Synchronous Languages—Lecture 02

Prof. Dr. Reinhard von Hanxleden

Christian-Albrechts Universität Kiel
Department of Computer Science
Real-Time Systems and Embedded Systems Group

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Esterel I—Overview

Overview

Introduction to Esterel

- Imperative, textual language
- Concurrent
- Based on synchronous model of time
  - Program execution synchronized to an external clock
  - Like synchronous digital logic
  - Suits the cyclic executive approach

Thanks to Stephen Edwards (Columbia U), Klaus Schneider (U Kaiserslautern) and Gerald Luettgen (U Bamberg) for providing part of the following material

History

- Developed at Centre de Mathématiques Appliquées (CMA), Ecole des Mines de Paris
- J.-P. Marmorat and J.-P. Rigault built an autonomous vehicle
- They were not satisfied by traditional programming languages (no adequate support for reactive control flow, non-determinism due to language and/or OS)

$\leadsto$ and developed a first version of Esterel

- Estérel is a mountain area between Cannes and St. Raphaël, the name sounds like "real-time" in french (*temps-réel*)
- G. Berry developed a formal semantics for Esterel

Esterel Dialects

- Esterel v5: Has been stable since late 1990s
- Esterel v7: same principles as in v5, several extensions (e. g., multi-clock designs, refined type system). There is an IEEE standardization draft.

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- Sequentially Constructive Esterel (SCEst): Extension of Esterel, based on Sequentially Constructive Model of Computation (SC MoC)

Graphical Variants

There are several graphical languages following a similar MoC as Esterel, using a Statechart-like syntax:

- Argos: first graphical language
- SyncCharts : successor of Argos
- Safe State Machines (SSMs): equivalent to SyncCharts, the name of the modeling language supported by the commercial tool Esterel Studio, which uses Esterel as intermediate step in code generation

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- Sequentially Constructive Statecharts (SCCharts): Extension of SyncCharts/SSMs based on SC MoC
- In this class, we will mainly consider Esterel v5, SCEst and SCCharts

Signals

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- These are like wires
  - Each signal is either present or absent in each tick
  - Can't take multiple values within a tick
- Presence/absence not held between ticks
- Broadcast across the program
  - Any process can read or write a signal

Signals

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- Status of local or output signal is determined per tick
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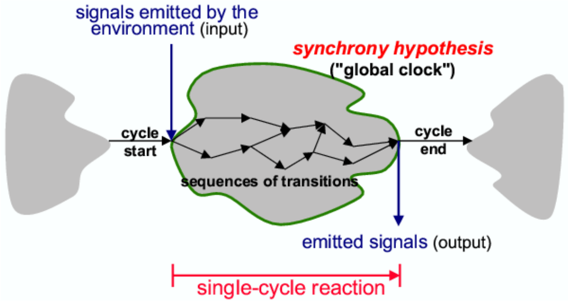
  - Must execute an "`emit S`" statement to set signal `S` present
- `await A`:
  - Waits for A and terminates when A occurs

Synchrony Hypothesis

- Computations are considered to
  - take no time
  - be atomic



G. Luettgen 2001

Perfect Synchrony

Definition [Perfect Synchrony]
A system works in perfect synchrony, if all reactions of the system are executed in zero time. Hence, outputs are generated at the same time, when the inputs are read.

- Of course, this is only an idealized programmer's model
- In practice, 'zero time' means before the next interaction
- Physical time between interactions may not always be the same
- Synchronous programs use natural numbers for *logical time*, where only interactions, *i. e.*, macro steps, are counted

Synchronous Model of Computation

To summarize: the synchronous model of computation of SSMs/Esterel is characterized by:

1. Computations considered to take no time (synchrony hypothesis)
2. Time is divided into discrete ticks
3. Signals are either present or absent in each tick

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2. Time is divided into discrete ticks
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Sometimes, "synchrony" refers to just the first two points (*e.g.*, in the original Statecharts as implemented in Statemate); to explicitly include the third requirement as well, we also speak of the strict synchrony

Perfect Synchrony and Worst-Case Execution Time

- *When are real-time constraints considered?*
- Macro steps consist of *only finitely many micro steps*, *i. e.*, there are no data dependent loops in a macro step
- Hence, the runtime of a single macro step can be easily checked (at least compared to non-synchronous languages) for a specific platform (processor)

⇝ Low-level worst case execution time analysis (WCET), also called worst case reaction time analysis (WCRT)

- Additionally, one can check how many macro steps are required from one system state to another (high-level WCET analysis)

The Multiform Notion of Time

- Some "classical" programming languages already include a concept of real-time
- Consider the following Ada code fragment, which signals minutes to a task B:

```
loop
  delay 60;
  B.Minute
end
```

- This works in principle
- However, it is not deterministic!

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- A design goal of synchronous languages:
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- Approach:
  - Replace notion of *physical time* with notion of *order*
  - Only consider *simultaneity* and *precedence* of events
- Hence, physical time does not play any special role
  - Is handled like any other event from program environment
  - This is called multiform notion of time

The Multiform Notion of Time

- Consider following requirements:
  - "The train must stop within 10 seconds"
  - "The train must stop within 100 meters"

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  - "The train must stop within 10 seconds"
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- These are conceptually of the same nature!
- In languages where physical time plays particular role, these requirements are typically expressed completely differently
- In synchronous model, use similar precedence constraints:
  - "The event stop must precede the 10th (respectively, 100th) next occurrence of the event second (respectively, meter)"

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- At each tick, an arbitrary number of events (including 0) occurs
- Event occurrences that happen at the same logical tick are considered simultaneous
- Other events are ordered as their instances of occurrences

Basic Esterel Statements

`emit S`

- Make signal `S` present in the current instant
- A signal is absent unless it is emitted

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- Stop and resume after the next cycle after the pause

`present S then` *stmt1* `else` *stmt2* `end`

- If signal `S` is present in the current instant, immediately run *stmt1*, otherwise run *stmt2*

Esterel's Model of Time

- The standard CS model (e.g., Java's) is asynchronous
  - Threads run at their own rate
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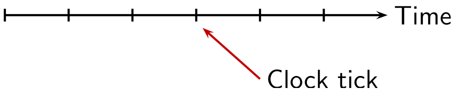
  - Threads run at their own rate
  - Synchronization is done (for example) through calls to `wait()` and `notify()`
- Esterel's model of time is synchronous like that used in hardware. Threads march in lockstep to a global clock.



Basic Esterel Statements

```
module EXAMPLE1:
output A, B, C;

emit A;
present A then emit B end;
pause;
emit C

end module
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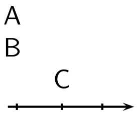

EXAMPLE1 makes signals A & B present the first instant, C present the second

Signal Coherence Rules

- Each signal is only present or absent in a cycle, never both
- All writers run before any readers do
- Thus

```
present A else
   emit A
end
```

is an erroneous program

Advantage of Synchrony

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- Speed of actual computation nearly uncontrollable
- Allows function and timing to be specified independently
- Makes for deterministic concurrency
- Explicit control of "before" "after" "at the same time"

Time Can Be Controlled Precisely

This guarantees every 60th S an M is emitted:

```
every 60 S do
  emit M
end
```

`every` invokes its body every 60th S

`emit` takes no time (cycles)

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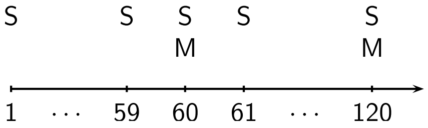

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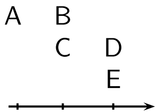

Communication Is Instantaneous

A signal emitted in a cycle is visible immediately

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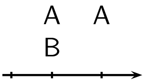

Bidirectional Communication

Processes can communicate back and forth in the same cycle

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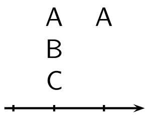

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- Signals are the only way for concurrent processes to communicate
- Esterel does have variables, which (unlike signals) can be sequentially modified within a tick, but they cannot be shared
- **Signal coherence rules ensure deterministic behavior**
- Language semantics clearly defines who must communicate with whom when

The Await Statement

- The `await` statement waits for a particular cycle
- `await S` waits for the **next** cycle in which `S` is present

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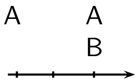

The Await Statement

- `await` normally waits for a cycle before beginning to check
- `await immediate` also checks the **initial** cycle

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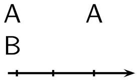

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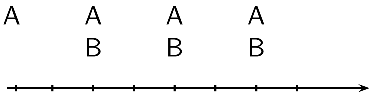

Loops and Synchronization

Instantaneous nature of loops plus `await` provide very powerful synchronization mechanisms

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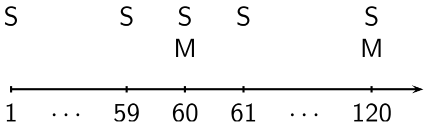

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- E.g., Ctrl-C in Unix: stop the currently-running program
- Esterel has many constructs for handling preemption

The Abort Statement

- Basic preemption mechanism
- General form:

```
abort
  statement
when condition
```

- Runs *statement* to completion
- If *condition* ever holds, abort terminates immediately.

The Abort Statement

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abort
  pause;
  pause;
  emit A
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emit C
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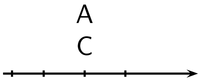

Normal termination

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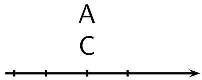

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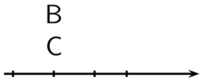

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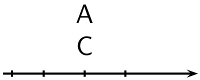

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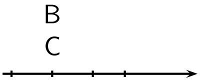

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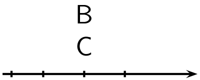

Aborted termination;
`emit A` preempted

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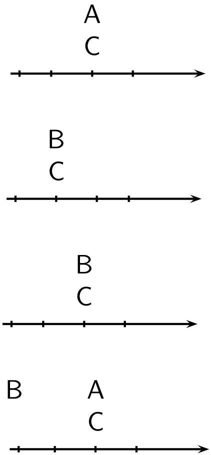

Normal termination

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Normal termination
`B` not checked in first cycle
(like `await`)

Strong vs. Weak Preemption

- Strong preemption:
  - The body does not run when the preemption condition holds
  - The previous example illustrated strong preemption

Strong vs. Weak Preemption

- Strong preemption:
  - The body does not run when the preemption condition holds
  - The previous example illustrated strong preemption
- Weak preemption:
  - The body is allowed to run even when the preemption condition holds, but is terminated thereafter
  - `weak abort` implements this in Esterel

Strong vs. Weak Abort

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  pause;
  pause;
  emit A;
  pause
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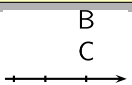

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weak abort
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when B;
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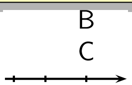

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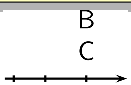

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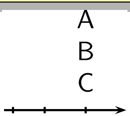

emit A does run, body terminated afterwards

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Erroneous!

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weak abort
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Ok!

Nested Preemption

```
module RUNNER
input LAP, METER, MORNING, SECOND, STEP;
output ... ;

every MORNING do
  abort
    loop
      abort run RUNSLOWLY when 15 SECOND;
      abort
        every STEP do
          run JUMP || run BREATHE
        end every
      when 100 METER;
      run FULLSPEED
    each LAP
  when 2 LAP
end every
end module
```

Exceptions—The Trap Statement

- Esterel provides an exception facility for *weak* preemption
- Interacts nicely with concurrency
- Rule: outermost trap takes precedence

The Trap Statement

```
trap T in
[
  pause;
  emit A;
  pause;
  exit T
||
  await B;
  emit C
]
end trap;
emit D
```

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emit D
```
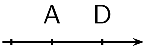
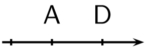



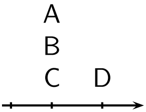
Normal termination from first process

The Trap Statement

```
trap T in
[
  pause;
  emit A;
  pause;
  exit T
||
  await B;
  emit C
]
end trap;
emit D
```



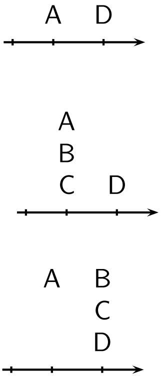
Normal termination from first process



emit C also runs

The Trap Statement

```
trap T in
[
  pause;
  emit A;
  pause;
  exit T
||
  await B;
  emit C
]
end trap;
emit D
```



Normal termination from first process

`emit C` also runs

Second process allowed to run even though first process has exited

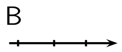
Nested Traps

```
trap T1 in
  trap T2 in
  [
    exit T1
    ||
    exit T2
  ]
  end;
  emit A
end;
emit B
```

Nested Traps

```
trap T1 in
  trap T2 in
  [
    exit T1
    ||
    exit T2
  ]
  end;
  emit A
end;
emit B
```

- Outer trap takes precedence; control transferred directly to the outer trap statement.
- `emit A` not allowed to run.



Combining Abortion and Exceptions

```
trap HEARTATTACK in
  abort
    loop
      abort RUNSLOWLY when 15 SECOND;
      abort
        every STEP do
          JUMP || BREATHE || CHECKHEART
        end every
      when 100 METER;
      FULLSPEED
    each LAP
  when 2 LAP
handle HEARTATTACK do
  GOTOHOSPITAL
end trap
```

The Suspend Statement

- Preemption (`abort`, `trap`) terminate something, but what if you want to pause it?

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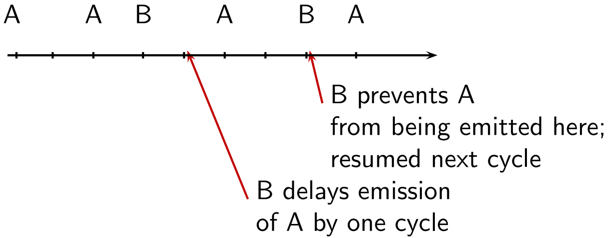
- Like the POSIX Ctrl-Z

The Suspend Statement

- Preemption (`abort`, `trap`) terminate something, but what if you want to pause it?
- Like the POSIX Ctrl-Z
- Esterel's `suspend` statement pauses the execution of a group of statements
- Only strong preemption: statement does not run when condition holds

The Suspend Statement

```
suspend
  loop
    emit A;
    pause;
    pause
  end
when B
```



Summary

- Esterel assumes perfect synchrony, with reactions discretized into *ticks*
- Information in Esterel is passed via broadcast of *signals*, which (unlike in SCEst) cannot be sequentially updated within a tick
- Esterel includes various preemption mechanisms
- Distinguish *strong* and *weak* preemption
- Orthogonally distinguish *delayed* (default) and *immediate* preemption

To Go Further

- Gérard Berry, The Foundations of Esterel, Proof, Language and Interaction: Essays in Honour of Robin Milner, G. Plotkin, C. Stirling and M. Tofte, editors, MIT Press, *Foundations of Computing Series*, 2000, `http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.53.6221`
- Gérard Berry, The Esterel v5 Language Primer, Version v5_91, 2000 `http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.15.8212`