# Synchronous Languages—Lecture 23

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*Sequentially Constructive Concurrency II*





## The 5-Minute Review Session

1. How do *SCCharts* and *SyncCharts* differ?
2. What does the *initialize-update-read protocol* refer to?
3. What is the *SCG*?
4. What are *basic blocks*? What are *scheduling blocks*?
5. When compiling from the SCG, what types of *low-level synthesis* do we distinguish? How do they compare?





## Recall: Aim of Sequential Constructiveness

**Sequential Languages**

- Asynchronous schedule
  - ☹ No guarantees of determinism or deadlock freedom
  - ☺ Intuitive programming paradigm

**Synchronous Languages**

- Clocked, cyclic schedule
  - ☺ Deterministic concurrency and deadlock freedom
  - ☹ Heavy restrictions by constructiveness analysis

$\Longrightarrow$

**Sequentially Constructive Model of Computation (SC MoC)**

- ☺ Deterministic concurrency and deadlock freedom
- ☺ Intuitive programming paradigm





## Goals and Challenges

The idea behind SC is simple – but getting it "right" not so!

What we are up to:

1. Want to be conservative wrt "Berry constructiveness"
   - An Esterel program should also be SC
2. Want maximal freedom without compromising determinism
   - A deterministic program should also be SC
   - An SC program must be deterministic
3. Want to exploit sequentiality as much as possible
   - But what exactly *is* sequentiality?
4. Want to define not only the exact concept of SC, but also a practical strategy to implement it
   - In practice, this requires conservative approximations
   - Compiler must not accept Non-SC programs
   - Compiler may reject SC programs

## Overview

Static Concepts
- The SC Language (SCL) and the SC Graph (SCG)
- Thread Terminology
- Thread / Statement Reincarnation

Run-Time Concepts

Sequential Constructiveness





## The Sequentially Constructive Language (SCL)

- Foundation for the SC MoC
- Minimal Language
- Adopted from C/Java and Esterel

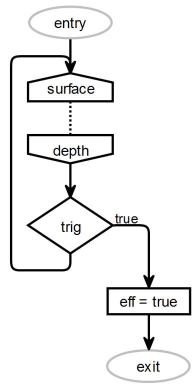
$$s ::= \quad x = e \mid s;s \mid \textbf{if } (e)\ s \textbf{ else } s \mid l : s \mid \textbf{goto } l \mid \textbf{fork } s \textbf{ par } s \textbf{ join} \mid \textbf{pause}$$

$s$ Statement
$x$ Variable
$e$ Expression
$l$ Program label





## The SC Graph (SCG)




The concurrent and sequential control flow of an SCL program is given by an SC Graph (SCG)

Internal representation for
- Semantic foundation
- Analysis
- Code generation

SC Graph:
Labeled graph $G = (N, E)$
- Nodes $N$ correspond to statements of sequential program
- Edges $E$ reflect sequential execution control flow





## Node Types in the SCG

Node $n \in N$ has statement type $n.st$

- $n.st \in$ {entry, exit, goto, $x = ex$, if ($ex$), fork, join, surf, depth}
- $x$: variable, $ex$: expression.

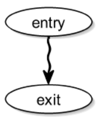
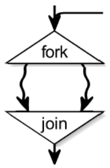
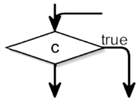
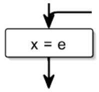
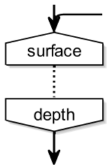
## Edge Types in the SCG

Edge $e \in E$ has edge type $e.type$

- $e.type \in \{seq, tick, wr, wi, ir, ww\}$
- Specifies the nature of the particular ordering constraint expressed by $e$
- For $e.type = \alpha$, write $e.src \rightarrow_\alpha e.tgt$
- $n_1 \rightarrow_{seq} n_2$: sequential successors
- $n_1 \rightarrow_{tick} n_2$: tick successors
- $n_1 \rightarrow_{seq} n_2$, $n_1 \rightarrow_{tick} n_2$: flow successors, induced directly from source program
- $\twoheadrightarrow_{seq}$: reflexive and transitive closure of $\rightarrow_{seq}$
- Note: $n_1 \rightarrow_{seq} n_2$ does not imply fixed run-time ordering between $n_1$ and $n_2$ (consider loops)



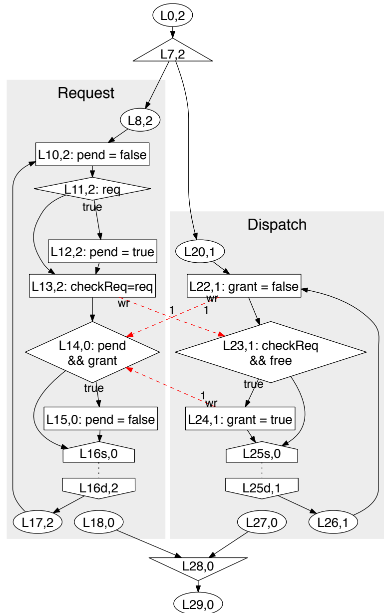
## Mapping SCL & SCG

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





## SCL & SCG – The Control Example




```
module Control
input bool free, req;
output bool grant, pend;
{
  bool checkReq;
  fork {
    // Thread Request
    Request entry:
    pend = false;
    if (req)
      pend = true;
    checkReq = req;
    if (pend && grant)
      pend = false;
    pause;
    goto Request entry;
  }
  par {
    // Thread Dispatch
    Dispatch entry:
    grant = false;
    if (checkReq && free)
      grant = true;
    pause;
    goto Dispatch entry;
  }
  join;
}
```



## Sequentiality vs. Concurrency Static vs. Dynamic Threads

Recall: We want to distinguish between *sequential* and *concurrent* control flow.
But what do "sequential" / "concurrent" mean?
This distinction is not as easy to formalize as it may seem . . .

To get started, distinguish

- Static threads: Structure of a program (based on SCG)
- Dynamic thread instance: thread in execution

# Static Threads

- Given: SCG $G = (N, E)$
- Let $T$ denote the set of threads of $G$
- $T$ includes a top-level Root thread
- With each thread $t \in T$, associate unique
  - entry node $t_{en} \in N$
  - exit node $t_{ex} \in N$
- Each $n \in N$ belongs to a thread $th(n)$ defined as
  - Immediately enclosing thread $t \in T$
  - such that there is a flow path to $n$ that originates in $t_{en}$ and that does not traverse any other entry node $t'_{en}$, unless that flow path subsequently traverses $t'_{ex}$ also
- For each thread $t$, define $sts(t)$ as the set of statement nodes $n \in N$ such that $th(n) = t$



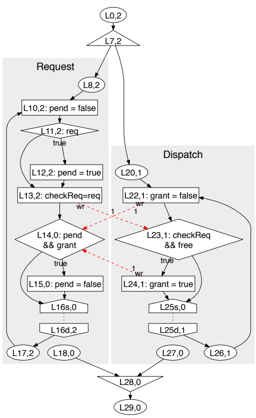
# Static Thread Concurrency and Subordination

Let $t$, $t_1$, $t_2$ be threads in $T$

- $fork(t) =_{def}$ fork node immediately preceding $t_{en}$
- For every thread $t \neq$ Root:
  $p(t) =_{def} th(fork(t))$, the parent thread
- $p^*(t) =_{def} \{t, p(t), p(p(t)), \ldots, \text{Root}\}$, the recursively defined set of ancestor threads of $t$
- $t_1$ is subordinate to $t_2$, written $t_1 \prec t_2$, if $t_1 \neq t_2 \wedge t_1 \in p^*(t_2)$
- $t_1$ and $t_2$ are (statically) concurrent, denoted $t_1 || t_2$, iff $t_1$ and $t_2$ are descendants of distinct threads sharing a common fork node, *i. e.*:
  $\exists t'_1 \in p^*(t_1), t'_2 \in p^*(t_2) : t'_1 \neq t'_2 \wedge fork(t'_1) = fork(t'_2)$
  - Denote this common fork node as $lcafork(t_1, t_2)$, the least common ancestor fork
  - Lift (static) concurrency notion to nodes:
    $th(n_1) || th(n_2) \Rightarrow lcafork(n_1, n_2) = lcafork(th(n_1), th(n_2))$

# Threads in Control Example

```
1  module Control
2  input bool free, req;
3  output bool grant, pend;
4  {
5    bool checkReq;
6
7    fork {
8      // Thread Request
9      Request entry:
10     pend = false;
11     if (req)
12       pend = true;
13     checkReq = req;
14     if (pend && grant)
15       pend = false;
16     pause;
17     goto Request entry;
18   }
19   par {
20     // Thread Dispatch
21     Dispatch entry:
22     grant = false;
23     if (checkReq && free)
24       grant = true;
25     pause;
26     goto Dispatch entry;
27   }
28   join;
29 }
```




- Threads $T = \{Root, Request, Dispatch\}$
- *Root* thread consists of the statement nodes $sts(Root) = \{L0, L7, L28, L29\}$
- The remaining statement nodes of $N$ are partitioned into $sts(Dispatch)$ and $sts(Request)$

# Concurrency and Subordination in Control-Program

```
1  module Control
2  input bool free, req;
3  output bool grant, pend;
4  {
5    bool checkReq;
6
7    fork {
8      // Thread Request
9      Request entry:
10     pend = false;
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29 }
```
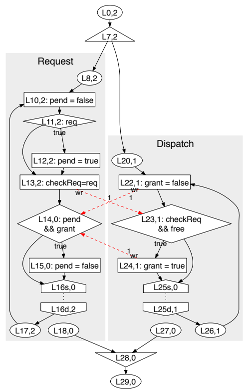




- $Root \prec Request$ and $Root \prec Dispatch$
- $Request \, || \, Dispatch$, $Root$ is not concurrent with any thread

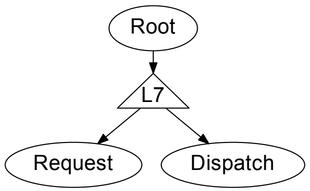
**Note:** Concurrency on threads, in contrast to concurrency on node instances, is purely static and can be checked with a simple, syntactic analysis of the program structure.

# Thread Trees

A Thread Tree illustrates the static thread relationships.

- Contains subset of SCG nodes:
  1. Entry nodes, labeled with names of their threads
  2. Fork nodes, attached to the entry nodes of their threads
- Similar to the AND/OR tree of Statecharts

Thread tree for Control example:

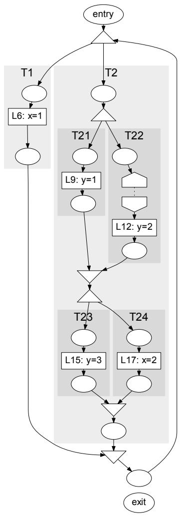


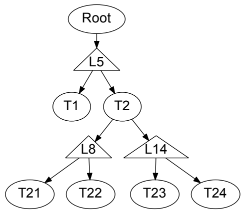





# Thread Trees – The Reinc2 Example

```
module Reinc2
output int x, y;
{
 loop:
  fork { // Thread T1
    x = 1; }
  par { // Thread T2
    fork { // Thread T21
      y = 1; }
    par { // Thread T22
      pause;
      y = 2; }
    join;
    fork { // Thread T23
      y = 3; }
    par { // Thread T24
      x = 2; }
    join}
 join;
 goto loop;
}
```




Alternative definition for static thread concurrency:

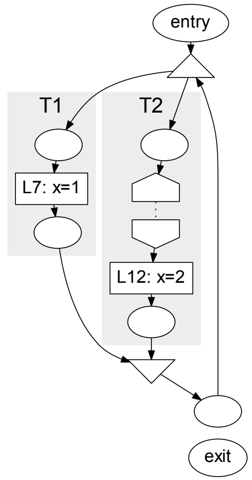
- Threads are concurrent iff their least common ancestor (lca) in thread tree is a fork node





# Thread Reincarnation – The Reinc Example

```
module Reinc
output int x, y;
{
loop:
 fork {
   // Thread T1
   x = 1;
 }
 par {
   // Thread T2
   pause;
   x = 2;
 }
 join;
 goto loop;
}
```

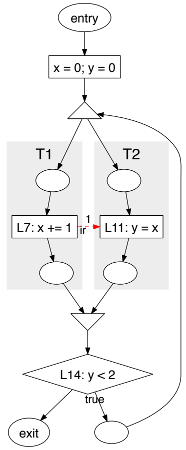



Are interested in run-time concurrency, *i. e.*, whether ordering is up to discretion of a scheduler. Observations:

- T2 exhibits thread reincarnation
- Assignments to $x$ are both executed in the same tick, yet are sequentialized
- Thus, **static thread concurrency not sufficient to capture run-time concurrency**!



# Statement Reincarnation I

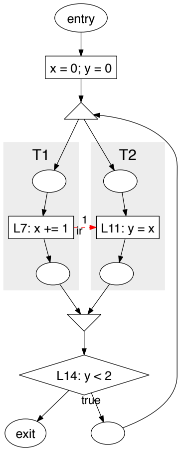



```
1  module InstLoop
2  output int x = 0, y = 0;
3  {
4  loop:
5   fork {
6    // Thread T1
7    x += 1;
8   }
9   par {
10   // Thread T2
11   y = x;
12  }
13  join;
14  if (y < 2)
15   goto loop;
16 }
```

- Accesses to $x$ in *L7* and *L11* executed twice within tick
- Denote this as statement reincarnation
- Accesses are (statically) concurrent
- Data dependencies ⇒ Must schedule *L7* before *L11*
  - But only within the same loop iteration!

Not enough to impose an order on the program statements
⇒ Need to distinguish statement instances

## Statement Reincarnation II




```
module InstLoop
output int x = 0, y = 0;
{
loop:
 fork {
  // Thread T1
  x += 1;
 }
 par {
  // Thread T2
  y = x;
 }
 join;
 if (y < 2)
  goto loop;
}
```

☹ Traditional synchronous languages: Reject

- *Instantaneous loops* traditionally forbidden

☺ SC: Deterministic ⇒ Accept

- One might still want to ensure that a program **always terminates**
- But this issue is **orthogonal to determinism** and having a well-defined semantics.



## Macroticks

- Given: SCG $G = (N, E)$
- (Macro) tick $R$, of length $len(R) \in \mathbb{N}_{\leq 1}$: mapping from micro tick indices $1 \leq j \leq len(R)$, to nodes $R(j) \in N$

A macro tick is also: Linearly ordered set of node instances

- Node instance: $ni = (n, i)$, with statement node $n \in N$, micro tick count $i \in \mathbb{N}$
- Can identify macro tick $R$ with set $\{(n, i) \mid 1 \leq i \leq len(R), n = R(i)\}$





## Overview

Static Concepts

Run-Time Concepts
- Micro/Macroticks, Runs, Traces
- Free Scheduling
- Confluence

Sequential Constructiveness





## Runs and Traces

- Run of $G$: sequence of macro ticks $R^a$, indexed by $a \in IN_{\leq 1}$
- Trace: externally visible output values at each macro tick $R$

## Run-Time Concurrency

Given: macro tick $R$, index $1 \leq i \leq len(R)$, node $n \in N$
Def.: $last(n, i) = max\{j \mid j \leq i, R(j) = n\}$,
retrieves last occurrence of $n$ in $R$ at or before index $i$

Given: macro tick $R$, $i_1, i_2 \in \mathbb{N}_{\leq len(R)}$, and $n_1, n_2 \in N$.
Def.: Two node instances $ni_1 = (n_1, i_1)$ and $ni_2 = (n_2, i_2)$ are (run-time) concurrent in $R$, denoted $ni_1 \mid_R ni_2$, iff

1. they appear in the micro ticks of $R$, *i. e.*, $n_1 = R(i_1)$ and $n_2 = R(i_2)$,
2. they belong to statically concurrent threads, *i. e.*, $th(n_1) \mid\mid th(n_2)$, and
3. their threads have been instantiated by the same instance of the associated least common ancestor fork, *i. e.*, $last(n, i_1) = last(n, i_2)$ where $n = lcafork(n_1, n_2)$





## Continuation Pool & Configuration

Continuation pool: finite set $C$ of continuations

- $C$ is valid if $C$ meets some coherence properties, *e. g.*, threads in $C$ adhere to thread tree structure

Configuration: pair $(C, \rho)$

- $C$ is continuation pool
- $\rho$ is memory assigning values to variables accessed by $G$

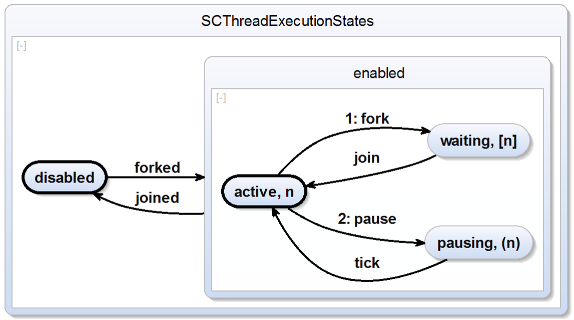
A configuration is called valid if $C$ is valid



## Continuations & Thread Execution States

A continuation $c$ consists of

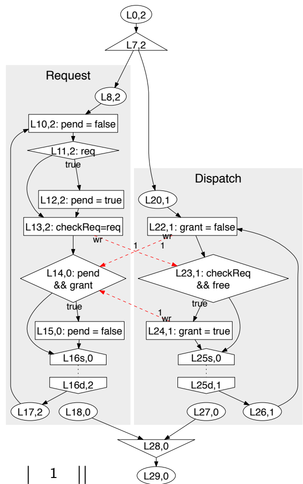
1. Node $c.node \in N$, denoting the current state of each thread, *i. e.*, the node (statement) that should be executed next, similar to a program counter
2. Status $c.status \in \{active, waiting, pausing\}$




In a trace (see next slide), round/square/no parentheses around $n = c.node$ denote $c.status$, for enabled continuations $c$

```
module Control
input bool free, req;
output bool grant, pend;
{
  bool checkReq;

  fork {
    // Thread Request
    Request entry:
    pend = false;
    if (req)
      pend = true;
    checkReq = req;
    if (pend && grant)
      pend = false;
    pause;
    goto Request entry;
  }
```

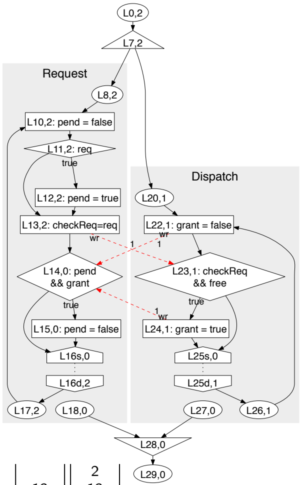
```
  par {
    // Thread Dispatch
    Dispatch entry:
    grant = false;
    if (checkReq && free)
      grant = true;
    pause;
    goto Dispatch entry;
  }
  join;
}
```




| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Macro tick* | $a$ | 1 | | | | | | | | | | | | 1 |
| *Micro tick* | $i$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 12 |
| *Input* | free | **t** | | | | | | | | | | | | *t* |
| *vars* | req | **f** | | | | | | | | | | | | *f* |
| *Output* | grant | $\perp$ | | | | | | | | *f* | | | | **f** |
| *vars* | pend | $\perp$ | | | | *f* | | | | | | | | **f** |
| *Local var* | checkReq | $\perp$ | | | | | | *f* | | | | | | *f* |
| | $C_{Root}$ | L0 | L7 | [L28] | | | | | | | | | | [L28] |
| *Continuations* | $C_{Request}$ | $\perp$ | | L8 | L10 | L11 | L13 | L14 | L14 | L14 | L14 | L14 | L16s | (L16s) |
| | $C_{Dispatch}$ | $\perp$ | | L20 | L20 | L20 | L20 | L20 | L22 | L23 | L25s | (L25s) | (L25s) | (L25s) |
| *Scheduled nodes* $R_i^a$ | | L0 | L7 | L8 | L10 | L11 | L13 | L20 | L22 | L23 | L25s | L14 | L16s | |

```
1   module Control
2   input bool free, req;
3   output bool grant, pend;
4   {
5     bool checkReq;
6
7     fork {
8       // Thread Request
9       Request entry:
10      pend = false;
11      if (req)
12        pend = true;
13      checkReq = req;
14      if (pend && grant)
15        pend = false;
16      pause;
17      goto Request entry;
18    }
```

```
19    par {
20      // Thread Dispatch
21      Dispatch entry:
22      grant = false;
23      if (checkReq && free)
24        grant = true;
25      pause;
26      goto Dispatch entry;
27    }
28    join;
29  }
```




| *Macro tick* | *a* | 2 | | | | | | | | | | | | | 2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Micro tick* | *i* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 13 |
| *Input vars* | free | **t** | | | | | | | | | | | | | *t* |
| | req | **t** | | | | | | | | | | | | | *t* |
| *Output vars* | grant | *f* | | | | | | | *f* | | *t* | | | | **t** |
| | pend | *f* | | *f* | | *t* | | | | | | | | *f* | **f** |
| *Local var* | checkReq | *f* | | | | | *t* | | | | | | | | *t* |
| *Continuations* | $C_{\text{Root}}$ | [L28] | | | | | | | | | | | | | [L28] |
| | $C_{\text{Request}}$ | L16d | L10 | L11 | L12 | L13 | L14 | L14 | L14 | L14 | L14 | L14 | L15 | L16s | (L16s) |
| | $C_{\text{Dispatch}}$ | L25d | L25d | L25d | L25d | L25d | L25d | L22 | L23 | L24 | L25s | (L25s) | (L25s) | (L25s) | (L25s) |
| *Scheduled nodes* $R_i^a$ | | L16d | L10 | L11 | L12 | L13 | L25d | L22 | L23 | L24 | L25s | L14 | L15 | L16s | |



# Free Scheduling

Now define free scheduling, to set the stage for later defining "initialize-update-read" protocol
($\rightarrow$ SC-admissible scheduling)

Only restrictions:

1. Execute only $\prec$-maximal threads
   - If there is at least one continuation in $C_{cur}$, then there also is a $\prec$-maximal one, because of the finiteness of the continuation pool
2. Do so in an interleaving fashion





# Micro Steps I

Micro step: transition $(C_{cur}, \rho_{cur}) \xrightarrow{c}_{\mu s} (C_{nxt}, \rho_{nxt})$ between two micro ticks

- $(C_{cur}, \rho_{cur})$: current configuration
- $c$: continuation selected for execution
- $(C_{nxt}, \rho_{nxt})$: next configuration

The free schedule is permitted to pick any one of the $\prec$-maximal continuations $c \in C_{cur}$ with $c.status =$ active and execute it in the current memory $\rho_{cur}$





# Micro Steps II

(Recall:) Micro step: transition $(C_{cur}, \rho_{cur}) \xrightarrow{c}_{\mu s} (C_{nxt}, \rho_{nxt})$

- Executing $c$ yields a new memory $\rho_{nxt} = upd(c, \rho_{cur})$ and a (possibly empty) set of new continuations $nxt(c, \rho_{cur})$ by which $c$ is replaced, *i. e.*, $C_{nxt} = C_{cur} \setminus \{c\} \cup nxt(c, \rho_{cur})$
- If $nxt(c, \rho_{cur}) = \emptyset$: status flags set to active for all $c \in C_{nxt}$ that become $\prec$-maximal by eliminating $c$ from $C$
- Actions $upd$ and $nxt$ (made precise in TR) depend on the statement $c.node.st$ to be executed
- $(C_{nxt}, \rho_{nxt})$ uniquely determined by $c$, thus may write $(C_{nxt}, \rho_{nxt}) = c(C_{cur}, \rho_{cur})$

# Clock Steps I

Quiescent configuration $(C, \rho)$:

- No active $c \in C$
- All $c \in C$ pausing or waiting

If $C = \emptyset$:

- Main program terminated

Otherwise:

- Scheduler can perform a global clock step





# Clock Steps II

Global clock step $(C_{cur}, \rho_{cur}) \xrightarrow{\alpha}_{tick} (C_{nxt}, \rho_{nxt})$

- Transition between last micro tick of the current macro tick to first micro tick of the subsequent macro tick
- $\alpha$ is external input
- All pausing continuations of $C$ advance from their surf node to the associated depth node:

$$\begin{aligned} C_{nxt} \quad = \quad & \{c[\text{active} :: \mathit{tick}(n)] \mid c[\text{pausing} :: n] \in C_{cur}\} \ \cup \\ & \{c[\text{waiting} :: n] \mid c[\text{waiting} :: n] \in C_{cur}\} \end{aligned}$$





# Clock Steps III

Global clock step updates the memory:

- Let $I = \{x_1, x_2, \ldots, x_n\}$ be the designated input variables of the SCG, including input/output variables
- Memory is updated by a new set of external input values $\alpha = [x_1 = v_1, \ldots, x_n = v_n]$ for the next macro tick
- All other memory locations persist unchanged into the next macro tick.

Formally,

$$\rho_{nxt}(x) = \begin{cases} v_i, & \text{if } x = x_i \in I, \\ \rho_{cur}(x), & \text{if } x \notin I. \end{cases}$$



# Macro Ticks

Scheduler runs through sequence

$$(C_0^a, \rho_0^a) \xrightarrow{c_1^a}_{\mu s} (C_1^a, \rho_1^a) \xrightarrow{c_2^a}_{\mu s} \cdots \xrightarrow{c_{k(a)}^a}_{\mu s} (C_{k(a)}^a, \rho_{k(a)}^a) \qquad (1)$$

to reach final quiescent configuration $(C_{k(a)}^a, \rho_{k(a)}^a)$

Sequence (1) is macro tick (synchronous instant) $a$:

$$(C_0^a, \rho_0^a) \overset{\alpha^a / R^a}{\Longrightarrow} (C_{k(a)}^a, \rho_{k(a)}^a) \qquad (2)$$

- $\alpha^a$: projects the initial input, $\alpha^a(x) = \rho_0^a(x)$ for $x \in I$
- $\rho_{k(a)}^a$: response of $a$

$R^a$: sequence of statement nodes executed during $a$

- $len(R^a) = k(a)$ is length of $a$
- $R^a$ is function mapping each micro tick index $1 \leq j \leq k(a)$ to node $R^a(j) = c_j^a.node$ executed at index $j$

# Determinism

Recall:

$$(C_0^a, \rho_0^a) \xrightarrow{c_1^a}_{\mu s} (C_1^a, \rho_1^a) \xrightarrow{c_2^a}_{\mu s} \cdots \xrightarrow{c_{k(a)}^a}_{\mu s} (C_{k(a)}^a, \rho_{k(a)}^a) \quad (1)$$

$$(C_0^a, \rho_0^a) \overset{\alpha^a/R^a}{\Longrightarrow} (C_{k(a)}^a, \rho_{k(a)}^a) \quad (2)$$

- Macro (tick) configuration: end points of a macro tick (2)
- Micro (tick) configuration: all other intermediate configurations $(C_i^a, \rho_i^a)$, $0 < i < k(a)$ seen in (1)

Synchrony hypothesis:

- only macro configurations are observable externally (in fact, only the memory component of those)
- **Suffices to ensure that sequence of macro ticks $\Longrightarrow$ is deterministic**
- Micro tick behavior $\rightarrow_{\mu s}$ may well be non-deterministic





# Active and Pausing Continuations are Concurrent

Given:

- $(C, \rho)$, reachable (micro or macro tick) configuration
- $c_1, c_2 \in C$, active or pausing continuations with $c_1 \neq c_2$

Then:

- $c_1.node \neq c_2.node$
- $th(c_1.node) \,||\, th(c_2.node)$

(Proof: see TR)





# Concurrency vs. Sequentiality Revisited I

Recall: Want to exploit sequentiality as much as possible

- Thus, consider only run-time concurrent data dependencies

Recall: Static concurrency $\not\Rightarrow$ run-time concurrency

- Consider Reinc example
- Thus, can ignore some statically concurrent data dependencies





# Concurrency vs. Sequentiality Revisited II

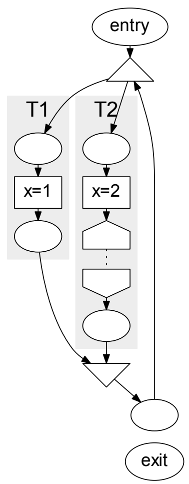
Question: Does (static) sequentiality preclude run-time concurrency?

- Then we could ignore data dependencies between nodes that are sequentially ordered
- But the answer is: **no**

Counterexample: Reinc3 (SCG shown on left)

- Assignments to x run-time concurrent? Yes!
- Assignments to x sequentially ordered? Yes!

Thus, concurrency and (static) sequentiality are not **mutually exclusive, but orthogonal**! However, *run-time* sequentiality (on node *instances*) does exclude run-time concurrency



## Notes on Free Scheduling I

Key to determinism:
rule out uncertainties due to unknown scheduling mechanism

- Like the synchronous MoC, the SC MoC ensures macro-tick determinism by inducing certain scheduling constraints on variable accesses
- **Unlike** the synchronous MoC, the SC MoC tries to take **maximal advantage of the execution order already expressed by the programmer** through sequential commands
- A scheduler can only affect the order of variable accesses through **concurrent** threads





## Notes on Free Scheduling II

Recall:

- If variable accesses are already sequentialized by $\rightarrow_{seq}$, they cannot appear simultaneously in the active continuation pool
- Hence, no way for thread scheduler to reorder them and thus lead to a non-deterministic outcome

Similarly, threads are not concurrent with parent thread

- Because of path ordering $\prec$, a parent thread is always suspended when a child thread is in operation
- Thus, not up to scheduler to decide between parent and child thread
- No race conditions between variable accesses performed by parent and child threads; no source of non-determinism





## The Aim

Want to find a suitable restriction on the "free" scheduler which is

1. easy to compute
2. leaves sufficient room for concurrent implementations
3. still (predictably) sequentialises any concurrent variable accesses that may conflict and produce unpredictable responses

In the following, will define such a restriction:
the SC-admissible schedules





## Guideline for SC-admissibility

- Initialize-Update-Read protocol, for concurrent accesses
- Want to conservatively extend Esterel's "Write-Read protocol" (must emit *before* testing)
- But does Esterel *always* follow write-read protocol?

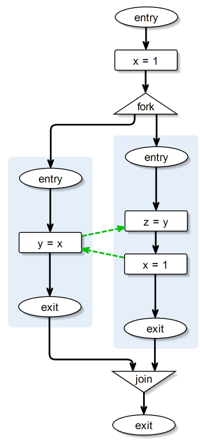
# Write After Read Revisited

```
module WriteAfterRead
output x, y, z;

emit x;
[
  present x then
    emit y
  end
||
  present y then
    emit z
  end;
  emit x
]
end
```

Esterel version

```
module WriteAfterRead
output int x, y, z;
{
  x = 1;
  fork
    y = x;
  par
    z = y;
    x = 1;
  join
}
```

SCL version




- Concurrent emit *after* present test
- But WriteAfterRead is BC – hence should also be SC!
- Observation: second emit is ineffective
- One approach: permit concurrent ineffective writes after read

# Ineffectiveness – 2nd Try

```
1  module InEffective2
2  output bool x = false;
3   int y;
4  {
5   fork
6     if (!x) {
7       y = 1;
8       x = x xor true
9     }
10    else
11      y = 0
12  par
13    x = x xor true;
14  join
15 }
```

"x = x xor true"

- Relative writes
- Equivalent to "x = !x"

Sequence L13; L6; L11:

- y = 0

Sequence L6; L7; L8; L13:

- Q: Is L13 ineffective *relative to L5*?
- A: Yes!
- L13 is out-of-order ...
- but writes x = true, which is what L5 read!
- y = 1 (→ again non-determinism!)

- Again, both schedules would be permitted under a scheduling regime that permits ineffective writes
- → Replace "ineffectiveness" by "confluence"

# Ineffectiveness – 1st Try

```
1  module InEffective1
2  output int x = 2;
3   int y;
4  {
5   fork
6     if (x == 2) {
7       y = 1;
8       x = 7
9     }
10    else
11      y = 0
12  par
13    x = 7
14  join
15 }
```

If L13 is scheduled before L6:

- L13 is effective
- No out-of-order write
- y = 0

If L13 is scheduled after L8 (and L6):

- L13 is out-of-order write
- However, L13 is ineffective
- y = 1 (→ non-determinism!)
- The problem: L8 hides the potential effectiveness of L13 wrt. L6!

- Both schedules would be permitted under a scheduling regime that permits ineffective writes
- → Strengthen notion of "ineffective writes":
- Consider writes "ineffective" only if they do not change read!



# Confluence of Nodes

Given:

- Valid configuration $(C, \rho)$ of SCG
- Nodes $n_1, n_2 \in N$

$n_1, n_2$ are conflicting in $(C, \rho)$ iff

1. $n_1, n_2$ active in $C$,
   *i. e.*, $\exists c_1, c_2 \in C$ with
   $c_i.status = active$ and $n_i = c_i.node$
2. $c_1(c_2(C, \rho)) \neq c_2(c_1(C, \rho))$

$n_1, n_2$ are confluent with each other in $(C, \rho)$,
written: $n_1 \sim_{(C,\rho)} n_2$, iff

- $\nexists$ Sequence of micro steps $(C, \rho) \twoheadrightarrow_{\mu s} (C', \rho')$ such that $n_1$ and $n_2$ are conflicting in $(C', \rho')$

## Notes on Confluence

(From definition:) $n_1 \sim_{(C,\rho)} n_2$ iff

- $\nexists$ Sequence of micro steps $(C,\rho) \twoheadrightarrow_{\mu s} (C',\rho')$ such that $n_1$ and $n_2$ are conflicting in $(C',\rho')$

Observations I

- Confluence is taken *relative* to valid configurations $(C,\rho)$ and *indirectly* as the absence of conflicts
- Instead of requiring that confluent nodes commute with each other for *arbitrary* memories, we only consider those configurations $(C',\rho')$ that are *reachable* from $(C,\rho)$
- *E. g.*, if it happens for a given program that in all memories $\rho'$ reachable from a configuration $(C,\rho)$ two expressions $ex_1$ and $ex_2$ evaluate to the same value, then the assignments $\mathrm{x} = ex_1$ and $\mathrm{x} = ex_2$ are confluent in $(C,\rho)$





## Notes on Confluence

(From definition:) $n_1 \sim_{(C,\rho)} n_2$ iff

- $\nexists$ Sequence of micro steps $(C,\rho) \twoheadrightarrow_{\mu s} (C',\rho')$ such that $n_1$ and $n_2$ are conflicting in $(C',\rho')$

Observations II

- Similarly, if the two assignments are never jointly active in any reachable continuation pool $C'$, they are confluent in $(C,\rho)$, too
- Thus, statements may be confluent for some program relative to some reachable configuration, but not for other configurations or in another program
- However, notice that relative writes of the same type are confluent in the absolute sense, *i. e.*, for all valid configurations $(C,\rho)$ of all programs





## Notes on Confluence

(From definition:) $n_1 \sim_{(C,\rho)} n_2$ iff

- $\nexists$ Sequence of micro steps $(C,\rho) \twoheadrightarrow_{\mu s} (C',\rho')$ such that $n_1$ and $n_2$ are conflicting in $(C',\rho')$

Observations III

- Confluence $n_1 \sim_{(C,\rho)} n_2$ requires conflict-freeness for *all* configurations $(C',\rho')$ reachable from $(C,\rho)$ by *arbitrary* micro-sequences under *free scheduling*
- Will use this notion of confluence to define the restricted set of *SC-admissible* macro ticks
- Since compiler will ensure SC-admissibility of the execution schedule,
  one might be tempted to define confluence relative to these SC-admissible schedules;
  however, this would result in a logical cycle





## Notes on Confluence

(From definition:) $n_1 \sim_{(C,\rho)} n_2$ iff

- $\nexists$ Sequence of micro steps $(C,\rho) \twoheadrightarrow_{\mu s} (C',\rho')$ such that $n_1$ and $n_2$ are conflicting in $(C',\rho')$

Observations IV

- This relative view of confluence keeps the scheduling constraints on SC-admissible macro ticks sufficiently weak
- Note: two nodes confluent in some configuration are still confluent in every later configuration reached through an arbitrary sequence of micro steps
- However, there more nodes may become confluent, because some conflicting configurations are no longer reachable
- Exploit this in following definition of confluence *of node instances* by making confluence of node instances within a macro tick relative to the index position at which they occur

# Confluence of Node Instances

Given:

- Macro tick $R$
- $(C_i, \rho_i)$ for $0 \leq i \leq len(R)$, the configurations of $R$
- Node instances $ni_1 = (n_1, i_1)$ and $ni_2 = (n_2, i_2)$ in $R$, *i. e.*, $1 \leq i_1, i_2 \leq len(R)$, $n_1 = R(i_1)$, $n_2 = R(i_2)$

Call node instances confluent in R, written $ni_1 \sim_R ni_2$, iff

- $n_1 \sim_{(C_i, \rho_i)} n_2$
- for $i = min(i_1, i_2) - 1$



# InEffective2 Revisited

```
1  module InEffective2
2  output bool x = false;
3    int y;
4  {
5   fork
6     if (!x) {
7       y = 1;
8       x = x xor true
9     }
10    else
11      y = 0
12   par
13     x = x xor true;
14   join
15 }
```

Recall sequence L6; L7; L8; L13:

- Q: Is L13 ineffective *relative to L5*?
- A: Yes!
- L13 is out-of-order ...
- but writes x = true, which is what L5 read!
- Q: Are L5 and L13 confluent?
- A: No!

→ Current def. of SC-admissibility – specifically, the underlying scheduling relations – use confluence condition



# Overview







# (Recall:) Scheduling Relations I

For macro tick $R$, and **concurrent but not confluent** node instances (executed statements) $ni_1$, $ni_2$, define scheduling relations:

$ni_1 \rightarrow^R ni_2$: "happens before" (linear order)

- $ni_1$ occurs before $ni_2$ in $R$

$ni_1 \leftrightarrow^R_{ww} ni_2$: "write / write conflict"

- $ni_1$ and $ni_2$ both perform absolute writes on the same variable
- or both perform relative writes of different type on the same variable
- $\nexists$ **Impossible to find linear order!**

## (Recall:) Scheduling Relations II

For macro tick $R$, and **concurrent but not confluent** node instances (executed statements) $ni_1$, $ni_2$, define scheduling relations:

$ni_1 \rightarrow^R_{wr} ni_2$: "write before read", or "initialize before read"

- $ni_1$ is absolute write
- $ni_2$ is read of the same variable

$ni_1 \rightarrow^R_{ir} ni_2$: "increment before read", or "update before read"

- $ni_1$ is relative write
- $ni_2$ is read of the same variable

$ni_1 \rightarrow^R_{wi} ni_2$: "write before increment", or "initialize before update"

- $ni_1$ is absolute write
- $ni_2$ is relative write of the same variable





## (Recall:) Sequential Admissibility

| | | |
|---|---|---|
| $ni_1 \rightarrow^R ni_2$ | : | "happens before" |
| $ni_1 \leftrightarrow^R_{ww} ni_2$ | : | "write / write" |
| $ni_1 \rightarrow^R_{wr} ni_2$ | : | "write before read" |
| $ni_1 \rightarrow^R_{ir} ni_2$ | : | "increment before read" |
| $ni_1 \rightarrow^R_{wi} ni_2$ | : | "write before increment" |

**Definition:** A run is SC-admissible iff
for all macro ticks $R$ and all node instances $ni_1$, $ni_2$ in $R$:

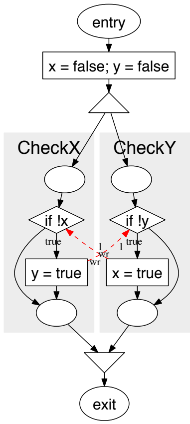
$$\neg(ni_1 \leftrightarrow^R_{ww} ni_2) \wedge$$
$$((ni_1 \rightarrow^R_{wr} ni_2) \vee (ni_1 \rightarrow^R_{ir} ni_2) \vee (ni_1 \rightarrow^R_{wi} ni_2)) \Rightarrow ni_1 \rightarrow^R ni_2)$$





## SC-admissibility vs. Determinism

```
module NonDet
output bool x = false, y = false;
{
 fork { // Thread CheckX
  if (!x)
   y = true;
 }
 par { // Thread CheckY
  if (!y)
   x = true
 }
 join
}
```




Multiple admissible runs but non-deterministic outcome

Thus: **SC-admissibility $\not\Rightarrow$ Determinism**





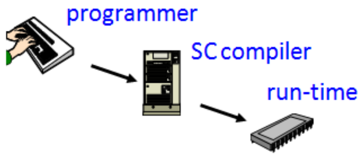
## SC-admissibility vs. Determinism

```
module Fail
output bool z = false;
{
 fork {
  if (!z)
   z = true;
 }
 par {
  if (z)
   z = true
 }
 join
}
```

Deterministic outcome but no SC-admissible schedule

Thus: **Determinism $\not\Rightarrow$ SC-admissibility**

## (Recall:) Sequential Constructiveness – Definition




**Definition:** A program is sequentially constructive (SC) iff for each initial configuration and input sequence:

1. There exists an SC-admissible run
2. Every SC-admissible run generates the same determinate sequence of macro responses





## Summary I

Underlying idea of sequential constructiveness rather simple

- Prescriptive instead of descriptive sequentiality
- Thus circumventing "spurious" causality problems
- Initialize-update-read protocol

However, precise definition of SC MoC not trivial

- Challenging to ensure conservativeness relative to Berry-constructiveness
- Plain initialize-update-read protocol does not accomodate, *e. g.*, signal re-emissions
- Restricting attention to *concurrent*, *non-confluent* node instances is key





## Summary II

ASC-schedulability

- Is conservative approximation to SC
- Basis for practical implementation

Future work

- Plenty of it (SC+, optimized code gen, improved SCCharts transformations, ...)
- Talk to us if you want to be part of it





## To Go Further

DFG-funded PRETSY Project: `www.pretsy.org`

R. von Hanxleden, M. Mendler, J. Aguado, B. Duderstadt, I. Fuhrmann, C. Motika, S. Mercer, and O. O'Brien. *Sequentially Constructive Concurrency – A conservative extension of the synchronous model of computation*. In Proc. Design, Automation and Test in Europe Conference (DATE'13), Grenoble, France, March 2013. `http://rtsys.informatik.uni-kiel.de/~biblio/downloads/papers/date13.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*. Technical Report 1308, Christian-Albrechts-Universität zu Kiel, Department of Computer Science, Aug 2013. `http://rtsys.informatik.uni-kiel.de/~biblio/downloads/papers/report-13seqc.pdf`

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.