Synchronous Languages—Lecture 03

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Esterel II—The Full Language

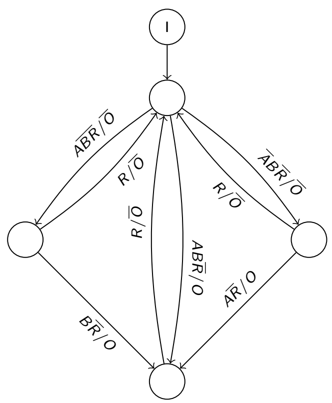
Overview

The Hello World of Synchronous Programming: ABRO

The system has boolean valued inputs `A`, `B`, `R`, and an output `O`. Output `O` shall be true as soon as both inputs `A` and `B` have been true. This behavior should be restarted if `R` is true.

- Question: what if `A`, `B` and `R` are true at the same time?
- Should we make `O` present? —we consider both possibilities
- Nondeterminism? Not possible in Esterel!

Mealy Machine for ABRO



- Circles are automaton states
- Label $A\overline{BR}/O$ means: if $A = true$ and $B = R = false$ is read, then output $O = true$ is generated
- *Default behavior:* remain in state
- *Finite state machines (FSMs) are perfectly synchronous!*

⇝ use FSMs to explain the semantics

Write Things Once

- The disadvantage of this (flat) notation:
  - Size grows exponentially
  - A little change to the specification may incur a major change to the automaton (often ends with full rewriting)
- The answer:
  - Add hierarchy
  - More generally: Write Things Once (WTO)
- Analogy from language theory:
  - Use regular expressions to represent large (possibly infinite) sets of strings

Esterel Program ABRO

```
module ABRO:
input A,B,R;
output O;
loop
  [await A || await B];
  emit O
each R
end module
```

- Declarations of inputs and outputs
- Module body contains a statement
- Modules have names
- Esterel programs are a list of modules

- Quoting Berry: "*Although it is not always made explicit, the Write Things Once or WTO principle is clearly the basis for loops, procedures, higher-order functions, object-oriented programming and inheritance, concurrency vs choice between interleavings etc.*"

Remarks on Signal Declarations

- Signals are special data types with a presence status $\in \{true, false\}$
- If S= *true* holds, S is said to be present, otherwise absent
- Signals describe events, thus they **do not store the status** when control flow proceeds to the next macro step
- Status of input signals is generated by the environment
- Status of output signals is made present by executing `emit S`
- Output signals are present iff they are currently emitted
- `emit S` does not take time

Remarks on Signal Declarations

- Signal status is uniquely determined per macro step
- This may lead to the fact that "information flows backwards":

```
present R then emit S end;
emit R
```

- In the above program, the emission of R is also seen by the conditional statement (present R checks the status of R)
- This may lead to causality problems, but implements the perfect synchrony

General Remarks on Statements

- Statements p are started at step $t \in \mathbf{N}$ and terminate in a (not necessarily strictly) later step $t + \delta$ $(0 \leq \delta)$
- If $\delta = 0$ holds, p is called instantaneous:
  - Its execution does not take time
  - p does only execute micro steps
- Whether p is instantaneous or not depends on current inputs
- If p is not instantaneous, the control flow enters p and will stop somewhere inside p to wait for the next macro step
- Due to concurrency, the control flow may rest at several locations

Remarks on `emit`

- `emit S` is always instantaneous
- Executing `emit S` makes S immediately present for the current macro step
- There are also delayed emissions (since Esterel version 7):
  - `emit next S` makes S present in the next macro step
  - Executing `emit next S` is also instantaneous
- Input signals may also be emitted

Remarks on `await`

- When started, control remains at `await S`
- At the **next** macro step, S is tested:
  - if S holds, `await S` terminates
  - otherwise, the behavior is repeated at the next macro step
- `await S` *always* consumes time (*i. e.*, is *never* instantaneous)
- The variant `await immediate S` tests S also at starting time, and therefore may also be instantaneous
- S can either be a signal or a signal expression

Remarks on Parallel Statements

`p || q` means parallel execution of `p` and `q`

- if `p || q` is started at time t, both `p` and `q` are started at time t
- if `p` and `q` terminate at time $t + \delta_p$ and $t + \delta_q$, respectively, then `p || q` terminates at time $t + \max\{\delta_p, \delta_q\}$
- ⇝ as long as the control is inside `p` and `q`, both `p` and `q` *execute their macro steps synchronously*
- `p` and `q` may interact during concurrent execution

Brackets `[...]` are used to control statement scoping to avoid ambiguities due to the grammar

Remarks on Loops

- Esterel knows several loop constructs
- `loop p each S` behaves as follows:
  - if `loop p each S` is started at time t, then `p` is started at time t
  - in subsequent instants, `p` is restarted whenever `S`= *true* holds (`S` is present)
  - if `p` terminates, then the program waits for the next step where `S`= *true* holds
  - note that `p` is aborted when it is currently active and `S` holds
  - ⇝ no dynamic thread generation
  - ⇝ this guarantees finitely many control states

Remarks on Sequences

- `p;q` is a sequence
  - if `p;q` is started at time t, at least `p` is started at time t
  - if `p` terminates at time $t + \delta_p$, then `q` is started at time $t + \delta_p$
  - note that $\delta_p = 0$ may hold, which implies that `p` and `q` are both started at time t
  - `p;q` terminates when `q` terminates
- Moving the control from `p` to `q` does not take time
- ⇝ the sequence operator `;` does not take time

Generic ABRO Program

```
module ABCRO :
input A,B,C,R;
output O;
loop
  [
    await A ||
    await B ||
    await C
  ];
  emit O
each R
end module
```

- ABRO can be easily extended for more events
- To this end, only a new thread with an `await` statement has to be added
- For n inputs, the program has size $O(n)$
- But the finite state machine has $O(2^n)$ states
- ⇝ **Esterel programs can be exponentially more compact than finite state machines**

Program SPEED

The system has inputs *cm* and *sec*. If *sec* holds, the number of macro steps where *cm* holds should be counted. If *sec* holds again, the number of so far seen *cm* signals should be reported, reset to zero, and the behavior should be repeated.

- Question: what if *cm* and *sec* hold at the same time?
- We first exclude this case, and consider solutions for that later

Program SPEED

```
module SPEED:
input cm, sec;
output Speed:integer;
relation cm # sec;
loop
  var distance := 0 : integer in
    abort
      every cm do
        distance := distance + 1
      end every
    when sec do
      emit Speed(distance)
    end abort
  end var
end loop
end module
```

New constructs:

- Valued signals
- Input relations
- Local variables
- Process preemption (abortion)

Remarks on Valued Signals

- Input restriction 'R#S'
  tells the compiler that `R` and `S` cannot be both present
- `S:`α declares a valued signal of type α
  - such a signal has a present/absent status
  - and a value of type α that is denoted as `?S`
  - the value is stored, unless changed by an emission `emit S(v)` that immediately changes the value to `v`
  - as the status, the value is uniquely defined per macro step
- Note: **Emissions immediately change the values, hence, `emit S(?S+1)` makes no sense!**
- For that, use delayed emissions: `emit next(S(v))`
  - `v` is immediately evaluated
  - But the value of `S` is changed in the next macro step

Remarks on Local Variables

- `var x :=` τ`:`α `in p end var` declares a local variable `x` of type α which is initialized by τ and is visible in statement `p`.
- Differences between variables and signals:
  - variables do not have a status, but only a value
  - variables store values unless these are changed by assignments `x:=`τ
  - variables can be *changed by micro steps*, hence, they may have several values in a macro step
  - for this reason, there are restrictions on the use of variables in parallel threads: if a local variable declaration contains parallel threads and the variable is written to within a thread, none of the concurrent threads may access (read or write) that variable
  - $\leadsto$ assignments to a variable never have write conflicts

Remarks on Local Declarations

- There are also local signals: `signal S:` α `in p end signal`
- These are treated like output signals inside *S*
- Like output signals, local signals may have a value or not
- Status and value of a local signal is uniquely determined per macro step
- This may result in write conflicts (as with valued signals in general), e.g.: `emit S(2); emit S(3)`
- In contrast to local variables, threads may interact via local signals

Remarks on Loops

- `loop p end` is the basic loop
  - if `loop p end` is started at time t, then `p` is started at time t
  - **execution of** `p` **must always take time**, *i. e.*, there must not be inputs such that `p` becomes instantaneous
  - if *S* terminates at time $t + \delta > t$, then `p` is started at time $t + \delta > t$
  - ⇝ `loop p end` is equivalent to `p; loop p end`
  - however, such statements can be terminated by surrounding process abortion
- `every S do p end every`
  - is equivalent to `await S; loop p each S`
  - hence, every time `S` holds, `p` is started (and possibly aborted)

Remarks on abort

- `abort p when S do q end abort`
  - if started at time t, `p` is started at time t without checking `S`
  - if `p` terminates at time t, then the entire statement terminates
  - otherwise, the execution of `p` takes time:
    - in all macro steps that start inside `p`, `S` is checked
    - if `S` does not hold, `p` is executed for this macro step
    - if `S` holds, **no action of** `p` **is executed**, instead, `q` is started
    - if the latter happens, `q` is executed without checking `S`
- ⇝ Abortion is also called process preemption
- Note: the abort handler (`do q`) is optional

Variants of Process Abortion

- `abort` comes in four variants:
  - `abort p when S do q end abort`
  - `weak abort p when S do q end abort`
  - `abort p when immediate S do q end abort`
  - `weak abort p when immediate S do q end abort`
- weak abortion differs in macro steps where abortion takes place:
  - weak abort executes all micro steps of `p` at abortion time (*i. e.*, `p` **may execute a “last wish”** even when it is aborted)
- immediate abortions consider `S` **also at starting time**
  - if `S` holds at starting time, strong abort immediately starts `q`
  - weak abort additionally executes all micro steps of `p` that were executed if abortion would not take place

Other immediate Statements

- Many other statements have immediate variants
  - `await immediate S`
  - `every immediate S do p end`
- We will see later that this is because these statements contain in some sense abortion statements
- Note: There is no immediate variant of `loop p each S`. Why? Because otherwise this would lead to an instantaneous loop.
- Note: `every immediate S do p end` expands to `await immediate S; loop p each S end`

Weak Abortion in Program SPEED

```
module SPEED:
input cm, sec;
output Speed:integer;
loop
  var distance1 := 0 : integer in
    weak abort
      every cm do
        distance1 := distance1 + 1
      end every
    when sec do
      emit Speed(distance1)
    end abort
  end var
end loop
end module
```

Changes by weak abortion:

- if sec holds, the abortion takes place
- if additionally cm holds, distance is once more incremented
- and thus, this cm is added to the current interval

Using 'immediate' in Program SPEED

```
module SPEED:
input cm, sec;
output Speed:integer;
loop
  var distance2 := 0 : integer in
    abort
      every immediate cm do
        distance2 := distance2 + 1
      end every
    when sec do
      emit Speed(distance2)
    end abort
  end var
end loop
end module
```

Changes by 'immediate':

- if `sec` holds, the abortion takes place
- if additionally `cm` holds, `distance` is not incremented (strong abort)
- after emission of `Speed`, every immediately executes its body statement
- thus, this `cm` is added to the next interval

Using Modules

```
module TwoStates :
input Pressed;
output StateOff, StateOn;
loop
  abort
    sustain StateOff;
  when Pressed;
  abort
    sustain StateOn;
  when Pressed;
end loop
end module
```

- Starting `sustain S` immediately emits `S`
- Control flow rests inside `sustain S`
- and repeats `emit S` for all macro steps, unless abortion by `Pressed` takes place
- Hence, each time `Pressed` is present, the control flow toggles between the two sustain statements

Using Modules

```
module TwoStates:
input Pressed;
output StateOff, StateOn;
loop
  abort
    sustain StateOff;
  when Pressed;
  abort
    sustain StateOn;
  when Pressed;
end loop
end module
```

```
module NoName:
input Button;
output inactive;

  run TwoStates
    [signal
      Button/Pressed,
      inactive/StateOff
    ]
||
  ...
end module
```


Using Modules

- If module `m` has already been defined, then `m` can be instantiated in other module bodies
- This is done by executing the statement '`run m`'
- ⤳ compiler replaces `run m` with the body of `m`
- Additionally, declared objects in m can be renamed:

  `run m` $[t_1\ y_1/x_1, \ldots, t_n\ y_n/x_n]$, where

  $t_i\ x_i$ is a declaration of module `m`
- **no recursive module calls allowed** (possibly infinite recursion)
- Primitive recursion (which always terminates) could be allowed

Overview

Esterel Statements Discussed So Far

- `emit S` and `emit S(v)`
- `sustain S` and `sustain S(v)`
- sequence: `p; q`
- parallel: `p || q`
- loops
  - `loop p end`
  - `loop p each S`
  - `every [immediate] S do p end`
- `await [immediate] S`
- `[weak] abort p when [immediate] S do q end abort`
- local declarations
  - `var x:`α `in p end var`
  - `signal S:`α `in p end signal`

Further Esterel Statements

- `nothing`
- `pause`
- `halt`
- `present S then p else q end`
- `if E then p else q end`
- `repeat n times p end repeat`
- `suspend p when [immediate] S`
- `trap T in p end trap` with `exit T`
- `call P(`$x_1,\dots,x_n$`)(`$v_1,\dots,v_m$`)`
- `exec P(`$x_1,\dots,x_n$`)(`$v_1,\dots,v_m$`) return R`

Further Basic Statements

- `nothing` does nothing and needs no time to do nothing
- `pause` waits for the next macro step
- `halt` waits for all the time, *i. e.*, `halt` ≡ `loop pause end`

Conditionals

`present S then p else q end present`

- if started, evaluate expression `S`
- if `S` holds, immediately execute `p`, otherwise `q`
- both the `then` and the `else` branches are optional

More general form:

```
present
case S_1 do p_1
 ...
case S_n do p_n
else q
end present
```

:≡

```
present S_1 then p_1
else present S_2 then p_2
...
else present S_n then p_n
else S_q
end present
...
end present
```


Conditionals

- `if E then p else q end if`
  - if started, evaluate expression `E`
  - if `E` holds, immediately execute `p`, otherwise execute `q`
- `present S` is restricted for signal expressions
- `if` instead checks variable values.
- Note: In Esterel v7, `if` may also be used as a synonym for `present`.

Process Suspension

`suspend p when S`

- If started at time t, p is started at time t without checking S
- If p terminates at time t, then the entire statement terminates
- Otherwise, the execution of p takes time. In all macro steps that start inside p:
  - S is checked first
  - If S does not hold, p is executed for this macro step
  - If S holds, the control flow rests at the current locations, and no action of p is executed
  - Hence, the **control flow is frozen** whenever S holds

For comparison: in Unix, a process is aborted with ^C, suspended with ^Z, and released again with fg

Process Suspension

Similar to abort, there are 2 × 2 variants:

- `suspend p when S`
- `weak suspend p when S`
- `suspend p when immediate S`
- `weak suspend p when immediate S`

Process Suspension

Immediate suspend can be transformed into non-immediate suspend:

```
suspend
  p
when immediate S
```

≡

```
suspend
  present S then
    pause
  end;
  p
when S
```

Note: the immediate variant implies an additional control point (behaving like a pause statement) where control may rest between ticks.

```
suspend
  nothing
when immediate tick
```

≡

```
loop
  pause
end loop
```


Weak Process Suspension

`weak suspend p when S`

- Behaves like (strong) suspend at initial tick.
- In all macro steps that start inside p, S is again checked first
  - If S does not hold, p is executed for this macro step
  - If S holds, the control flow rests at the current locations—**but the actions of p for the current tick are still executed**
  - Note: if S holds, the execution is still limited to p, *i. e.*, no actions following the suspend statement get executed

`weak suspend p when immediate S`

- Similar to non-immediate variant, except that S is also checked in initial tick
- Again, an additional control point gets introduced at the beginning of p where control may resume at the next tick

Weak Process Suspension

Weak suspend may hide a loop:

```
weak suspend
  pause;
  emit next(S(?S+1))
when true
```

:≡

```
loop
  pause;
  emit next(S(?S+1))
end loop
```


Resolution Functions

Signals can be emitted in one macro step with different values
$\leadsto$ write conflicts

Solving write conflicts by resolution functions

- `output O: combine` α `with f`
- f is used to compute the final value by applying f to the emitted values
- Example: `output votes: combine integer with +` resolves `emit votes(2); emit votes(3)` so that `votes` has value $2 + 3 = 5$
- $f : \alpha \times \alpha \to \alpha$ must be commutative and associative
- Commutativity and associativity of f makes the value independent of the ordering of the values

Input Restrictions

- Compilers for synchronous languages have to analyze the program
- Most problems are undecidable, so (conservative) heuristics have to be used
- Known information about inputs should be given to compiler

$\leadsto$ input restrictions
  - inclusion: `relation R -> S` means that presence of `R` implies presence of `S`
  - exclusion: `relation S_1 # S_2 # ...# S_n` means that at most one of the signals `S_i` can be present per macro step
- Examples
  - `relation minute -> second`
  - `relation liftup # liftdown`

Further Loops

`repeat n times p end repeat`

- n, an integer expression, is immediately evaluated
- then execute n times `p`
- `p` must not be instantaneous

Equivalent:

```
var i,j: integer in
  i := 0; j := n;
  signal stop in
    weak abort
      loop
        if i<j then p; i := i+1
        else emit stop
        end if
      end loop
    when stop
  end signal
end var
```

Wait ... does this work?
No—this is a (potentially) instantaneous loop.
How would you fix it?
Add a pause statement after `emit stop`

Further Await Statements

`await [immediate] S` can be generalized as follows:

```
await [immediate]
case S_1 do p_1
...
case S_n do p_n
end await
```

:≡

```
await [immediate] S_1 or ... or S_n;
present
case S_1 do p_1
...
case S_n do p_n
end present
```


Priorities of Nested Aborts

- Nested aborts have different priorities
- Example:

```
abort
  abort
    p
  when S_1 do
    e
  end abort
when S_2
end abort
```

- If control is inside p, and both S_1 and S_2 hold, then e is not executed, since **the outer abortion has priority**
- Question: what happens if one or the other is weak? Try it!

Further Abort Statements

`[weak] abort p when S do q` can be generalized as follows:

```
[weak] abort p when
case S_1 do p_1
...
case S_n do p_n
end abort
```

:≡

```
[weak] abort p when S_1 or ... or S_n
do
  present
  case S_1 do p_1
  ...
  case S_n do p_n
  end present
end abort
```


Trap Statements

`trap T in p end trap` with `exit T`

- `exit T` is similar to `emit T`, but refers to the trap T
- when the statement is started, p starts immediately
- if `exit T` is executed inside p, p is immediately aborted

Differences to abort:

- `exit T` can only be executed within p (due to scope of T)
- abortion due to `trap` is neither really weak nor really strong
- instead: 'asynchronous abortion'
- `exit T` works like a goto in that those micro steps are executed up to the micro step where `exit T` is executed, but no further ones

⇝ `exit T` terminates the trap statement

Trap vs. Abort

P_1
```
trap T in
  emit A;
  exit T;
  emit B;
end trap
```

P_2
```
signal T in
  weak abort
    emit A;
    emit T;
    emit B;
  when T
end
```

P_3
```
signal T in
  abort
    emit A;
    emit T;
    emit B;
  when immediate T
end
```

P_4
```
signal T in
  weak abort
    emit A;
    emit T;
    emit B;
  when immediate T
end
```

Emitted Signals:

P_1	P_2	P_3	P_4
{A}	{A,B}	⊥	{A,B}

P_3 is inconsistent:

it is aborted due to the emission of T, thus, T can not be emitted

Trap vs. Abort

- Is this a solution?

```
trap T in
  p
end
```

⟹

```
signal T in
  weak abort
    p[exit T / emit T; pause]
  when immediate T
end
```

- p[exit T / emit T; pause] means: exit T is replaced by emit T; pause
- The control flow will never rest on this pause statement, since the abort will instantaneously take place

Trap vs. Abort

P1
```
trap T in
  emit A;
  exit T;
  emit B
end trap
```

P5
```
signal T in
  weak abort
    emit A;
    emit T;
    pause;
    emit B
  when immediate T
end
```

Emitted Signals:

P1	P5
{A}	{A}

that works!, however, . . .

Trap vs. Abort

P_problem
```
trap T_1 in
  trap T_2 in
    exit T_1
  ||
    exit T_2
  end trap
  emit A
end trap
```

P_problem'
```
signal T_1 in
  weak abort
    signal T_2 in
      weak abort
        emit T_1; pause
      ||
        emit T_2; pause
      when immediate T_2
    end signal;
    emit A
  when immediate T_1
end signal
```

Emitted Signals:

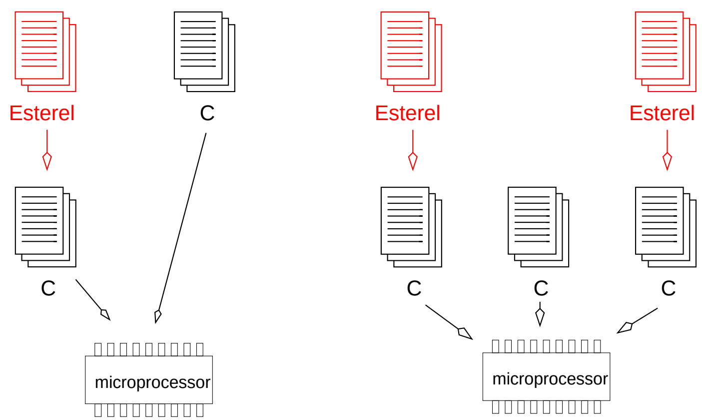
P_problem	P_problem'
{}	{A}

- If started, P_problem exits both T_1 and T_2
- The trap with the highest (outermost) priority (T_1) is raised
- Hence, A is not emitted by P_problem, but is emitted by P_problem'
- Trap and abort have different priority schemes
- How can this be repaired?

Esterel and the Host Language

- Esterel has only a few data types
- Data types and functions can be imported from host languages
- Esterel programs are translated to the host language
- Esterel mainly cares about compiling multi-threaded programs to a single thread
- To this end, all thread interaction is handled at compile time
- After successful compilation, the programs are free of runtime errors due to concurrency like write conflicts and deadlocks
- **The result is a deterministic system** (rather unusual for multi-threaded systems)

Esterel and the Host Language (Software)



Host Language

- Esterel (v5) does not implement many data types has only boolean, integer, float, and string
- There are no means to define new data types
- or simple (instantaneous) functions on user-defined data types
- However:
  - Esterel programs are translated to program of a host language
  - for software, often C is used
  - obtained C program can be linked with other C programs
- **Esterel can import data types, functions and procedures from the host language**

Imported Data Types and Functions

- `type` α imports a data type from host language
- This type must be implemented in the host language
- `function` $f(\alpha_1, \ldots, \alpha_n) : \alpha$ imports a function
- Esterel is able to perform type checking, but knows nothing else of f
- Arguments are passed-by-value
- Functions f must not have side effects
- Functions are used to generate expressions
- Therefore, **function calls are instantaneous**

Imported Procedures

- procedure P($\alpha_1, \ldots, \alpha_n$)($\beta_1, \ldots, \beta_m$) imports a procedure from host language with types α_i and β_i
- Arguments of first argument list are given with call-by-reference
- Arguments of second argument list are given with call-by-value
- Procedures have no return value, but can change the variables that were given in the first argument list
- Procedure calls call P($x_1, \ldots, x_n$)($\tau_1, \ldots, \tau_m$) **are instantaneous**

Imported Tasks

- task P($\alpha_1, \ldots, \alpha_n$)($\beta_1, \ldots, \beta_m$) imports a task from host language with types α_i and β_i
- Arguments are the same as with procedures
- exec P($x_1, \ldots, x_n$)($\tau_1, \ldots, \tau_m$) return R executes task p, which may not be instantaneous
- The exec statement terminates when the task terminates; **Tasks are not instantaneous**
- P runs in parallel with Esterel threads
- P may correspond to a C-program, or also to a physical process ("Robot drives distance X")
- No interaction with Esterel threads, except for termination of P
- Termination of p is signaled by R
- R is a return signal, declared at module interface analogous to input/output signals

Abortion of Tasks

```
abort
  exec P(X)(23) return R
when S
```

- If R holds before S, then X is updated and the abort terminates
- If S holds before R, then task P is aborted and X is not updated
- If R and S both hold, then the abort terminates and X is not updated
- Using weak abort allows to update X

Multiple Task Execution

```
exec
  case T_1 ... return R_1 do p_1
  ...
  case T_n ... return R_n do p_n
end exec
```

- When started, all tasks T_1,...,T_n are concurrently started
- When at least one return signal occurs:
  - Let R_i be the first return signal in the case-list that is present
  - Update only reference arguments corresponding to R_i
  - Abort all non-terminated tasks

Overview

Kernel Language: Esterel

`nothing`	(empty statement)
`pause`	(separation of macro step)
`emit S`	(signal emission)
`present S then p else q end`	(conditional)
`suspend p when S`	(process suspension)
`p;q`	(sequence)
`p || q`	(synchronous concurrency)
`loop p end`	(infinite loop)
`trap T in p end`	(exception handling)
`exit T`	(exception raising)
`signal S in p end`	(local declarations)

Kernel Language

- Many Esterel statements p can be viewed as macros
- Important: write-things-once-principle (WTO)

$\leadsto$ guarantees expanded statements of size $O(\|p\|)$

- For programming, redundant statements (called syntactic sugar) are important to directly express what is meant
- However, compilation should be based on few constructs

$\leadsto$ *using small kernel language*

Summary

- The `ABRO` example, the "hello world" of Esterel, illustrates reactive control flow
- Traps are similar to weak aborts, but there are subtle differences
- Esterel can be thought of as a "coordination language" that allows deterministic concurrency and preemption, while much of the computational details is left to a host language (typically C)
- All Esterel statements can be derived from a few kernel statements

To Go Further

- Gérard Berry, The Esterel v5 Language Primer, Version v5_91, 2000
  http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.15.8212