Synchroneous Programming

- Two simple ways of implementing reactive systems:
  - Event-driven approach
  - Sampling

```
<Initialize Memory>
Foreach input_event do
        <Compute Outputs>
        <Update Memory>
End
```

Event-driven

```
<Initialize Memory>
Foreach period do
        <Read Inputs>
        <Compute Outputs>
        <Update Memory>
End
```

Sampling

Synchroneous Programming

- Program typically implements an automaton:
  - state: valuations of memory
  - transition: reaction, possibly involving many computations
- Synchroneous paradigm: reactions are considered atomic, ie they take no time. (Computational steps execute like combinatorial circuits.)
- Synchroneous broadcast: instantaneous communication, ie each automaton in the system considers the outputs of others as being part of its own inputs.
- Atomic reactions are called instants.

Overview

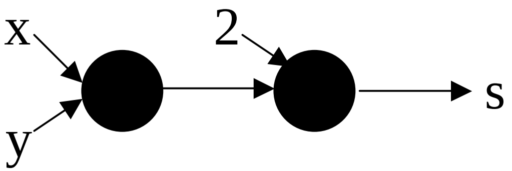
- StateCharts:
  - First, and probably most popular formal language for the design of reactive systems.
  - Focus on specification and design, not designed as a programming language.
  - Determinism is not ensured.
  - No standardized semantics.
- Programming languages for designing reactive systems:
  - ESTEREL [Berry]: imperative language.
  - LUSTRE [Caspi, Halbwachs], SIGNAL [Le Guernic, Beneviste]: data-flow languages.
- ARGOS: purely synchroneous variant of StateCharts.

LUSTRE

- Based on synchroneous data-flow model:
  - Each variable takes a value at every cycle of the program.
- Programs are structured into nodes:
  - Node: subprogram defining its output parameters as functions of its input parameters.
  - Definition given by unordered set of equations.
- Variables are defined via equations, e.g. X=E with variable X and expression E.
- Expressions:
  - identifiers,
  - constants,
  - arithmetic, boolean and conditional operators,
  - 'previous' operator pre,
  - 'followed by' operator ->.

LUSTRE

- Specific Operators:
  - $(\text{pre}(E))_0$ = nil (undefined)
  - $(\text{pre}(E))_n = E_{n-1}$
  - $(E\text{->}F)_0 = E_0$
  - $(E\text{->}F)_n = F_n$
  - Example: x = 0->(pre(x)+y)



At any cycle n:
$s_n = 2*(x_n+y_n)$

LUSTRE – Example Program

```
node Counter (init, incr: int; reset: bool)
      returns (count:int);
let
      count = init -> if reset then init
                      else pre(count)+incr;
tel
```

ESTEREL - Principles

- Imperative language.
- Tailored for programming hardware or software synchroneous controllers domintated by control-handling aspects.
- Most ESTEREL statements are conceptually instananeous, ie are executed in the same reaction than other statements that sequentially precede or follow them in the program.

ESTEREL – Example Program

```
module Speedometer:
input Second, Meter;
output Speed: integer in
  loop
    var Distance:=0: integer in
      do
        every Meter do
          Distance:=Distance+1
        end every
      upto Second;
      emit Speed(Distance)
      end var
    end loop
end module
```

```
module SpeedSupervisor:
input Second, Meter;
output TooFast in
  signal Speed: integer in
  [ run Speedometer
    ||
    every Speed do
      if ?Speed > MaxSpeed
      then emit TooFast
      end if
    end every
  ]
  end signal
end module
```

Compilation of Synchroneous Languages

- Causality Analysis
  - Causality problem: the presence of a signal seems to depend on itself (problem of combinatorial loops in synchroneous circuits).
  - Goal: have one (reactivity) and only one (determinism) consistent solution for each configuration of input signals.
  - Example situations:

```
module P1:
output O;
  present O
    else emit O
  end present
end module
```

inconsistent

```
module P2:
output O;
  present O
    then emit O
  end present
end module
```

non-deterministic

```
module P3:
input I;
output O;
  signal S in
    present I then emit S end
    ||
    present S then emit O end
  end signal
end module
```

correct

Compilation of Synchroneous Languages

```
module P4:
output O1,O2;
  present O1 then emit O1 end
  ||
  present O1 then
    present O2 else emit O2 end
  end present
end module
```

Logically correct, but rejected by *Constructive Causality*:
no constructive explanation for solution.

Compilation of Synchroneous Languages

- Sequential code generation
  - LUSTRE:
    - Generating single loop, after sorting the equations according to their dependences.
  - ESTEREL:
    - Compilation of control part into explicit automaton (ESTEREL -V2 and –V3 compilers).
      - efficient, but
      - possibly exponential expansion of code size.
    - Single loop code generation (ESTEREL-V4, and –V5 compilers).

Now: Esterel in more Depth

- Syntax and intuitive semantics
- Causality
- Documentation and Esterel-Distribution can be downloaded from www.cs.uni-sb.de/~kaestner/ES0203.html

Esterel: General Structure

```
module M:
input names;
output names;
   statement
end module
```

Interface declaration

- Interface declaration specifies which objects a module exports or imports:
  - Data objects, which are declared abstractly in Esterel. Their actual value is given in the host language.
  - Signals and sensors. Host objects implementing them depend on the host language.
- Body is an executable statement.

Interface Declaration

```
module WATCH:

input UL,UR,LL,LR;
type Time;
constant Noon:Time;
constant WordLength = 16: integer;
function CompareTime (Time,Time): boolean;
procedure IncrementTime (Time) (integer);
type Beep;
output Beeper: Beep;
output CurrentTime := Noon : Time;
```

Signal declaration

Data declarations

Possibly modified (Call by reference)

Not modified (Call by value)

Signals and Sensors

- Interface signals or local signals, declared by the signal statement (see later).
- Instantaneously broadcast throughout the program.
- Pure signals: status is present or absent.
- In addition to their status, valued signals carry a value of arbitrary type.
- One predefined signal tick:
  - pure signal
  - represents activation clock of the reactive program
  - Status is present in each instant.

- Sensors have a value but no status;
  Example: `sensor temperature : integer;`

Statements

- A statement starts in some instant t, remains active for a while, and may terminate in some instant t >= t'.
  - t=t': statement is instantaneous
  - t'>t: statement takes time

Kernel Statements

- Selection of basic statements, most other statements can be programmed with:
  - `nothing`
  - `pause`
  - `emit` ***S***
  - ***p*** **;** ***q***
  - ***p*** **||** ***q***
  - `present` ***S*** `then` ***p*** `else` ***q*** `end`
  - `suspend` ***p*** `when` ***S***
  - `loop` ***p*** `end`
  - `trap` ***T*** `in` ***p*** `end`
  - `exit` ***T***
  - `signal` ***S*** `in` ***p*** `end`

Informal Semantics

- Basic pure control statements:
  - nothing: does nothing, ie terminates instantaneously when started.
  - pause: pauses when started and terminates in the next instant.

- Signal emission:
  - emit *S*: emits signal *S* (ie sets its status to present) and terminates instantaneously.
  - emit *S(e)*: evaluates the data expression *e*, emits *S* with that value and terminates instantaneously.
  - Valid for the current instant only; happens only once.

Informal Semantics

- Sequencing (*p* ; *q*):
  - *p* is instantaneously started when *p* ; *q* is started and is executed up to completion or trap exit.
  - If *p* terminates, *q* is immediately started and the sequence behaves as *q* from then on.
  - If *p* exists via traps, the exits are immediately propagated and *q* is never started.

  - Example: emit S1; emit S2

Informal Semantics

- Parallel Statement (*p* || *q*):
  - Denotes explicit concurrency
  - Any signals emitted are instantaneously broadcast to all branches in each instant.
  - The sequencing operator ; binds tighter than ||.
  - Upon start both branches *p* and *q* are instantaneously started.
  - It terminates in the precise instant where both branches are terminated (branch synchronization).

  - Example: p;q||r vs [p;q]||r vs p;[q||r]

Informal Semantics

- present *S* then *p* else *q* end
  - immediately starts *p* if the signal *S* is present, otherwise *q* is immediately started.

- suspend *p* when *s*
  - *s* is a signal expression (see later)
  - When the suspend statement starts, *p* is immediately started.
  - *s* has no effect in the initial instant in which the statement becomes active.
  - If the signal expression *s* is true, *p* remains in its current state and the suspend statement pauses for the instant.
  - If *s* is false, *p* is executed for the instant. If *p* pauses, terminates or exits a trap, so does suspend.

Informal Semantics

- loop *p* end loop:
  - *p* is instantaneously restarted anew upon termination.
  - *p* must never be able to terminate instantaneously when started. Note: the condition check is static!
  - If *p* exists some enclosing trap, the loop is exited.

    trap *T*
    loop *p* end loop || present *S* then exit *T*
    end trap

  - Example: loop emit *S* end loop (not allowed)

Static Termination Check

```
loop
   present I then
        present J else
               p
        end present
   else
        q
   end present;
end loop
```

Program is rejected!

Informal Semantics

- trap *T* in *p* end
  - A trap defines a lexically scoped exit for *p*.
  - *p* is immediately started when the trap statement starts.
  - If *p* terminates so does the trap statement.
  - exit *T* (occurring inside of *p*) causes *T* to terminate immediately.
  - When traps are nested, the outer one takes priority.

```
trap U in
   trap T in
      p
    end trap;
    q
end trap;
r
```

- *p* exits *T* : *q* is immediately started
- *p* exits *U* : *r* is immediately started
- *p* exits *T* and *U* simultaneously: *U* takes priority.

Informal Semantics

- Local signal declaration: signal *S* in *p* end signal
  - Signal *S* is local to *p*.
  - Scoping is lexical, ie any redeclaration of a signal hides the outer declaration.
  - A local signal placed within a loop can be executed several times in the same instant. Then each execution declares a new copy / incarnation of the signal.
  - Example:

```
signal Alarm,
        Distance : integer,
in
        p
end signal
```

Further Statements

- Third basic control statement:
  halt: pauses forever and never terminates.
- sustain S / sustain S(e): continuous emission of signal
- Assignment (instantaneous):
  X := e where X is a variable and e is a data expression
- Procedure call (instantaneous): call P (X,Y) (e1,e2)
- repeat *e* times

  ```
  repeat e times
      p
  end repeat
  ```

- Local variable declaration:

```
var X : double,
        Count := ?Distance : integer
in
        p
end var
```

Further Statements

- if Data Test: if *e* then *p* else *q* end if
  - *e* is a data expression: The conditions are evaluated in sequence.
- await *d*
  - *d* is a delay expression
  - The delay is started when await is started. The statement pauses until the delay elapses and terminates in that instant.
- abort *p* when *d* / weak abort *p* when *d*
  - *p* is run until termination or until the delay *d* elapses.
  - If *p* terminates before the delay elapses, so does the abort statement. Otherwise, *p* is preempted when the delay elapses.
  - strong abort vs. weak abort:
    - strong abort: If the delay elapses before termination of *p*, *p* is preempted and not executed.
    - weak abort: If the delay elapses before termination, *p* is preempted and executed for a last time.

Valued Signals vs. Variables

The value can be changed only if the status is *present*. Unlike the status, the value is permanent: if it is unchanged in an instant, its value is that of the previous instant.	The value of a variable is written by an instantaneous assignment statement.
A valued signal has exactly one status and exactly one value at a time. Both the status and the value are broadcast.	Unlike a signal a variable can take several successive values in an instant. The order in which the values are taken is the internal control flow iof the program, the so-called constructive order.
A signal is shared throughout its scope (whole program for interface signal and the scope of its declaration for a local signal)	A variable is local to a thread in case the thread writes it. If the thread forks on ||, only two cases are legal: The variable is accessed in read-only mode in each subthread, or if the variable is written by some thread, then it can neither be read nor be written by concurrent threads.

Valued Signals vs Variables

- Forbidden:

  `X:=0;`

  `X:=X+1 || X:=1`

- Forbidden:

  `emit S(?S+1)`

- Allowed:

  `emit S(1) || emit S(2)`

- Allowed:

  `X:=X+1`