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
Signals and Synchrony
The multiform notion of time
A Preview of Esterel

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

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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)
  - and developed a first version of Esterel
- Estérêl 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.
- **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
- **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

- Esterel programs/SSMs communicate through signals
- 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

- Status of an input signal is determined by input event, and by local emissions
- Status of local or output signal is determined per tick
  - Default status: absent
  - Must execute an "emit S" statement to set signal S present
- await A:
  - Waits for A and terminates when A occurs
Introduction
Signals and Synchrony

Synchrony Hypothesis

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

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

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

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

This works in principle
However, it is not deterministic!

There are several sources of non-determinism in this code fragment:
The delay statement only imposes a minimal delay—how long the delay really is depends on several factors, such as timer resolution, OS overhead, etc.
The process receiving the signal—B—must be ready to do so
The actual time of when the rendezvous takes place is not specified
Furthermore, the signal cannot be broadcast—if there is another process that wants to be notified every minute, then we must explicitly send it another signal—different processes may therefore have different views of the global state of the program

A design goal of synchronous languages:
Fully deterministic behavior
Applies to functionality and (logical) timing

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

Consider following requirements:
“The train must stop within 10 seconds”
“The train must stop within 100 meters”
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)”
The Multiform Notion of Time

- **History** of system is a totally ordered sequence of logical ticks
- 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

Esterel’s Model of Time

- The standard CS model (e.g., Java’s) is **asynchronous**
  - 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

```
emit S
  ▶ Make signal S present in the current instant
  ▶ A signal is absent unless it is emitted
pause
  ▶ 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
```

```
module EXAMPLE1:
  output A, B, C;
  emit A;
  present A then emit B end;
  pause;
  emit C
end module
```

**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
- **Sneak Preview:** Unlike Esterel, SCEst allows this, as it allows sequential update of A!

### Advantages of Synchrony

- Easy to control time
- Synchronization comes for free
- 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”

```
\[
\begin{align*}
&\text{emit } A; \\
&\text{pause; emit } B; \\
&\text{||} \\
&\text{pause; emit } C; \\
&\text{pause; emit } D \\
&\text{}; \\
&\text{emit } E
\end{align*}
\]
```

### Time Can Be Controlled Precisely

This guarantees every 60th S an M is emitted:

- Every 60th S do
- Every invokes its body every 60th S
- Emit takes no time (cycles)

```
every 60 S do
emit M
emit takes no time (cycles)
end
```

\[
\begin{array}{cccc}
S & S & S & S \\
M & M \\
1 & \ldots & 59 & 60 & 61 & \ldots & 120
\end{array}
\]
Communication Is Instantaneous

A signal emitted in a cycle is visible immediately

```
[ pause; emit A;
pause; emit A
|| pause;
present A then
emit B end
]
```

Concurrency and Determinism

- 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

Bidirectional Communication

Processes can communicate back and forth in the same cycle

```
[ pause; emit A;
present B then
emit C end;
pause; emit A
|| pause;
present A then
emit B end
]
```

The Await Statement

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

```
[ emit A;
pause;
pause; emit A
|| await A; emit B
]
```
The Await Statement

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

```plaintext
[ emit A;
  pause;
  await A;
]
```

Loops

- Esterel has an infinite loop statement
- **Rule:** loop body cannot terminate instantly
  - Needs at least one pause, await, etc.
  - Can’t do an infinite amount of work in a single cycle

```plaintext
loop
  emit A;
  pause;
  pause;
  emit B
end
```

Preemption

- Often want to stop doing something and start doing something else
- E.g., Ctrl-C in Unix: stop the currently-running program
- Esterel has many constructs for handling preemption

```plaintext
loop
  await 60 S;
  emit M
end
```
The Abort Statement

- Basic preemption mechanism
- General form:
  ```
  abort
  statement
  when condition
  ```
- Runs statement to completion
- If condition ever holds, abort terminates immediately.

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

- Normal termination
  - `A` and `C`
- Aborted termination
  - `B` and `C`
- Aborted termination; `emit A` preempted
  - `B` and `C`
- Normal termination B not checked in first cycle (like `await`)
  - `B` and `C`
- `emit A` not allowed to run
  - `B` and `C`
- `emit A` does run, body terminated afterwards
  - `B` and `C`
Strong vs. Weak Preemption

▷ Important distinction
▷ Something cannot cause its own strong preemption

<table>
<thead>
<tr>
<th>abort</th>
<th>weak abort</th>
</tr>
</thead>
<tbody>
<tr>
<td>pause;</td>
<td>pause;</td>
</tr>
<tr>
<td>emit A when A</td>
<td>emit A when A</td>
</tr>
</tbody>
</table>

Erroneous!                                                      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

▷ In a LAP, the full sequence is executed only if the LAP is longer than 15 SECOND plus 100 METER
▷ If the LAP is shorter than 15 SECOND, one only does RUNSLOWLY
▷ If the LAP is shorter than 15 SECOND plus 100 METER, one never runs full speed
▷ The same happens if MORNINGs occurs very often
▷ Notice that any input can serve as a time unit in a preemption. In reactive programming, timing constraints should not be expressed only in seconds. When driving a car, if there is an obstacle at 30 meters, the timing constraint is "stop in less than 30 meters", no matter the time it takes to stop
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
```

Normal termination from first process

```
A D
```

Second process allowed to run even though first process has exited

```
A B
C D
```

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
```

Outer trap takes precedence; control transferred directly to the outer trap statement.

```
emit A not allowed to run.
```

```
B
```

Second process allowed to run even though first process has exited
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

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

B prevents A from being emitted here; resumed next cycle
B delays emission of A by one cycle

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