Synchronous Languages—Lecture 04

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Esterel II—Pragmatics

The 5-Minute Review Session

1. What is the difference between *transformational*/*interactive*/*reactive* systems?
2. What is *perfect synchrony*? What is the *synchronous model of computation*?
3. What is the motivation for the Esterel language?
4. What is the *multiform notion of time*?
5. What does it mean for an Esterel statement to be *instantaneous*? Name some instantaneous and non-instantaneous statements.

The 5-Minute Review Session

1. What is a *signal* in Esterel?
2. What are the *signal coherence rules*?
3. What are the differences between *signals* and *variables*?
4. What is the *WTO principle*?
5. What *control flow constructs* does Esterel have?

The 5-Minute Review Session

1. What is a *signal resolution function*? What are its requirements?
2. What is the difference between *immediate* and *non-immediate* abort?
3. What is the difference between *strong* and *weak abort*?
4. What is the difference between *strong* and *weak suspend*?
5. What is the difference between traps and weak aborts?

Overview

People Counter Example

Construct an Esterel program that counts the number of people in a room.

- People enter the room from one door with a photocell that changes from 0 to 1 when the light is interrupted, and leave from a second door with a similar photocell. These inputs may be true for more than one clock cycle. The two photocell inputs are called `ENTER` and `LEAVE`.
- There are two outputs: `EMPTY` and `FULL`, which are present when the room is empty and contains three people respectively.

Source: Mano, *Digital Design*, 1984, p. 336

Thanks to Stephen Edwards (Columbia U) for providing this and the following examples

Overall Structure

Conditioner detects rising edges of signal from photocell.
Counter tracks number of people in the room.

Implementing & Testing the Conditioner

```
module CONDITIONER:
input A;
output Y;

loop
  await A; emit Y;
  await [not A];
end

end module
```

```
% esterel -simul cond.strl
% gcc -o cond cond.c -lcsimul # may need -L
% ./cond
CONDITIONER> ;
--- Output:
CONDITIONER> A; # Rising edge
--- Output: Y
CONDITIONER> A; # Doesn't generate a pulse
--- Output:
CONDITIONER> ; # Doesn't generate a pulse
--- Output:
CONDITIONER> ;  # Sensitive to A again
--- Output:
CONDITIONER> A; # Another rising edge
--- Output: Y
CONDITIONER> ;
--- Output:
CONDITIONER> A;
--- Output: Y
```

Implementing & Testing the Counter: First Try

```
module COUNTER:
input ADD, SUB;
output FULL, EMPTY;

var count := 0 : integer in
  loop
    present ADD then if count < 3 then
       count := count + 1 end end;
    present SUB then if count > 0 then
       count := count - 1 end end;
    if count = 0 then emit EMPTY end;
    if count = 3 then emit FULL end;
    pause
  end
end

end module
```

```
COUNTER> ;
--- Output: EMPTY
COUNTER> ADD SUB;
--- Output: EMPTY
COUNTER> ADD;
--- Output:
COUNTER> SUB;
--- Output: EMPTY
COUNTER> ADD;
--- Output:
COUNTER> ADD;
--- Output:
COUNTER> ADD;
--- Output: FULL
COUNTER> ADD SUB;
--- Output: # Oops!
```


Implementing & Testing the Counter: Second Try

```
module COUNTER:
input ADD, SUB;
output FULL, EMPTY;

var c := 0 : integer in
  loop
    present ADD then
      present SUB else
        if c < 3 then c := c + 1 end end
    else
      present SUB then
        if c > 0 then c := c - 1 end end;
    end;
    if c = 0 then emit EMPTY end;
    if c = 3 then emit FULL end;
    pause
  end
end
end module
```

```
COUNTER> ;
--- Output: EMPTY
COUNTER> ADD SUB;
--- Output: EMPTY
COUNTER> ADD SUB;
--- Output: EMPTY
COUNTER> ADD;
--- Output:
COUNTER> ADD;
--- Output:
COUNTER> ADD;
--- Output: FULL
COUNTER> ADD SUB;
--- Output: FULL # Working
COUNTER> ADD SUB;
--- Output: FULL
COUNTER> SUB;
--- Output:
COUNTER> SUB;
--- Output:
COUNTER> SUB;
--- Output: EMPTY
COUNTER> SUB;
--- Output: EMPTY
```


Assembling the People Counter

```
module PEOPLECOUNTER:
input ENTER, LEAVE;
output EMPTY, FULL;

signal ADD, SUB in
  run CONDITIONER[signal ENTER / A, ADD / Y]
||
  run CONDITIONER[signal LEAVE / A, SUB / Y]
||
  run COUNTER
end

end module
```


Vending Machine Example

Design a vending machine controller that dispenses gum once.

- Two inputs, N and D, are present when a nickel and dime have been inserted.

  N =  D = 

- A single output, GUM, should be present for a single cycle when the machine has been given fifteen cents.

  GUM = 

- No change is returned.

Source: Katz, *Contemporary Logic Design*, 1994, p. 389

Vending Machine Solution

```
module VENDING:
input N, D;
output GUM;

loop
  var m := 0 : integer in
    trap WAIT in
      loop
        present N then m := m + 5; end;
        present D then m := m + 10; end;
        if m >= 15 then exit WAIT end;
        pause
      end
    end;
    emit GUM; pause
  end
end
end module
```


Alternative Solution

```
loop
  await
    case immediate N do await
      case N do await
        case N do nothing
        case immediate D do nothing
      end
      case immediate D do nothing
    end
    case immediate D do await
      case immediate N do nothing
      case D do nothing
    end
  end;
  emit GUM; pause
end
```

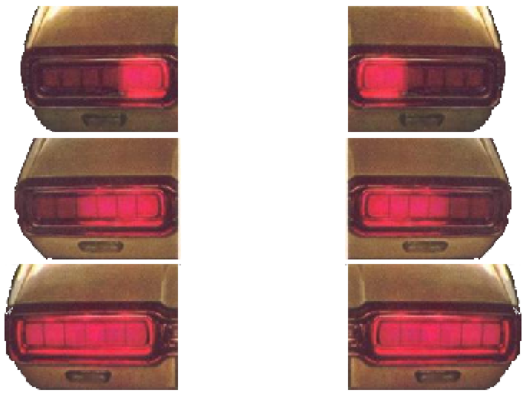
Note that in this example, the last `immediate` is not needed, as the case of an `immediate N` at this point is already handled in the first case. However, as this logic is somewhat intricate, this redundant `immediate`, which does not hurt, is probably the more obvious and preferred solution.

Tail Lights Example

Construct an Esterel program that controls the turn signals of a 1965 Ford Thunderbird.

Source: Wakerly, *Digital Design Principles & Practices*, 2ed, 1994, p. 550

Tail Light Behavior



Tail Lights

- There are three inputs, which initiate the sequences: `LEFT`, `RIGHT`, and `HAZ`
- Six outputs: `LA`, `LB`, `LC`, `RA`, `RB`, and `RC`
- The flashing sequence is

A Single Tail Light

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

  loop
    pause;
    emit A; pause;
    emit A; emit B; pause;
    emit A; emit B; emit C; pause
 end

end module
```

The T-Bird Controller Interface

```
module THUNDERBIRD :
input LEFT, RIGHT, HAZ;
output LA, LB, LC, RA, RB, RC;

...

end module
```


The T-Bird Controller Body

```
loop
  await
   case immediate HAZ do
     abort
       run LIGHTS[signal LA/A, LB/B, LC/C]
     ||
       run LIGHTS[signal RA/A, RB/B, RC/C]
     when [not HAZ]
   case immediate LEFT do
     abort
       run LIGHTS[signal LA/A, LB/B, LC/C]
     when [not LEFT]
   case immediate RIGHT do
     abort
       run Lights[signal RA/A, RB/B, RC/C]
     when [not RIGHT]
  end
end
```

- Note: In the above code, the signal `HAZ` is only reacted to if we are not already blinking left or right
- To change this, the abort condition for the `LEFT` case should be changed from `not LEFT` to `(not LEFT) or HAZ`, and similarly for the `RIGHT` case

Comments on the T-Bird

- This solution uses Esterel's innate ability to control the execution of processes, producing succinct easy-to-understand source but a somewhat larger executable.
- An alternative: Use signals to control the execution of two processes, one for the left lights, one for the right.
- A challenge: Synchronizing hazards.
- Most communication signals can be either level- or edge-sensitive.
- Control can be done explicitly, or implicitly through signals.

Traffic-Light Controller Example

Control a traffic light at the intersection of a busy highway and a farm road.

Source: Mead and Conway, *Introduction to VLSI Systems*, 1980, p. 85.

- Normally, the highway light is green
- If a sensor detects a car on the farm road:
  - The highway light turns yellow then red.
  - The farm road light then turns green until there are no cars or after a long timeout.
  - Then, the farm road light turns yellow then red, and the highway light returns to green.
- Inputs: The car sensor C, a short timeout signal S, and a long timeout signal L.
- Outputs: A timer start signal R, and the colors of the highway and farm road lights HG, HY, HR, FG, FY, and FR.

The Traffic Light Controller

```
module TLC:
input C, SEC;
output HG, HY, HR,
    FG, FY, FR;

signal R, L, S in
  run TIMER
||
  run FSM
end

end module
```

```
module TIMER:
input R, SEC;
output L, S;

loop
  weak abort
    await 3 SEC;
    [
       sustain S
    ||
       await 5 SEC;
       sustain L
    ]
  when R;
end
end module
```

```
module FSM:
input C, L, S;
output R, HG, HY, HR,
    FG, FY, FR;

loop
  emit HG; emit FR; emit R;
  await [C and L];
  emit HY; emit R;
  await S;
  emit HR; emit FG; emit R;
  await [(not C) or L];
  emit FY; emit R;
  await S;
end
end module
```


Overview

Interfacing with the Environment

- At some point, our reactive system must control real-world entities
- There are usually different options for the interface—differing in
  - Ease of use
  - Ease of making mistakes!
- Example: External device that can be ON or OFF
- Options:
  1. Single pure signal
  2. Two pure signals
  3. Boolean valued signal

Different Modes of Motor Control

```
input BUMPER;
output MOTOR;

abort
  sustain MOTOR
when BUMPER
```

Option 1: Single pure signal

- Motor is running in every instant which has the MOTOR signal present

Pro:

- Minimal number of signals

Con:

- High number of signal emissions (signal is emitted in every instant where the motor is on)—may be unnecessary run-time overhead
- Somewhat heavy/unintuitive representation

This is a possible interface between such a level-sensitive signal at the Esterel-level and an edge-sensitive interface at the BrickOS-level (Thanks to Christoph Jobmann/U Göttingen):

```
int motor_on = 0;        /* Global Variables */
int prev_motor_on = 0;
[...]
void MOTOR_O_MOTOR() {
  if(!prev_motor_on)  /* Motor was off? -> Switch it on! */
    switch_motor_on();
  motor_on = 1;
}

int main(void){
  [...]
  while (1) {
    initialize_inputs();     /* Test M_I_BUMBER etc. */
    prev_motor_on = motor_on; /* Buffer value of motor_on */
    motor_on = 0;            /* Re-initialize motor_on */
    MOTOR();                 /* Execute Automaton */

    if (prev_motor_on && !motor_on) /* Switch motor off */
      switch_motor_off();
  }
  [...]
}
```

Different Modes of Motor Control

Option 2: Two pure signals

- Motor is switched on with signal MOTOR_ON present
- Motor is switched off with signal MOTOR_OFF present
- If neither MOTOR_ON or MOTOR_OFF is present, motor keeps its previous state

```
input BUMPER;
output MOTOR_ON,
       MOTOR_OFF;

emit MOTOR_ON;
await BUMPER;
emit MOTOR_OFF;
```

Pro:

- Signal emissions truly indicate significant change of external state
- Simple representation in Esterel

Con:

- No way to control inconsistent outputs
- No memory

Inconsistent Outputs

- Problem with MOTOR_ON and MOTOR_OFF: undefined behavior with both signals present
- Can address this at host-language level
- Can (and should) also address this at Esterel-level:

```
[
  present BUMPER else
    emit MOTOR_ON;
    await BUMPER
  end present;
  emit MOTOR_OFF
]
||
[
  await immediate MOTOR_ON and MOTOR_OFF;
  exit INTERNAL_ERROR
]
```


- In this example, trap INTERNAL_ERROR is emitted if signals MOTOR_ON and MOTOR_OFF are emitted in one instant
- Note that also with Option 1 (single pure signal), it may be the case that different components of our reactive system are in conflict with regard to the state of the Motor. In this case, we cannot even detect this (one component issues the signal, the other doesn't). On the other hand, we have a clear resolution of this conflict—the component that emits the signal wins.

Valued Signal for Motor Control

Option 3: Boolean valued signal

- Merge pure signals MOTOR_ON and MOTOR_OFF into one valued signal MOTOR
- Motor is switched on if every emit-statement in that instant emits true

```
input BUMPER;
output MOTOR combine BOOLEAN with and;

emit MOTOR(true);
await immediate BUMPER;
emit MOTOR(false);
```

- Here: In case of conflicting outputs, motor stays switched off

- Note that we could also have decided that in case of conflicting outputs, the motor should be switched on (by using or as combination operator)

Valued Signal for Motor Control

Option 3 contd.

Pro:

- Again only one signal for motor control
- Explicit control of behavior for inconsistent outputs
- Valued signal has memory—can be polled in later instances, after emission
- Easy extension to finer speed control

Con:

- Inconsistent outputs are handled deterministically—but are not any more detected and made explicit
- For certain classes of analyses/formal methods that we may wish to apply, valued signals are more difficult to handle than pure signals

Events vs. State

- Excessive signal emissions
  - make the behavior difficult to understand
  - cause overhead if fed to the external environment
- State:
  - "Robot is turning left"
  - "Motor is on"
  - Esterel:
    - waiting for some signal
    - terminated thread
    - value of valued signal
- Event:
  - Change of State
  - "Turn motor on"
  - Esterel:
    - emit pure signal
    - change value of signal

Summary

- Esterel allows to specify precisely what happens if inputs arrive in combinations—but must consider this from application perspective as well
- Can memorize state in signal/variable values or as program state
- Several choices when interfacing with environment—must consider simplicity, robustness