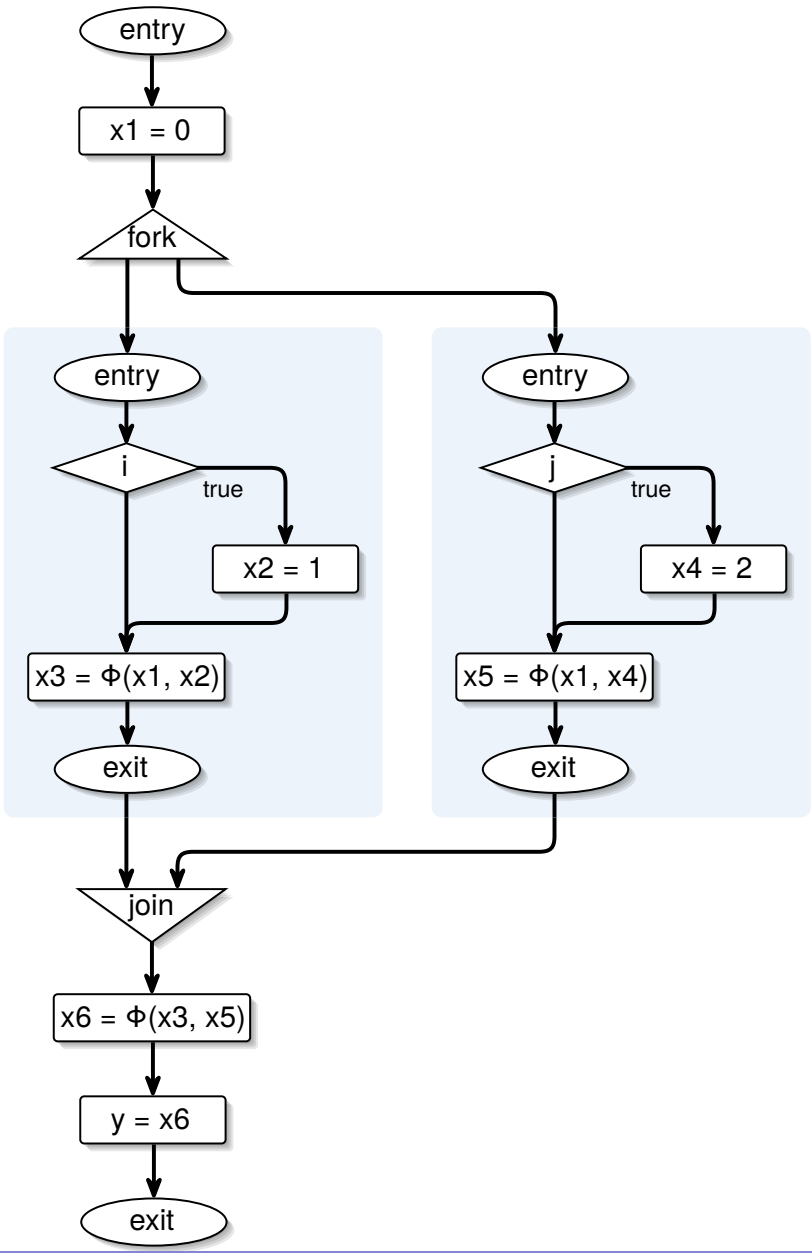

Problem

ϕ-functions cannot handle concurrency

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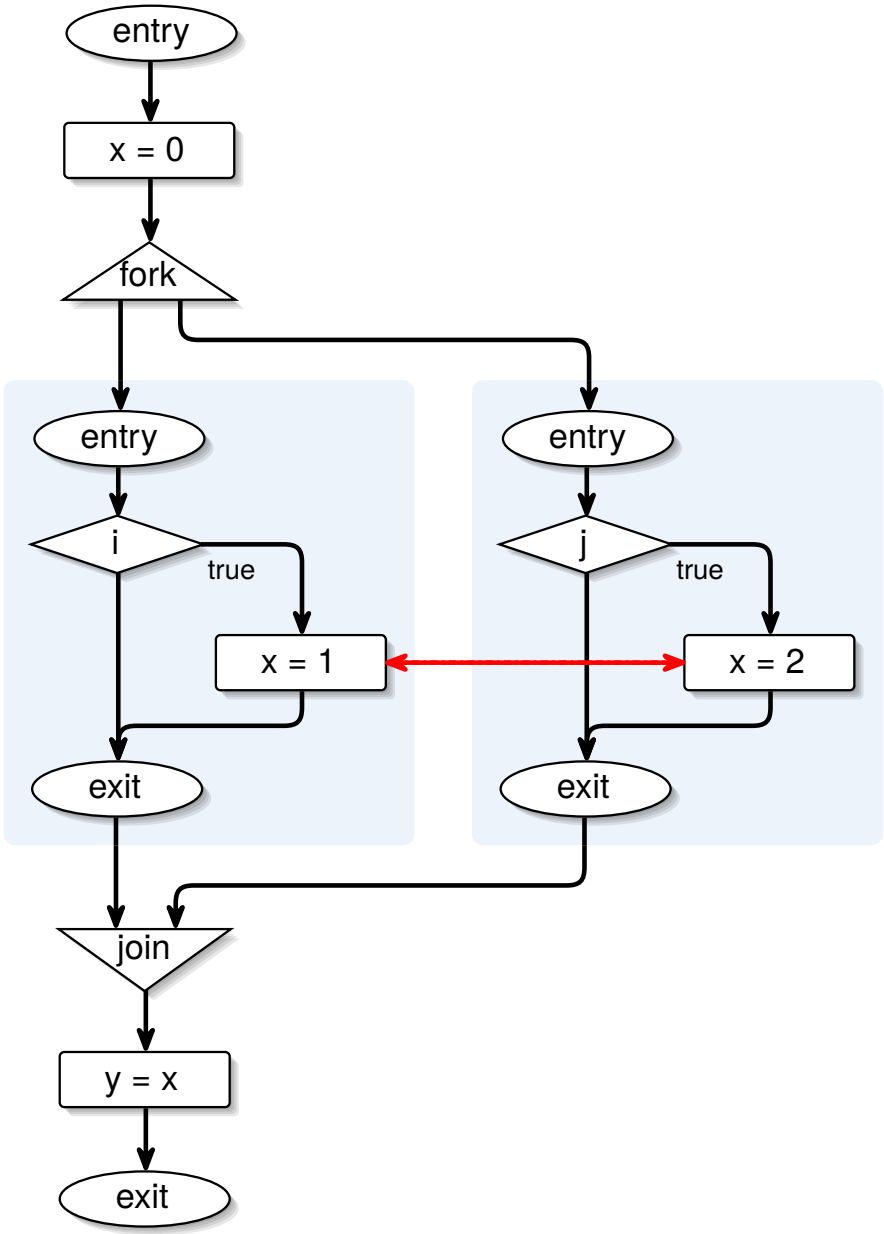

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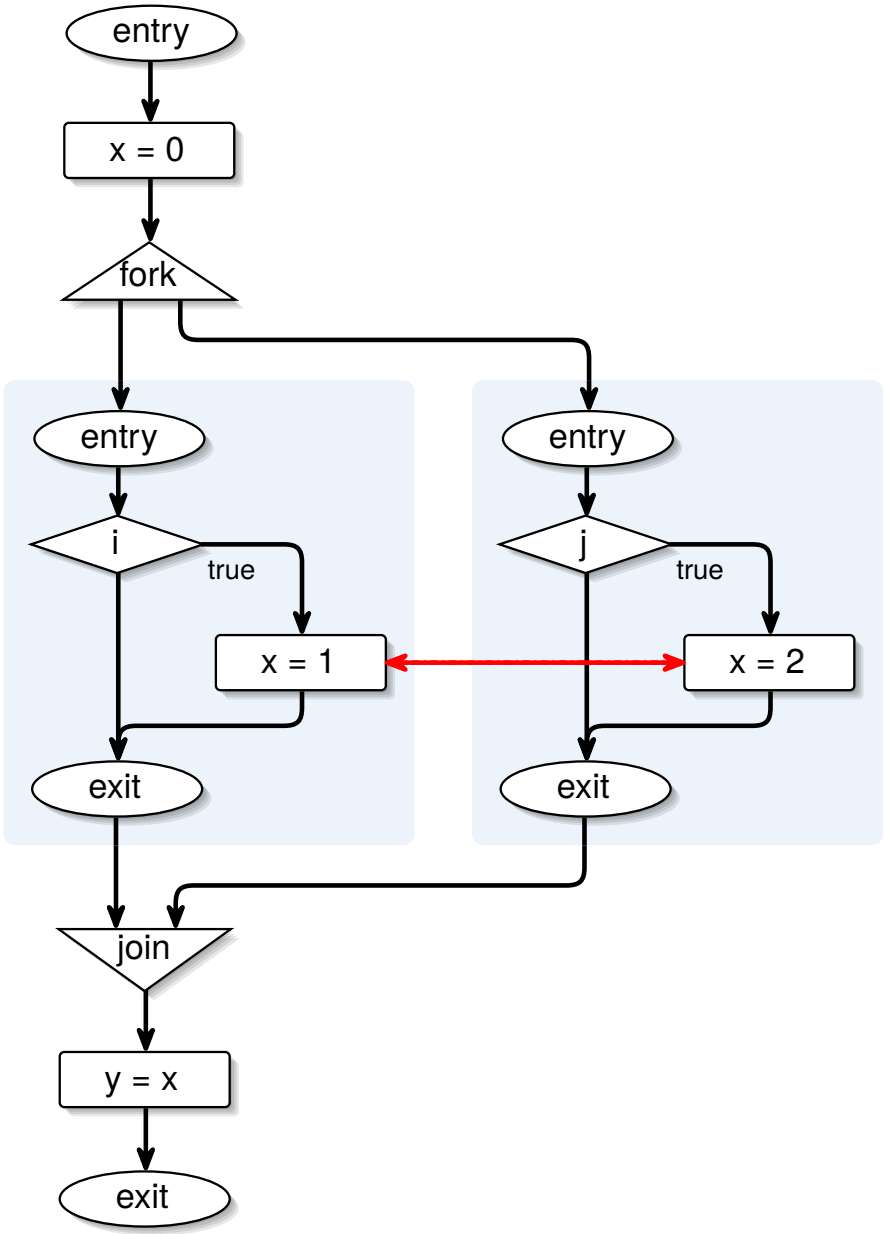

i	j	y
false	false	
false	true	
true	false	
true	true	

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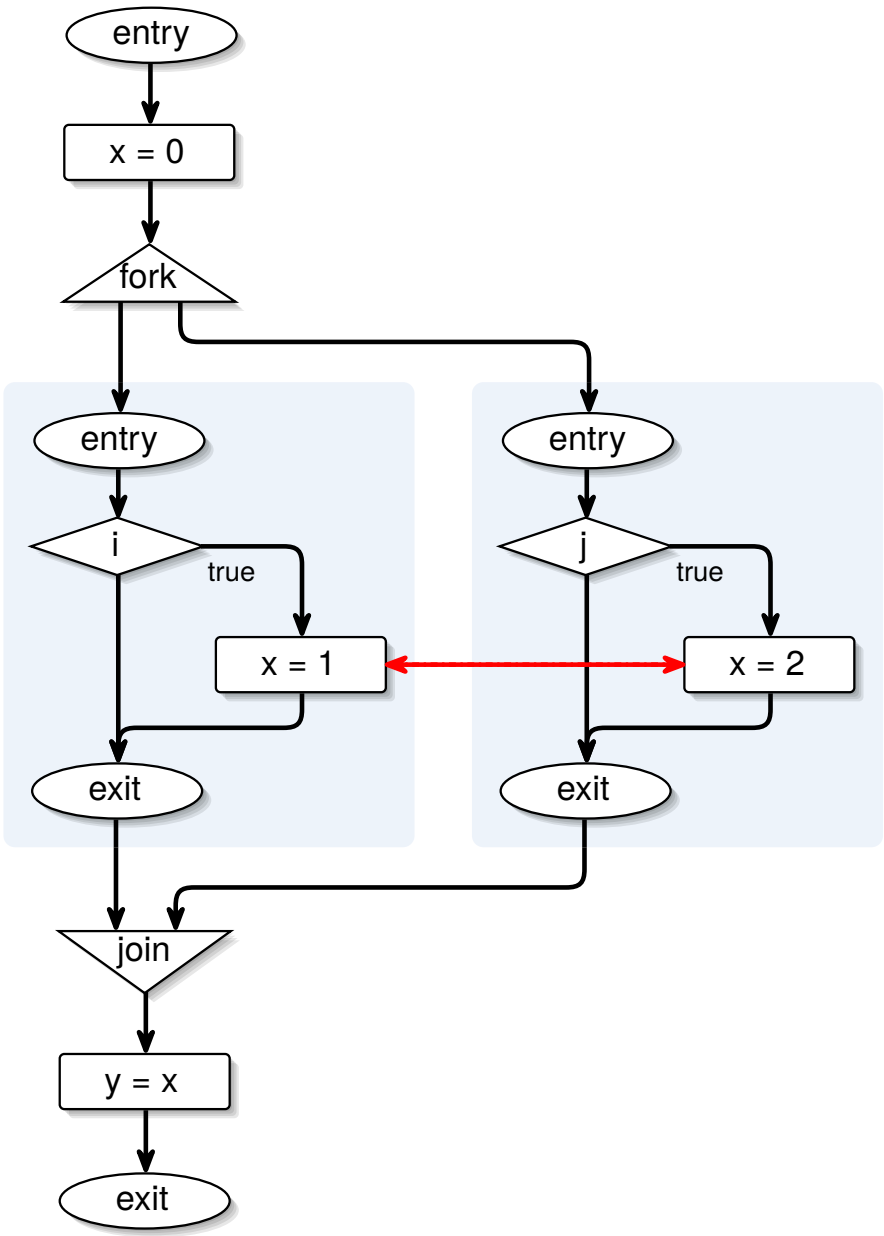

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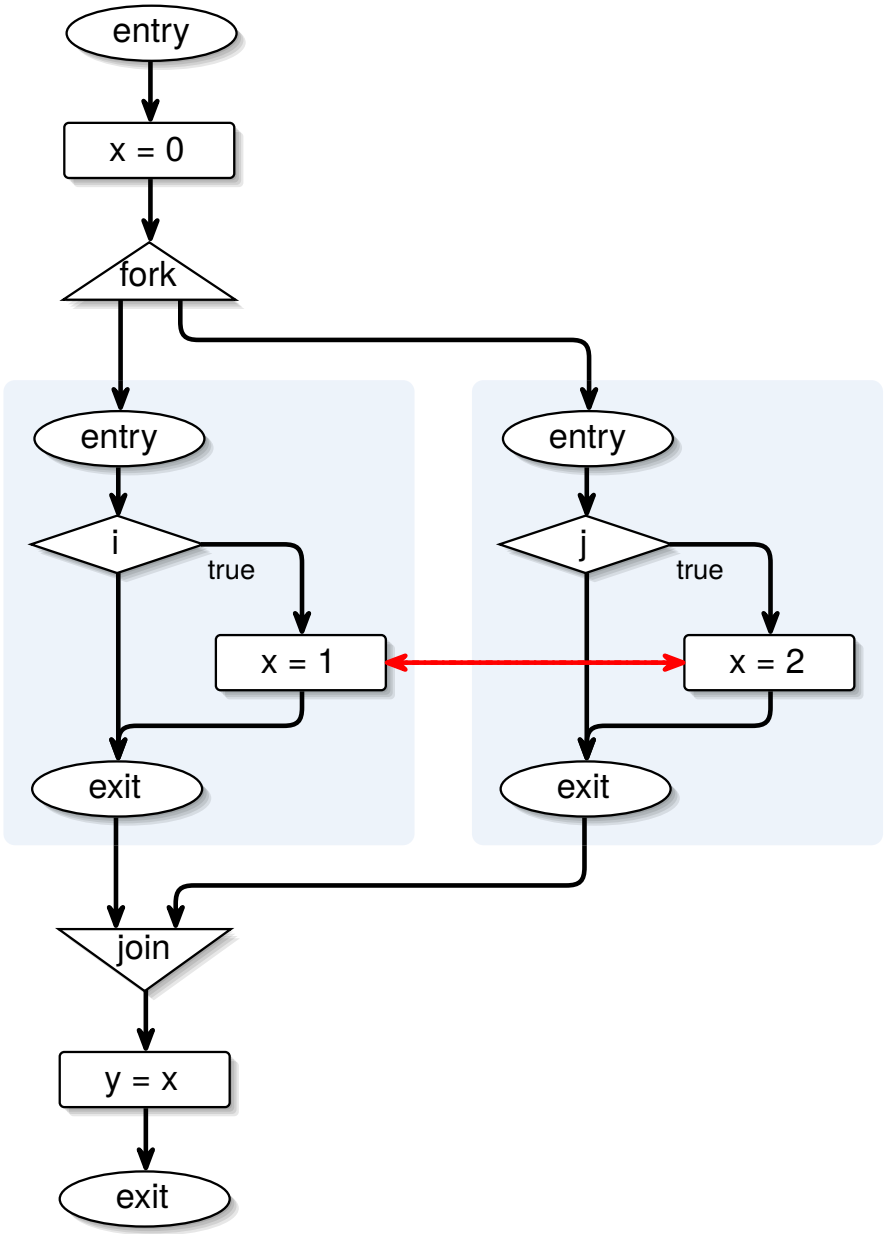

i	j	y
false	false	0
false	true	2
true	false	
true	true	

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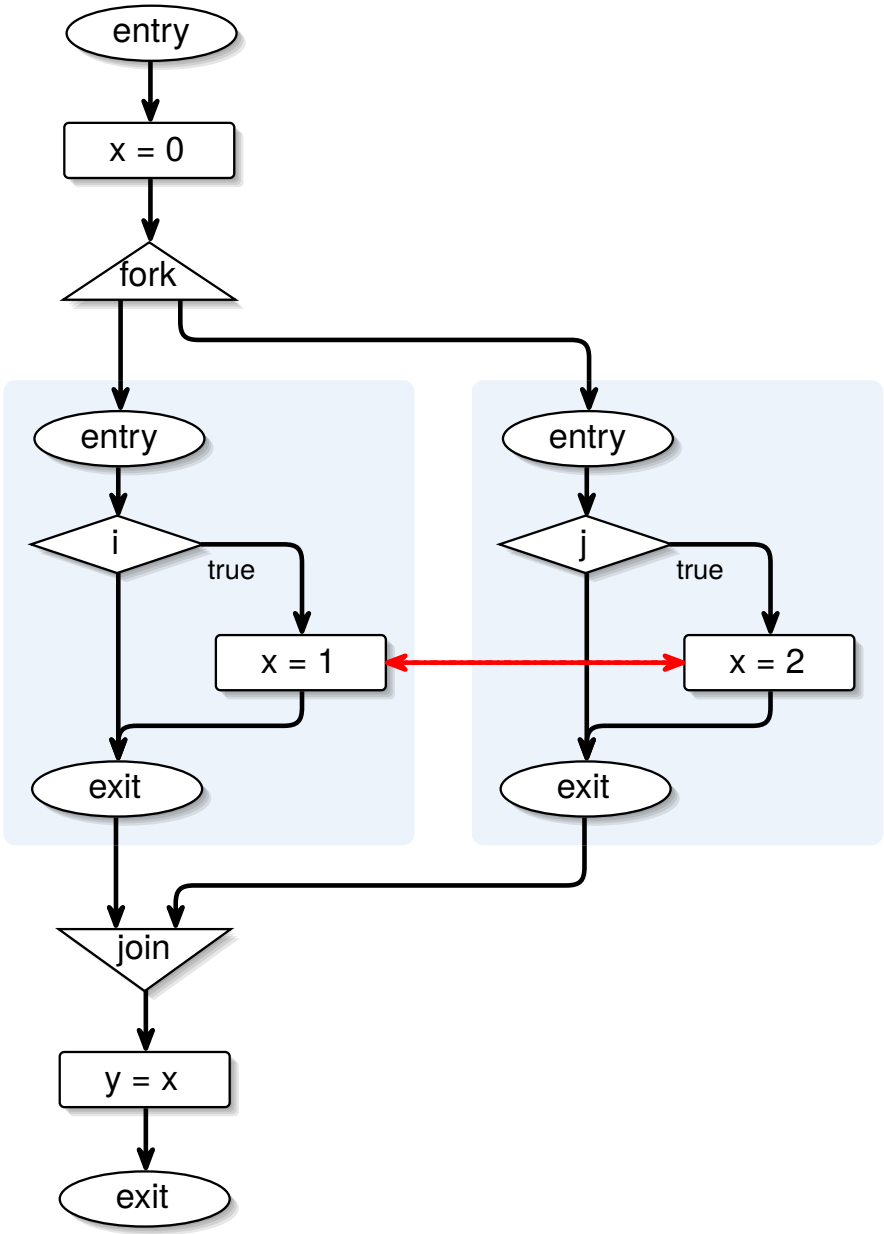

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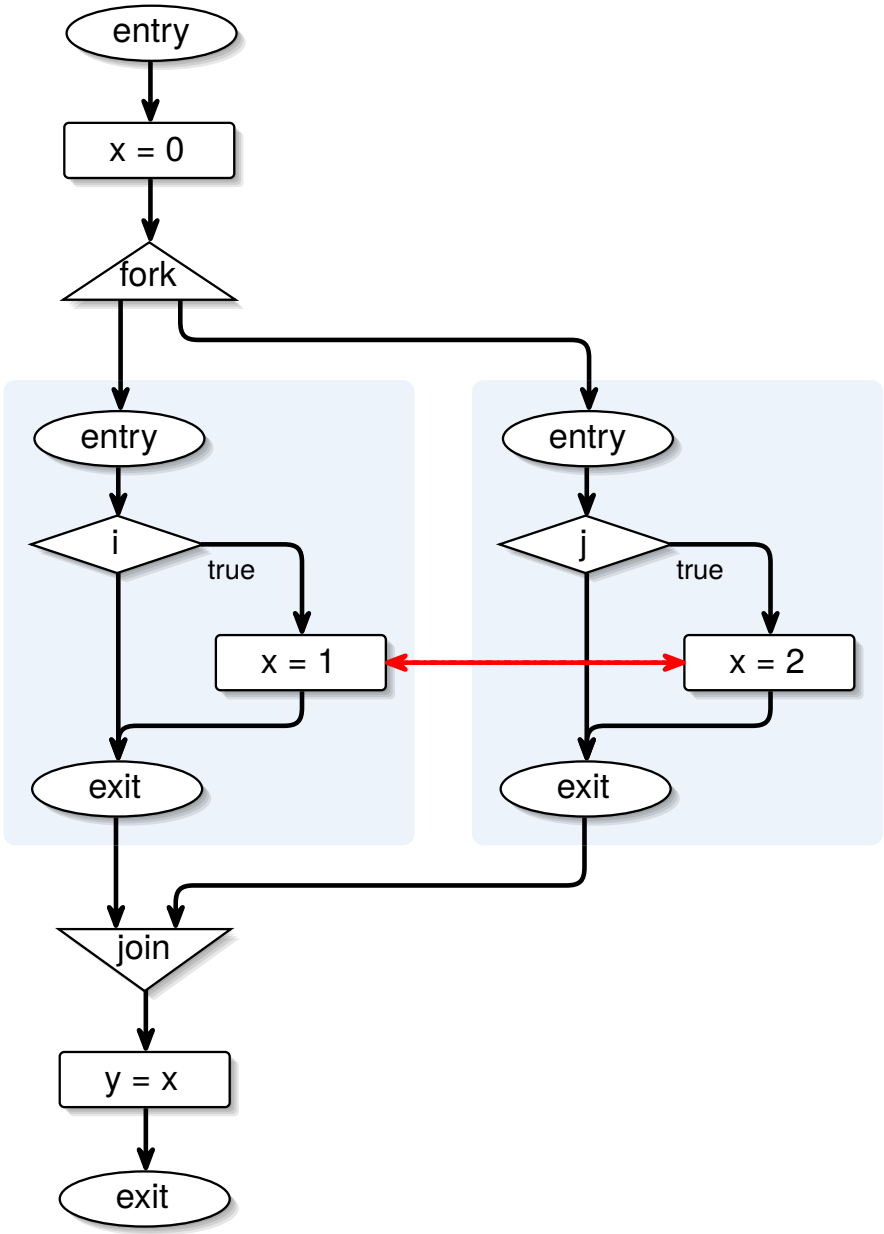

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Static Single Assignment Form for SC Programs

SC-specific merge functions:

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Inspired by valued signals.

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2 ‖   present x_j^p then
3 ‖     return ⟨x_j^p, x_j⟩
4 ‖   else
5 ‖     present x_i^p then
6 ‖       return ⟨x_i^p, x_i⟩
7 ‖     else
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2    present x_i^p then
3      present x_j^p then
4        if x_i == x_j then
5          return ⟨x_i^p, x_i⟩
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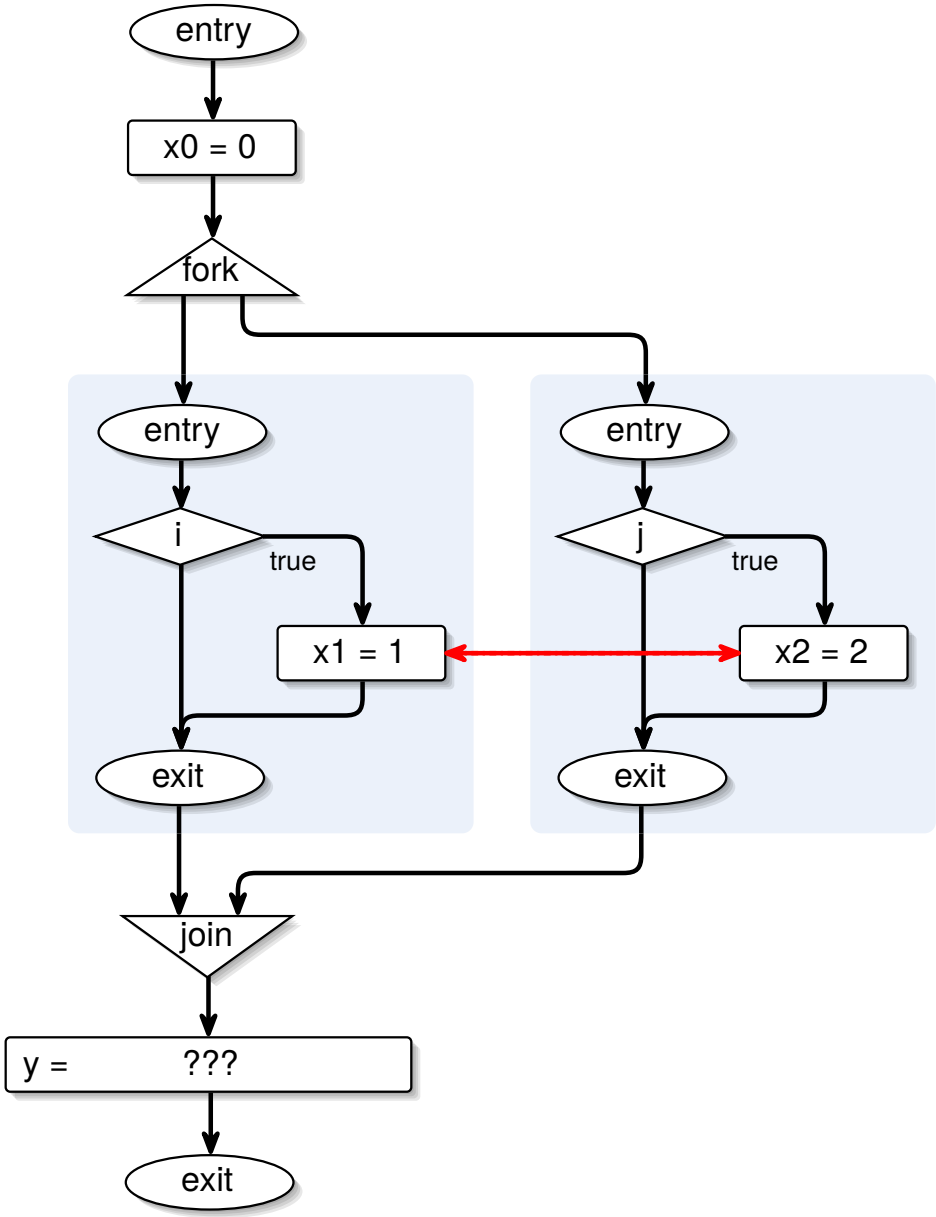

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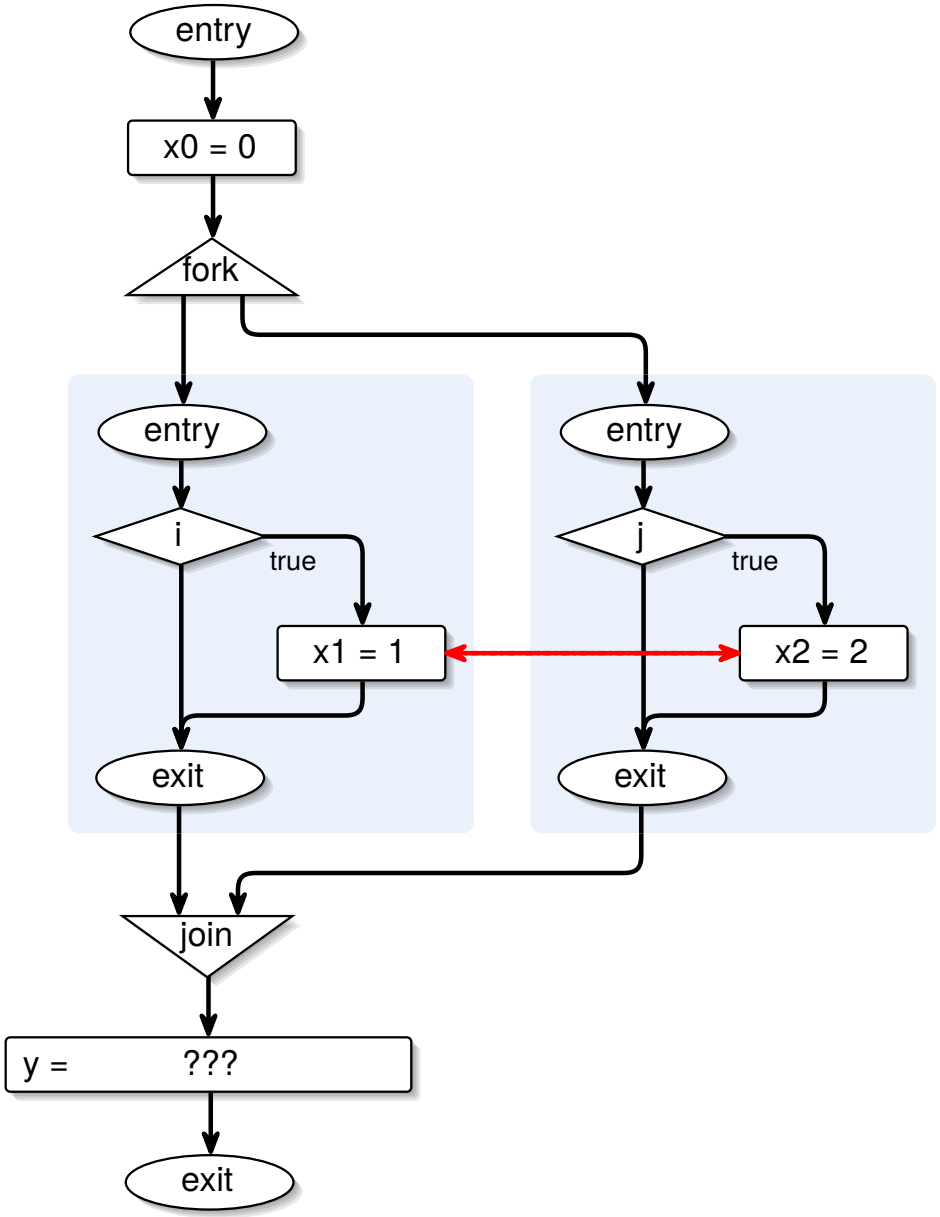

$\texttt{seq}(x_0,$

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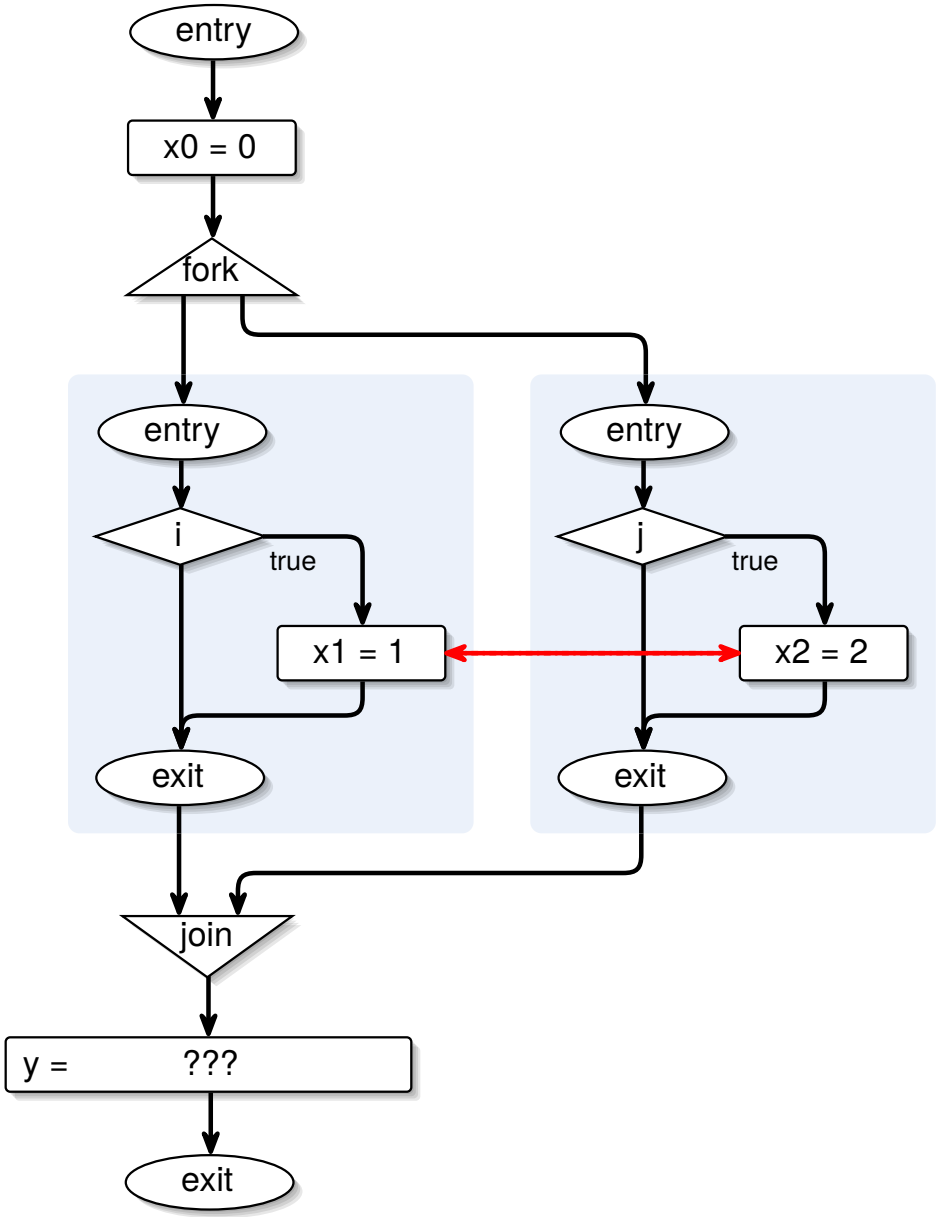

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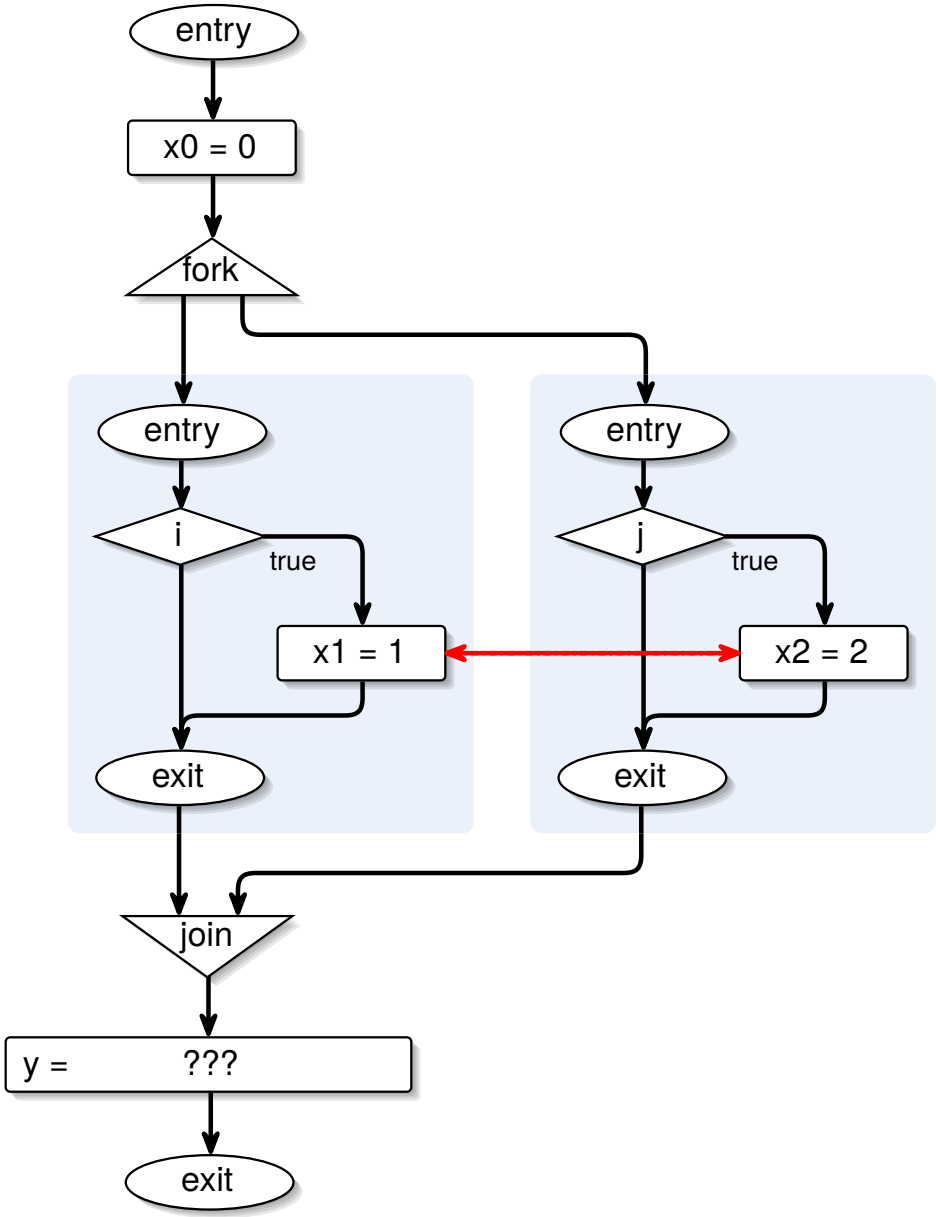

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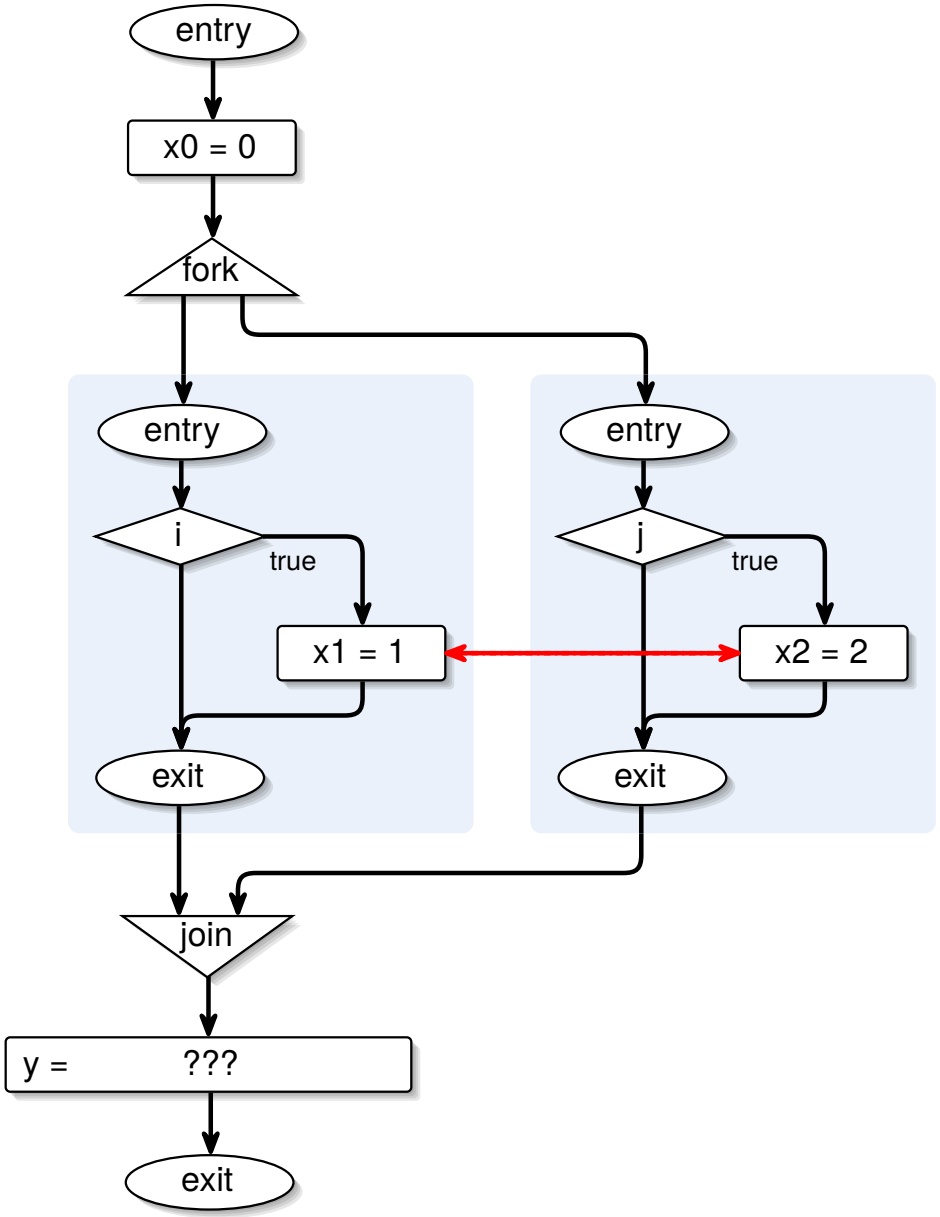

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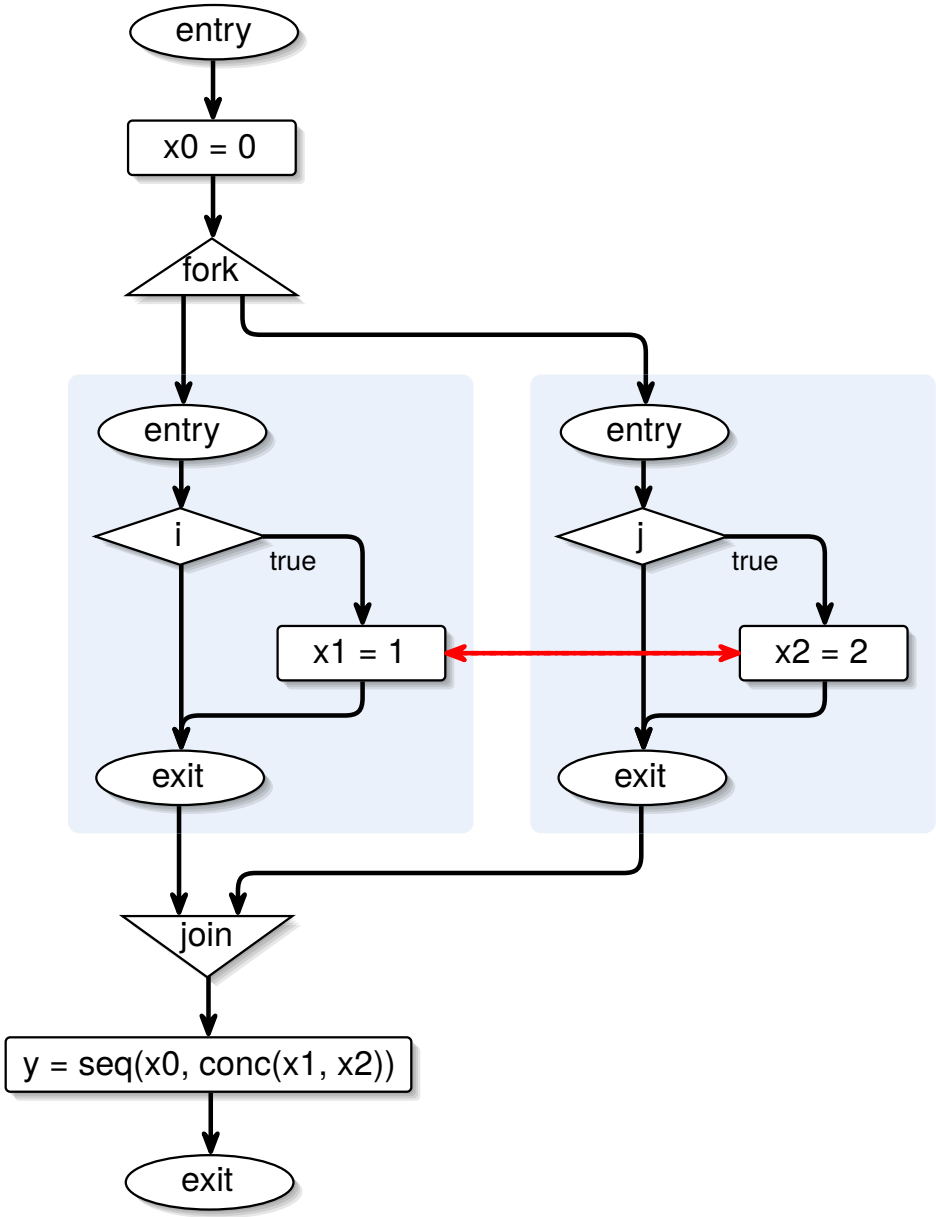

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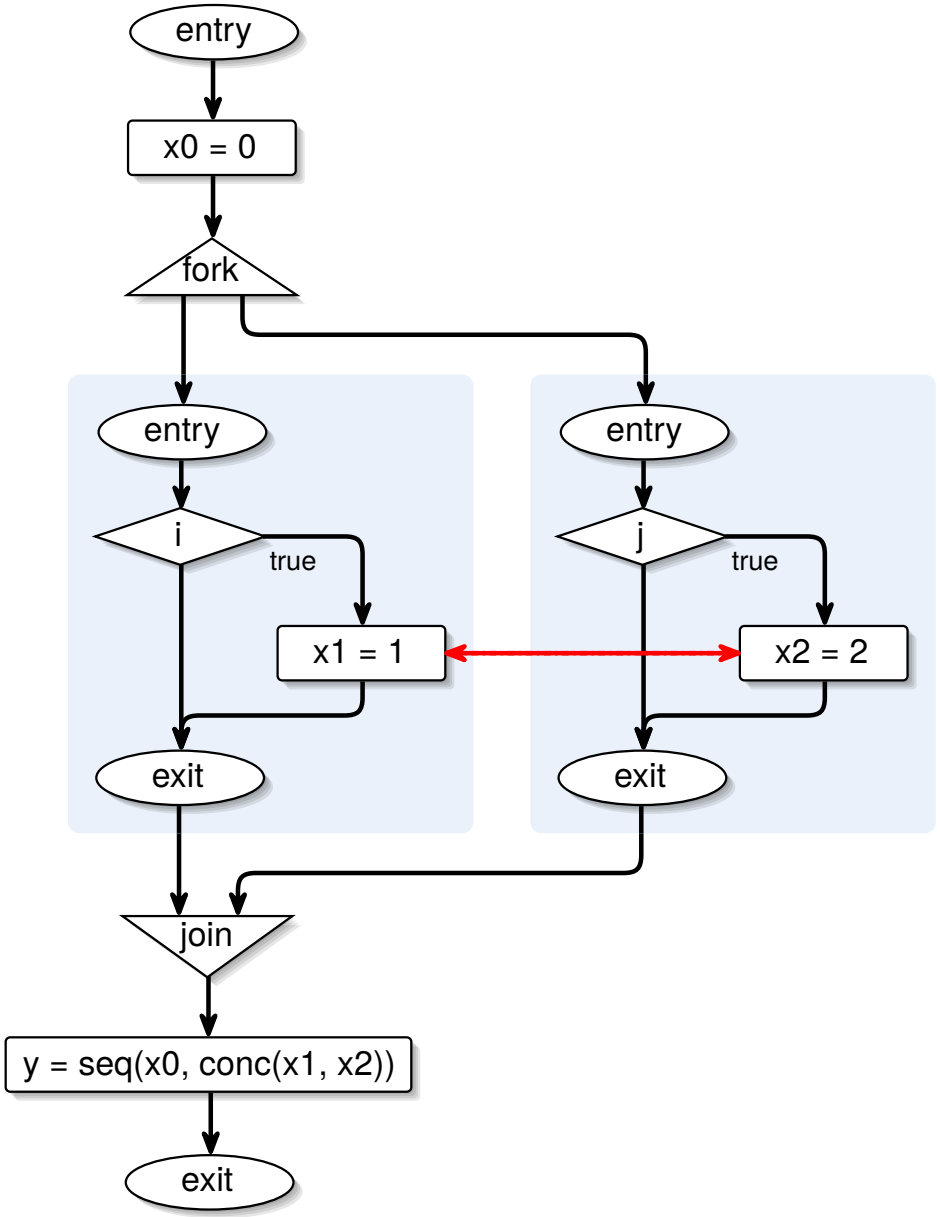

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false	false	0
false	true	2
true	false	1
true	true	**reject**

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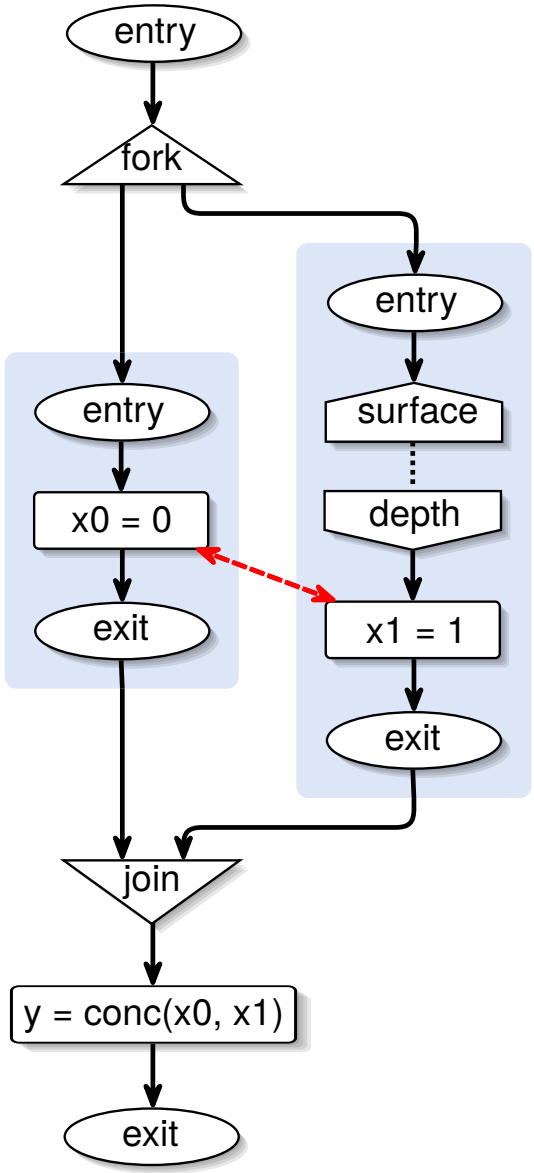
- Interface
  - SSA renaming

SSA Form: Delays



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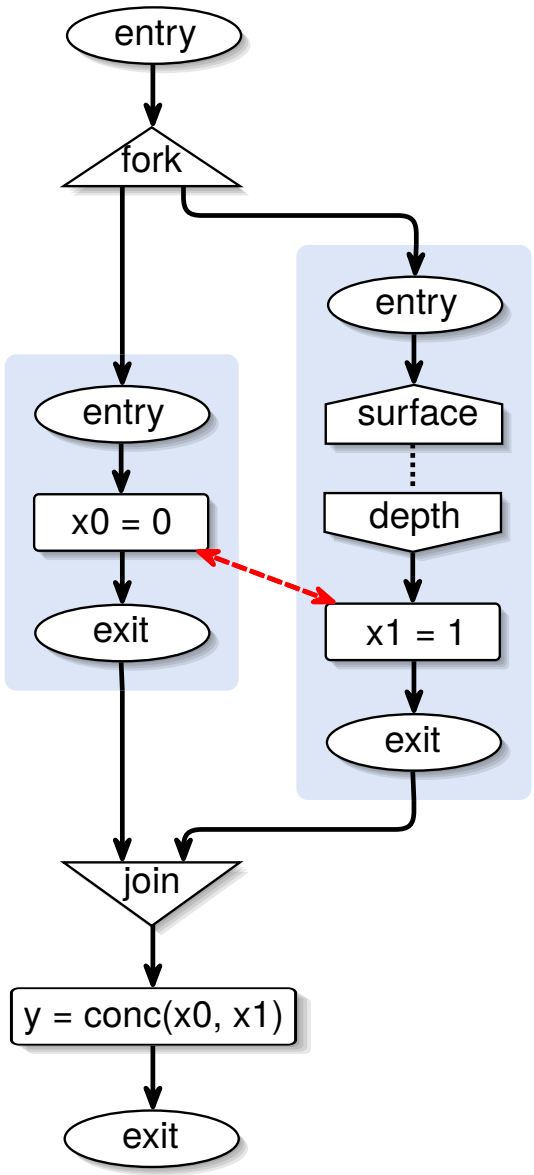


```
1  | conc(⟨x_i^p, x_i⟩, ⟨x_j^p, x_j⟩) :=
2  |   present x_i^p then
3  |     present x_j^p then
4  |       if x_i == x_j then
5  |         return ⟨x_i^p, x_i⟩
6  |       else
7  |         reject
8  |     else
9  |       return ⟨x_i^p, x_i⟩
10 |   else
11 |     present x_j^p then
12 |       return ⟨x_j^p, x_j⟩
13 |     else
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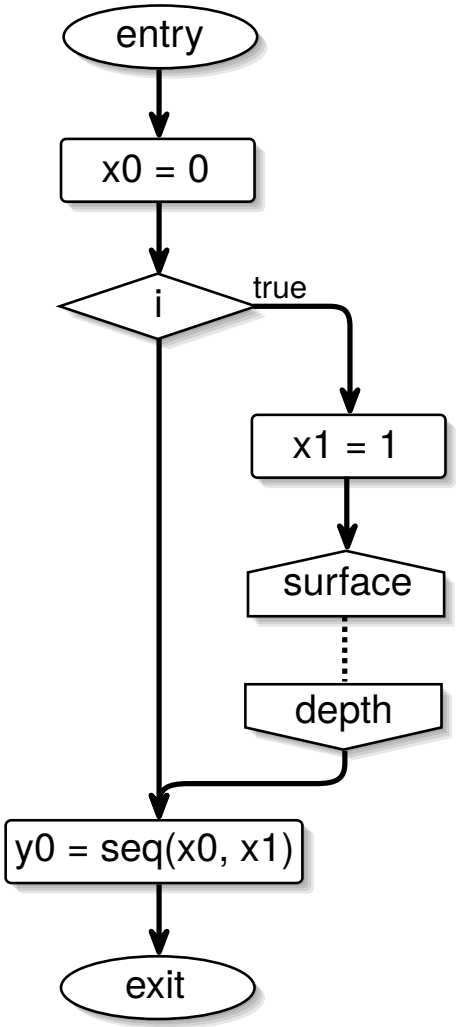

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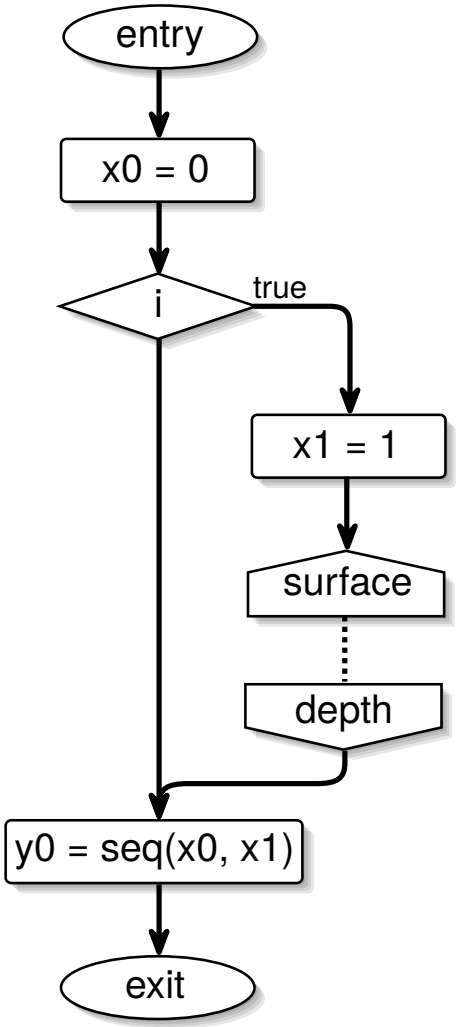


```
1 | seq(⟨x_i^p, x_i⟩, ⟨x_j^p, x_j⟩) :=
2 |   present x_j^p then
3 |     return ⟨x_j^p, x_j⟩
4 |   else
5 |     present x_i^p then
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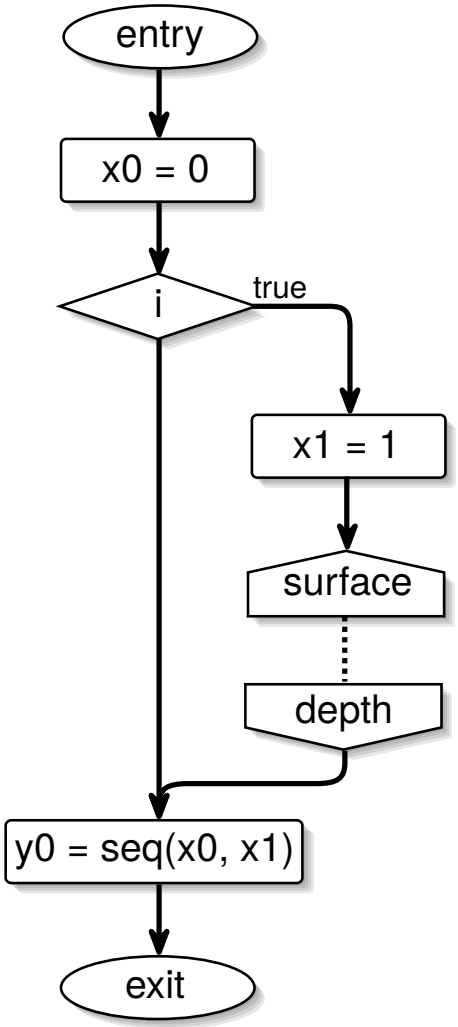
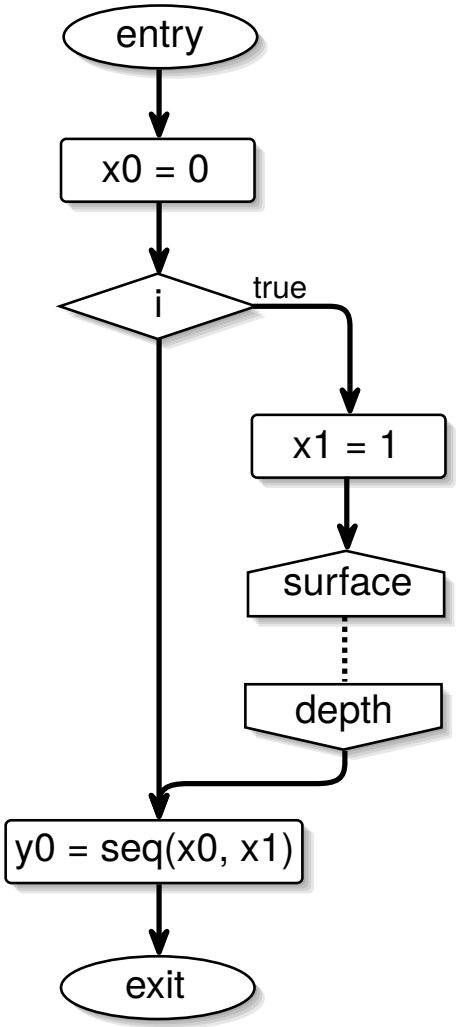


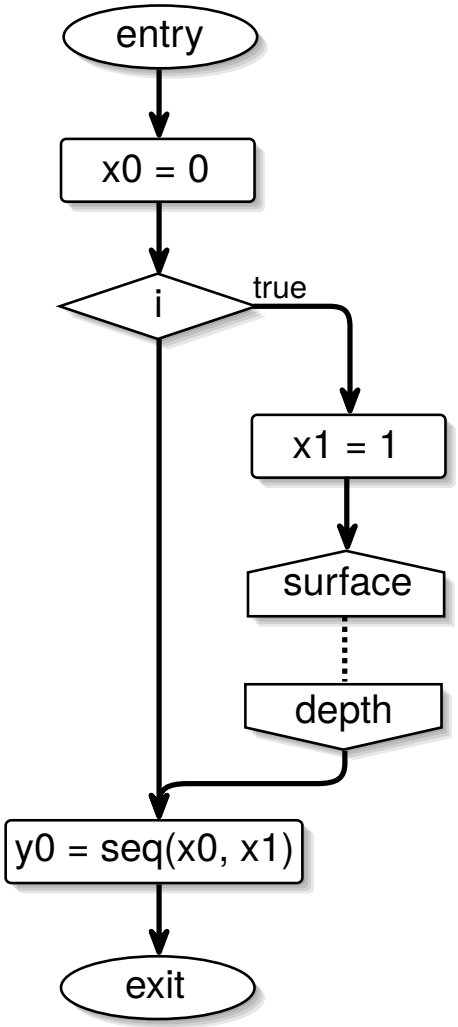
- Presence signals are reset to absent

SSA Form: Delays



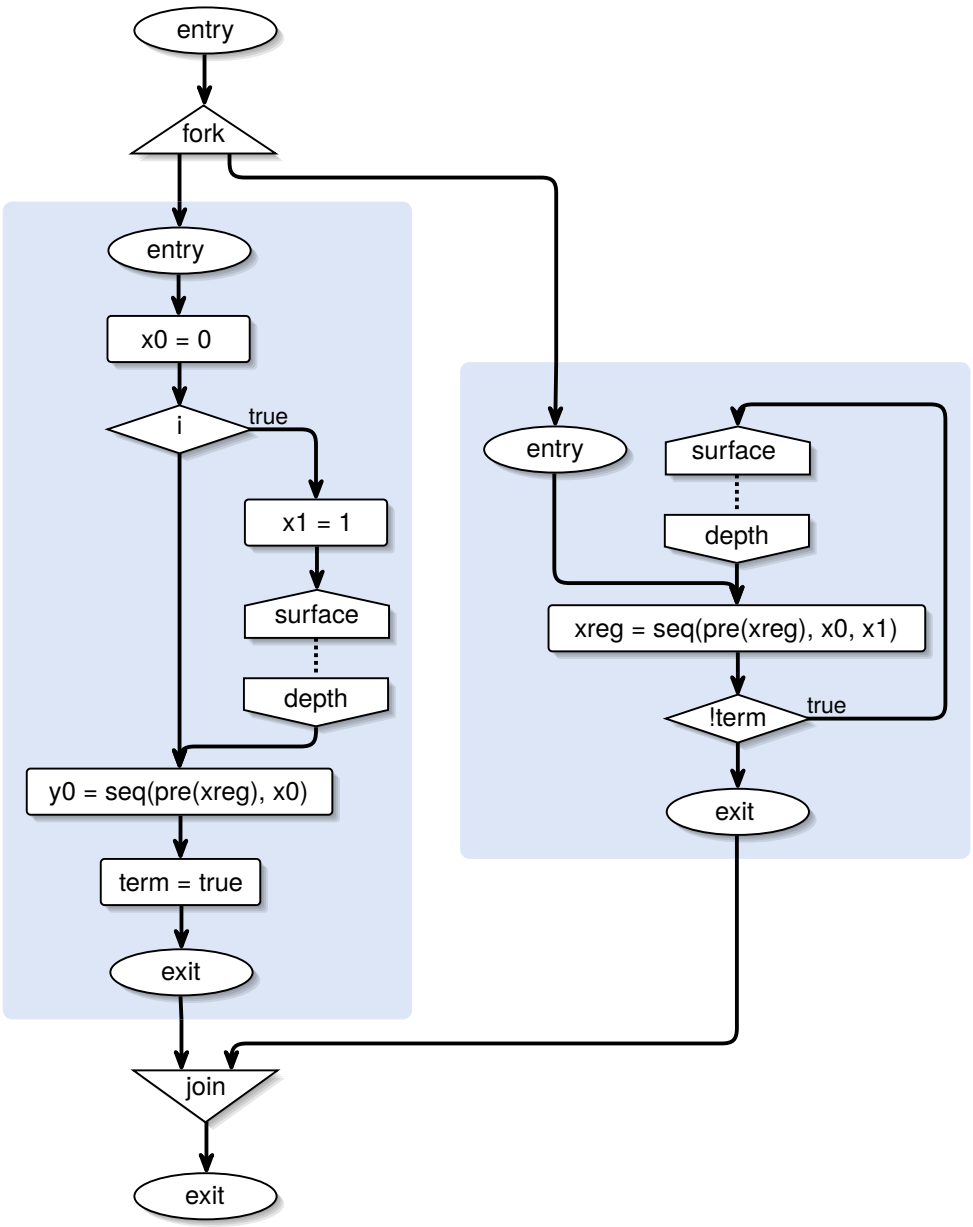
- Presence signals are reset to absent
- Runtime concurrent conflicts can be detected

SSA Form: Delays



- Presence signals are reset to absent
- Runtime concurrent conflicts can be detected
- Merge function cannot resolve value without write in the same tick

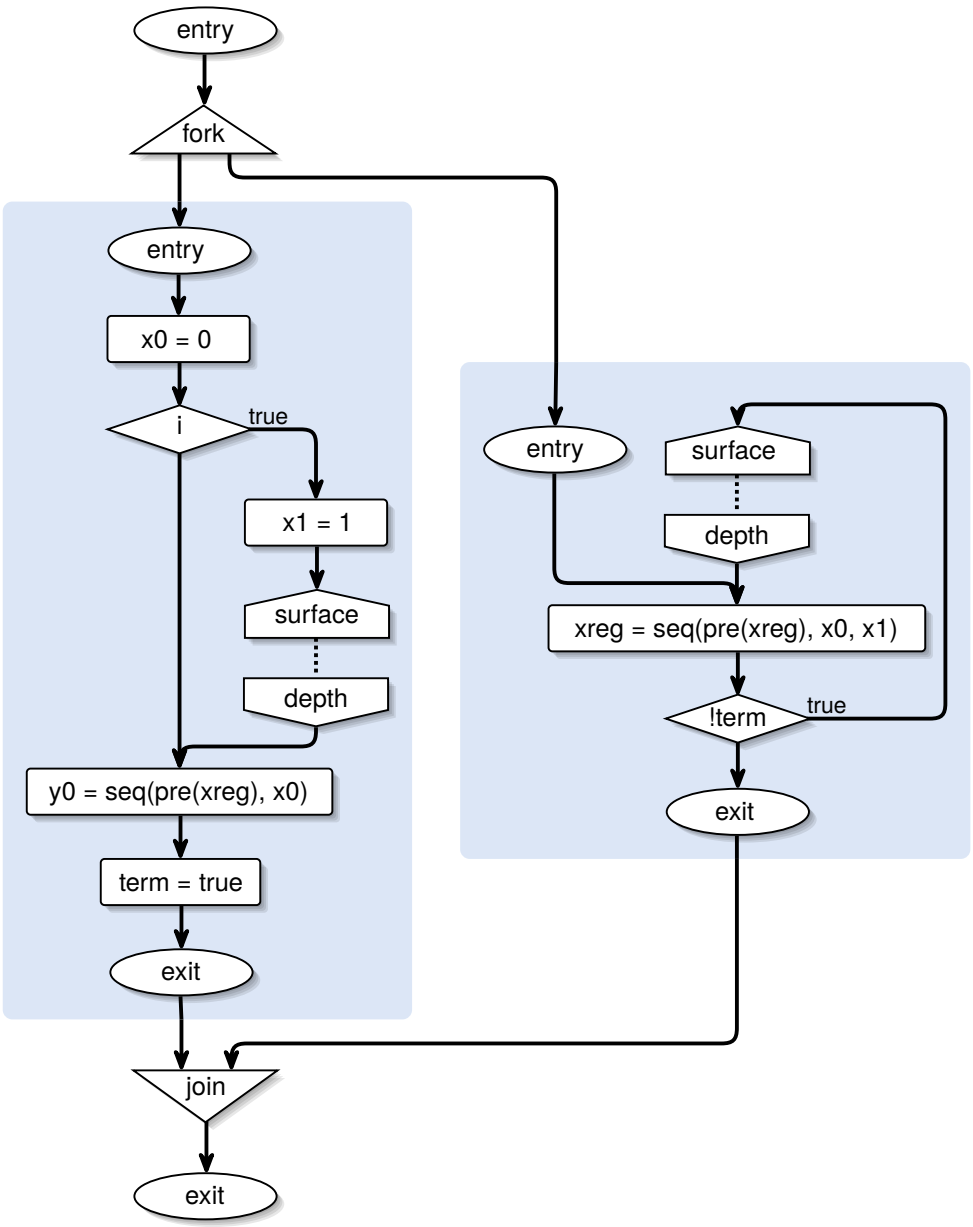
SSA Form: Delays Solved



Solution:

- Resolve and save variable values in each tick

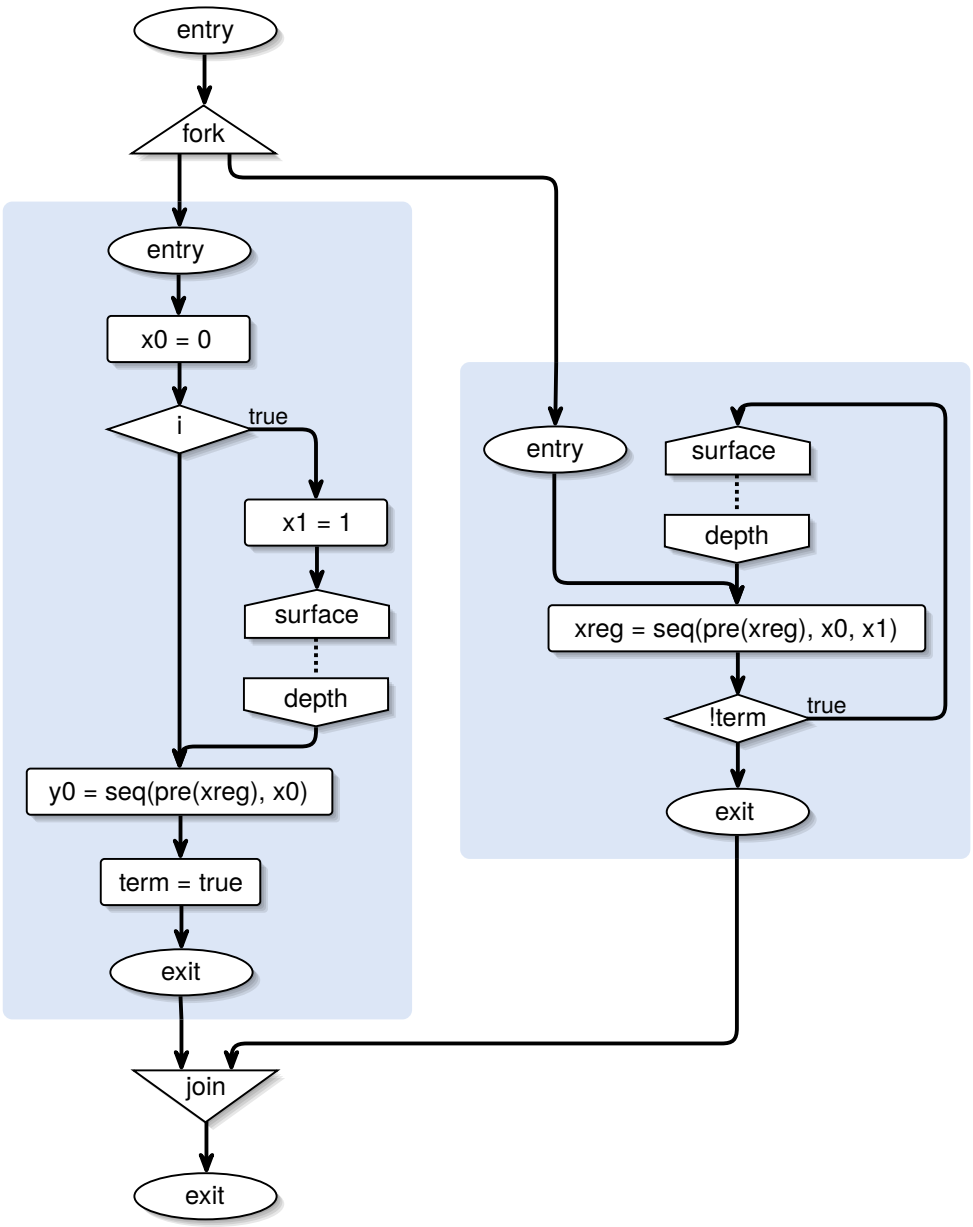
SSA Form: Delays Solved



Solution:

- Resolve and save variable values in each tick
- Store values in register variables

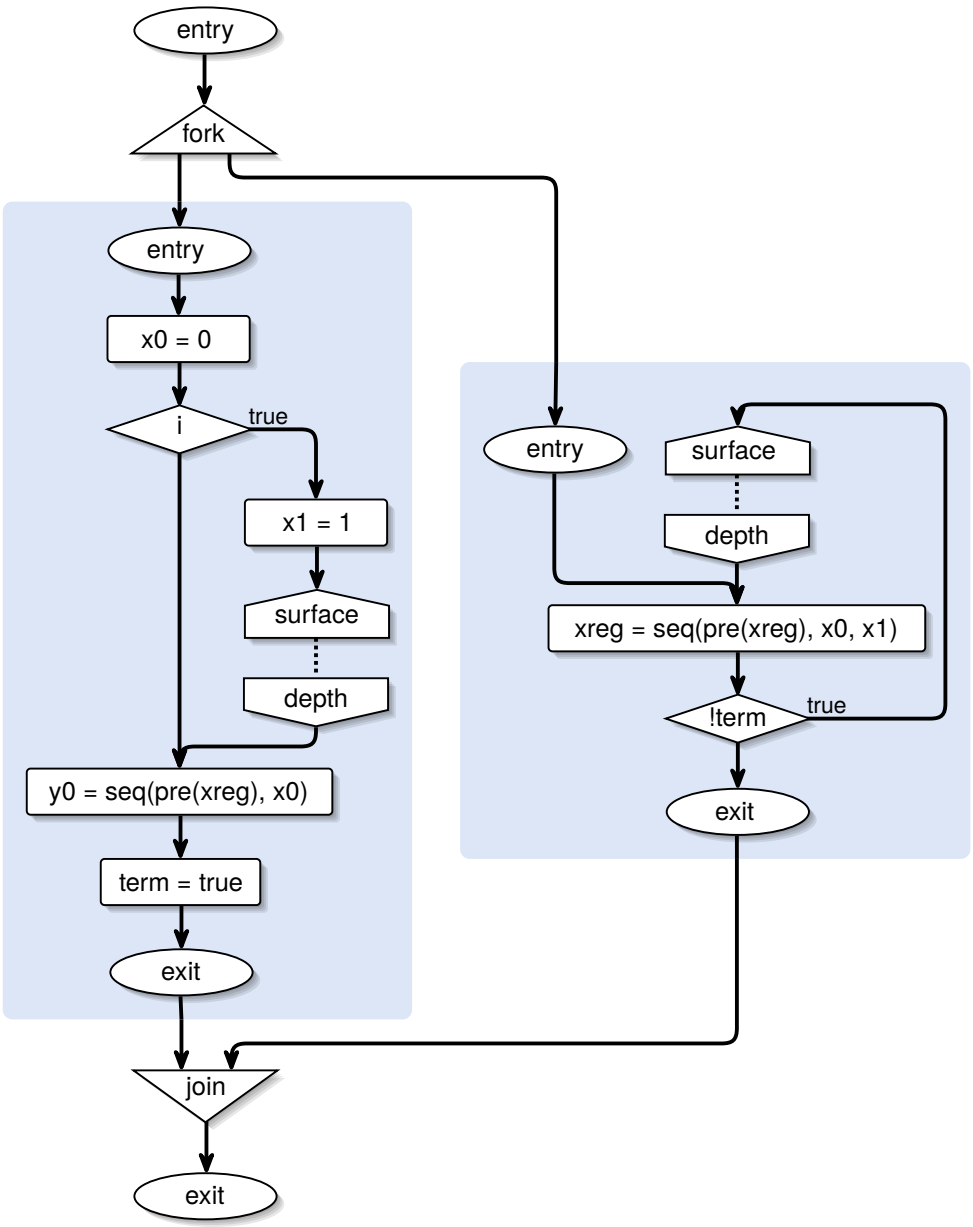
SSA Form: Delays Solved



Solution:

- Resolve and save variable values in each tick
- Store values in register variables
- Use *pre* to consider values of the previous tick in merge expressions

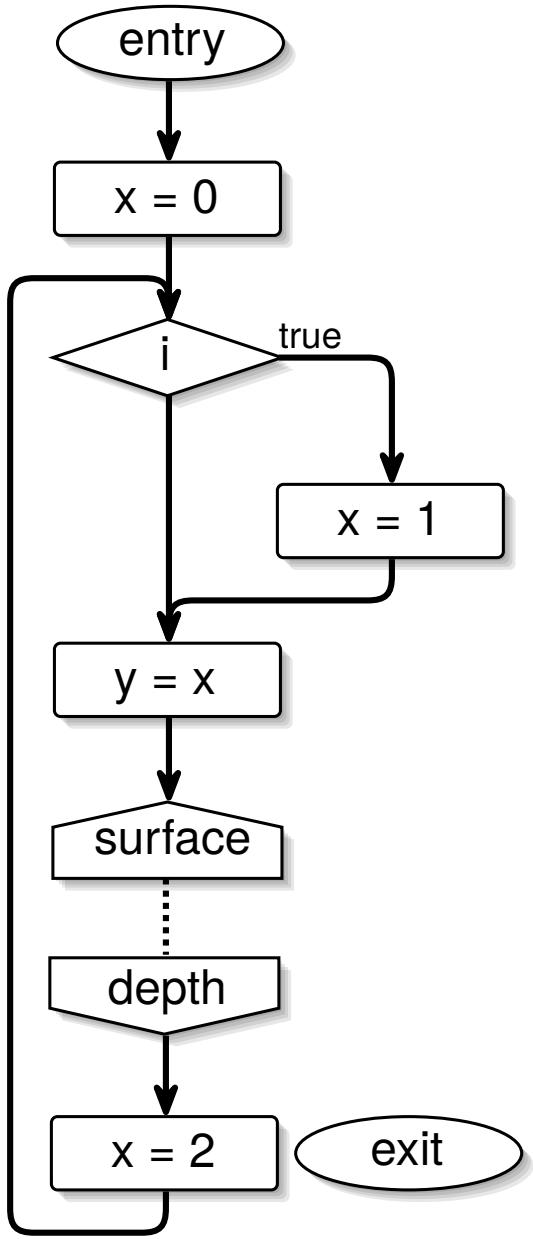
SSA Form: Delays Solved



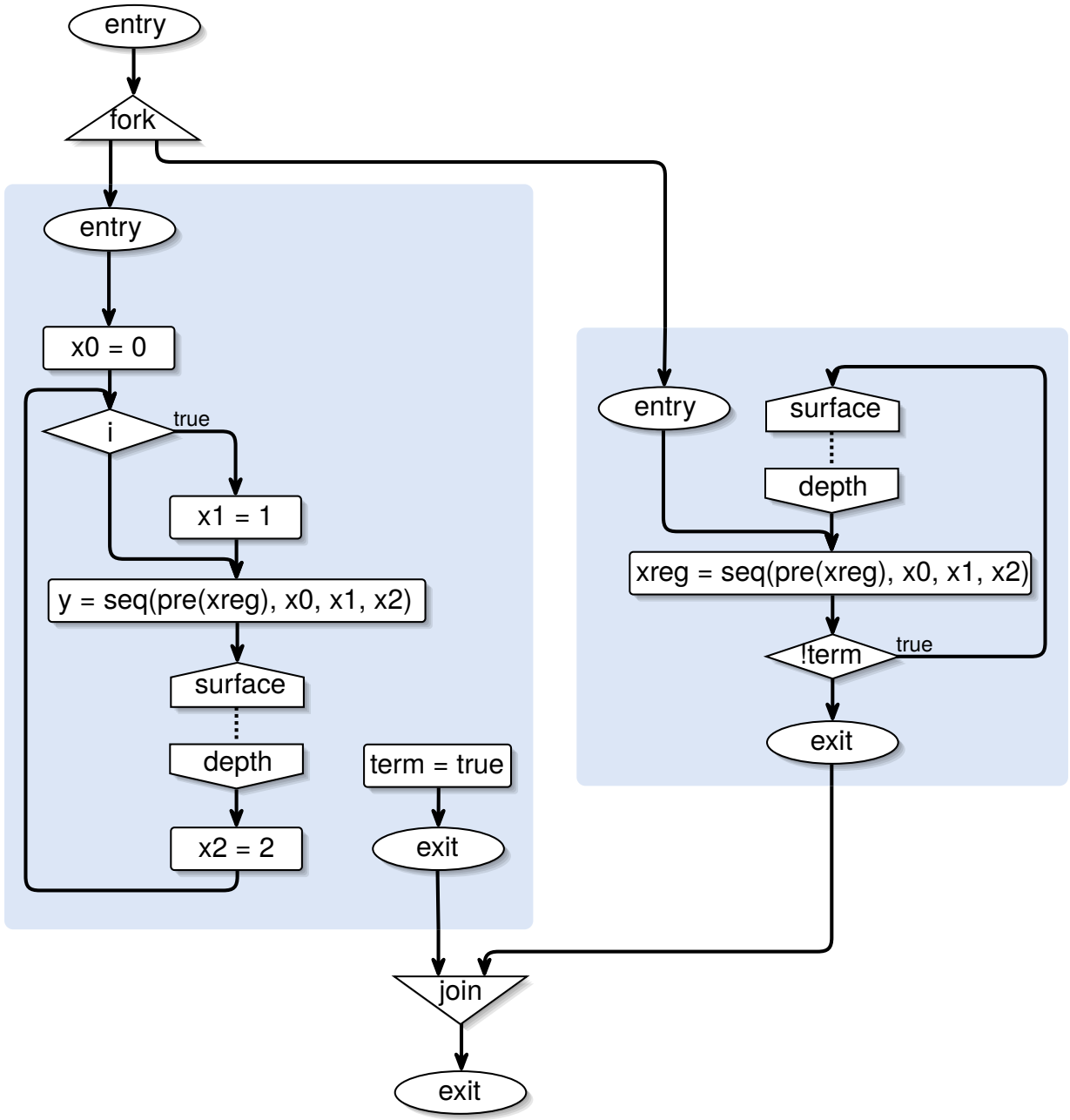
Solution:

- Resolve and save variable values in each tick
- Store values in register variables
- Use *pre* to consider values of the previous tick in merge expressions
- Reduce merge expression based on tick borders

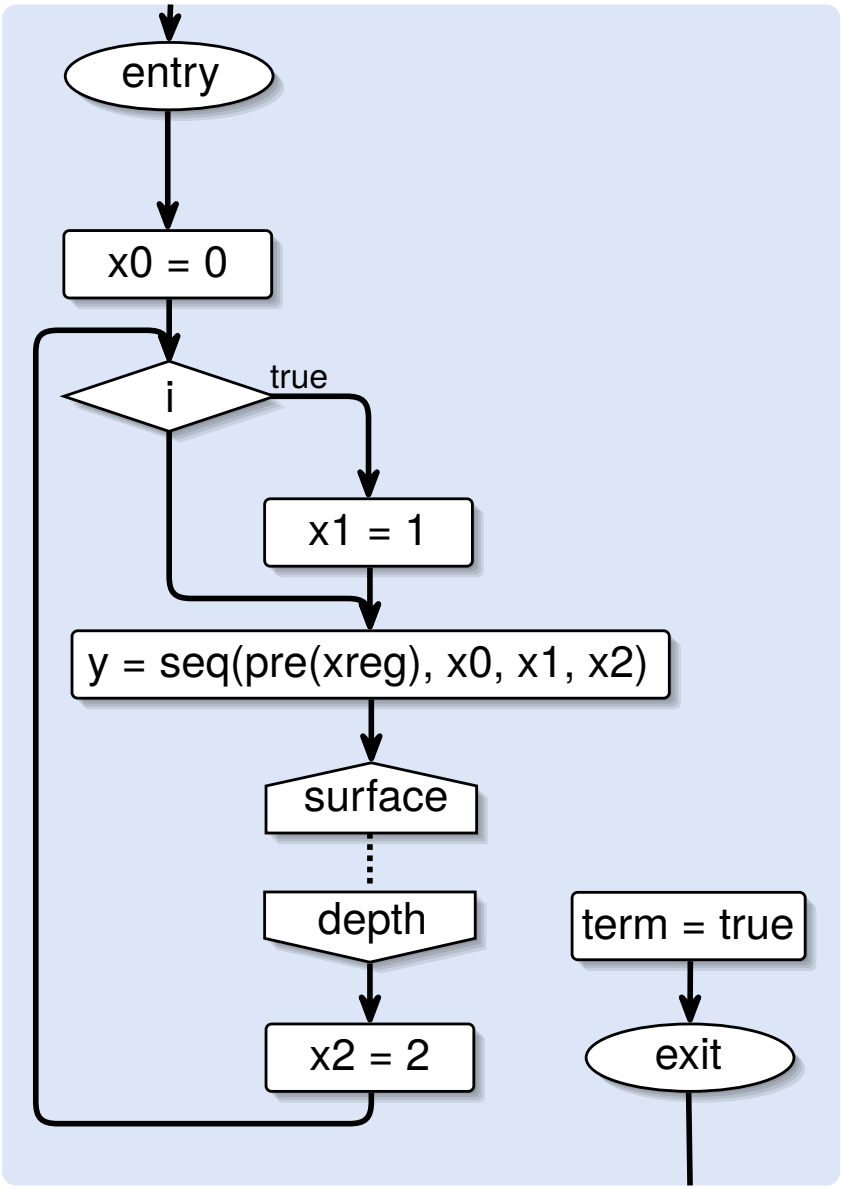
SSA Form: Loops



SSA Form: Loops

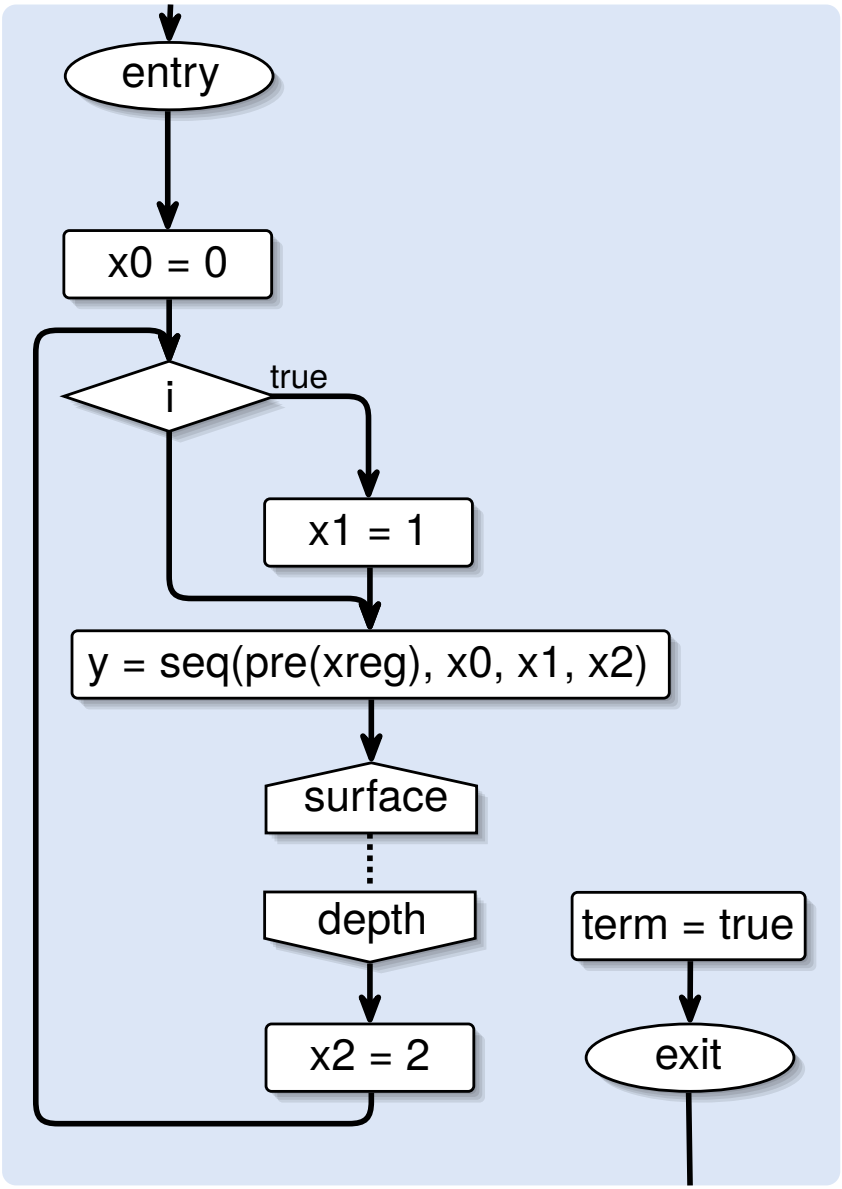


SSA Form: Loop Handling



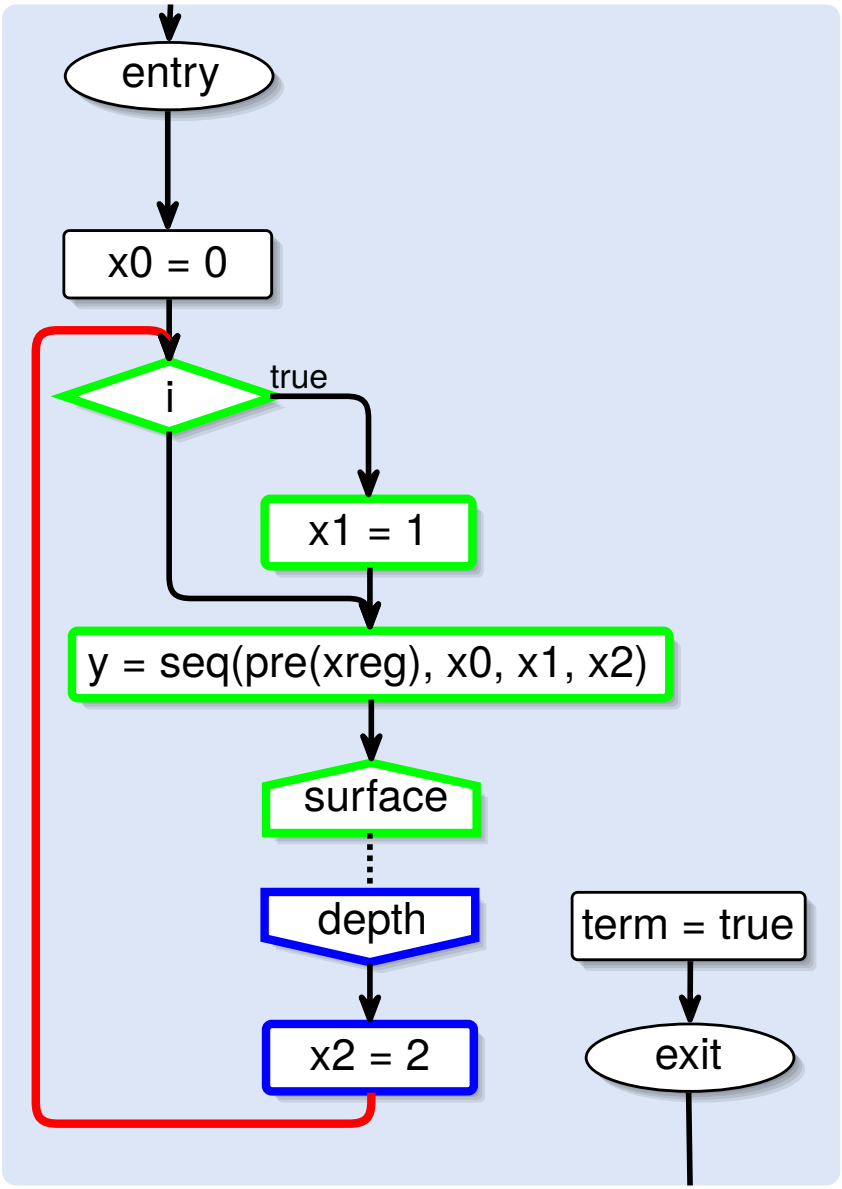
- Merge expressions require static ordering

SSA Form: Loop Handling



- Merge expressions require static ordering
- Wrong ordering due to simple structure analysis

SSA Form: Loop Handling

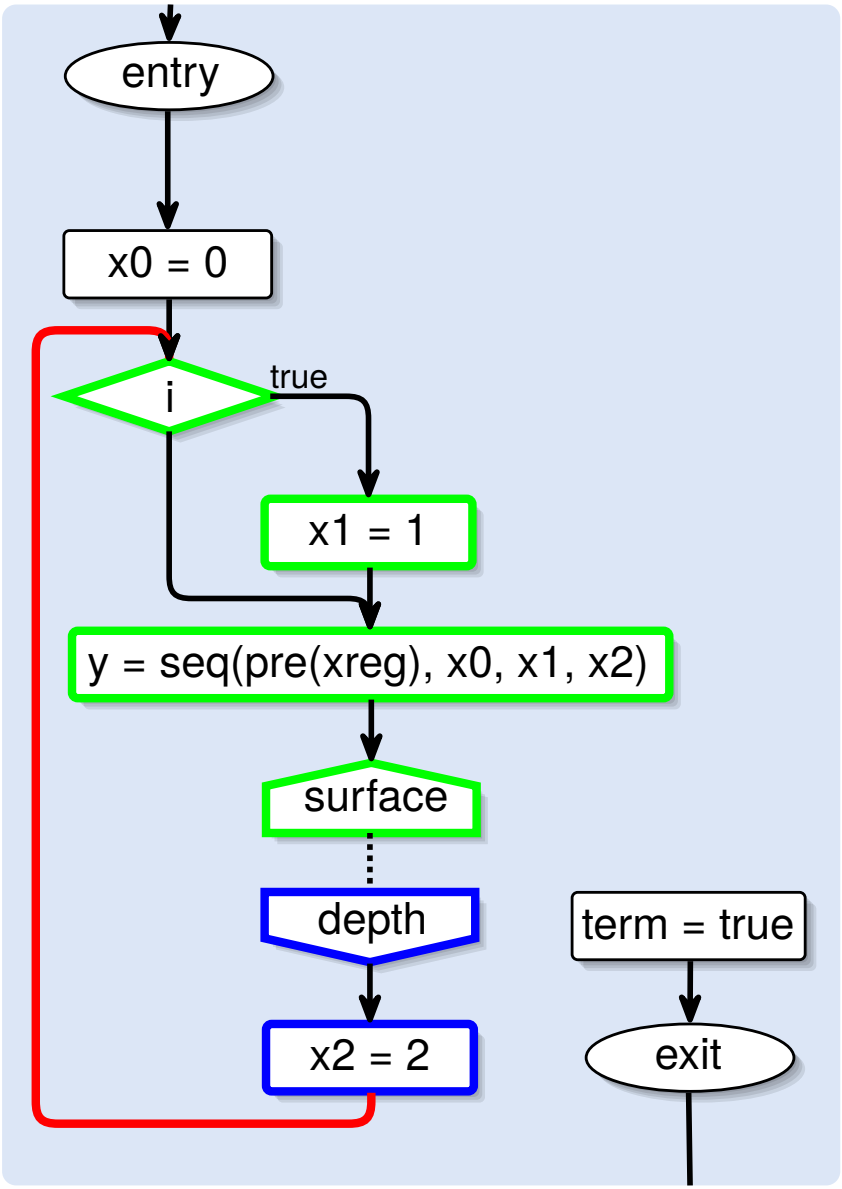


- Merge expressions require static ordering
- Wrong ordering due to simple structure analysis

Solution:

- Surface-Depth analysis

SSA Form: Loop Handling

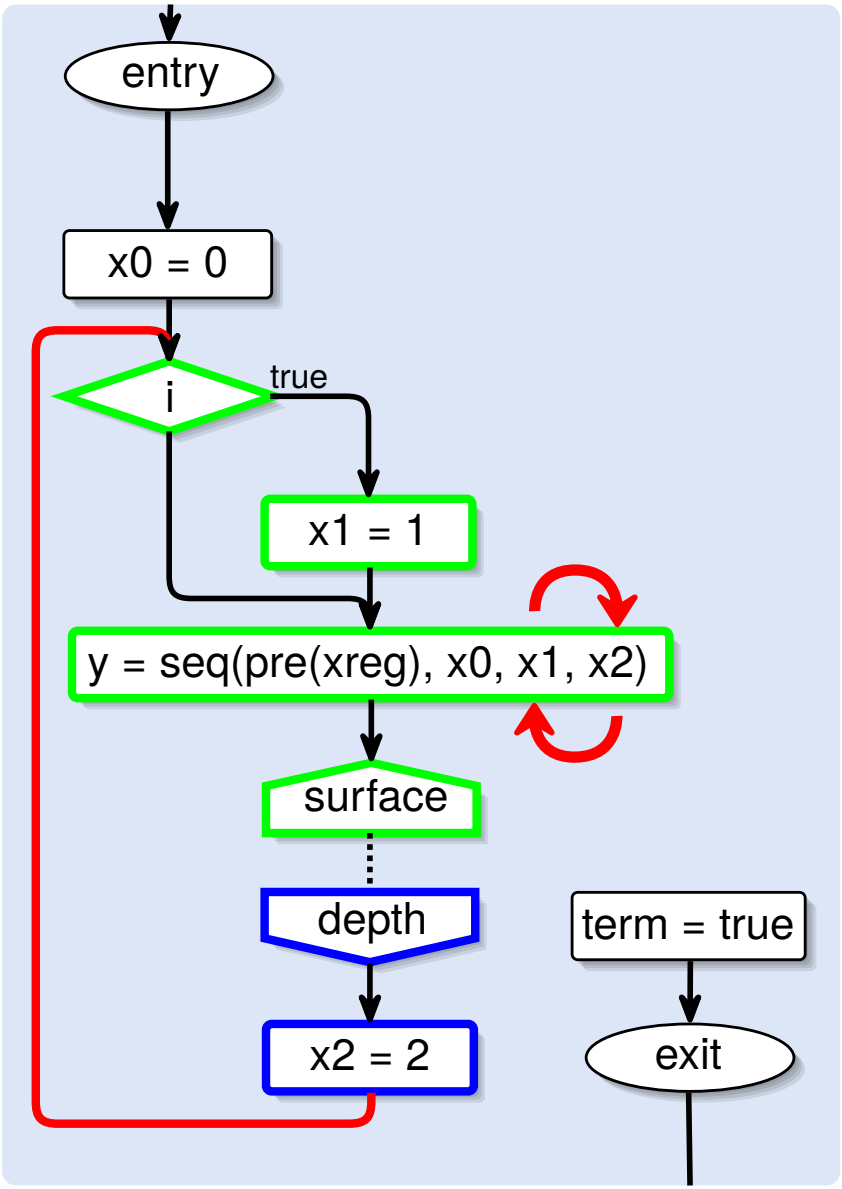


- Merge expressions require static ordering
- Wrong ordering due to simple structure analysis

Solution:

- Surface-Depth analysis
- Requires a pause that is always executed

SSA Form: Loop Handling

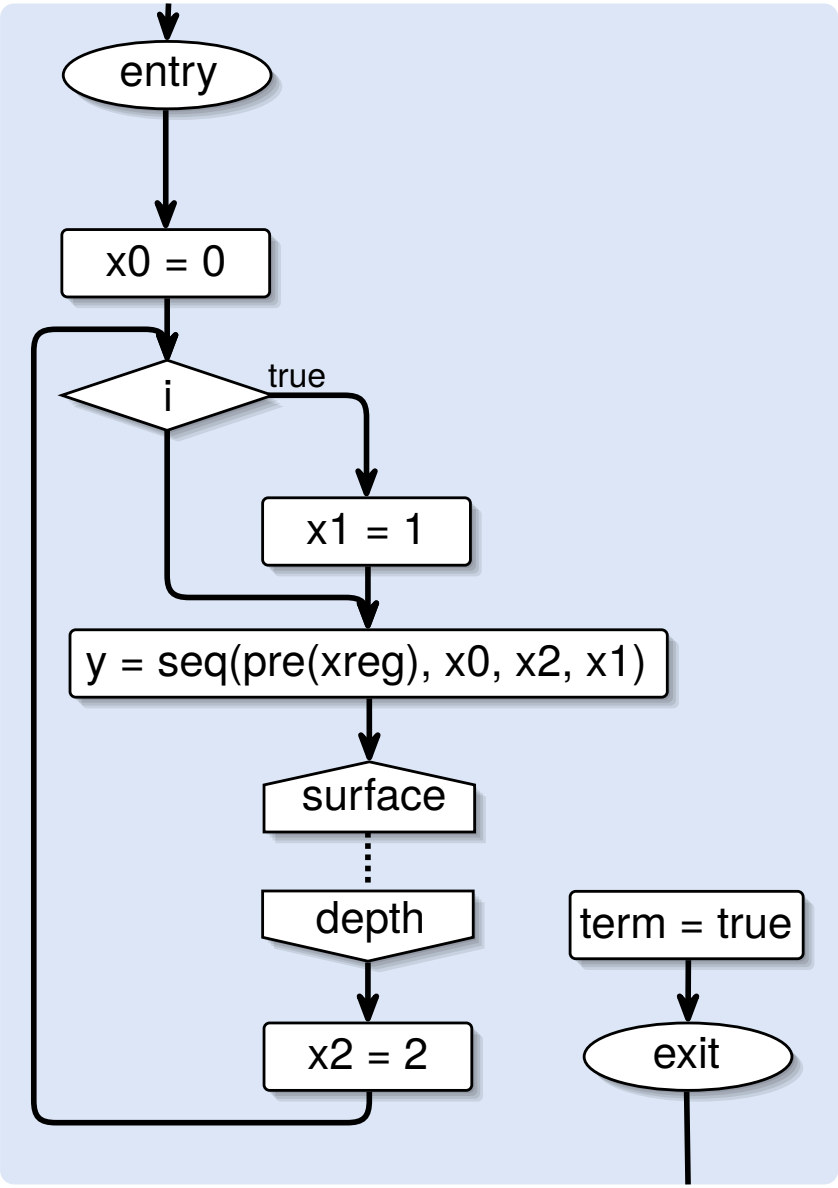


- Merge expressions require static ordering
- Wrong ordering due to simple structure analysis

Solution:

- Surface-Depth analysis
- Requires a pause that is always executed
- Switch order of writes in the surface with depth

SSA Form: Loop Handling

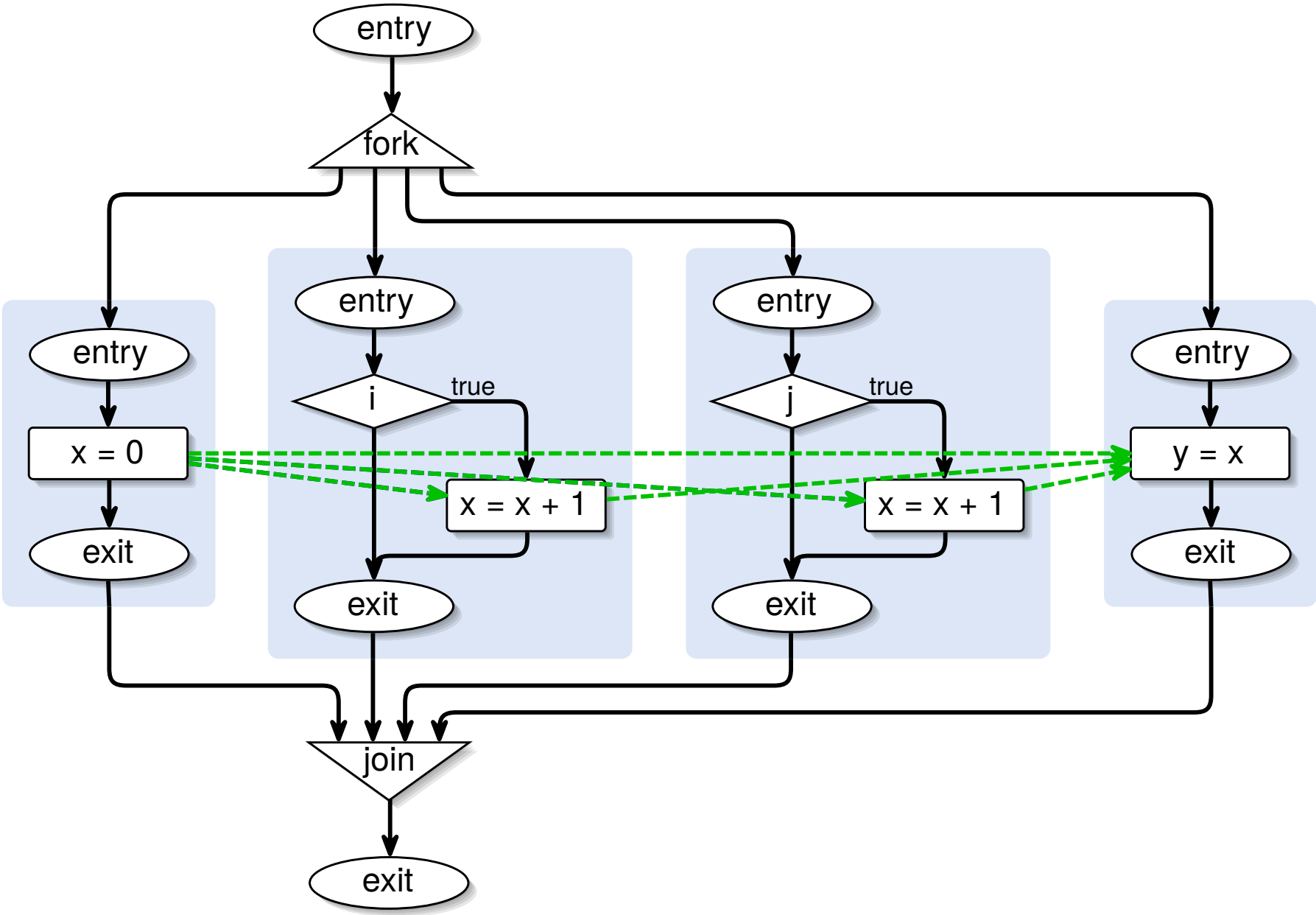


- Merge expressions require static ordering
- Wrong ordering due to simple structure analysis

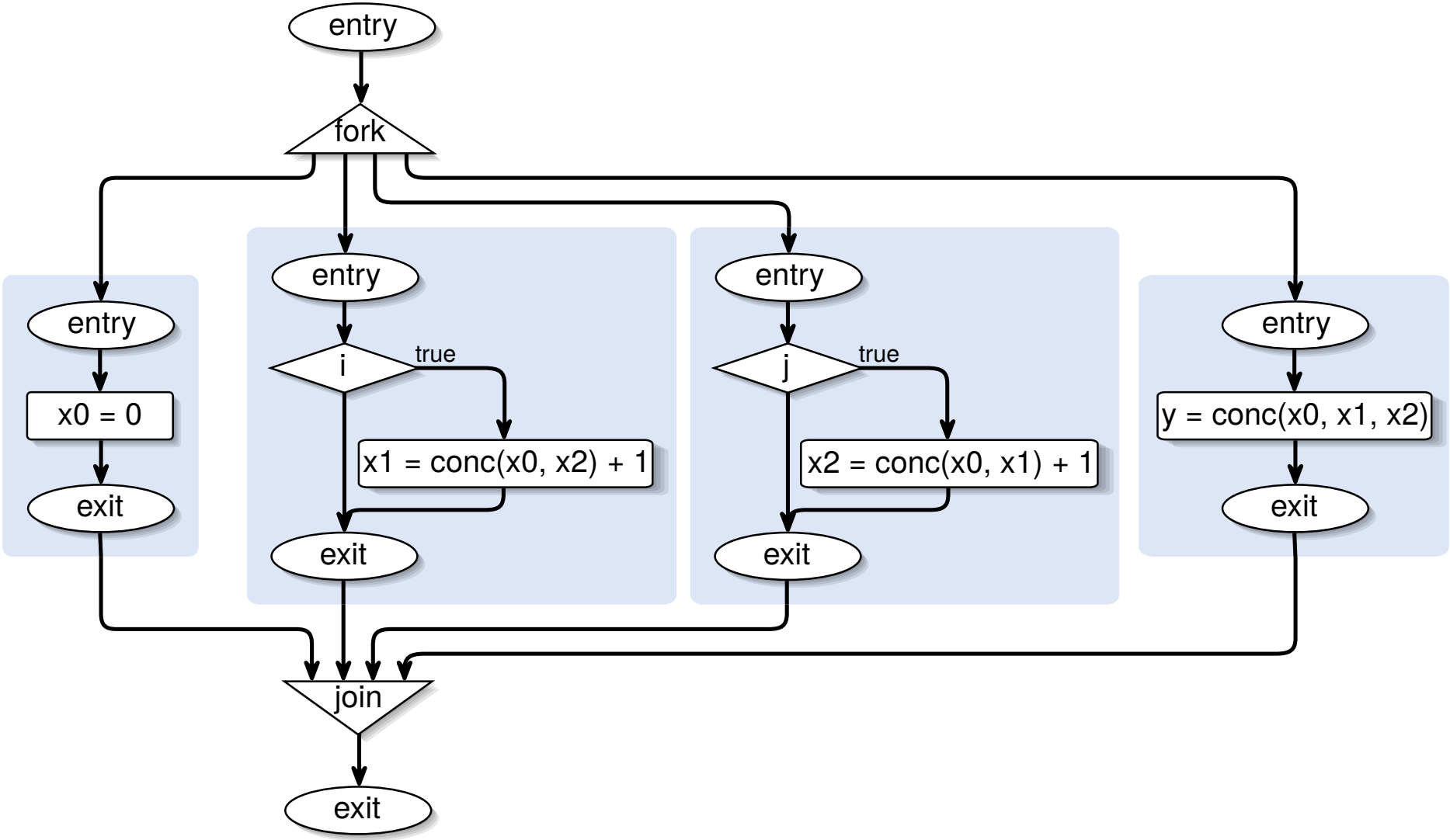
Solution:

- Surface-Depth analysis
- Requires a pause that is always executed
- Switch order of writes in the surface with depth

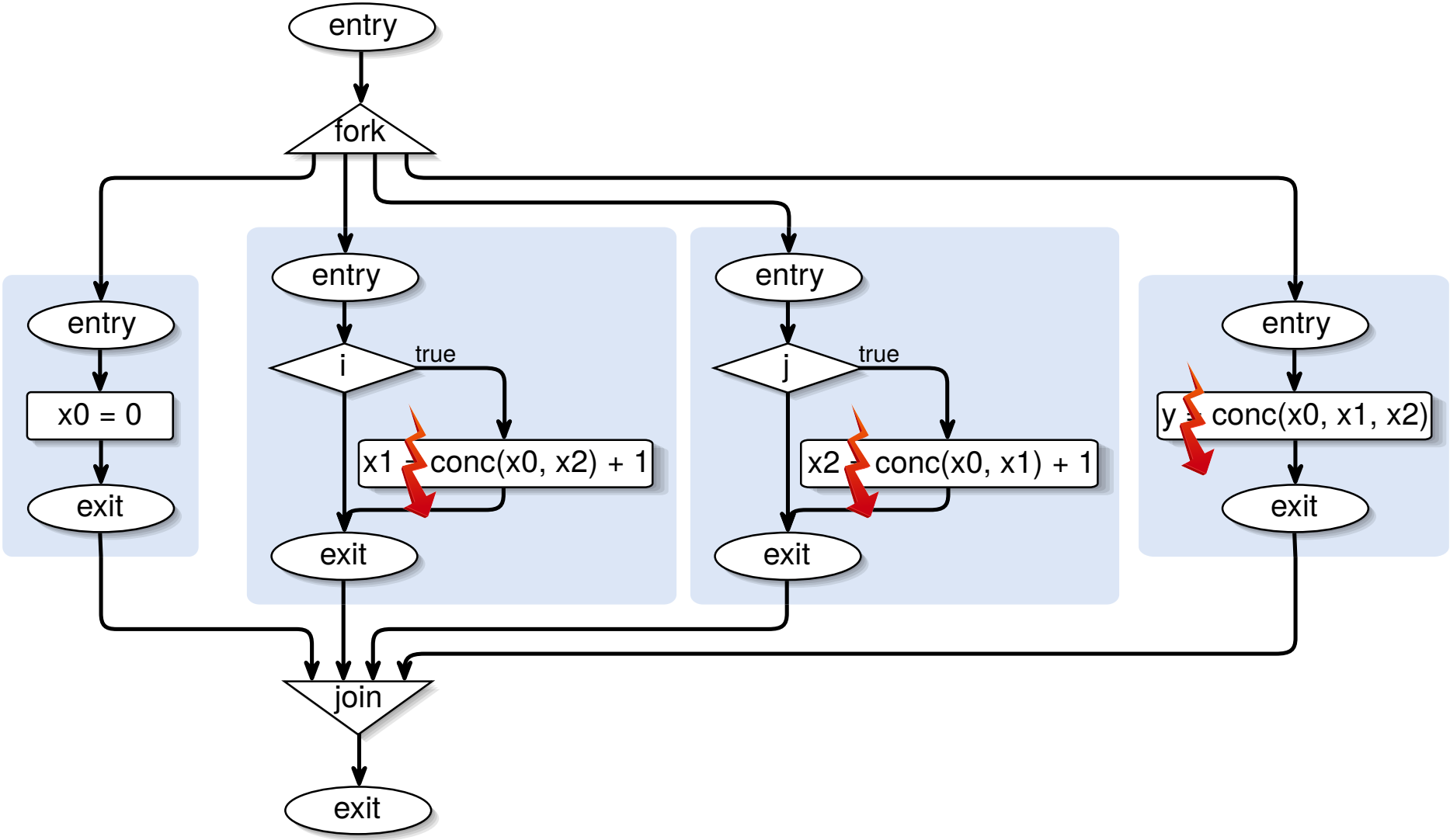
SSA Form: Updates



SSA Form: Updates



SSA Form: Updates



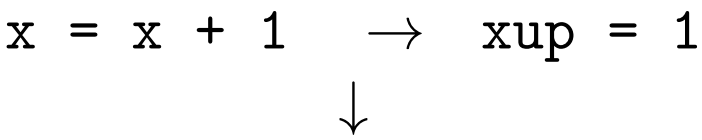
SSA Form: Update Handling

```
x = x + 1
```

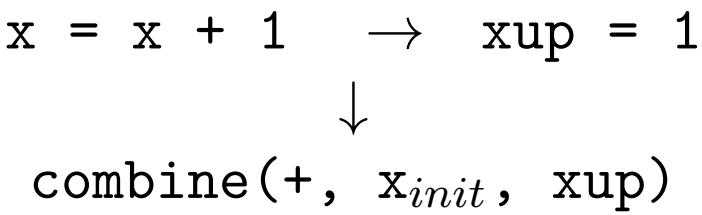
SSA Form: Update Handling

`x = x + 1` $\rightarrow$ `xup = 1`

SSA Form: Update Handling



SSA Form: Update Handling



SSA Form: Update Handling

```
x = x + 1   →   xup = 1
                  ↓
 combine(+, x_init, xup)
```

```
1  combine(f, ⟨x^p, x⟩, ⟨x^p_up, x_up⟩) :=
2    present x^p then
3      present x^p_up then
4        return ⟨x^p, f(x, x_up)⟩
5      else
6        return ⟨x^p, x⟩
7    else
8      present x^p_up then
9        reject
10     else
11       return ⟨absent, nil⟩
```

SSA Form: Update Handling

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x = x + 1   →   xup = 1
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```

- Special *seq* function for updates

SSA Form: Update Handling

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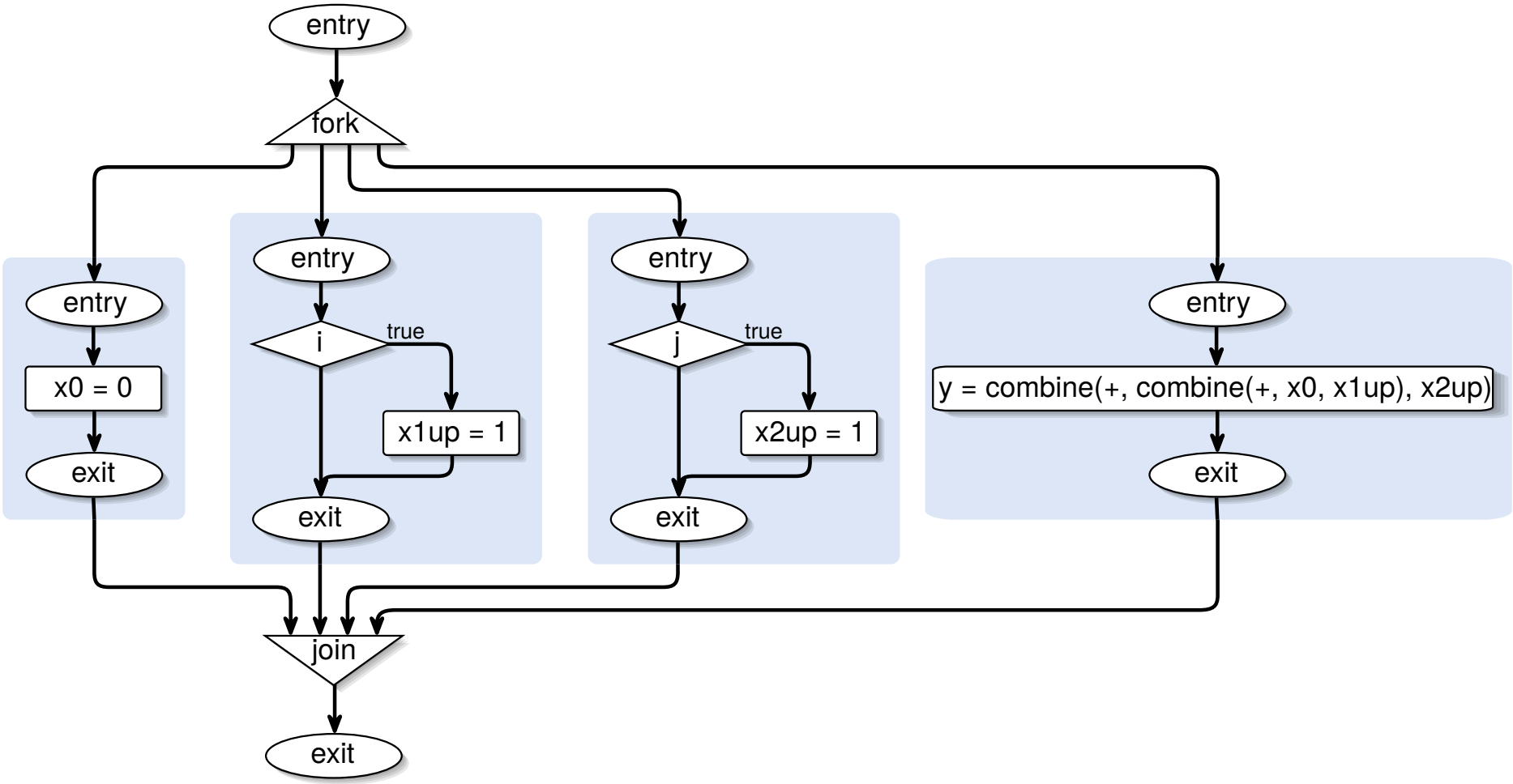
6        return ⟨x^p, x⟩
7    else
8      present x^p_up then
9        reject
10     else
11       return ⟨absent, nil⟩
```

- Special *seq* function for updates
- Requires partial static schedule to generate merge expressions

SSA Form: Updates Solved



SSA Form: Interface

```
1  module IO
2  input int I;
3  output int O;
4  {
5    if I < 0 then
6      I = 0
7    end;
8    O = I;
9    pause;
10   O = O * I
11 }
```

SSA Form: Interface

```
1  module IO
2  input int I;
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```

- SSA renaming should not violate the original interface

SSA Form: Interface

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- SSA renaming should not violate the original interface
- Inputs must be read from the environment in each tick

SSA Form: Interface

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- SSA renaming should not violate the original interface
- Inputs must be read from the environment in each tick
- Inputs can be locally overridden

SSA Form: Interface

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10   O = O * I
11 }
```
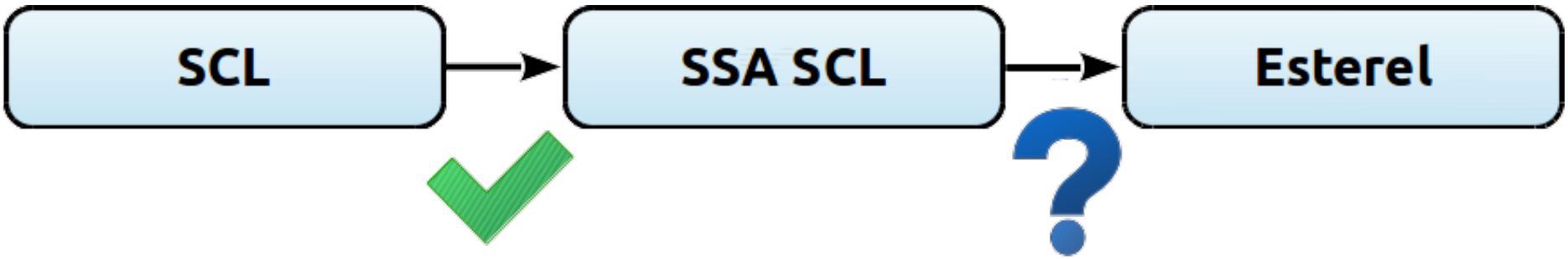

- SSA renaming should not violate the original interface
- Inputs must be read from the environment in each tick
- Inputs can be locally overridden
- Outputs must be conveyed to the environment in each tick

SSA Form: Interface Solved

```
1  module IO-SSA
2  input int I;
3  int IO;
4  output int O;
5  int O0, O1, Oreg;
6  bool term = false;
7  {
8    fork
9      if I < 0 then
10       IO = 0
11     end;
12     O0 = seq(I, IO)
13     pause;
14     O1 = pre(Oreg) * I;
15     term = true
16   par
17     PauseLoop:
18     Oreg = seq(pre(Oreg), O0, O1);
19     O = Oreg;
20     if !term then
21       pause;
22       goto PauseLoop
23     end
24   join
25 }
```


SCL
SSA SCL
Esterel

Translation into Esterel

Translation of

- program structure

Translation into Esterel

Translation of

- program structure
- variables

Translation into Esterel

Translation of

- program structure
- variables

Esterel data-types:

- Variables

Translation into Esterel

Translation of

- program structure
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Esterel data-types:

- Variables
- Valued signals

Translation into Esterel

Translation of

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Esterel data-types:

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Translation into Esterel

Translation of

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Esterel data-types:

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Presence Encoding

$\mathbf{x}_i^p \setminus \mathbf{x}_i$	**present**	**absent**
present	true	false
absent	undef	undef

Translation into Esterel

Translation of

- program structure
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Esterel data-types:

- Variables
- Valued signals
- Pure signals

Presence Encoding

$\mathbf{x}_i^p \setminus \mathbf{x}_i$	**present**	**absent**
present	true	false
absent	undef	undef

Dual-Rail Encoding

$\mathbf{x}_i \setminus$ **not_x**$_i$	**present**	**absent**
present	illegal	true
absent	false	undef

Dual-Rail Encoding

x_i = true $\longrightarrow$ **emit** x_i

Dual-Rail Encoding

x_i = true $\longrightarrow$ **emit** x_i

x_i = false $\longrightarrow$ **emit** not_x_i

Dual-Rail Encoding

x_i = true $\rightarrow$ emit x_i

x_i = false $\rightarrow$ emit not_x_i

$x_i = e \rightarrow$

```
present errorExpr(e) then
  emit error
else
  [
    present trueExpr(e) then
      emit x_i
    end
  ||
    present falseExpr(e) then
      emit not_x_i
    end
  ]
end
```

Dual-Rail Encoding

```
if (e) then
  //then-block
else
  //else-block
end
```

→

```
present errorExpr(e) then
  emit error
else
  [
    present trueExpr(e) then
      % then-block
    end
  ||
    present falseExpr(e) then
      % else-block
    end
  ]
end
```

Dual-Rail Encoding

$\mathtt{x}_i$:

trueExpr: $\mathtt{x}_i$

falseExpr: $\mathtt{not\_x}_i$

Dual-Rail Encoding

$\mathtt{x}_i$:

trueExpr: $\mathtt{x}_i$

falseExpr: $\mathtt{not\_x}_i$

conc(e_i, e_j):

errorExpr: $(\mathsf{trueExpr}(e_i) \wedge \mathsf{falseExpr}(e_j)) \vee (\mathsf{falseExpr}(e_i) \wedge \mathsf{trueExpr}(e_j))$

trueExpr: $\mathsf{trueExpr}(e_i) \vee \mathsf{trueExpr}(e_j)$

falseExpr: $\mathsf{falseExpr}(e_i) \vee \mathsf{falseExpr}(e_j)$

Dual-Rail Encoding

$\mathtt{x}_i$:

trueExpr: $\mathtt{x}_i$

falseExpr: $\mathtt{not\_x}_i$

conc(e_i, e_j):

errorExpr: $(\mathsf{trueExpr}(e_i) \wedge \mathsf{falseExpr}(e_j)) \vee (\mathsf{falseExpr}(e_i) \wedge \mathsf{trueExpr}(e_j))$

trueExpr: $\mathsf{trueExpr}(e_i) \vee \mathsf{trueExpr}(e_j)$

falseExpr: $\mathsf{falseExpr}(e_i) \vee \mathsf{falseExpr}(e_j)$

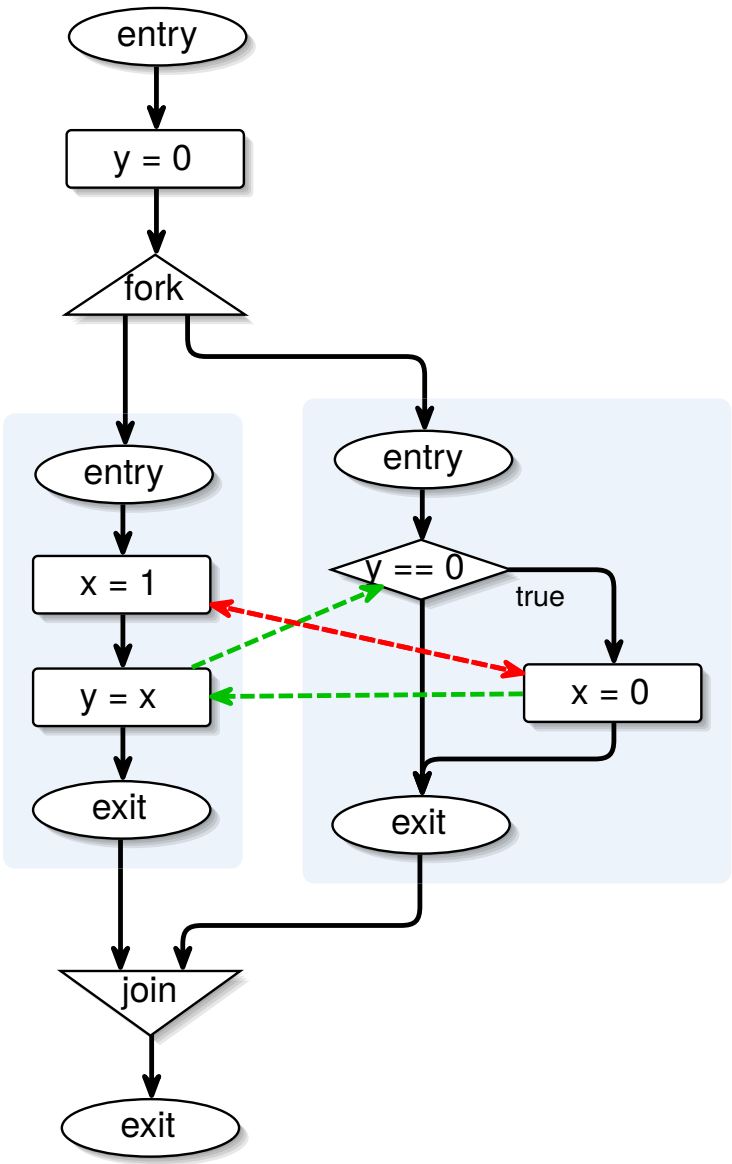
seq(e_i, e_j):

trueExpr: $\mathsf{trueExpr}(e_j) \vee (\neg\mathsf{falseExpr}(e_j) \wedge \mathsf{trueExpr}(e_i))$

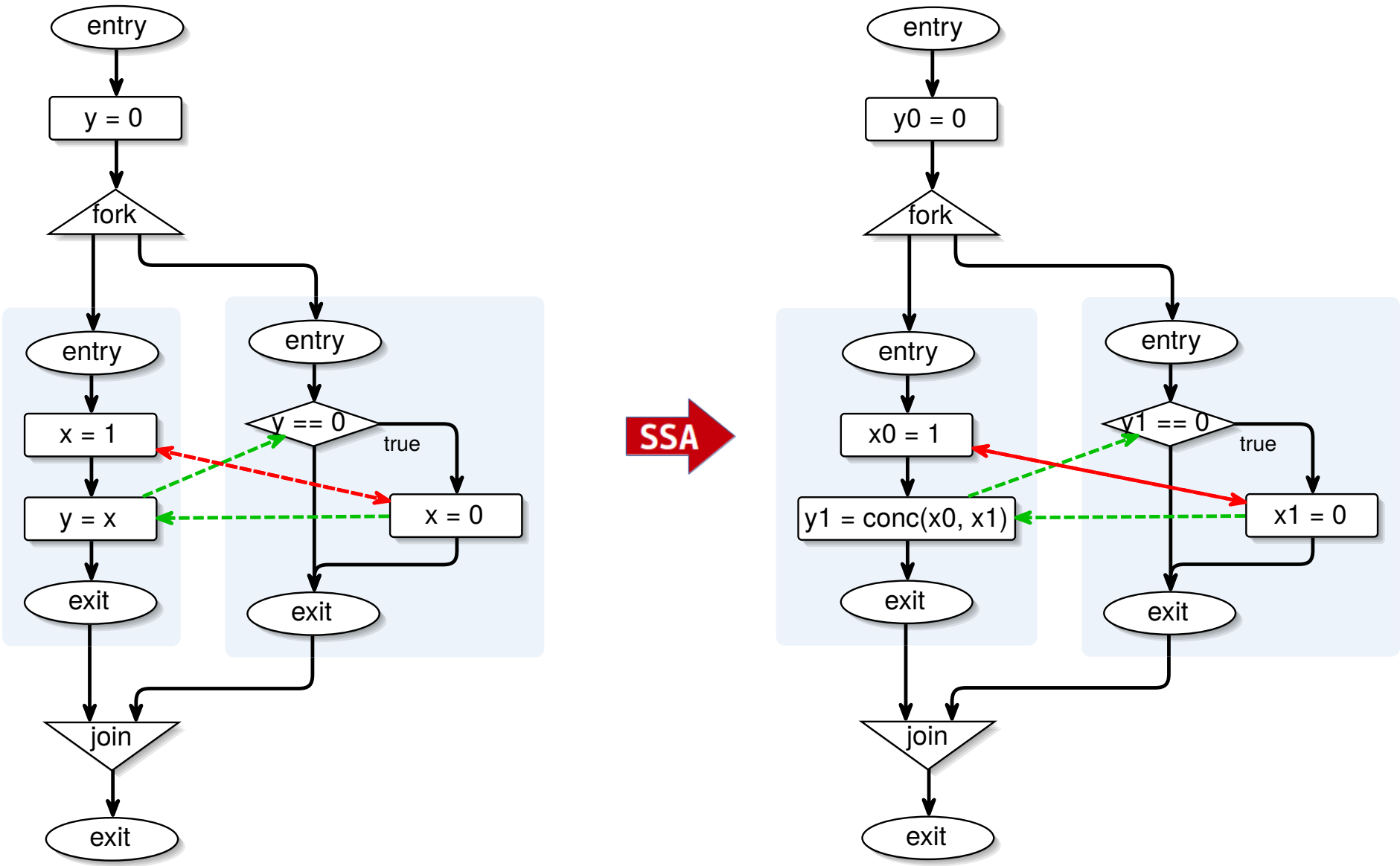
falseExpr: $\mathsf{falseExpr}(e_j) \vee (\neg\mathsf{trueExpr}(e_j) \wedge \mathsf{falseExpr}(e_i))$


SCL
SSA SCL
Esterel

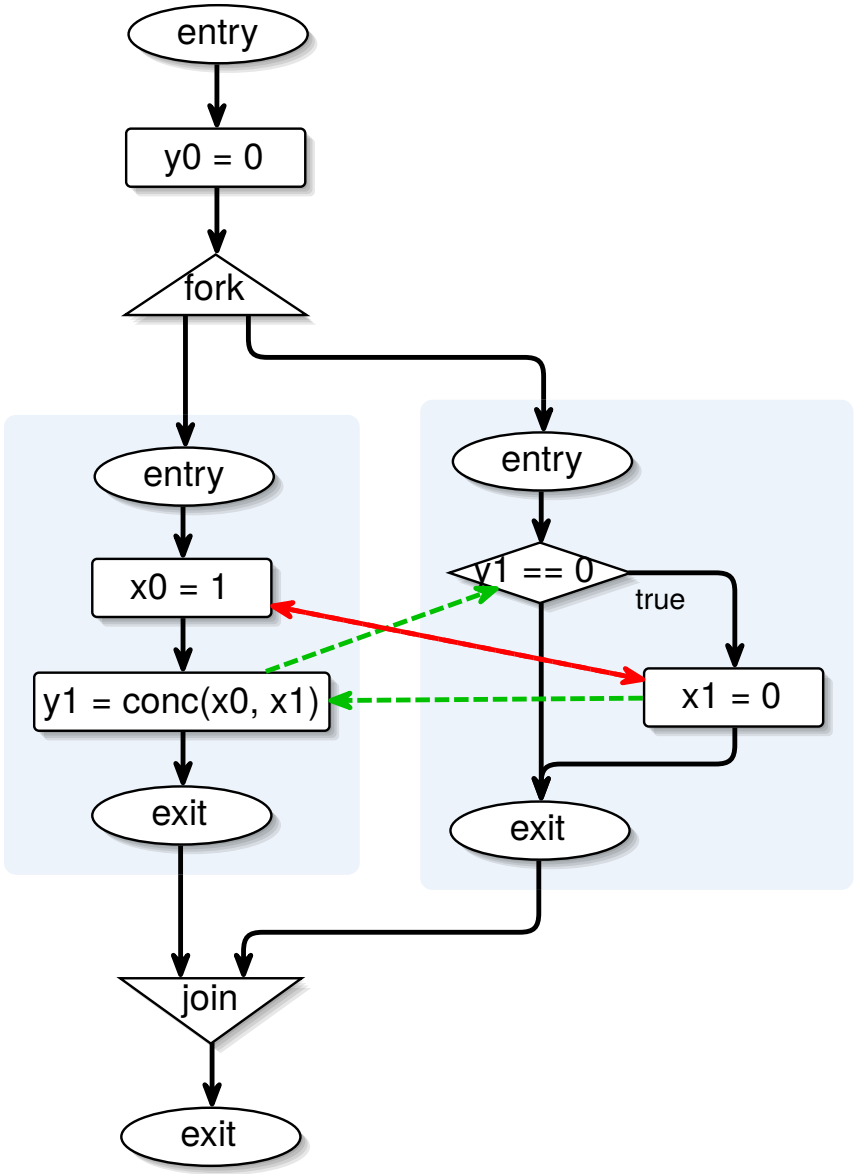
Back to P10



Back to P10


entry
y = 0
fork
entry
x = 1
y = x
exit
entry
y == 0
true
x = 0
exit
join
exit
SSA
entry
y0 = 0
fork
entry
x0 = 1
y1 = conc(x0, x1)
exit
entry
y1 == 0
true
x1 = 0
exit
join
exit

Back to P10


entry
y0 = 0
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entry
x0 = 1
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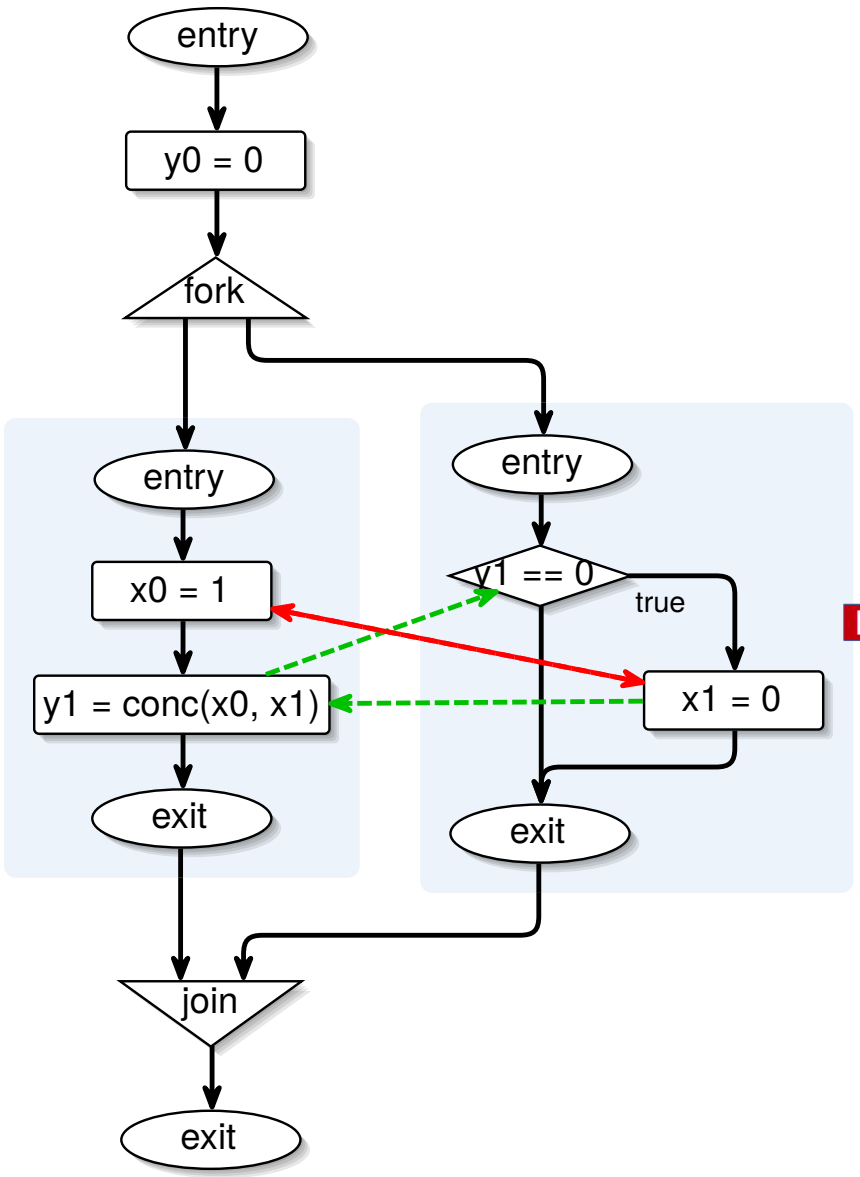
exit

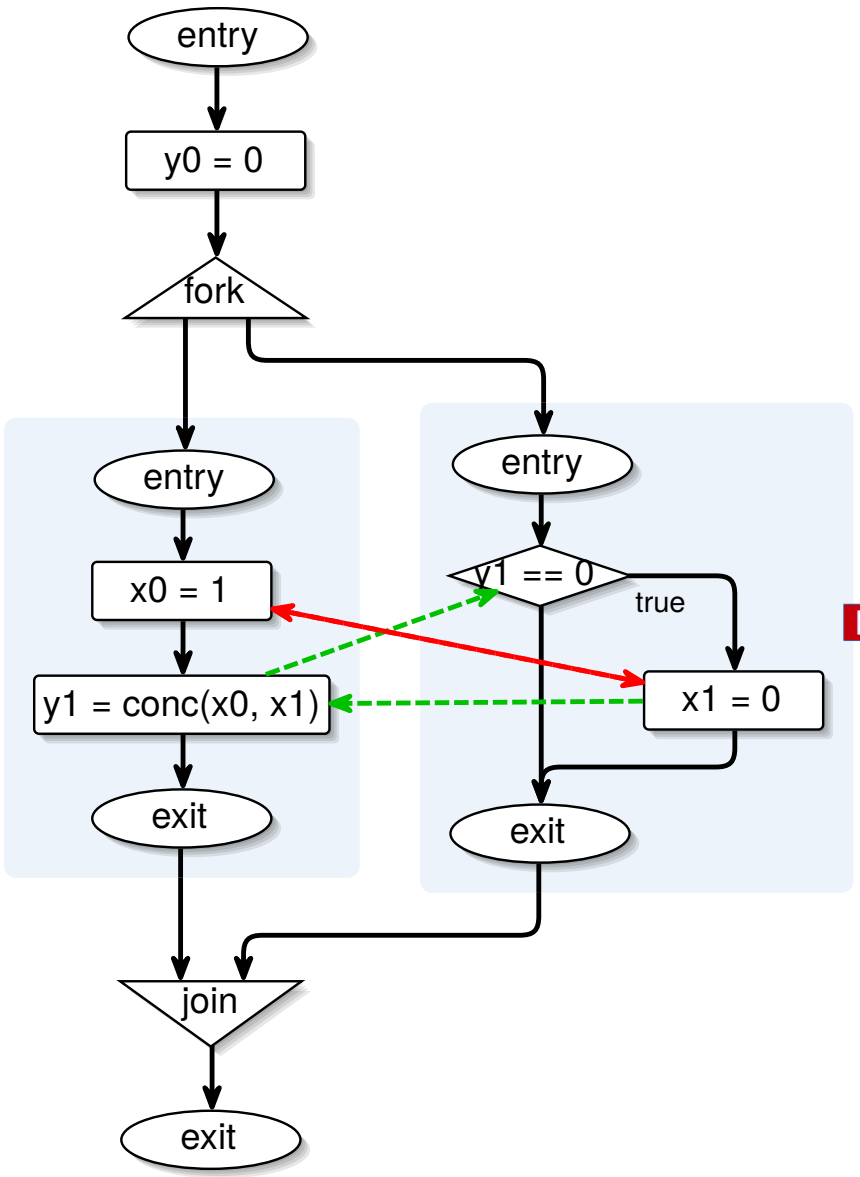
Back to P10



Esterel

```
1  module P10:
2  signal x0, not_x0, x1, not_x1 in
3  signal y0, not_y0, y1, not_y1 in
4  signal error in
5  [
6    emit not_y0;
7    [
8      emit x0;
9      present (x0 and not_x1) or
                  (not_x0 and x1) then
10       emit error
11     else
12       [
13         present x0 or x1 then
14           emit y1
15         end
16       ||
17         present not_x0 or not_x1 then
18           emit not_y1
19         end
20       ]
21     end
22   ||
23     present not_y1 then
24       emit not_x1
25     end
26   ]
27 ||
28   signal err in
29     present error then
30       present err else emit err end
31     end
32   end signal
```

Back to P10



Esterel

```
1  module P10:
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3  signal y0, not_y0, y1, not_y1 in
4  signal error in
5  [
6    emit not_y0;
7    [
8      emit x0;
9      present (x0 and not_x1) or
                 (not_x0 and x1) then
10       emit error
11     else
12       [
13         present x0 or x1 then
14           emit y1
15         end
16       ||
17         present not_x0 or not_x1 then
18           emit not_y1
19         end
20       ]
21     end
22   ||
23     present not_y1 then
24       emit not_x1
25     end
26   ]
27 ||
28   signal err in
29     present error then
30       present err else emit err end
31     end
32   end signal
```
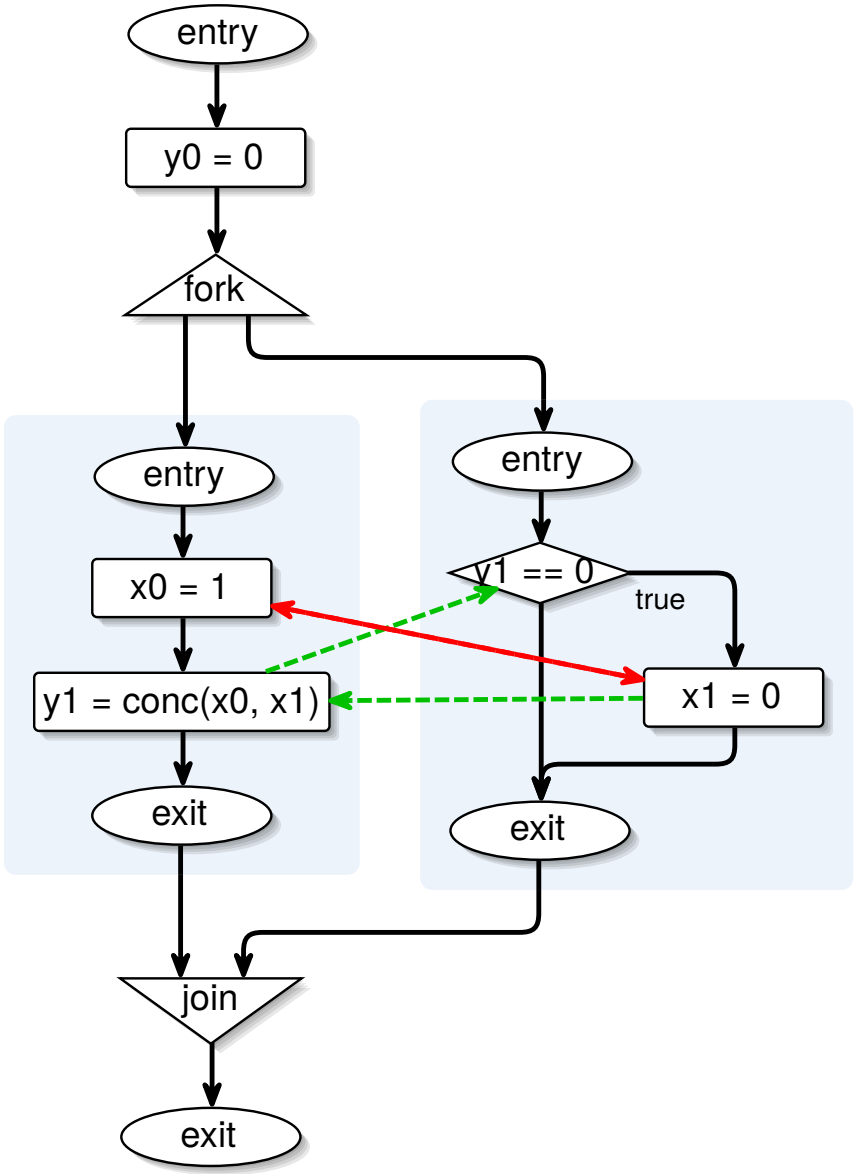
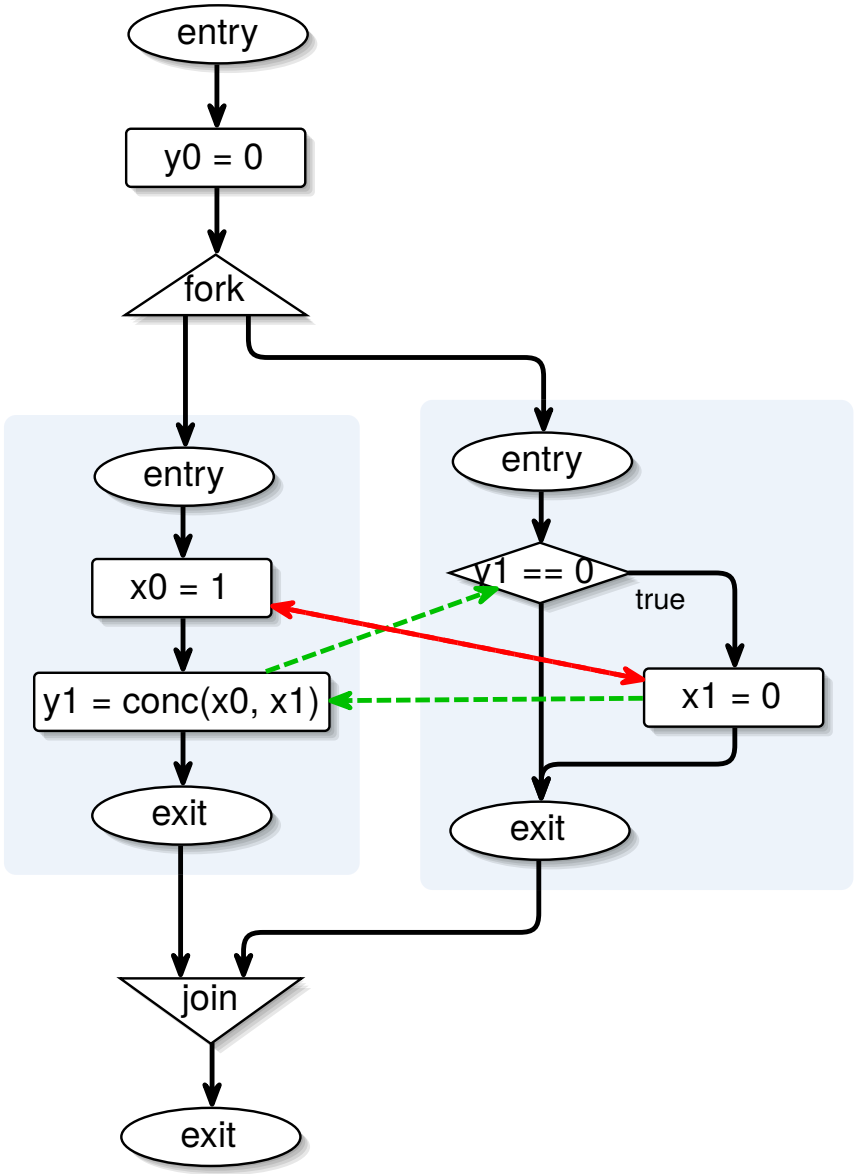

Back to P10

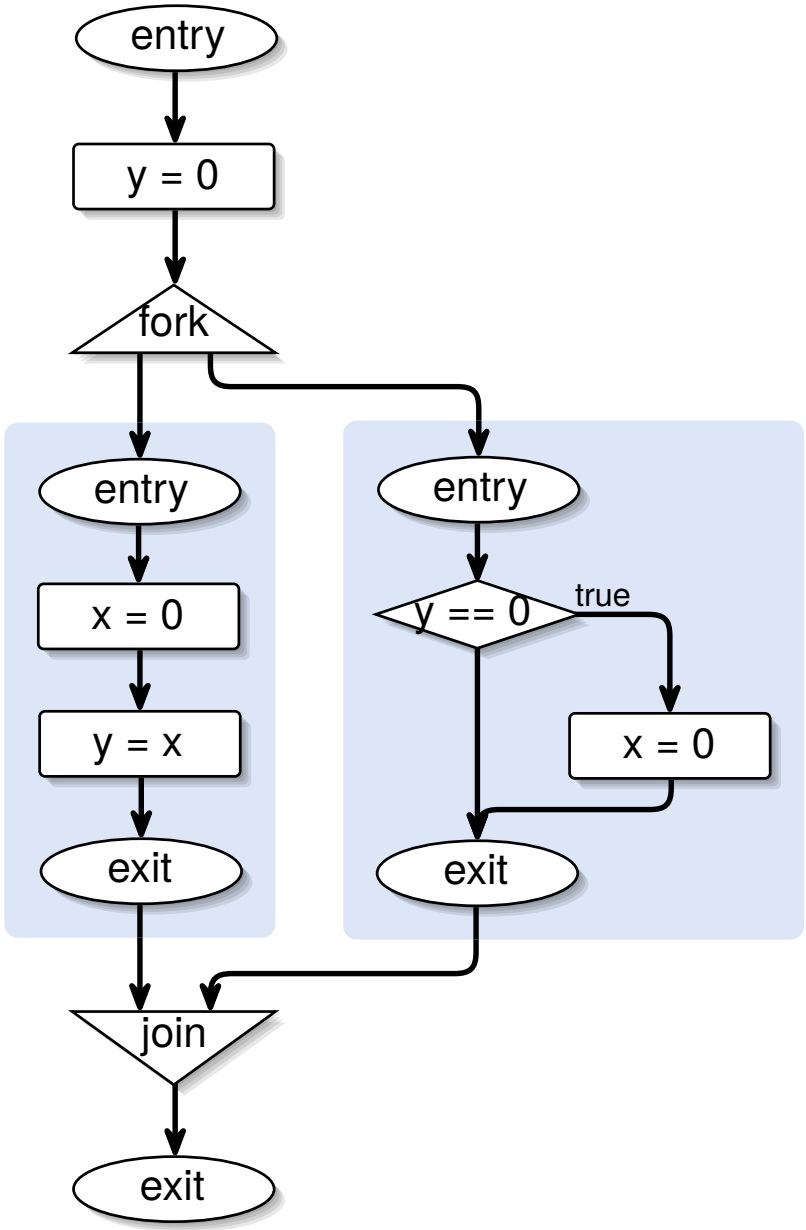

entry
y0 = 0
fork
entry
x0 = 1
y1 = conc(x0, x1)
exit
entry
y1 == 0
true
x1 = 0
exit
join
exit

Back to P10

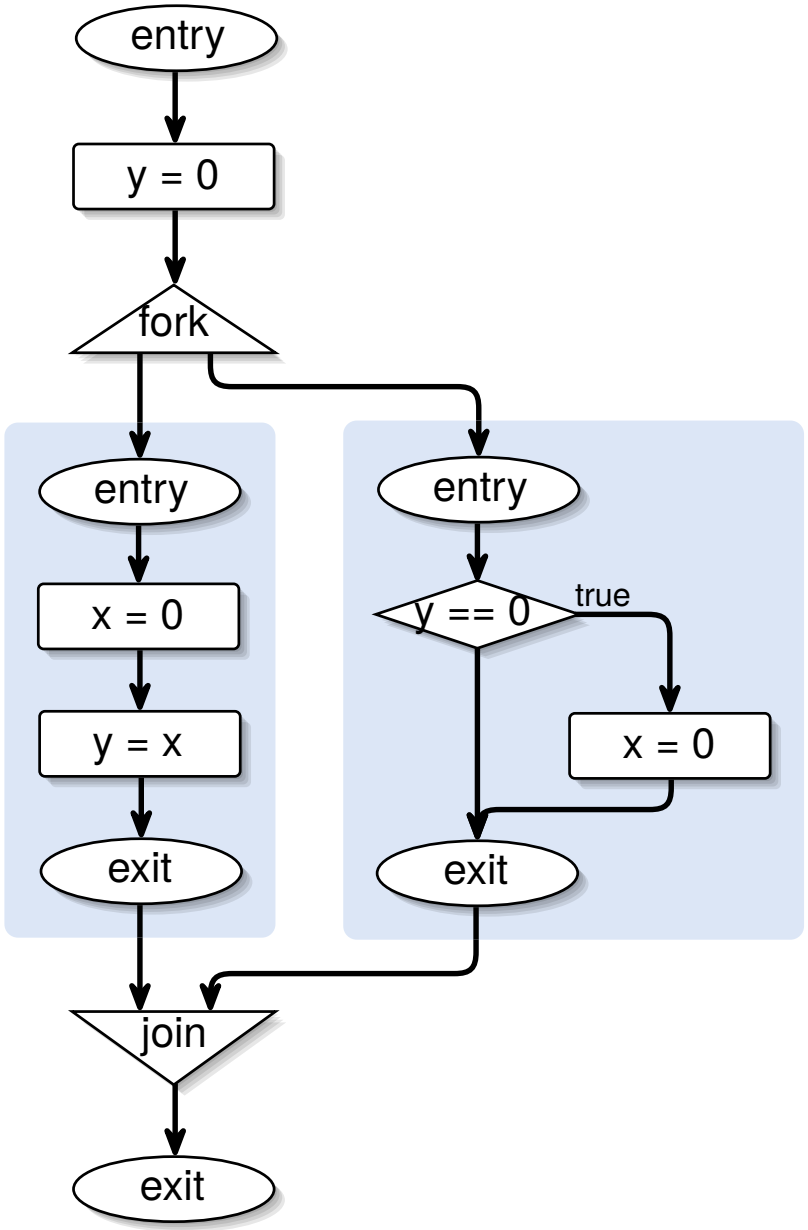


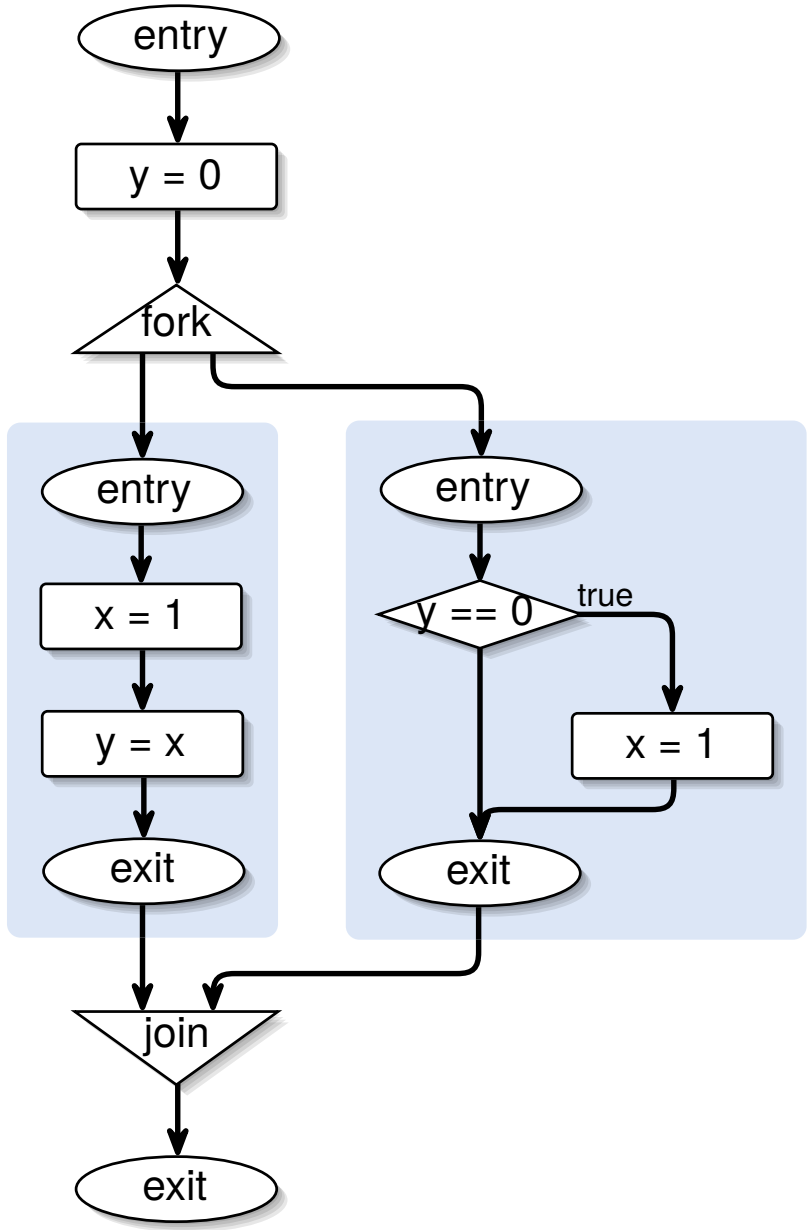
Not constructive in Esterel
$\Rightarrow$ not Strict SC

Confluent P10 Variants



Confluent P10 Variants



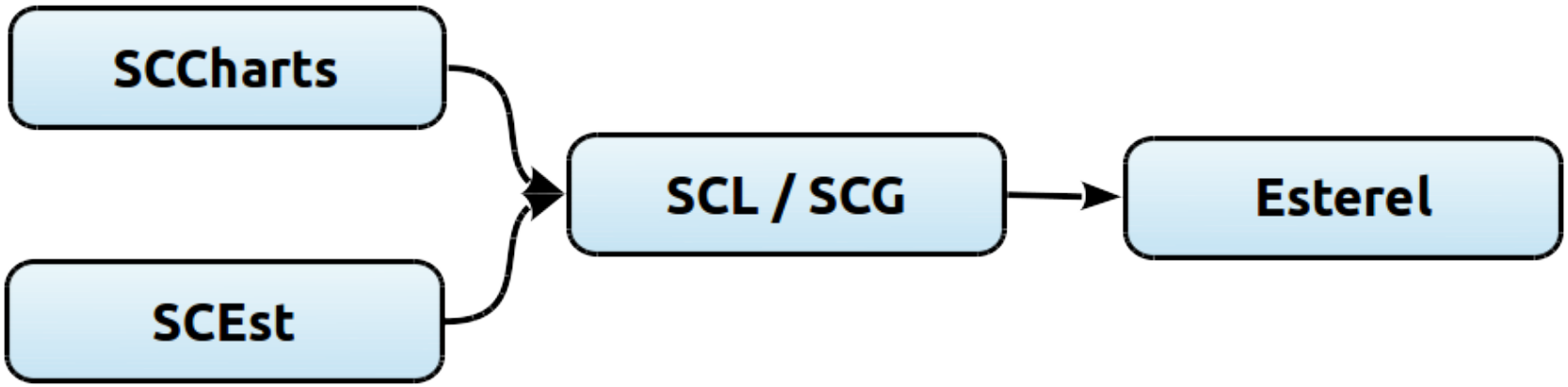


Confluent P10 Variants

```
[
  emit not_y0;
  [
    emit not_x0;
    present (x0 and not_x1) or (
         not_x0 and x1) then
      emit error
    else
      [
        present x0 or x1 then
          emit y1
        end
      ||
        present not_x0 or not_x1 then
          emit not_y1
        end
      ]
    end
  ||
    present not_y1 then
      emit not_x1
    end
  ]
||
  signal err in
  present error then
    present err else emit err end
  end
  end signal
]
```

```
[
  emit not_y0;
  [
    emit x0;
    present (x0 and not_x1) or (
         not_x0 and x1) then
      emit error
    else
      [
        present x0 or x1 then
          emit y1
        end
      ||
        present not_x0 or not_x1 then
          emit not_y1
        end
      ]
    end
  ||
    present not_y1 then
      emit x1
    end
  ]
||
  signal err in
  present error then
    present err else emit err end
  end
  end signal
]
```

New Compile Chain



Future Work

- Optimized translation for SCEst

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- Code optimization based on SSA

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- Optimized translation for SCEst
- Code optimization based on SSA
- Loop unrolling for (bounded) instantaneous loops
- Dynamic scheduling of updates
- Reduction merge expression insertion