Synchronous Languages—Lecture 12

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4 June 2020

Last compiled: June 2, 2020, 11:12 hrs

Code Generation for Sequential Constructiveness

The 5-Minute Review Session

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1. What are *Statecharts*?

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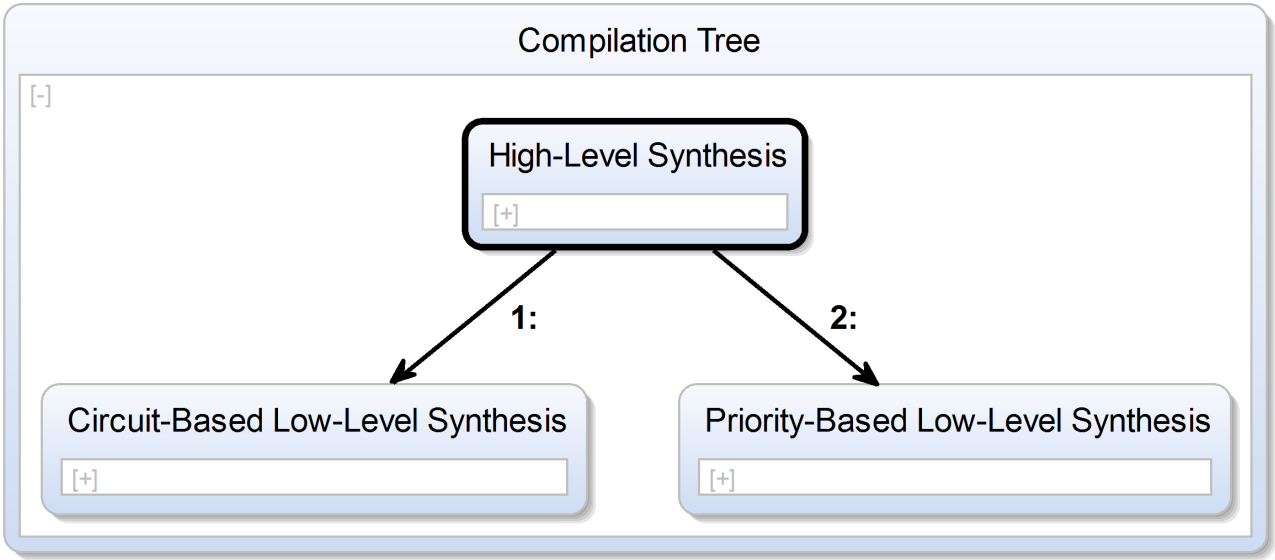
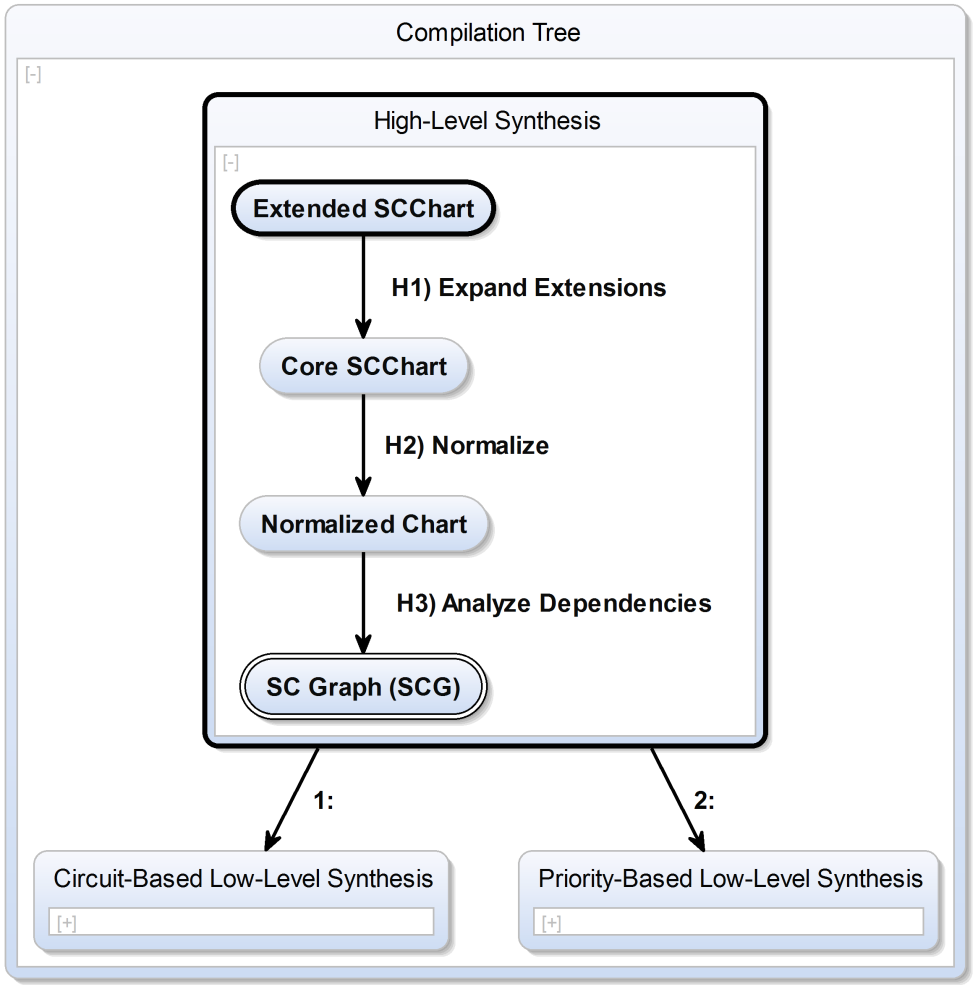
4. What are *SCCharts*? What is their motivation?
5. What are *Core SCCharts*?

Overview

Compilation — Overview



Compilation — High-Level Synthesis



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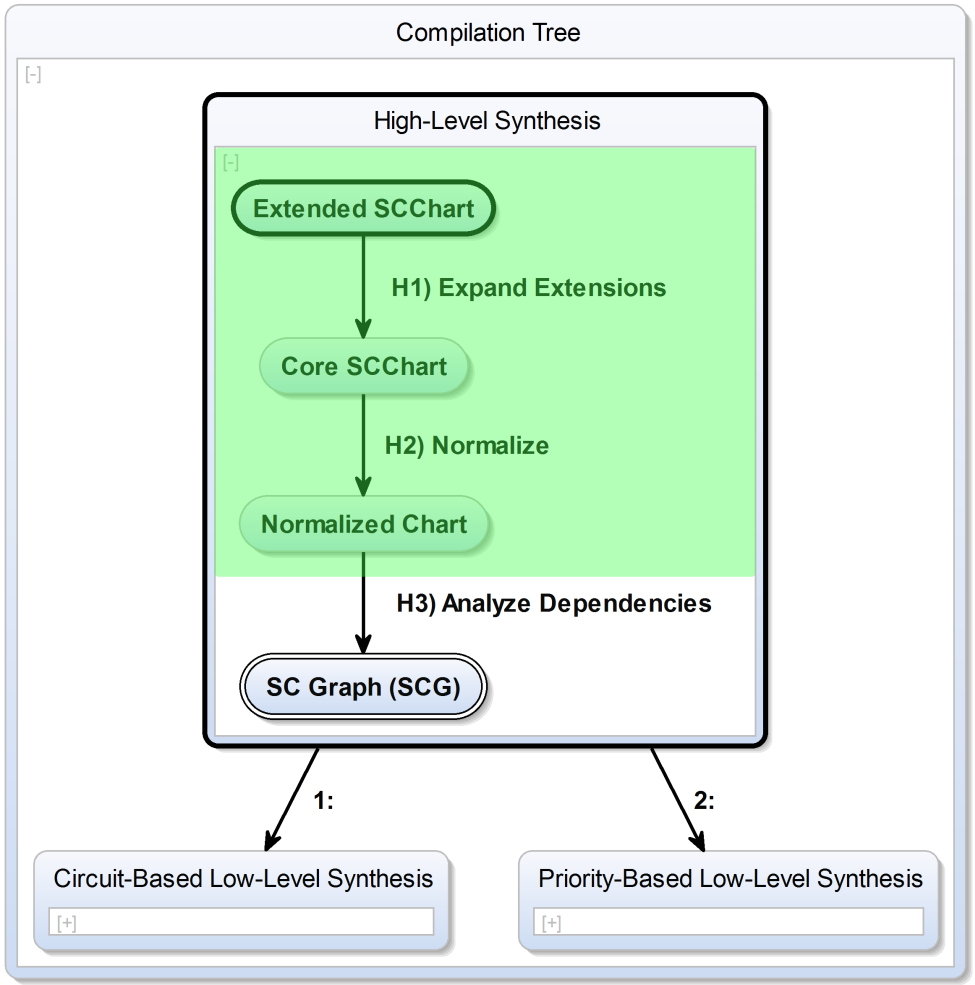
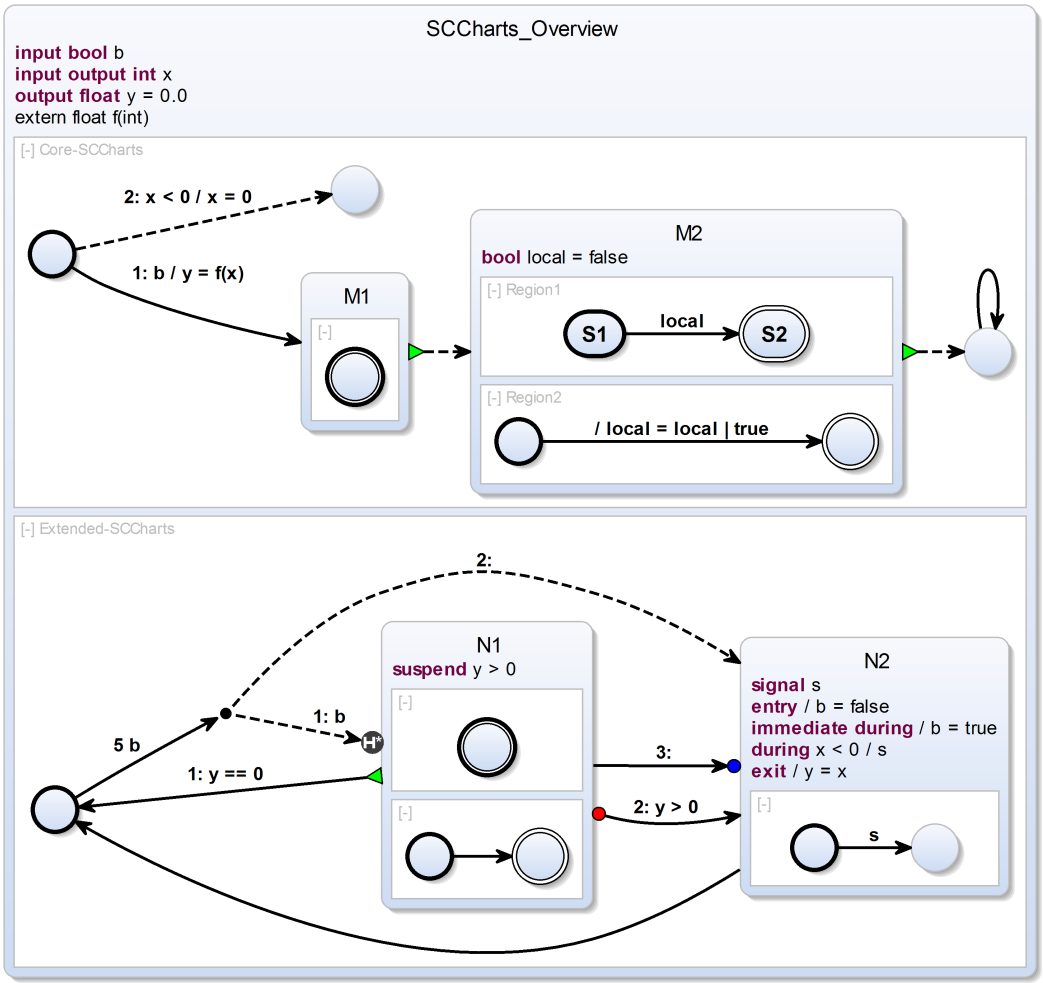


- Green:
  covered in
  previous lecture

(Recall) SCCharts - Core & Extended Features



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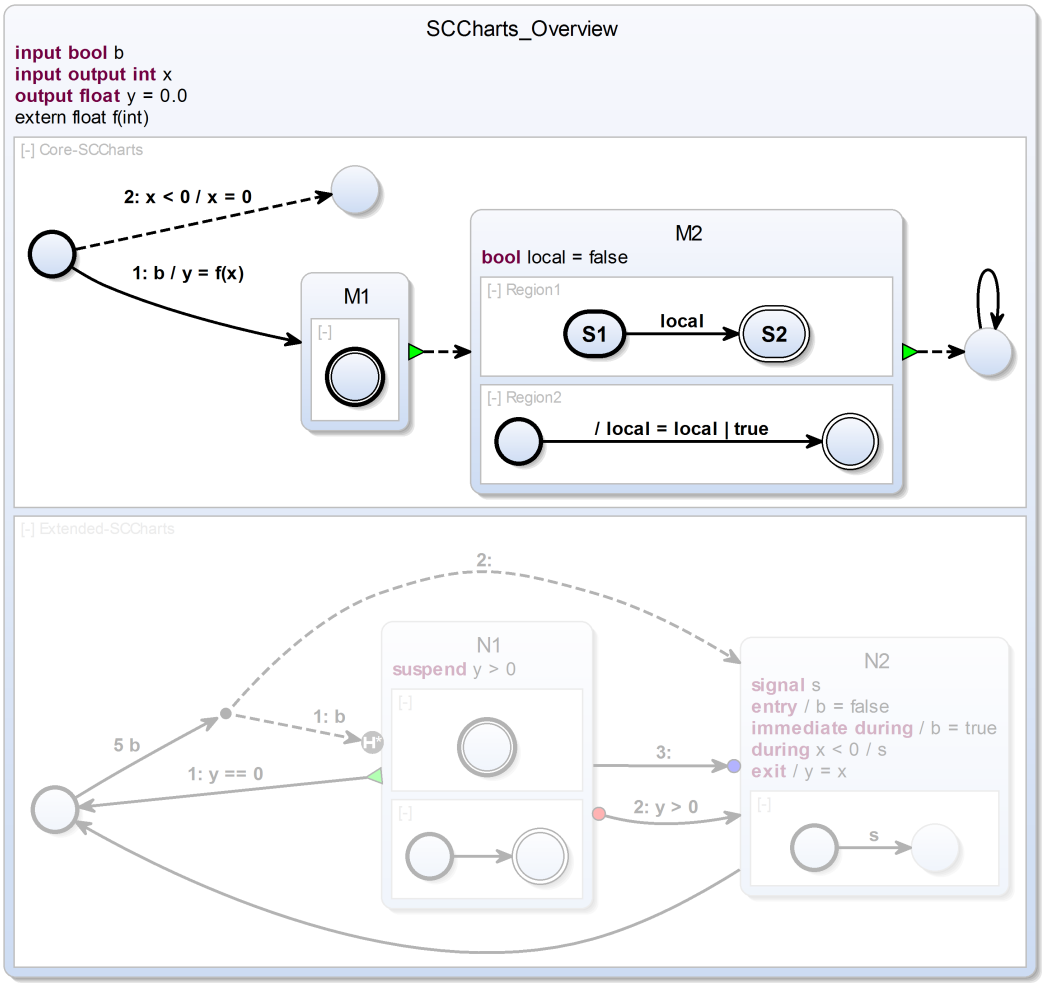

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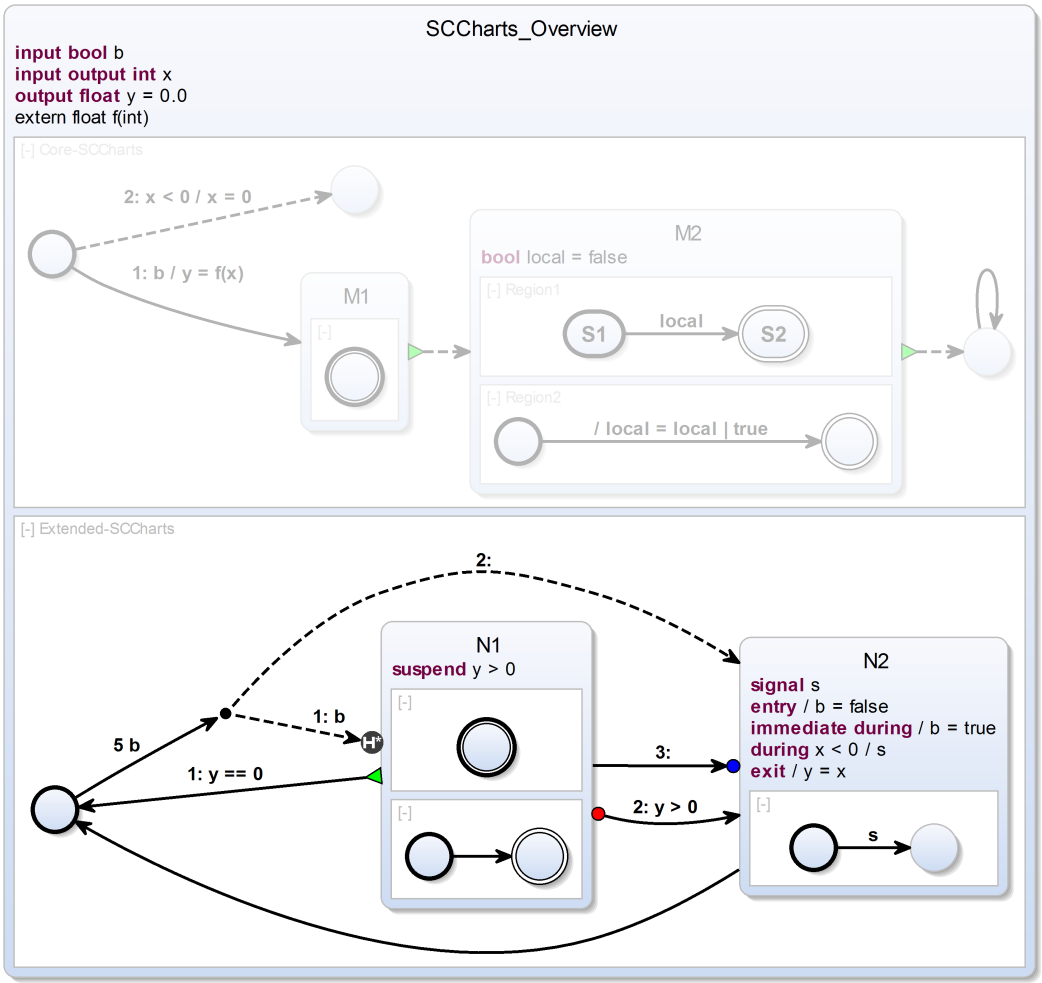

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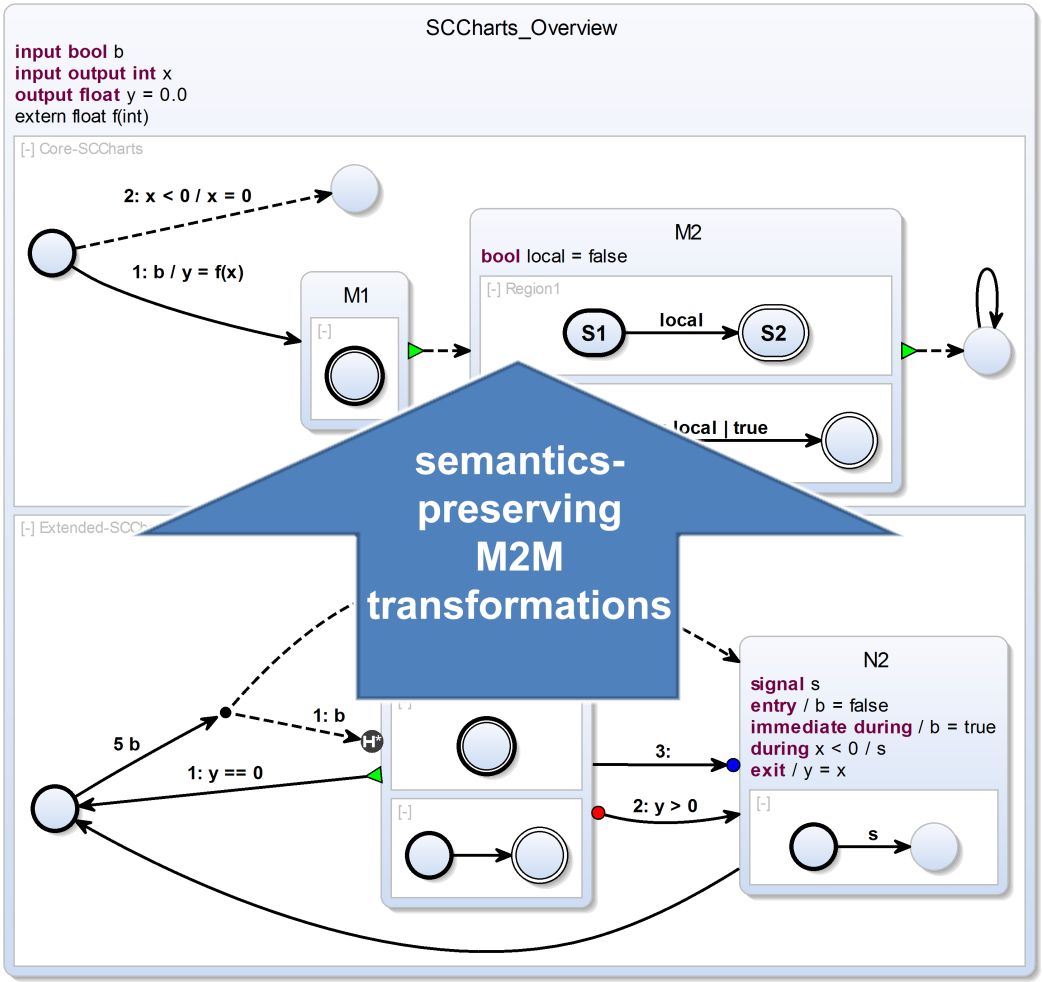

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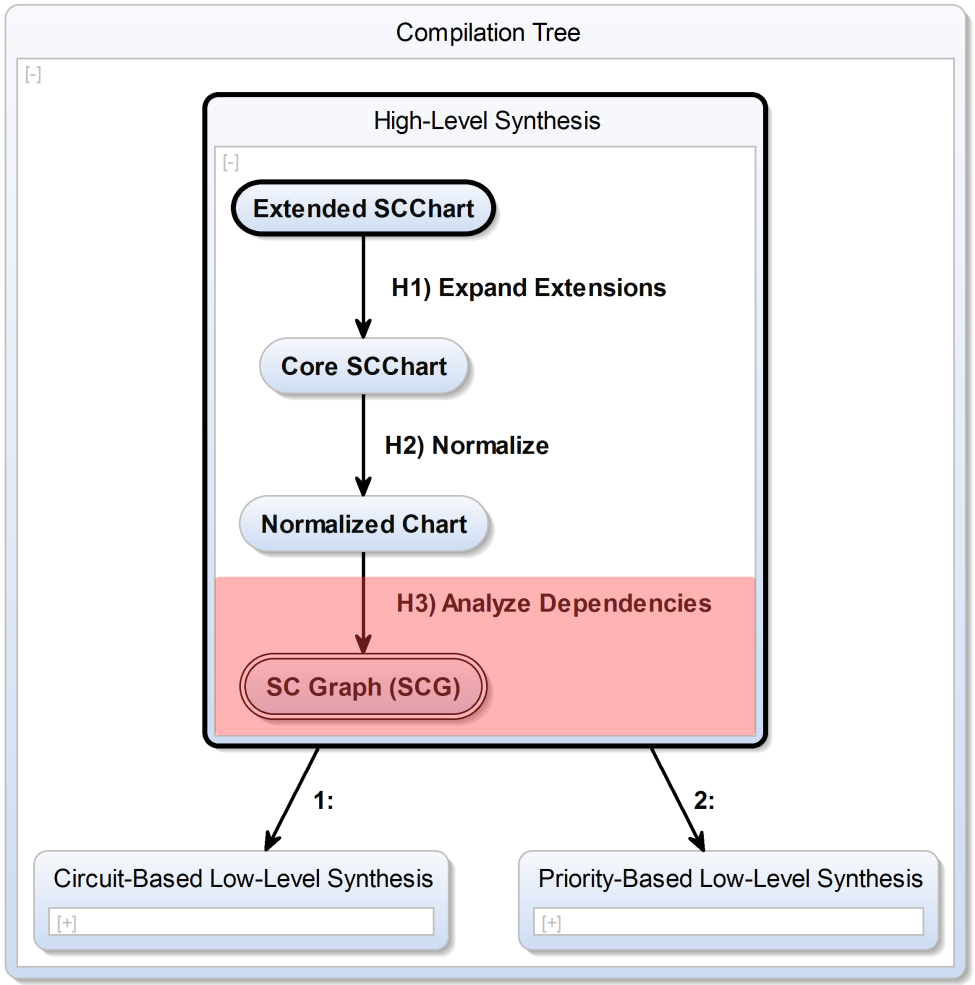
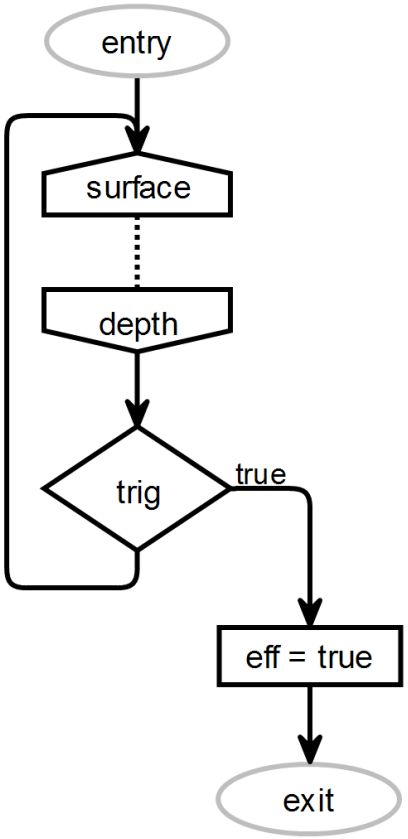


- Red:
  coming up now

Overview

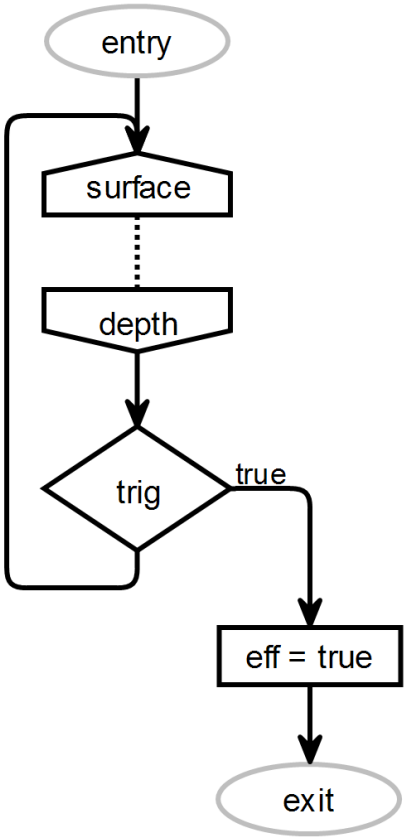
The SC Graph



SC Graph:

Labeled graph $G = (S, E)$

The SC Graph



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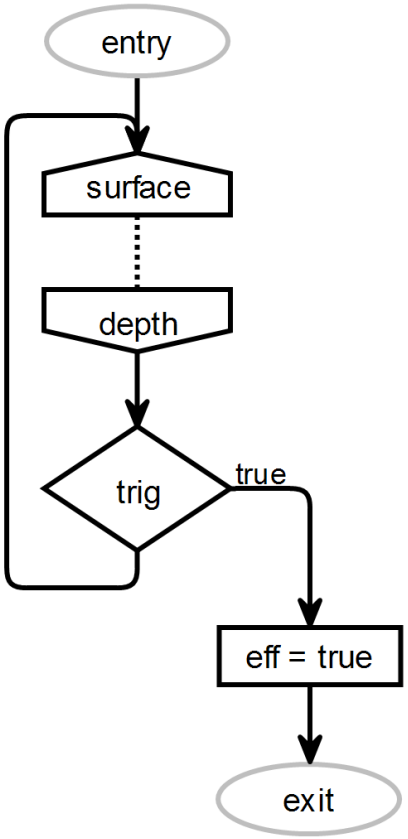
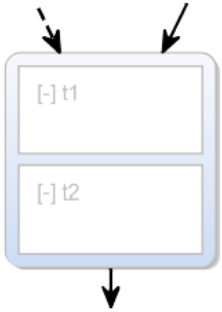
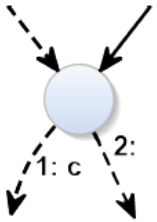
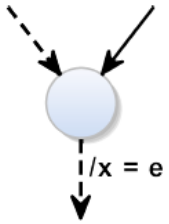
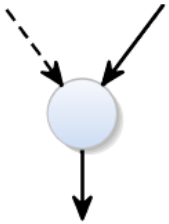


SC Graph:

Labeled graph $G = (S, E)$

- Nodes S correspond to statements of sequential program
- Edges E reflect sequential execution control flow

High-Level Step 3: Map to SC Graph

	Region (Thread)	Superstate (Concurrency)	Trigger (Conditional)	Effect (Assignment)	State (Delay)
SCCharts					

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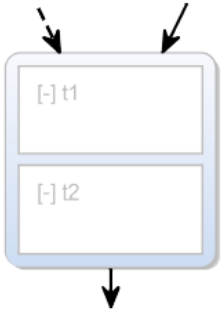
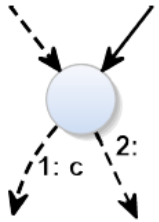
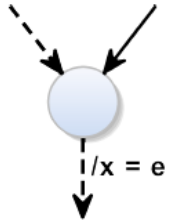
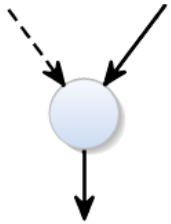
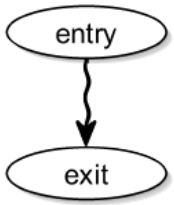
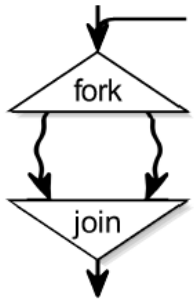
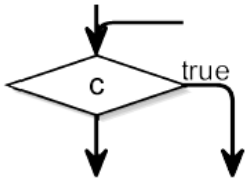
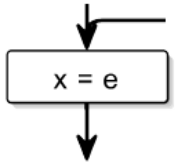
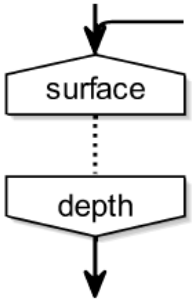
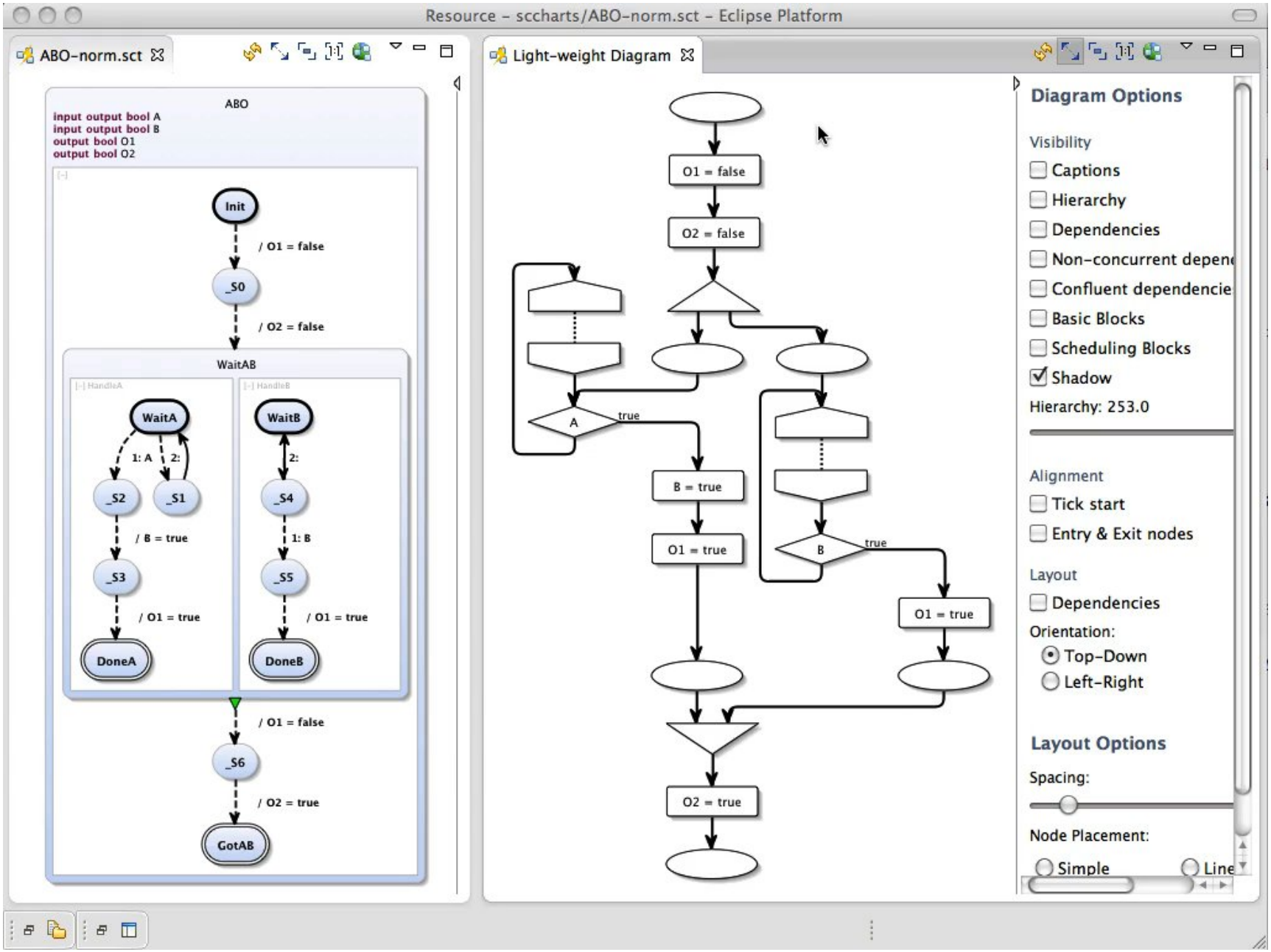
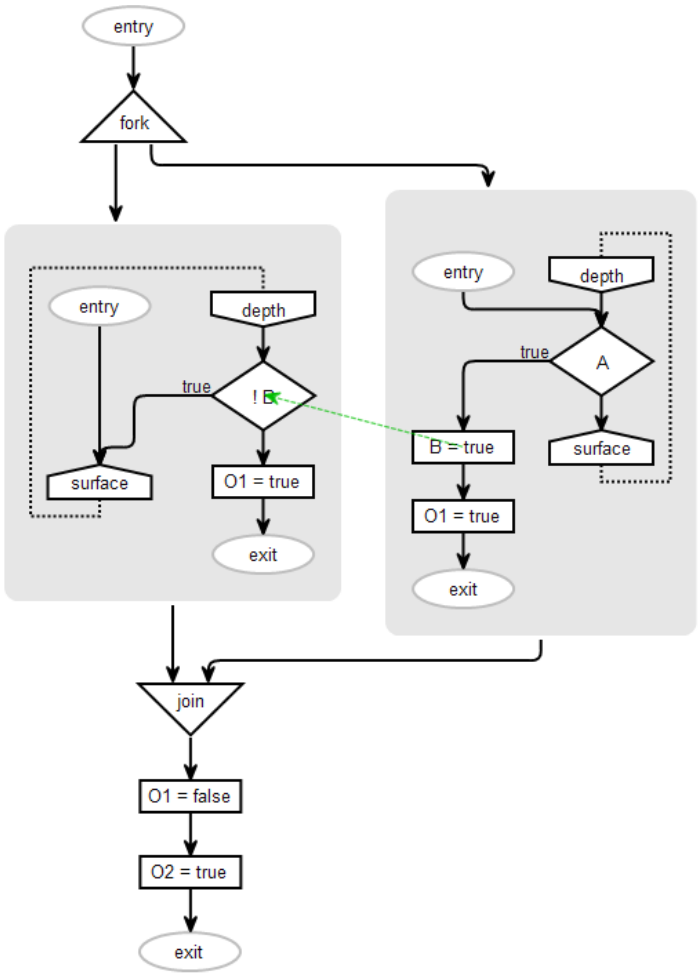
SCCharts					
SCG					
SCL	t	fork t_1 par t_2 join	if (c) s_1 else s_2	$x = e$	pause

Example: Mapping ABO to SCG



The SC Graph — Dependencies



Two assignments within the SC Graph are concurrent iff

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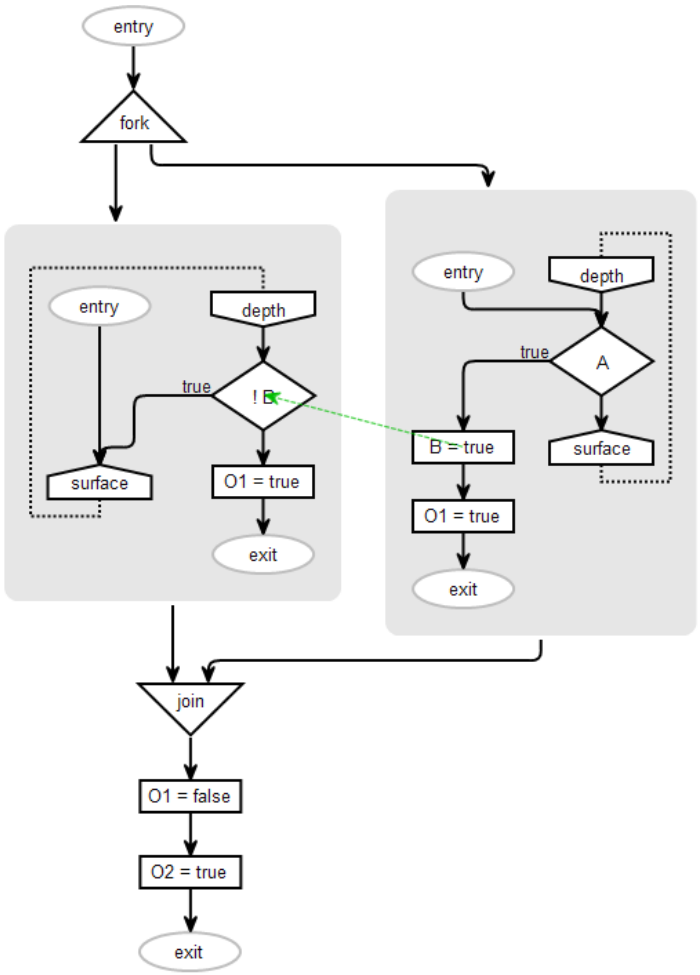

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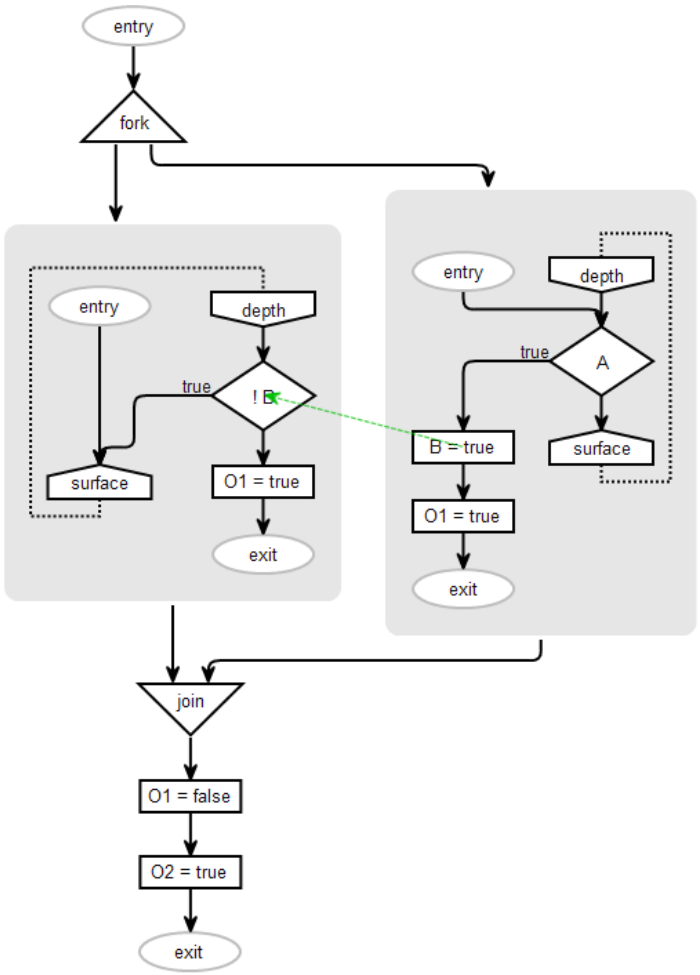

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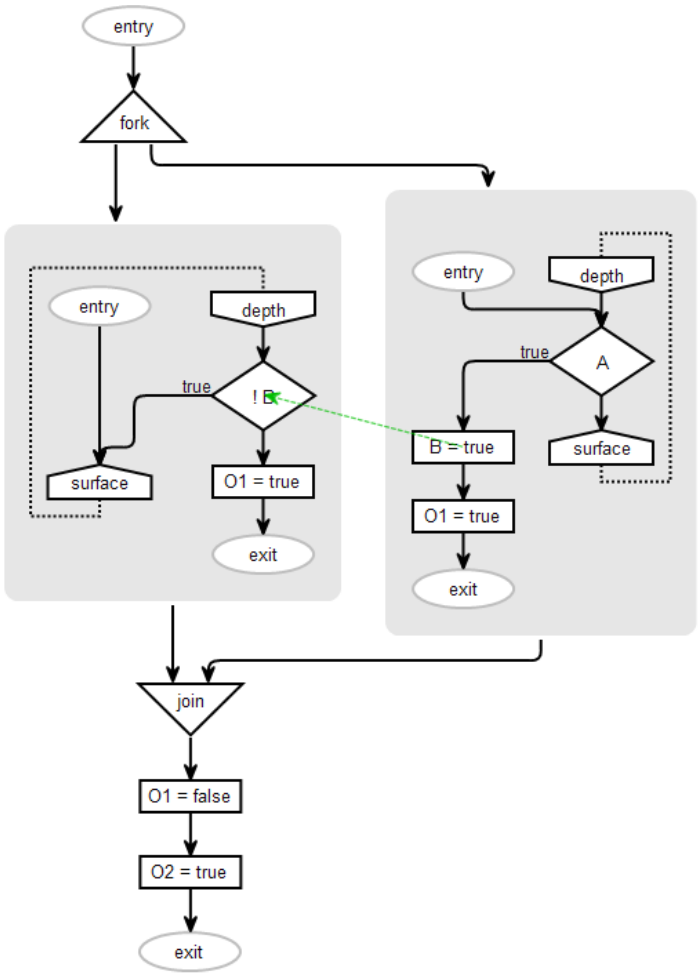

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Two assignments are confluent iff

- the order of their assignments does not matter.

Dependency Types

Dependencies are further categorized in

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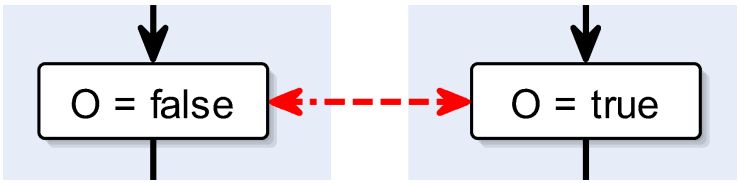

write—write

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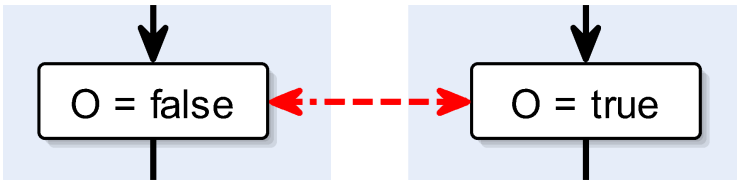

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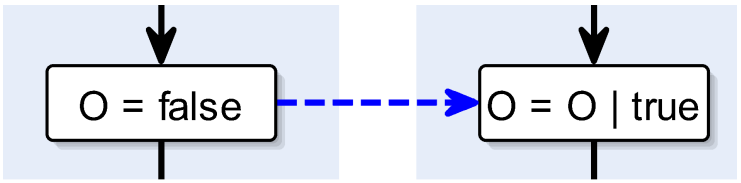

abs. write—rel. write

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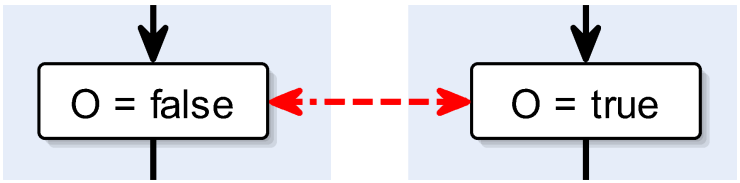

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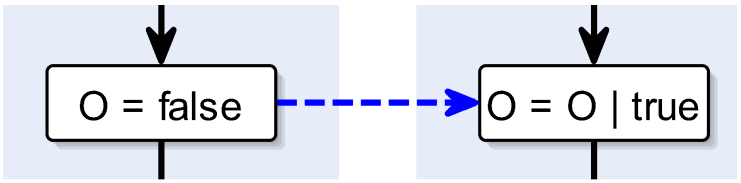

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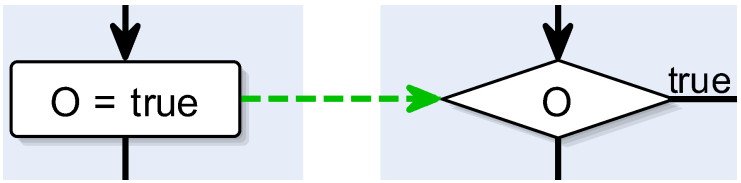

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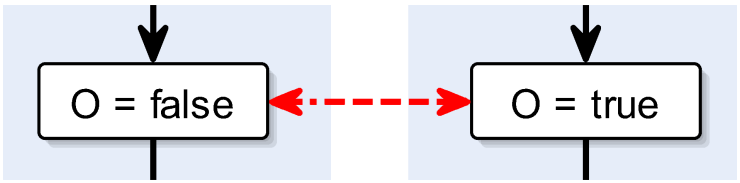

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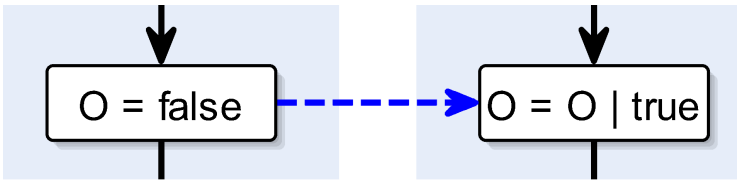

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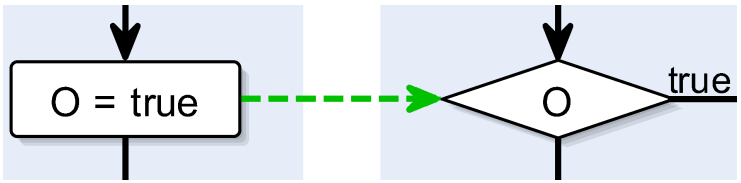

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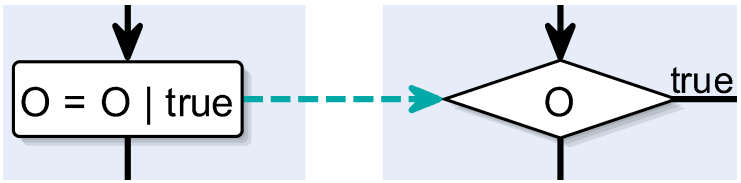

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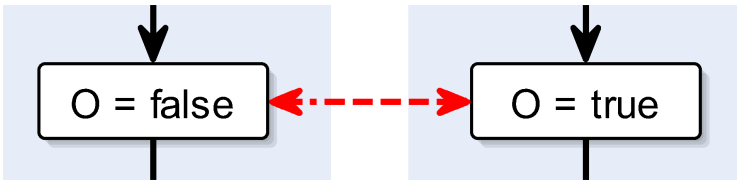

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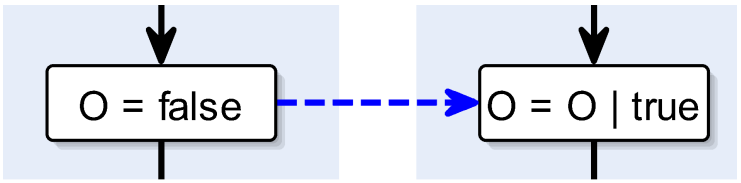

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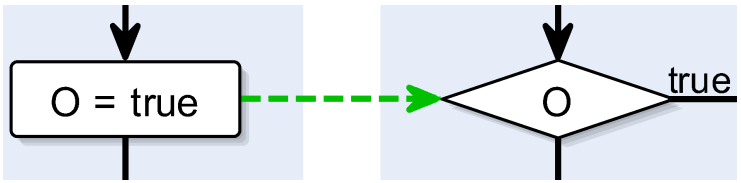

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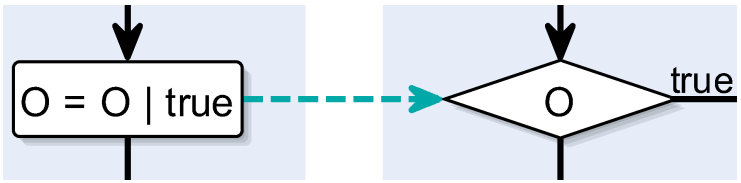


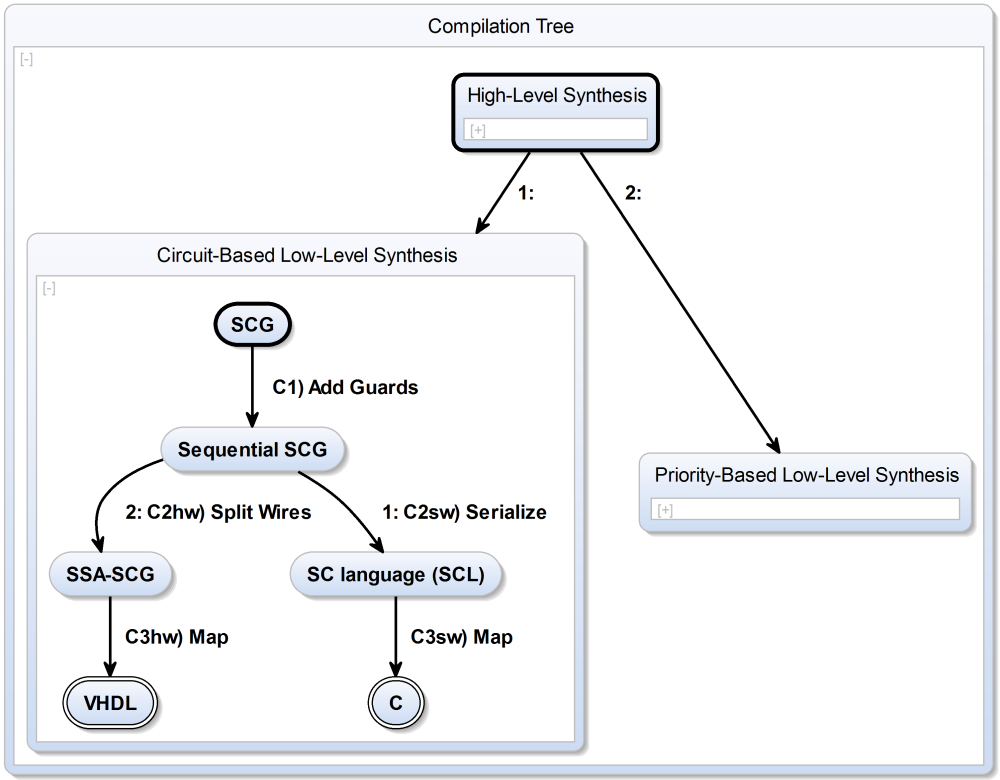
rel. write—read

The SC MoC employs a strict "initialize - update - read" protocol.

(More on the SC MoC will follow in next lecture.)

Overview

Low-Level Synthesis I: The Circuit Approach



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  Generate netlist
- Precondition:
  Acyclic SCG
  (with dependency edges, but without tick edges)
- Well-established approach for compiling SyncCharts/Esterel

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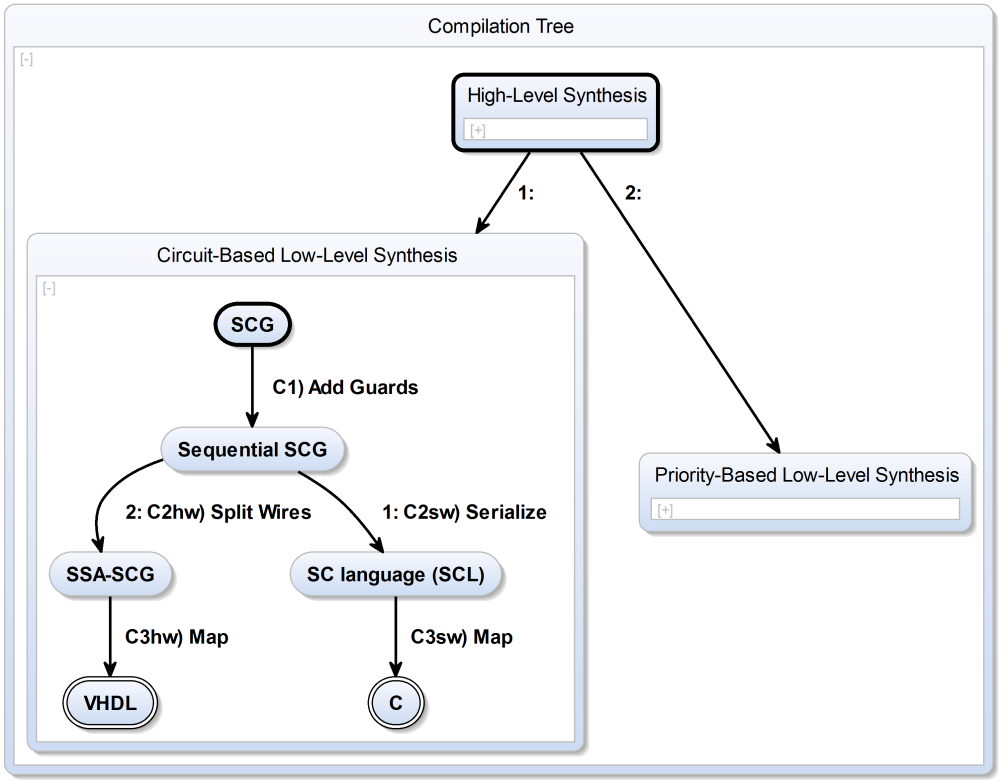

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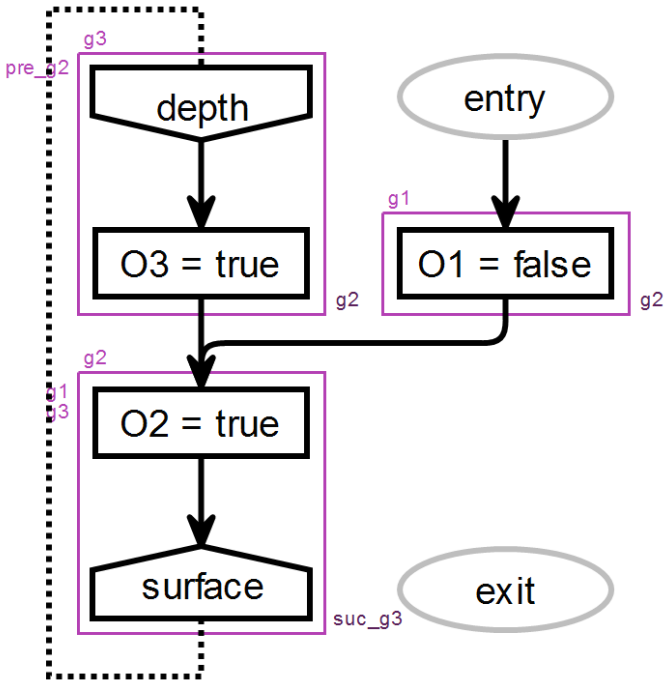
Differences to Esterel circuit semantics [Berry '02]

1. Simpler translation rules, as aborts/traps/suspensions already transformed away during high-level synthesis
2. SC MoC permits sequential assignments

Basic Blocks



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A collection of SCG nodes / SCL statements

- that can be executed monolithically

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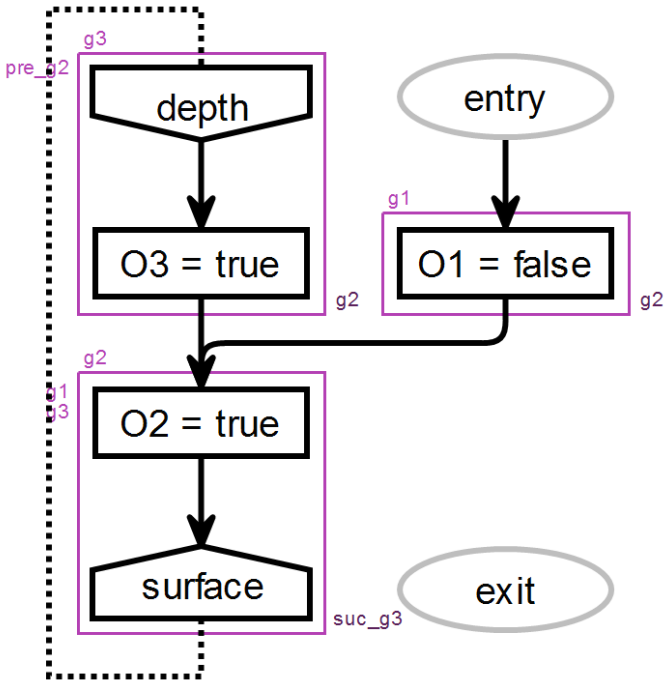

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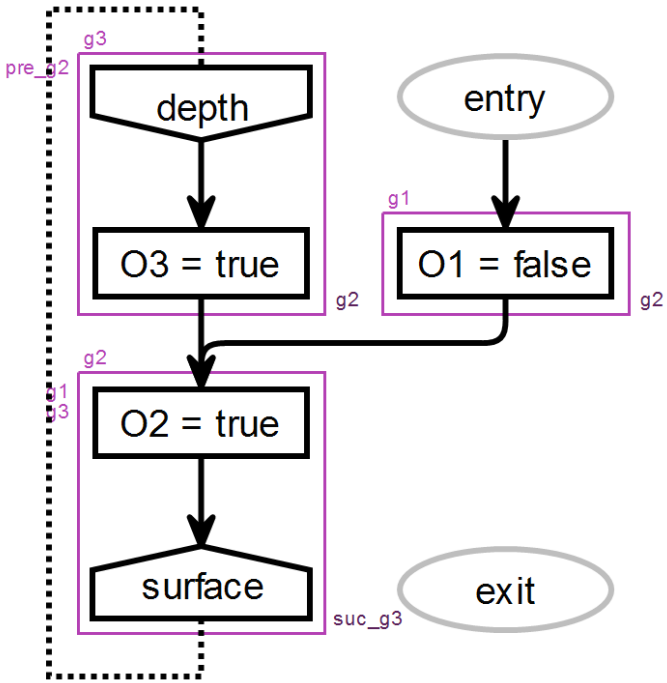

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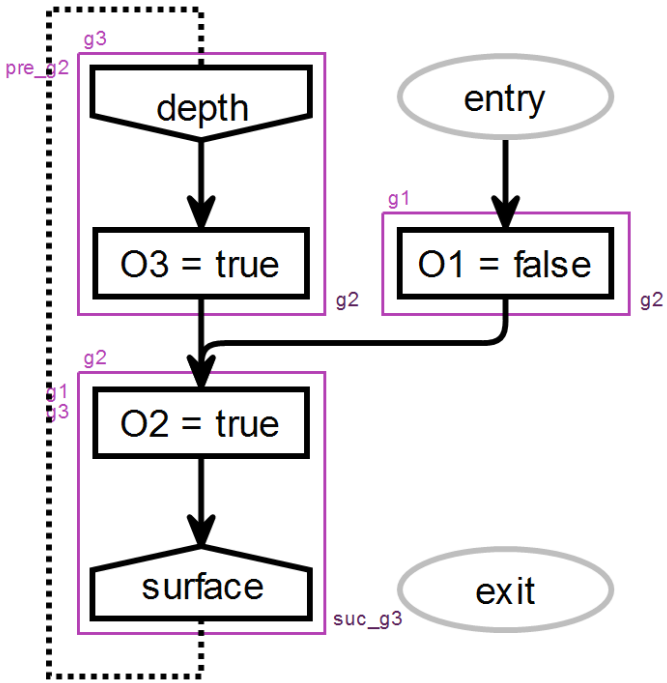

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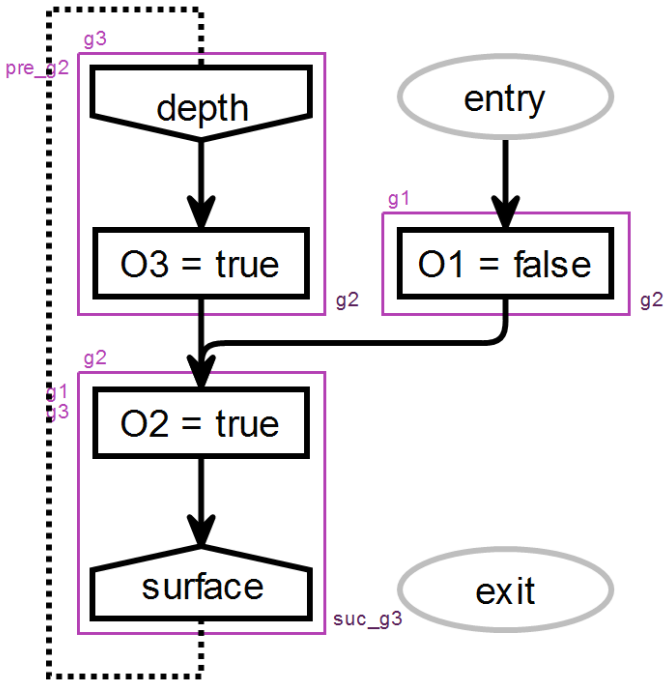

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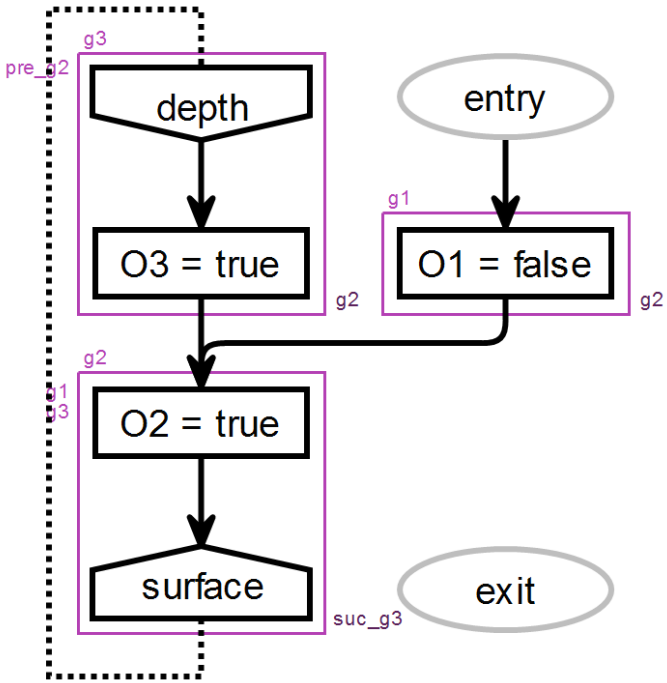
- Split at nodes with more than one outgoing control flow edge
- Split at tick edges
- Split after fork nodes and before join nodes

Basic Blocks



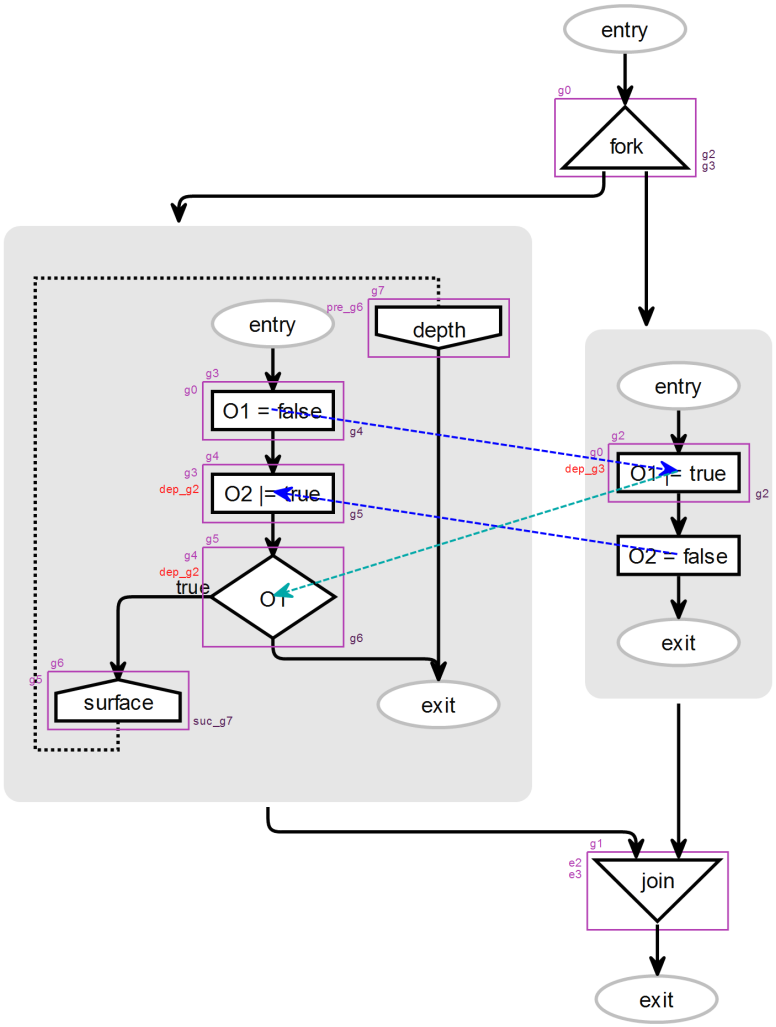
Basic Block:
A collection of SCG nodes / SCL statements

- that can be executed monolithically

Rules:

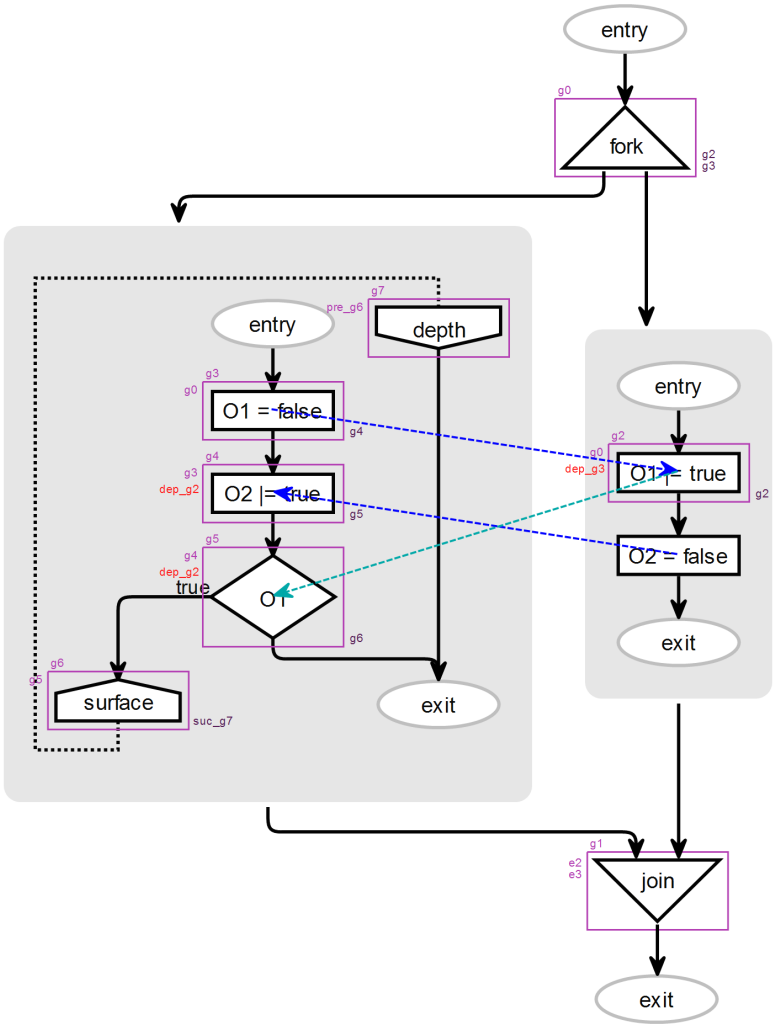
- Split at nodes with more than one incoming control flow edge
- Split at nodes with more than one outgoing control flow edge
- Split at tick edges
- Split after fork nodes and before join nodes
- **Each node can only be included in one basic block at any time**

Scheduling Blocks



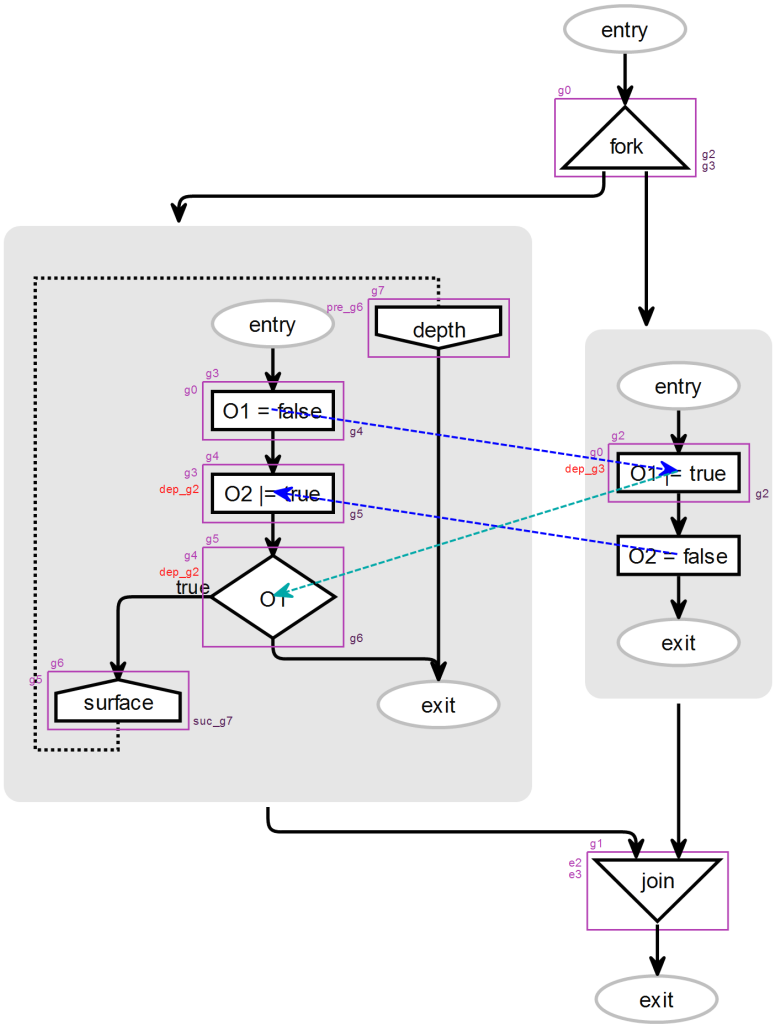
- Basic blocks may be interrupted when a data dependency interferes.

Scheduling Blocks



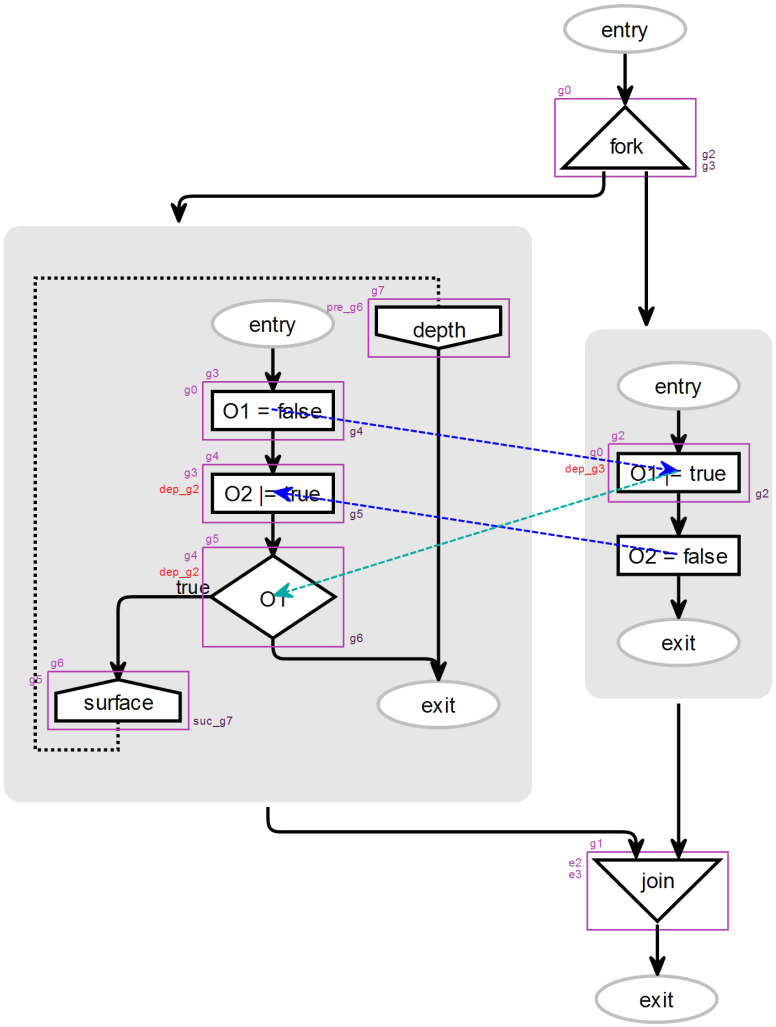
- Basic blocks may be interrupted when a data dependency interferes.
- Structure basic blocks further: Scheduling Blocks

Scheduling Blocks

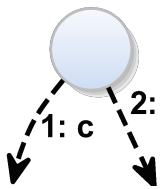
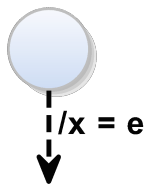
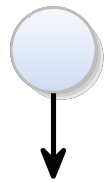
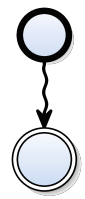
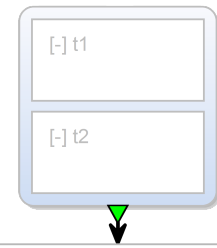


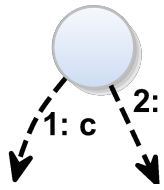
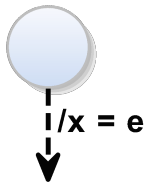
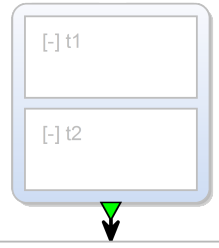
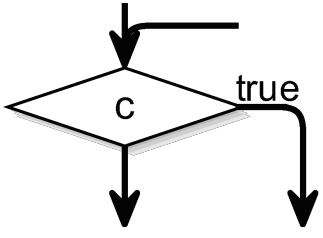
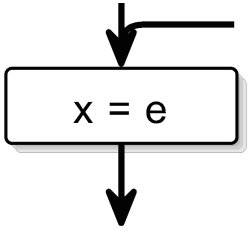
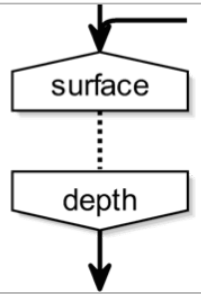
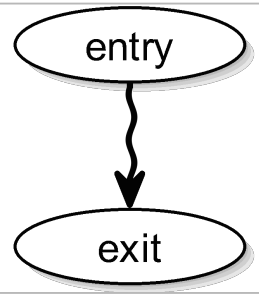
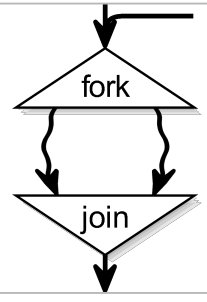
- Basic blocks may be interrupted when a data dependency interferes.
- Structure basic blocks further: Scheduling Blocks
- Rules:
  - Split a basic block at incoming dependency edge

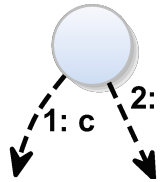
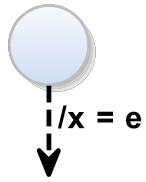
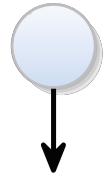
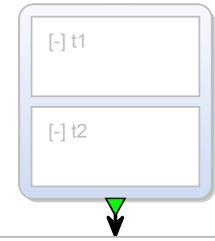
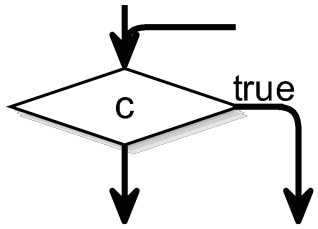
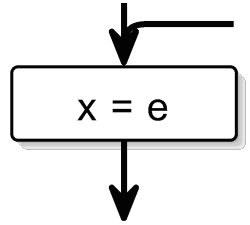
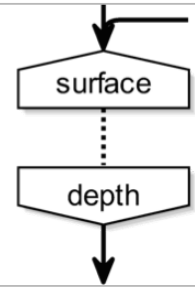
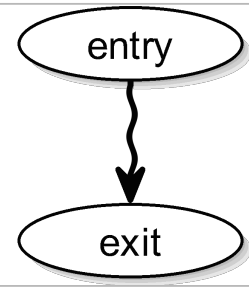
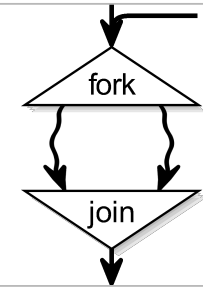
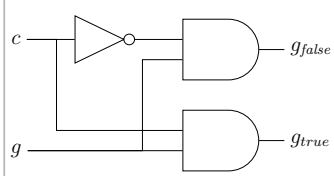
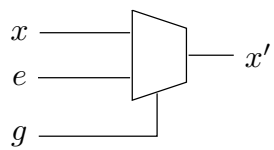
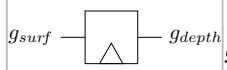
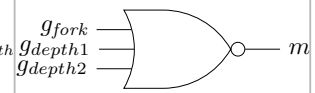
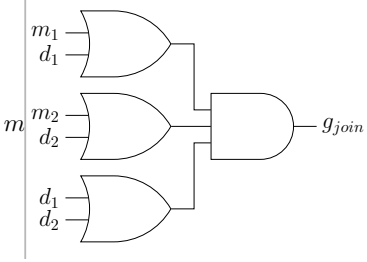
Scheduling Blocks



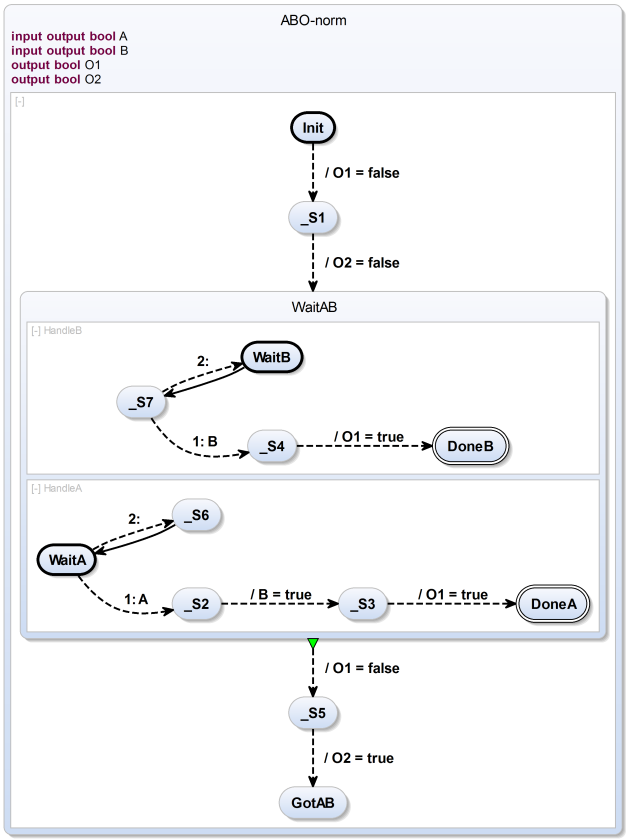
- Basic blocks may be interrupted when a data dependency interferes.
- Structure basic blocks further: Scheduling Blocks
- Rules:
  - Split a basic block at incoming dependency edge
- But...
  - want to minimize the number of context switches
  - $\Rightarrow$ Room for optimization!

	Trigger (Conditional)	Effect (Assignment)	State (Delay)	Region (Thread)	Superstate (Concurrency)
Normalized Core SCCharts					

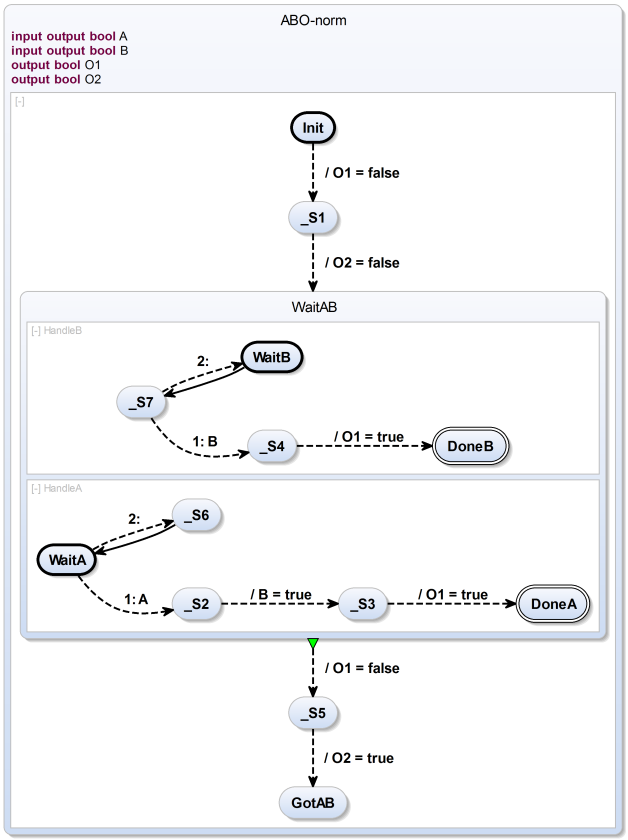
	Trigger (Conditional)	Effect (Assignment)	State (Delay)	Region (Thread)	Superstate (Concurrency)
Normalized Core SCCharts					
SCL	if (*c*) s_1 else s_2	$x = e$	pause	t	fork t_1 par t_2 join
SCG					

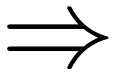
	Trigger (Conditional)	Effect (Assignment)	State (Delay)	Region (Thread)	Superstate (Concurrency)
Normalized Core SCCharts					
SCL	if (c) s_1 else s_2	$x = e$	pause	t	fork t_1 par t_2 join
SCG					
Data-Flow Code	$g = \vee g_{in}$ $g_{true} = g \wedge c$ $g_{false} = g \wedge \neg c$	$g = \vee g_{in}$ $x' = g \; ? \; e : x$	$g_{surf} = \vee g_{in}$ $g_{depth} =$ pre (g_{surf})	$d = g_{exit}$ $m = \neg (g_{fork} \vee$ $\bigvee_{depth \in t} g_{depth})$	$g_{fork} = \vee g_{in}$ $g_{join} = (d_1 \vee m_1)$ $\wedge (d_2 \vee m_2)$ $\wedge (d_1 \vee d_2)$
Circuits					

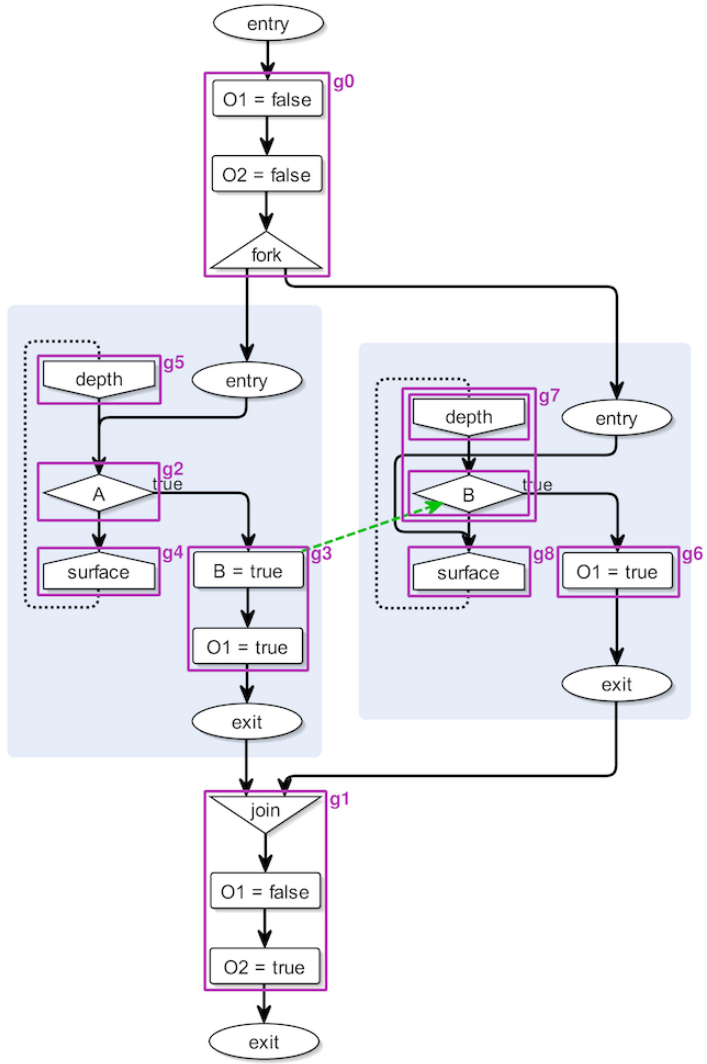
ABO SCG, With Dependencies and Scheduling Blocks

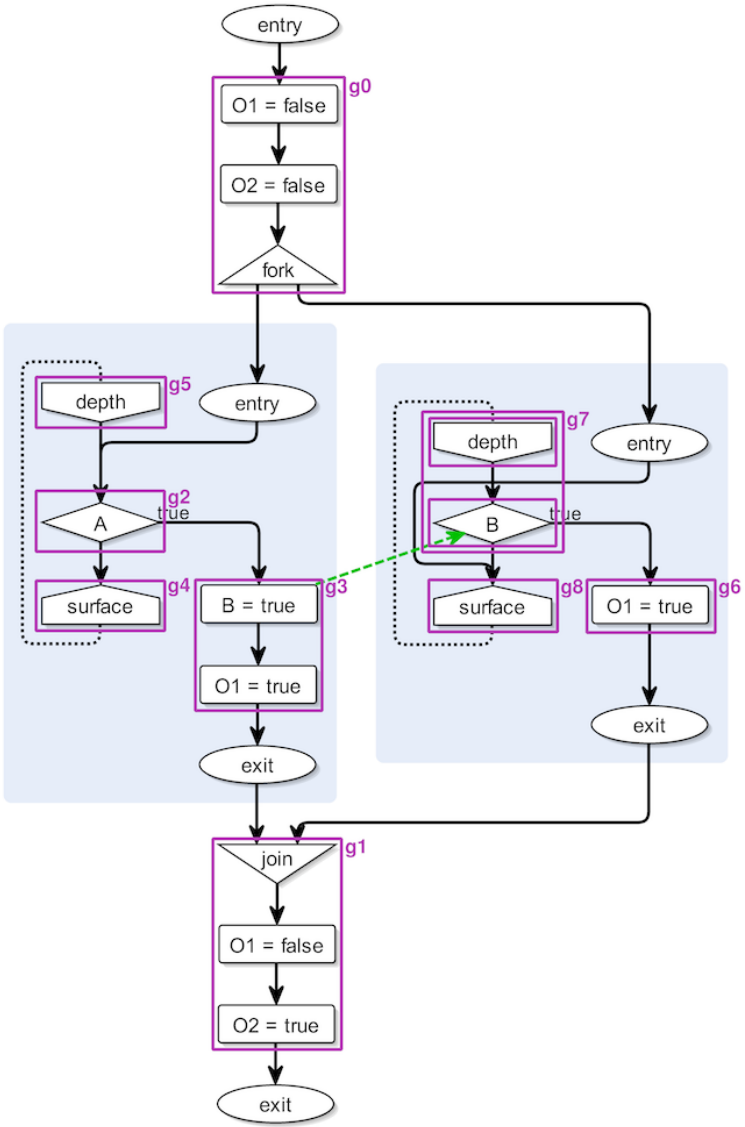


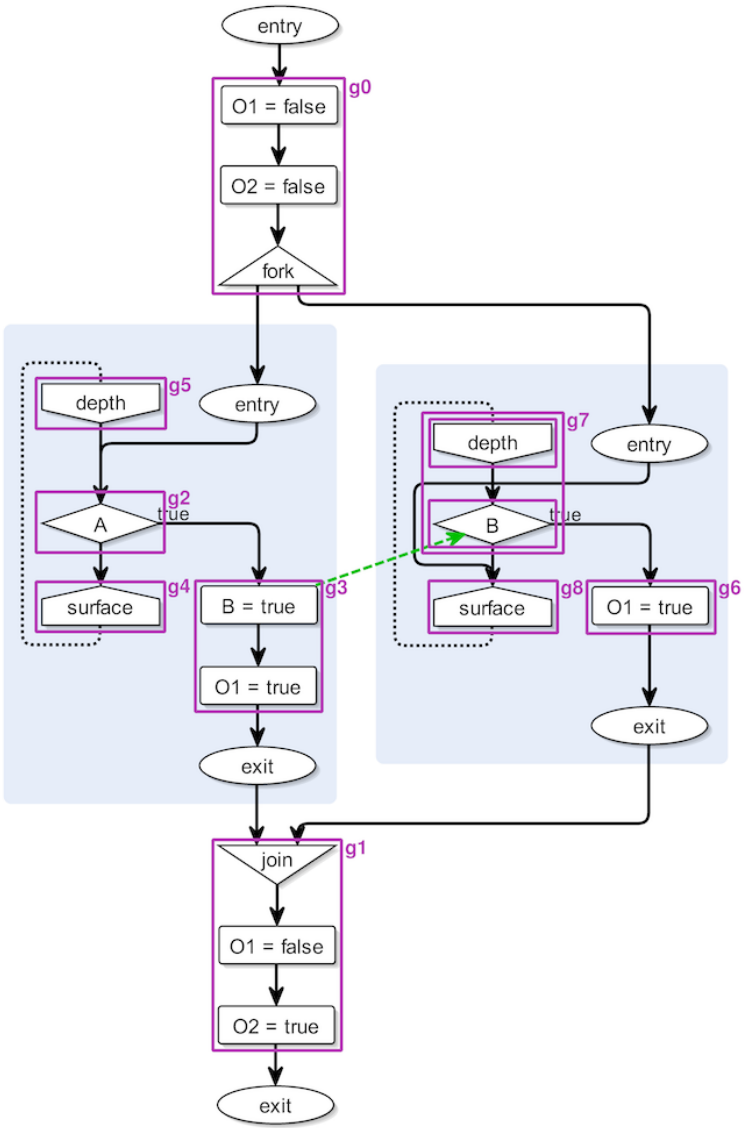
ABO SCG, With Dependencies and Scheduling Blocks



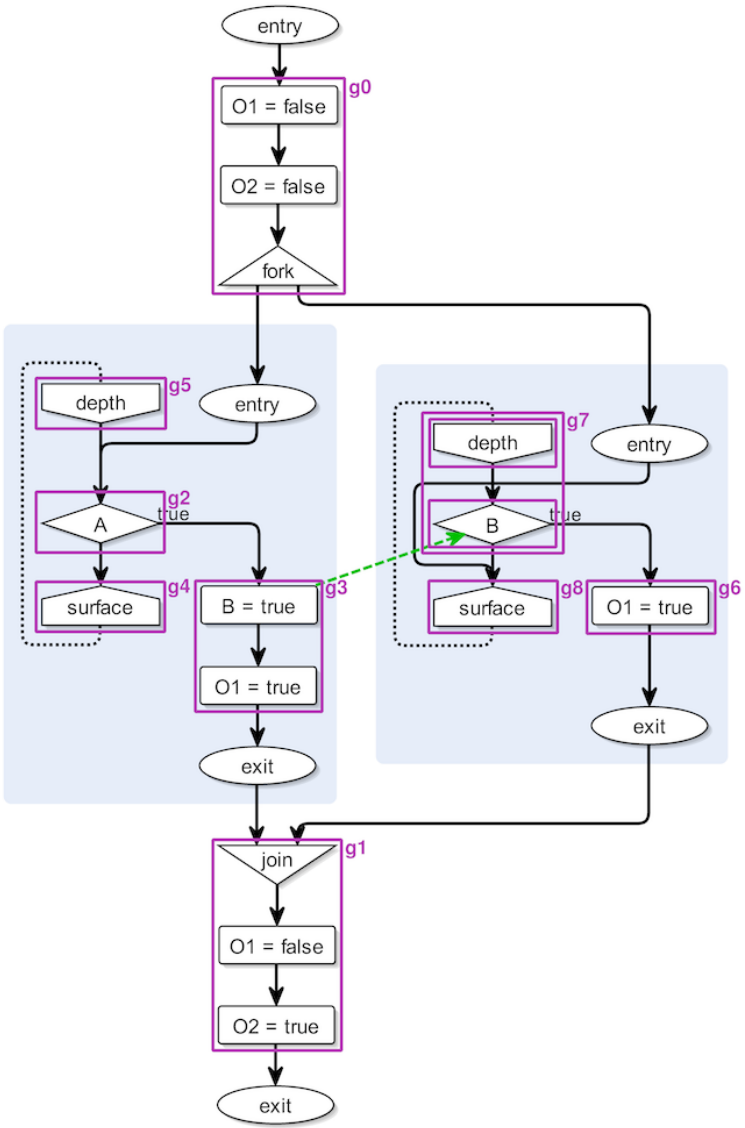





entry
O1 = false
O2 = false
fork
g0
depth
g5
entry
A
g2
true
surface
g4
B = true
g3
O1 = true
exit
depth
g7
entry
B
true
surface
g8
O1 = true
g6
exit
join
g1
O1 = false
O2 = true
exit




```
1 module ABO
2 input output bool
        A, B;
3 output bool O1,
       O2;
4 {
5   O1 = false;
6   O2 = false;
7   fork
8     HandleA:
9     if (!A) {
10      pause;
11      goto HandleA
              ;
12    };
13    B = true;
14    O1 = true;
15  par
16    HandleB:
17    pause;
18    if (!B) {
19      goto HandleB
              ;
20    };
21    O1 = true;
22  join;
23  O1 = false;
24  O2 = true;
25 }
```




```
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2  input output bool
       A, B;
3  output bool O1,
       O2;
4  {
5    O1 = false;
6    O2 = false;
7    fork
8      HandleA:
9      if (!A) {
10       pause;
11       goto HandleA
               ;
12     };
13     B = true;
14     O1 = true;
15   par
16     HandleB:
17     pause;
18     if (!B) {
19       goto HandleB
               ;
20     };
21     O1 = true;
22   join;
23   O1 = false;
24   O2 = true;
25 }
```
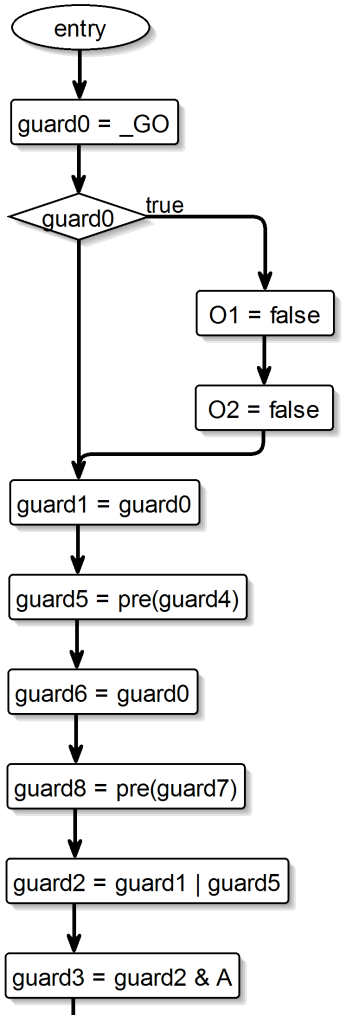
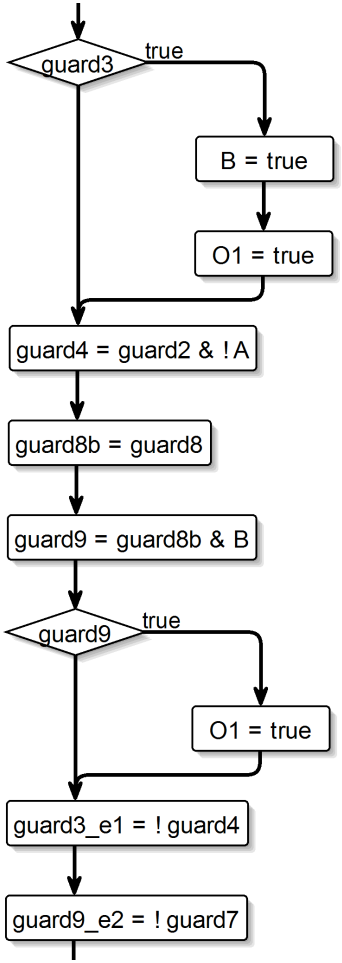
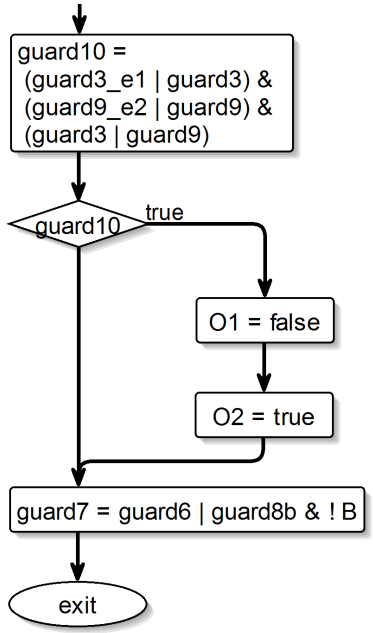

⇒

```
2  input output bool A, B;
3  output bool O1, O2;
4  bool GO, g0, g1, ...
5  {
6    g0 = GO;
7    if g0 {
8      O1 = false;
9      O2 = false;
10   };
11   g5 = g4_pre;
12   g7 = g8_pre;
13   g2 = g0 || g5;
14   g3 = g2 && A;
15   if g3 {
16     B = true;
17     O1 = true;
18   };
19   g4 = g2 && ! A;
20   g6 = g7 && B;
21   if g6 {
22     O1 = true;
23   };
24   g8 = g0 || (g7 && ! B);
25   e2 = ! g4;
26   e6 = ! g8;
27   g1 = (g3 || e2) &&
28      (g6 || e6) && (g3 ||
29   if g1 {
30     O1 = false;
31     O2 = true;
32   };
33   g4_pre = g4;
34   g8_pre = g8;
35 }
```

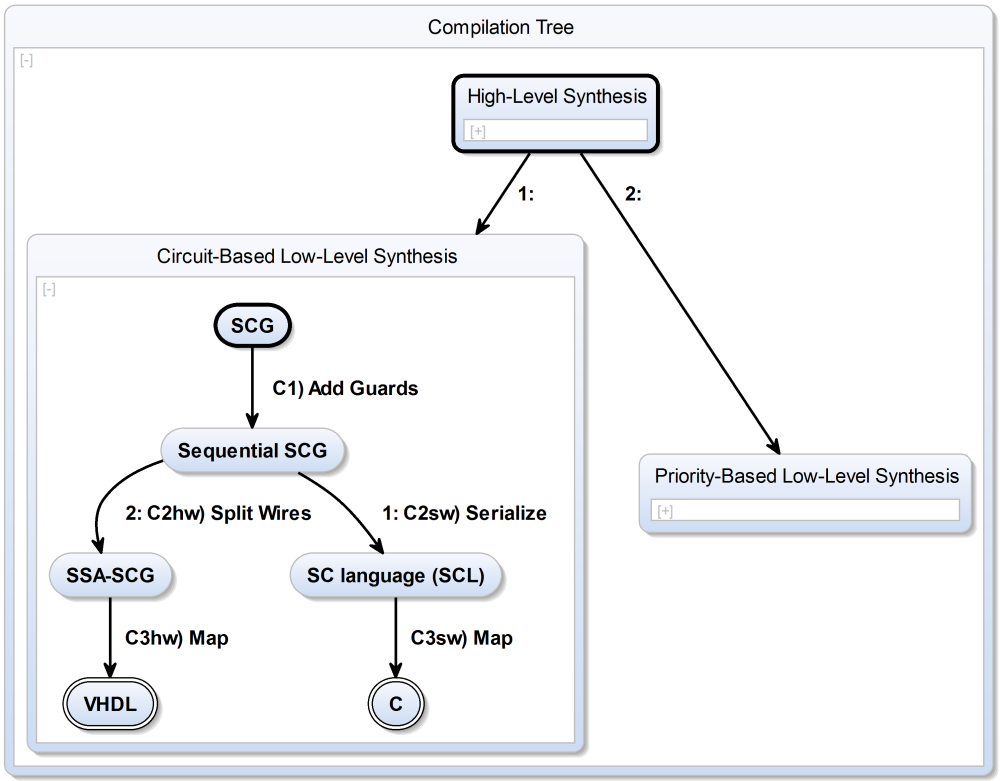
Sequential SCG — ABO







(Recall) Low-Level Synthesis I: The Circuit Approach



- Can use sequential SCL directly for SW synthesis
- Synthesizing HW needs a little further work ...

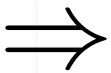
ABO SCL, Logic Synthesis (HW)

```
1 module ABO-seq
2 input output bool A, B;
3 output bool O1, O2;
4 bool GO, g0, g1, ...
5 {
6   g0 = GO;
7   if g0 {
8     O1 = false;
9     O2 = false;
10  };
11  g5 = g4_pre;
12  g7 = g8_pre;
13  g2 = g0 || g5;
14  g3 = g2 && A;
15  if g3 {
16    B = true;
17    O1 = true;
18  };
19  g4 = g2 && ! A;
20  g6 = g7 && B;
21  if g6 {
22    O1 = true;
23  };
24  g8 = g0 || (g7 && ! B);
25  e2 = ! g4;
26  e6 = ! g8;
27  g1 = (g3 || e2) &&
```

ABO SCL, Logic Synthesis (HW)

Difference to software

```
1  module ABO-seq
2  input output bool A, B;
3  output bool O1, O2;
4  bool GO, g0, g1, ...
5  {
6    g0 = GO;
7    if g0 {
8      O1 = false;
9      O2 = false;
10   };
11   g5 = g4_pre;
12   g7 = g8_pre;
13   g2 = g0 || g5;
14   g3 = g2 && A;
15   if g3 {
16     B = true;
17     O1 = true;
18   };
19   g4 = g2 && ! A;
20   g6 = g7 && B;
21   if g6 {
22     O1 = true;
23   };
24   g8 = g0 || (g7 && ! B);
25   e2 = ! g4;
26   e6 = ! g8;
27   g1 = (g3 || e2) &&
```



ABO SCL, Logic Synthesis (HW)

Difference to software

```
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2 input output bool A, B;
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4 bool GO, g0, g1, ...
5 {
6   g0 = GO;
7   if g0 {
8     O1 = false;
9     O2 = false;
10  };
11  g5 = g4_pre;
12  g7 = g8_pre;
13  g2 = g0 || g5;
14  g3 = g2 && A;
15  if g3 {
16    B = true;
17    O1 = true;
18  };
19  g4 = g2 && ! A;
20  g6 = g7 && B;
21  if g6 {
22    O1 = true;
23  };
24  g8 = g0 || (g7 && ! B);
25  e2 = ! g4;
26  e6 = ! g8;
27  g1 = (g3 || e2) &&
```
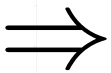
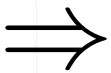



- All persistence (state, data) in external reg's ("_pre"-var's)
- Permit only one value per wire per tick ⇒ SSA

ABO SCL, Logic Synthesis (HW)

Difference to software

```
1 module ABO-seq
2 input output bool A, B;
3 output bool O1, O2;
4 bool GO, g0, g1, ...
5 {
6   g0 = GO;
7   if g0 {
8     O1 = false;
9     O2 = false;
10  };
11  g5 = g4_pre;
12  g7 = g8_pre;
13  g2 = g0 || g5;
14  g3 = g2 && A;
15  if g3 {
16    B = true;
17    O1 = true;
18  };
19  g4 = g2 && ! A;
20  g6 = g7 && B;
21  if g6 {
22    O1 = true;
23  };
24  g8 = g0 || (g7 && ! B);
25  e2 = ! g4;
26  e6 = ! g8;
27  g1 = (g3 || e2) &&
```



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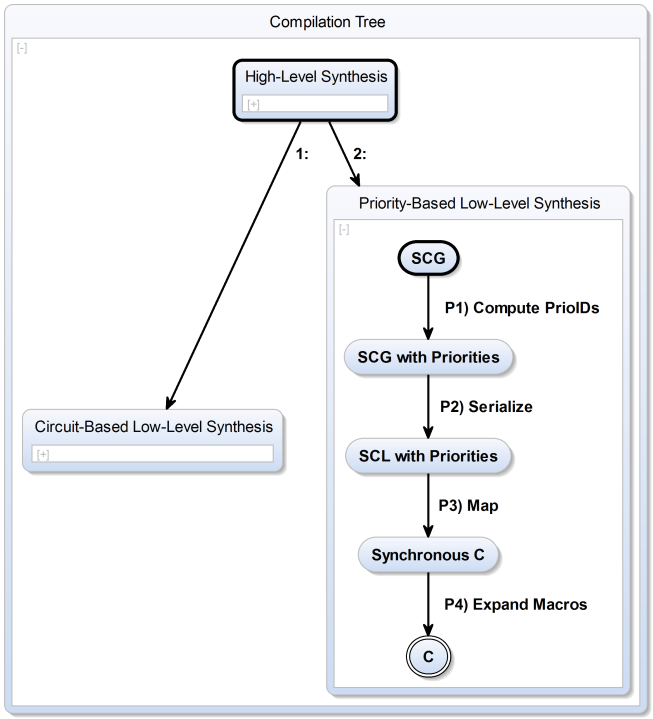
```
1 ARCHITECTURE behavior OF ABO IS
2 -- local signals definition, hidden
3 begin
4 -- main logic
5 g0 <= GO_local;
6 O1 <= false WHEN g0 ELSE O1_pre;
7 O2 <= false WHEN g0 ELSE O2_pre;
8 g5 <= g4_pre;
9 g7 <= g8_pre;
10 g2 <= g0 or g5;
11 g3 <= g2 and A_local;
12 B <= true WHEN g3 ELSE B_local;
13 O1_2 <= true WHEN g3 ELSE O1;
14 g4 <= g2 and not A_local;
15 g6 <= g7 and B;
16 O1_3 <= true WHEN g6 ELSE O1_2;
17 g8 <= g0 or (g7 and not B);
18 e2 <= not (g4);
19 e6 <= not (g8);
20 g1 <= (g3 or e2) and
```

Low-Level Synthesis II: The Priority Approach



- More software-like
- Don't emulate control flow with guards/basic blocks, but with program counters/threads
- Priority-based thread dispatching
- SCL$_P$: SCL + PrioIDs
- Implemented as C macros

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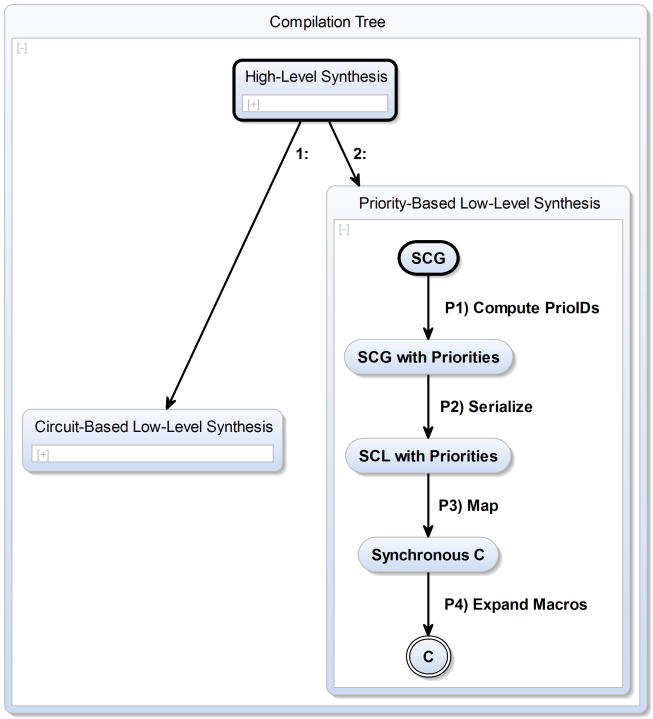

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Differences to Synchronous C [von Hanxleden '09]

- No preemption $\Rightarrow$ don't need to keep track of thread hierarchies
- Fewer, more light-weight operators
- RISC instead of CISC

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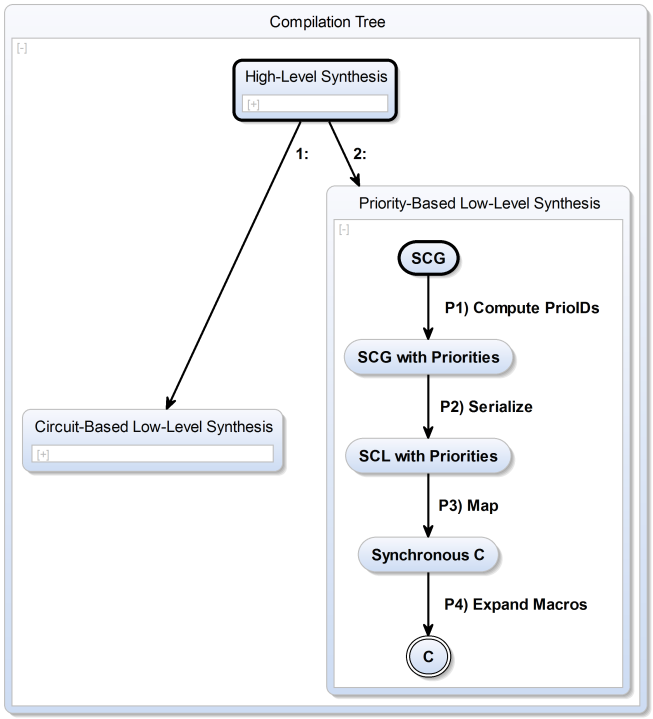

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Differences to Synchronous C [von Hanxleden '09]

- No preemption $\Rightarrow$ don't need to keep track of thread hierarchies
- Fewer, more light-weight operators
- RISC instead of CISC
- More human-friendly syntax

SCL$_P$ Macros I

```
1 // Declare Boolean type
2 typedef int bool;
3 #define false 0
4 #define true 1
5
6 // Generate "_L<line-number>" label
7 #define _concat_helper(a, b) a ## b
8 #define _concat(a, b) _concat_helper(a, b)
9 #define _label_    _concat(_L, __LINE__)
10
11 // Enable/disable threads with prioID p
12 #define _u2b(u)      (1 << u)
13 #define _enable(p) _enabled |= _u2b(p); _active |= _u2b(p)
14 #define _isEnabled(p) ((_enabled & _u2b(p)) != 0)
15 #define _disable(p) _enabled &= ~_u2b(p)
```

SCL$_P$ Macros II

```
17 // Set current thread continuation
18 #define _setPC(p, label) _pc[p] = &&label
19
20 // Pause, resume at <label> or at pause
21 #define _pause(label) _setPC(_cid, label); goto _L_PAUSE
22 #define pause      _pause(_label_); _label_:
23
24 // Fork/join sibling thread with prioID p
25 #define fork1(label, p) _setPC(p, label); _enable(p);
26 #define join1(p)   _label_: if (_isEnabled(p)) { _pause(_label_); }
27
28 // Terminate thread at "par"
29 #define par        goto _L_TERM;
30
31 // Context switch (change prioID)
32 #define _prio(p)  _deactivate(_cid); _disable(_cid); _cid = p; \
33  _enable(_cid); _setPC(_cid, _label_); goto _L_DISPATCH; _label_:
```

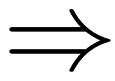
ABO SCL$_P$ I

```
85 int tick()
86 {
87   tickstart(2);
88   O1 = false;
89   O2 = false;
90
91   fork1(HandleB,
         1) {
92     HandleA:
93     if (!A) {
94       pause;
95       goto HandleA
             ;
96     }
97     B = true;
98     O1 = true;
99
100  } par {
```

```
85 int tick()
86 {
87   if (_notInitial) { _active = _enabled;
          goto _L_DISPATCH; } else { _pc[0]
          = &&_L_TICKEND; _enabled = (1 <<
         0); _active = _enabled; _cid = 2;
         ; _enabled |= (1 << _cid); _active
          |= (1 << _cid); _notInitial = 1;
         } ;
88   O1 = 0;
89   O2 = 0;
90
91   _pc[1] = &&HandleB; _enabled |= (1 <<
         1); _active |= (1 << 1); {
92     HandleA:
93     if (!A) {
94       _pc[_cid] = &&_L94; goto _L_PAUSE;
             _L94:;
95       goto HandleA;
96     }
97     B = 1;
98     O1 = 1;
99
100  } goto _L_TERM; {
```

ABO SCL$_P$ II

```
102     HandleB:
103     pause;
104     if (!B) {
105       goto HandleB
              ;
106     }
107     O1 = true;
108   } join1(2);
109
110   O1 = false;
111   O2 = true;
112   tickreturn;
113 }
```



```
102     HandleB:
103     _pc[_cid] = &&_L103; goto _L_PAUSE;
            _L103:;
104     if (!B) {
105       goto HandleB;
106     }
107     O1 = 1;
108   } _L108: if (((_enabled & (1 << 2)) !=
            0)) { _pc[_cid] = &&_L108; goto
           _L_PAUSE; };
109
110   O1 = 0;
111   O2 = 1;
112   goto _L_TERM; _L_TICKEND: return (
           _enabled != (1 << 0)); _L_TERM:
           _enabled &= ~(1 << _cid); _L_PAUSE
           : _active &= ~(1 << _cid);
           _L_DISPATCH: __asm volatile("bsrl
           %1,%0\n" : "=r" (_cid) : "r" (
           _active) ); goto *_pc[_cid];
113 }
```

Comparison of Low-Level Synthesis Approaches

	Circuit	Priority

Comparison of Low-Level Synthesis Approaches

	Circuit	**Priority**
Accepts instantaneous loops	–	+
Can synthesize hardware	+	–
Can synthesize software	+	+

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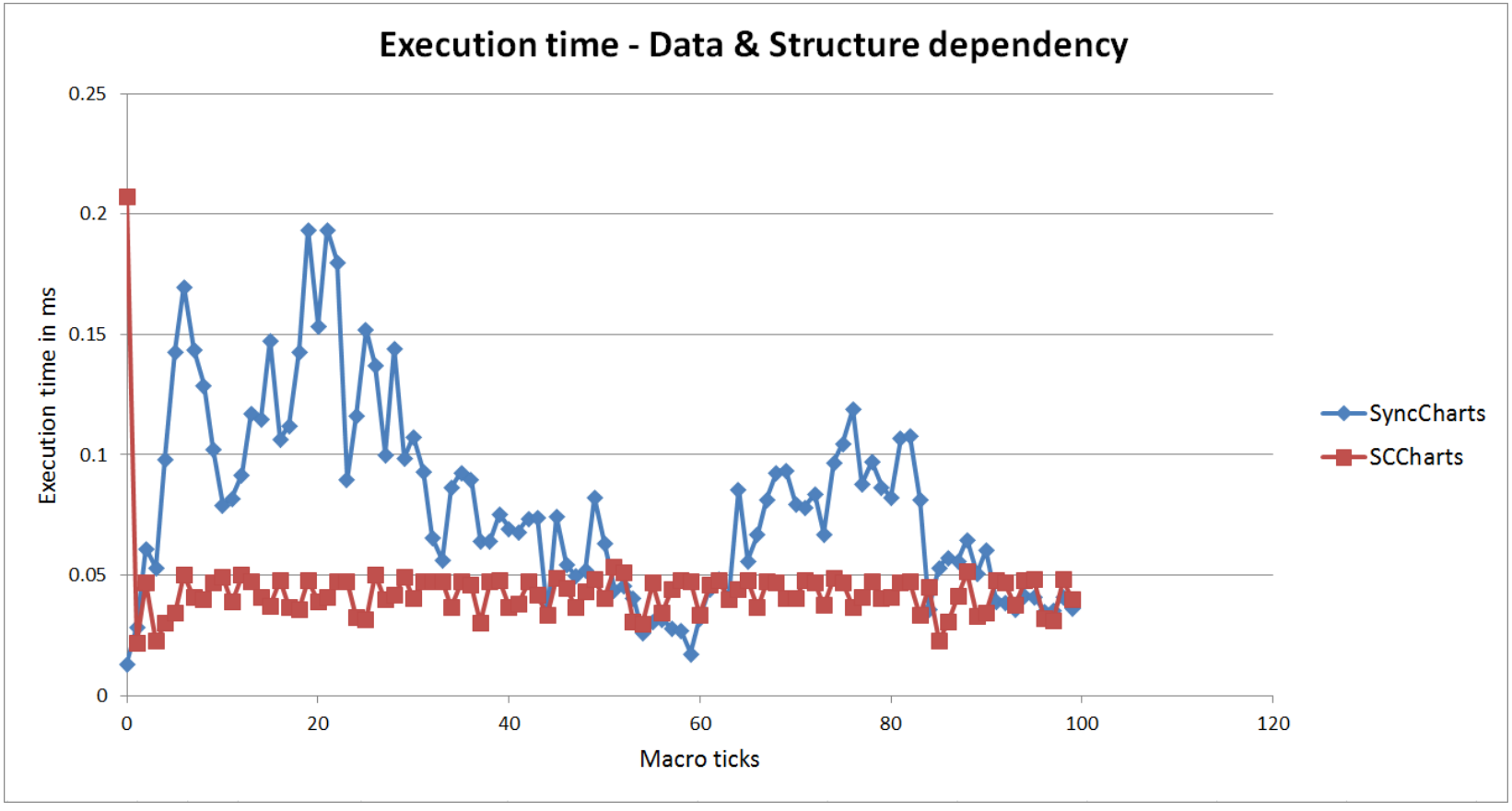
Size scales well (linear in size of SCChart)	+	+

Comparison of Low-Level Synthesis Approaches

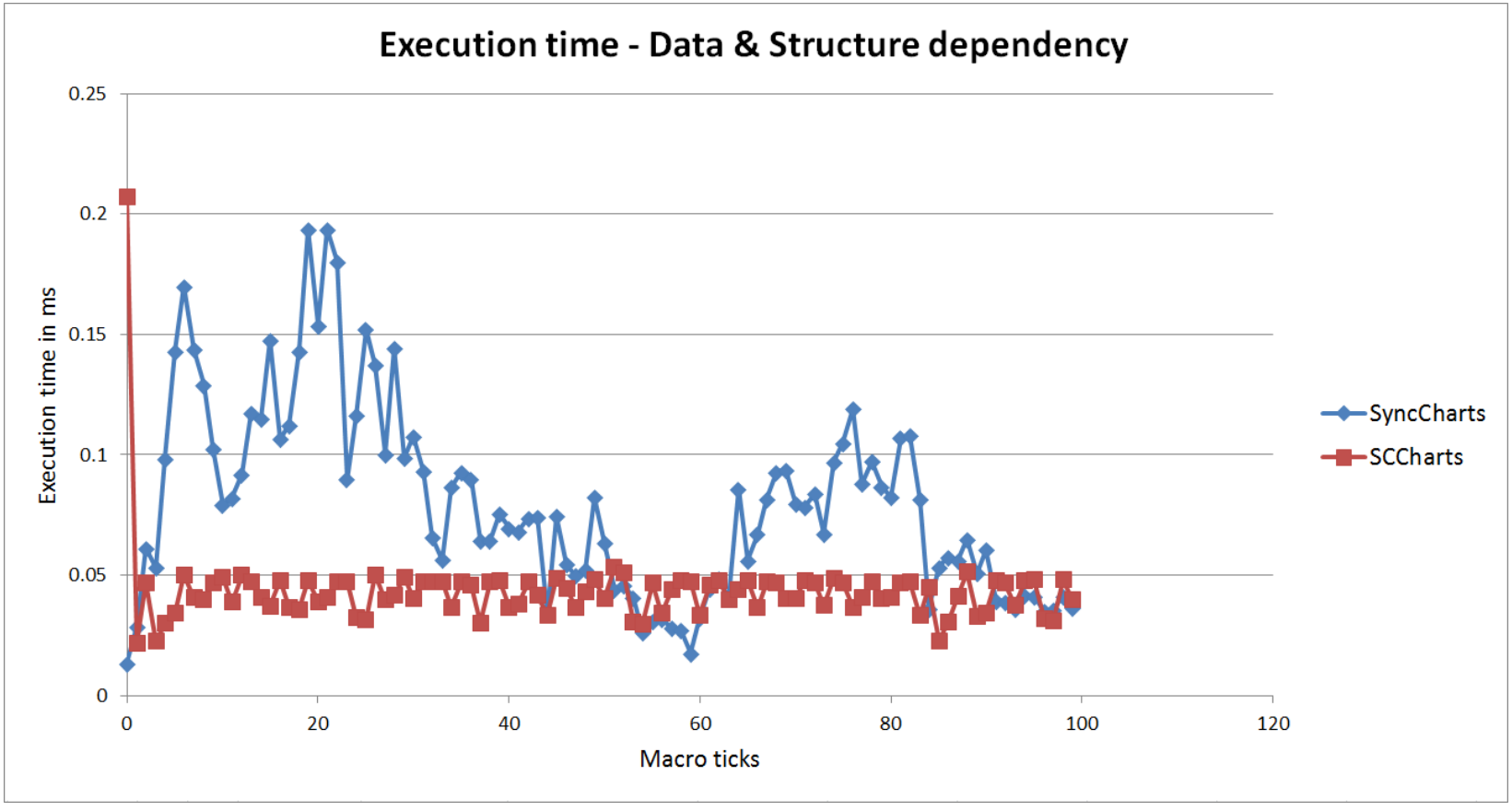
	Circuit	**Priority**
Accepts instantaneous loops	−	+
Can synthesize hardware	+	−
Can synthesize software	+	+
Size scales well (linear in size of SCChart)	+	+
Speed scales well (execute only "active" parts)	−	+
Instruction-cache friendly (good locality)	+	−
Pipeline friendly (little/no branching)	+	−
WCRT predictable (simple control flow)	+	+/−
Low execution time jitter (simple/fixed flow)	+	−

Comparison — Jitter



Execution time comparison of statecharts with multiple hierarchies depicts

Comparison — Jitter



Execution time comparison of statecharts with multiple hierarchies depicts

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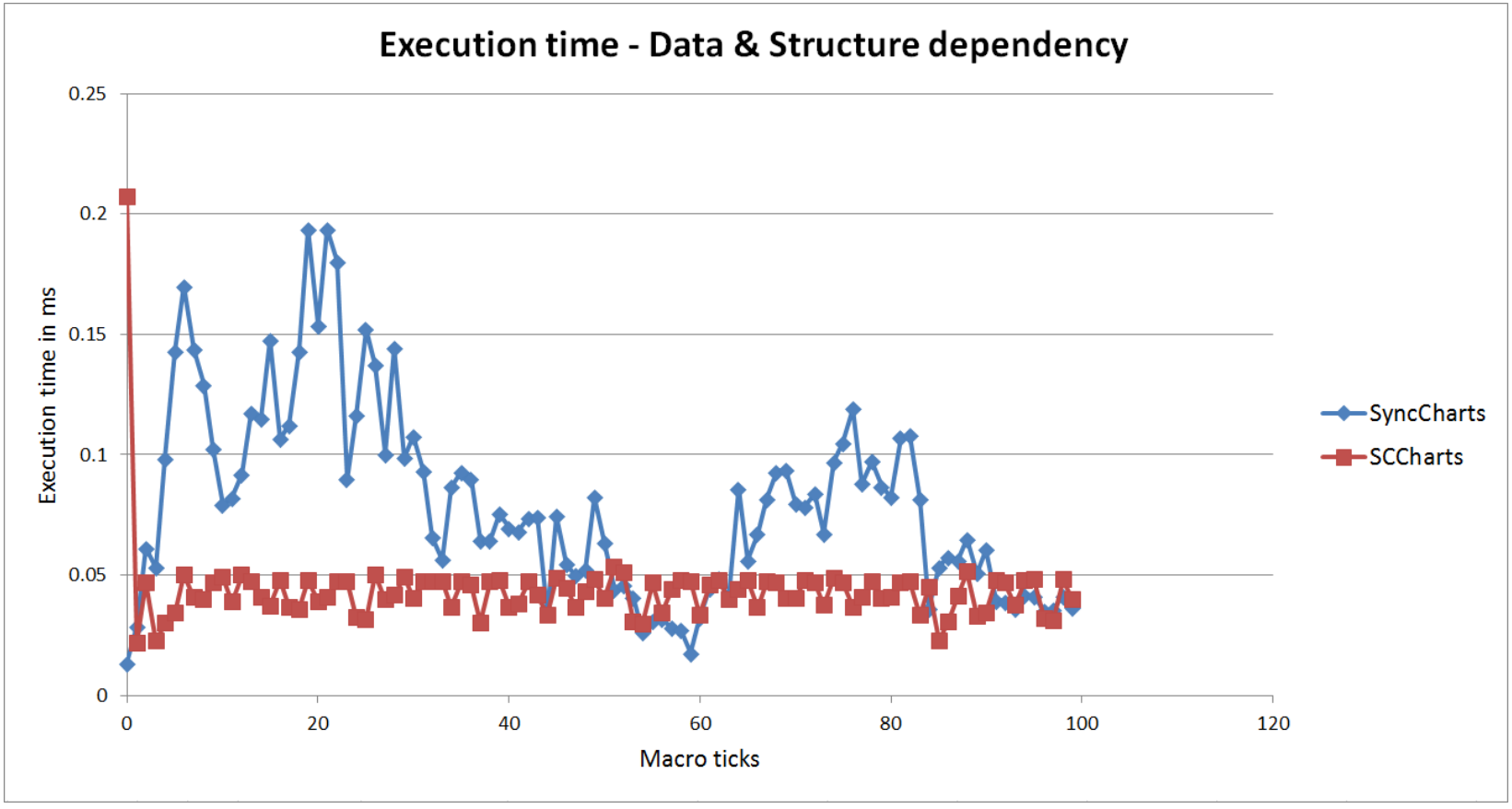

Execution time comparison of statecharts with multiple hierarchies depicts

- low jitter in circuit-based approach
- execution time in priority-based approach more dependant to structure and input data of the statechart

Overview

. . . What About That Acyclicity?

```
1 module schizo
2 output O;
3
4 loop
5   signal S in
6     present S
7       then
8       emit O
9     end;
10    pause;
11    emit S;
12  end;
13 end loop
14 end module
```

Esterel
[Tardieu & de Simone '04]

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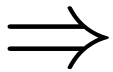

```
1 module schizo-conc
2 output bool O;
3 {
4   while (true) {
5     bool S, _Term;
6
7     fork
8       _Term = false;
9       O = S;
10      pause;
11      S = S || true;
12      _Term = true;
13    par
14      while (true) {
15        S = false;
16        if (_Term)
17          break;
18        pause;
19      }
20    join;
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```

SCL (1st try)

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⇒

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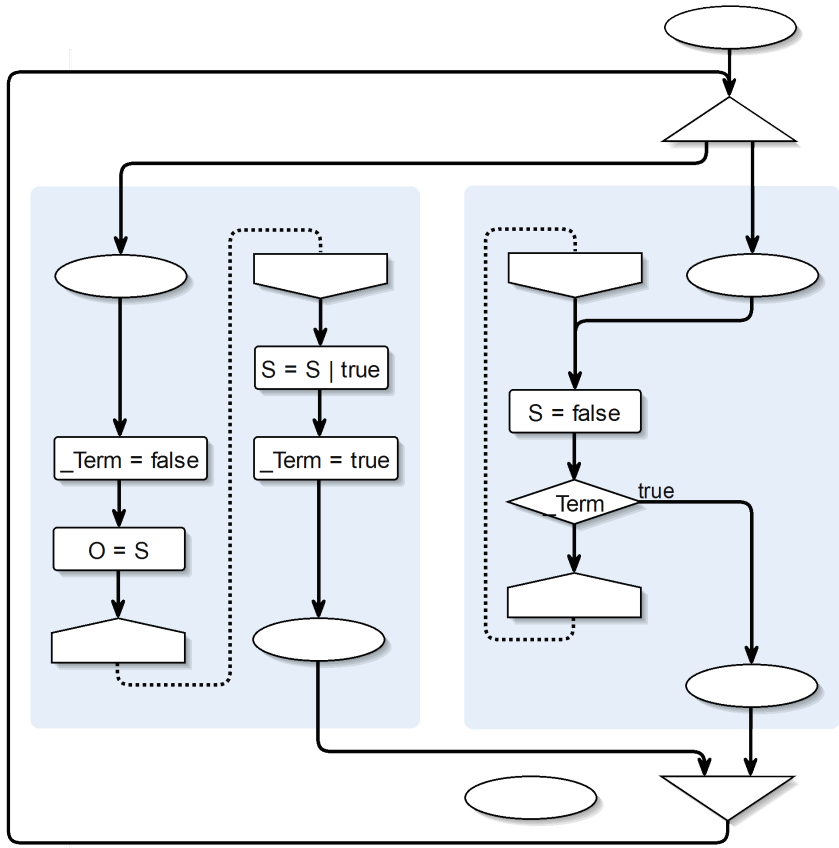

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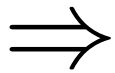

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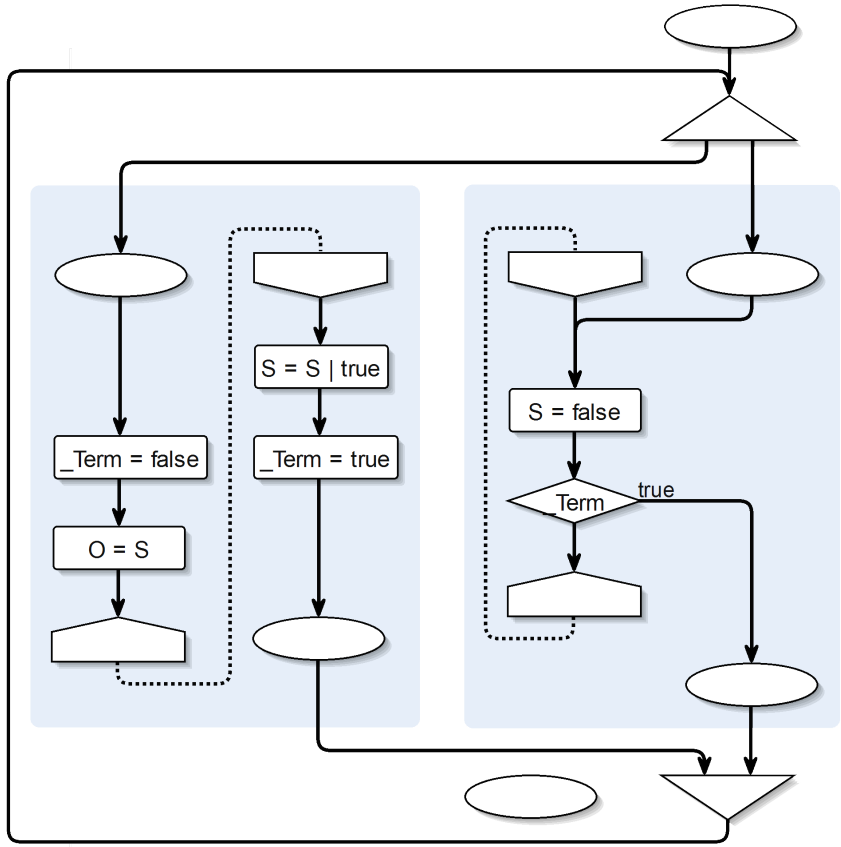

Q: The problem?

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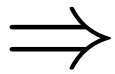

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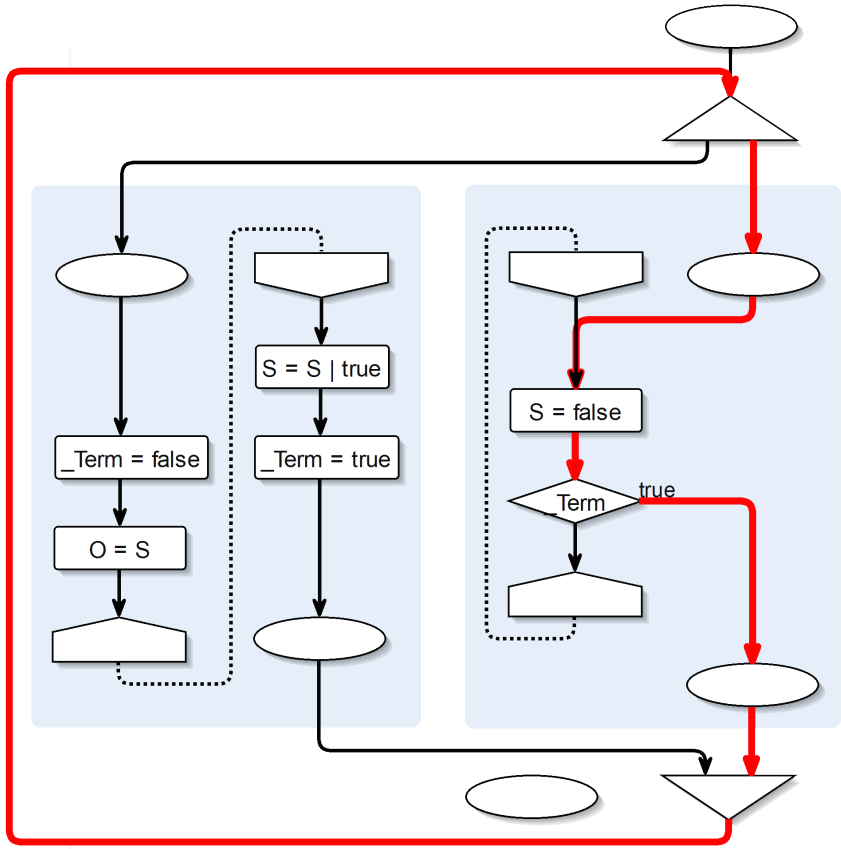

Q: The problem?
A: Instantaneous loop!

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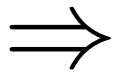
[Tardieu & de Simone '04]



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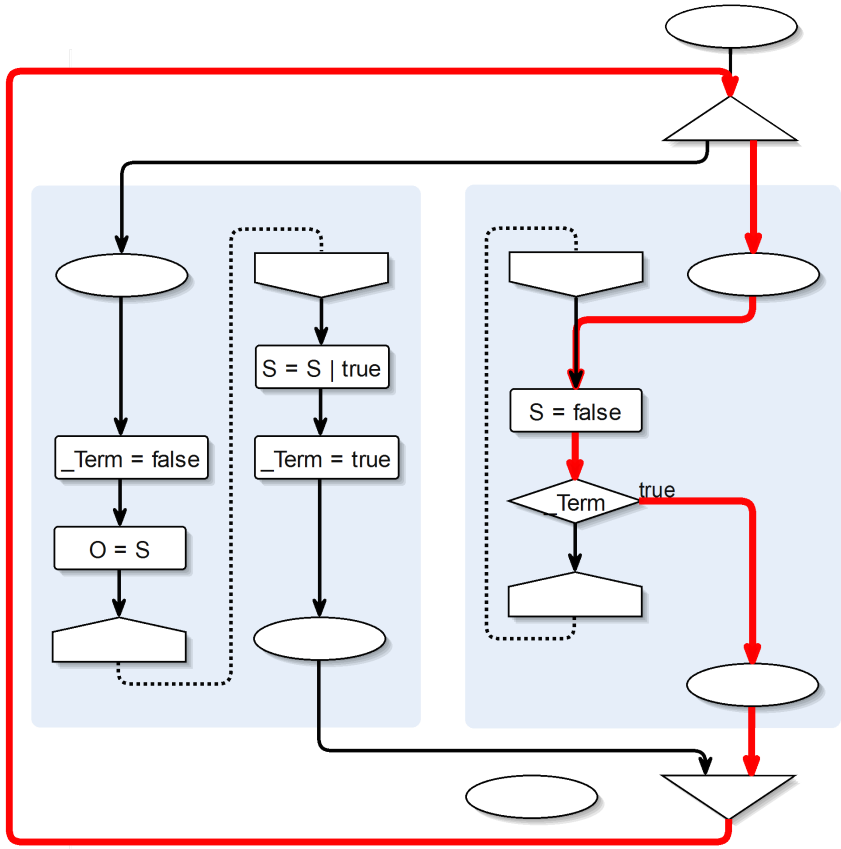

Q: The problem?
A: Instantaneous loop!
a.k.a. Signal reincarnation
a.k.a. Schizophrenia

A Solution

```
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Esterel

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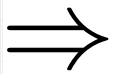
Esterel



```
1 module schizo-cured
2 output O;
3
4 loop
5   signal S in
6     present S then
7       emit O
8     end;
9     pause;
10    emit S;
11  end;
12  signal S' in
13    present S' then
14      emit O
15    end;
16    pause;
17    emit S';
18  end;
19 end loop
```

- Duplicated loop body to separate signal instances
- Q: Complexity?

A Solution

```
1 module schizo
2 output O;
3
4 loop
5   signal S in
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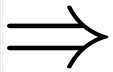
Esterel



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- Duplicated loop body to separate signal instances
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- A: Exponential ☹

A Better Solution

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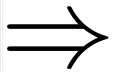

```
1 module
2 schizo-cured2-strl
3 output O;
4
5 loop
6   % Surface
7   signal S in
8     present S then
9       emit O
10    end;
11  end;
12
13  % Depth
14  signal S' in
15    pause;
16    emit S';
17  end;
18 end loop
```

[Tardieu & de Simone '04]
(simplified)

- Duplicated loop body
- "Surface copy" transfers control immediately to "depth copy"

A Better Solution

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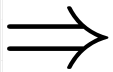

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9     end;
10    pause;
11    emit S;
12  end;
13 end loop
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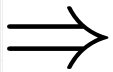
Esterel



```
1 module
2 schizo-cured2-strl
3 output O;
4
5 loop
6   % Surface
7   signal S in
8     present S then
9       emit O
10    end;
11  end;
12
13  % Depth
14  signal S' in
15    pause;
16    emit S';
17  end;
18 end loop
```

[Tardieu & de Simone '04]
(simplified)

- Duplicated loop body
- "Surface copy" transfers control immediately to "depth copy"
- Q: Complexity?
- A: Quadratic 😐

The SCL Solution

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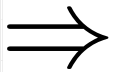

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2 output bool O;
3 {
4   while (true) {
5     bool S, _Term;
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7     // Surf init
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9     _Term = false;
10    fork
11      O = S;
12      pause;
13      S = S || true;
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15    par
16      do {
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20      } while (!_Term);
21    join;
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SCL

- "Surface initialization" at beginning of scope
- Delayed, concurrent "depth initialization"

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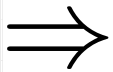

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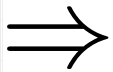

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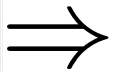

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- "Surface initialization" at beginning of scope
- Delayed, concurrent "depth initialization"
- Q: Complexity?
- A: Linear ☺
- Caveat: We only talk about **signal** reincarnation, *i. e.*, instantaneously exiting and entering a signal scope
- Reincarnated **statements** still require duplication (quadratic worst case?)

SCG for schizo-cured

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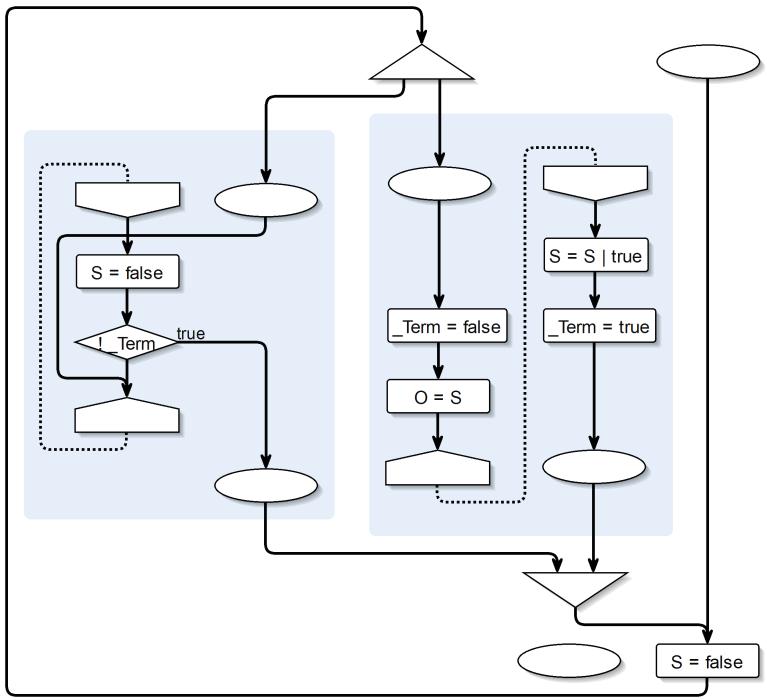

- Cycle now broken by delay
- Only the "depth initialization" of S creates a concurrent "initialize before update" scheduling dependence

Schizophrenic Parallel

- Recall the equations for joining (two) threads:
  $g_{join} = (d_1 \vee m_1) \wedge (d_2 \vee m_2) \wedge (d_1 \vee d_2)$, where for each thread t_i it is "done" $d_i = g_{exit}$ and "empty" $m_i = \neg(g_{fork} \vee \bigvee_{depth \in t_i} g_{depth})$

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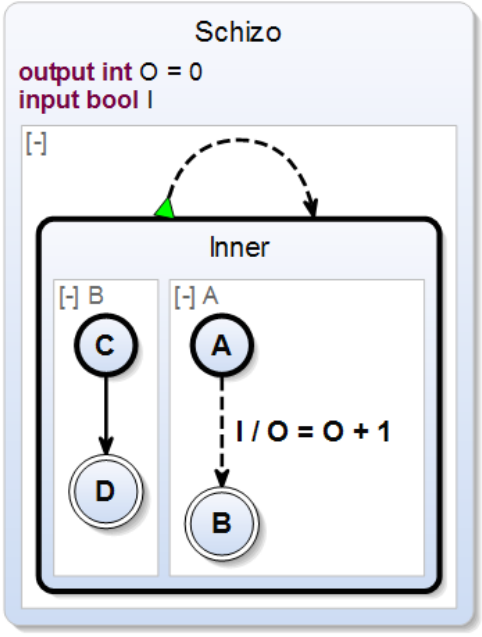
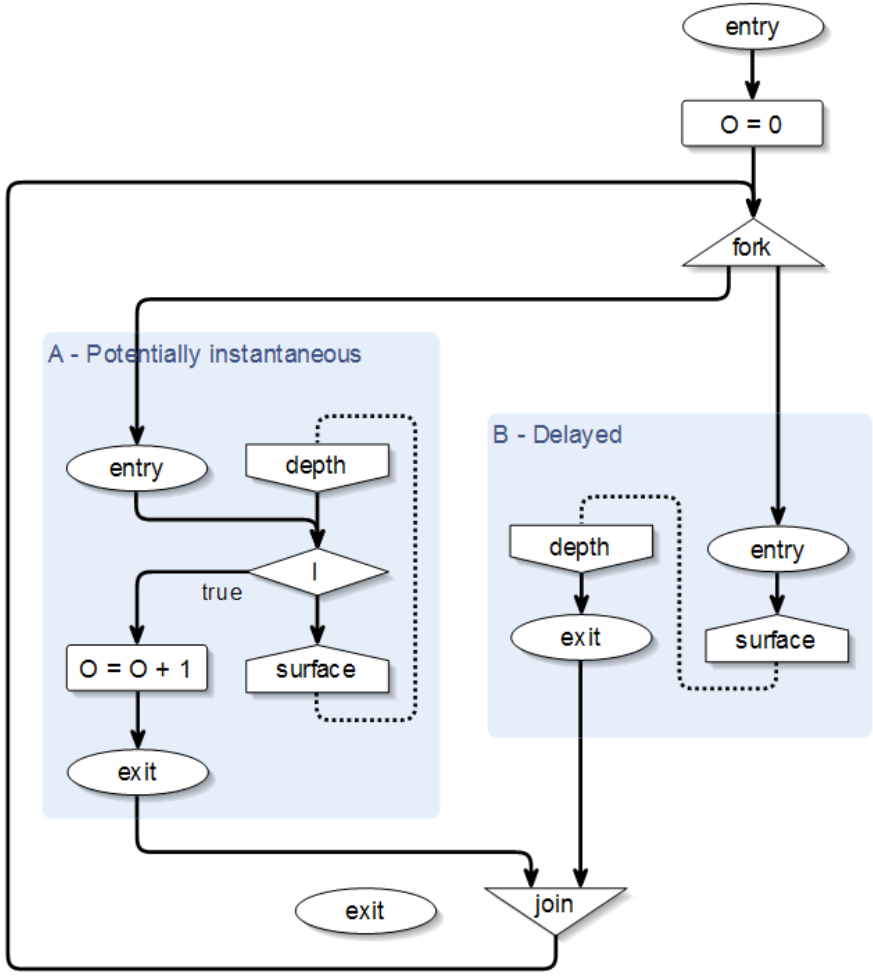
- If parallel is not instantaneous, only need g_{d-join}.
- In SCG, if thread terminates instantaneously in non-instantaneous parallel, we end in unjoined exit, visualized with small solid disk

Statement Reincarnation





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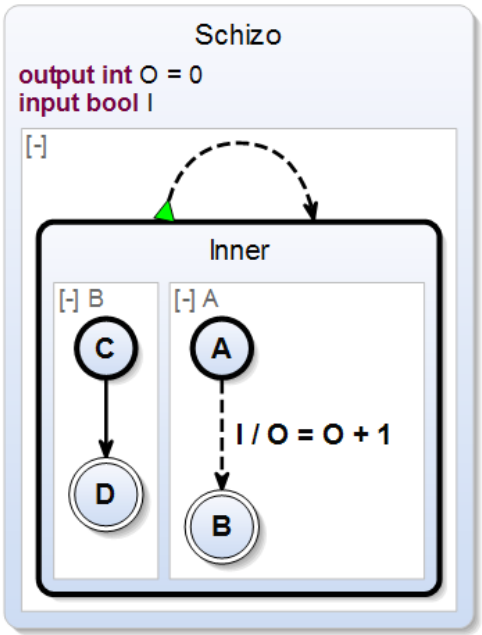

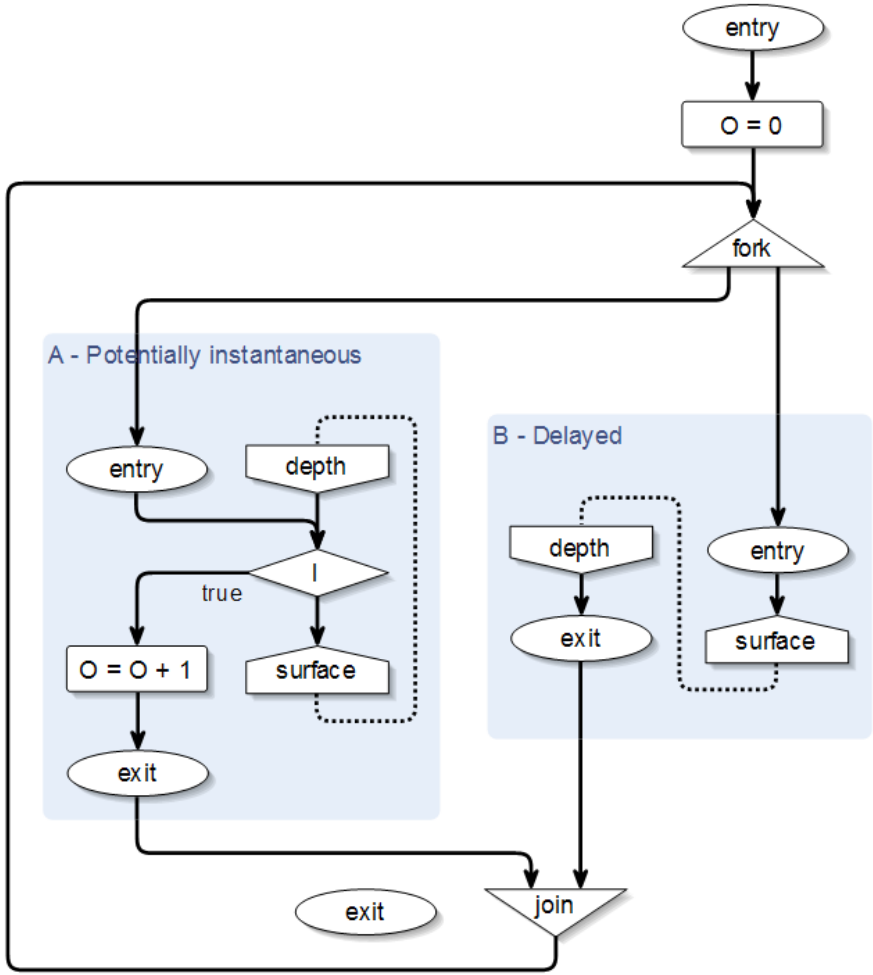

- Consider I absent in initial tick, present in next tick
- Must then increment O twice

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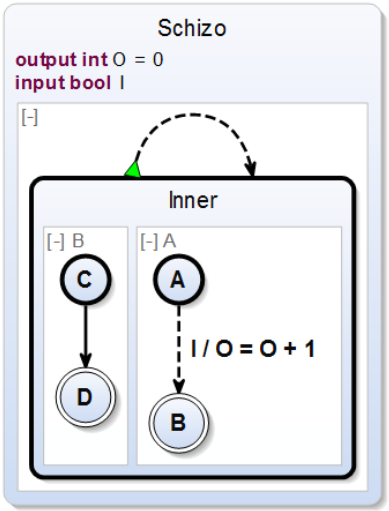

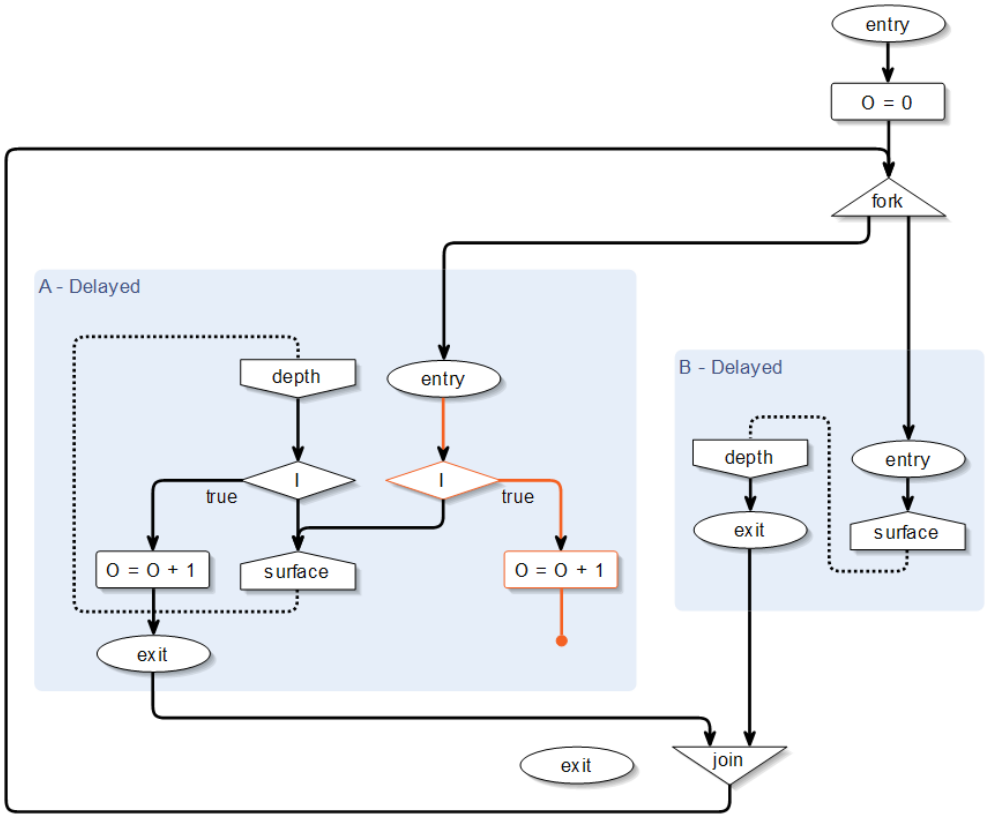

- To remove cycle, must duplicate the part of the surface of the thread that might instantaneously terminate, i.e., nodes on instantaneous path from entry to exit
- The second increment of O leads to unjoined exit

Summary

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4. Treating advanced constructs as syntactic sugar simplifies down-stream synthesis
   (CISC vs. RISC)
5. **Plenty of future work:** compilation of Esterel-like languages, trade-off RISC vs. CISC, WCRT analysis, timing-predictable design flows ($\rightarrow$ PRETSY), multi-clock, visualization, . . .

To Go Further

- J. Aguado, M. Mendler, R. von Hanxleden, I. Fuhrmann. *Grounding Synchronous Deterministic Concurrency in Sequential Programming*. In Proceedings of the 23rd European Symposium on Programming (ESOP'14), Grenoble, France, April 2014. `https://rtsys.informatik.uni-kiel.de/~biblio/downloads/papers/esop14.pdf`
- R. von Hanxleden, M. Mendler, J. Aguado, B. Duderstadt, I. Fuhrmann, C. Motika, S. Mercer, O. O'Brien, and P. Roop. *Sequentially Constructive Concurrency – A Conservative Extension of the Synchronous Model of Computation*. ACM Transactions on Embedded Computing Systems, Special Issue on Applications of Concurrency to System Design, July 2014, 13(4s). `https://rtsys.informatik.uni-kiel.de/~biblio/downloads/papers/tecs14.pdf`