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?
The 5-Minute Review Session

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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.
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4. What is the *multiform notion of time*?
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Examples
Interfacing with the Environment

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4. What is the *WTO principle*?
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?
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4. What is the difference between strong and weak suspend?
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

Examples

People Counter Example
Vending Machine Example
Tail Lights Example
Traffic-Light Controller Example

Interfacing with the Environment
People Counter Example

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


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


*Thanks to Stephen Edwards (Columbia U) for providing this and the following examples*
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
```
Examples
Interfacing with the Environment

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
```
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 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 module
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 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

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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.
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.

\[
N = \quad D =
\]
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.

\[
N = \text{Nickel} \quad D = \text{Dime}
\]

- A single output, \( \text{GUM} \), should be present for a single cycle when the machine has been given fifteen cents.

\[
\text{GUM} = \text{Wrigley's Doublemint Gum}
\]

Source: Katz, Contemporary Logic Design, 1994, p. 389
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.
  \[
  N = \quad D = 
  \]

- 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
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 module
Alternative Solution

```plaintext
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;
  emit GUM; pause
end
```
Tail Lights Example

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

Tail Light Behavior
Tail Light Behavior
Tail Light Behavior
Tail Lights

- There are three inputs, which initiate the sequences: LEFT, RIGHT, and HAZ
Tail Lights

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

<table>
<thead>
<tr>
<th>LC</th>
<th>LB</th>
<th>LA</th>
<th>step</th>
<th>RA</th>
<th>RB</th>
<th>RC</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 2 3 4
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

```language=ca
loop
  await
  case immediate HAZ do
    abort
    run LIGHTS[signal LA/A, LB/B, LC/C]
  end
  case immediate LEFT do
    abort
    run LIGHTS[signal LA/A, LB/B, LC/C]
  end
  case immediate RIGHT do
    abort
    run Lights[signal RA/A, RB/B, RC/C]
  end
end
```
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.
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- **An alternative:** Use signals to control the execution of two processes, one for the left lights, one for the right.

- **A challenge:** Synchronizing hazards.
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- Most communication signals can be either level- or edge-sensitive.
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- 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.

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- Normally, the highway light is green
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Control a traffic light at the intersection of a busy highway and a farm road.


- 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.
Traffic-Light Controller Example

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


- Normally, the highway light is green
- If a sensor detects a car on the farm road:
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  - 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 $L$. 

[Diagram of traffic lights and sensors]
Traffic-Light Controller Example

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


- 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
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
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

Examples

Interfacing with the Environment
Available Alternatives
Handling Inconsistent Outputs
Events vs. State
Interfacing with the Environment

▶ At some point, our reactive system must control real-world entities
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!
Interfacing with the Environment

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- Example: External device that can be ON or OFF.
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- **Example:** External device that can be ON or OFF
- **Options:**
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- **Example:** External device that can be ON or OFF
- **Options:**
  1. Single pure signal
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- **Example:** External device that can be ON or OFF
- **Options:**
  1. Single pure signal
  2. Two pure signals
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

Option 1: Single pure signal

▶ Motor is running in every instant
 which has the MOTOR signal present
Different Modes of Motor Control

Option 1: Single pure signal

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

```plaintext
input BUMPER;
output MOTOR;
abort
  sustain MOTOR
when BUMPER
```
Different Modes of Motor Control

Option 1: Single pure signal

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

Pro:

▶ Minimal number of signals
Different Modes of Motor Control

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

input BUMPER;
output MOTOR;
abort sustain MOTOR when BUMPER
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
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;
```
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

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

```plaintext
input BUMPER;
output MOTOR_ON, MOTOR_OFF;
emit MOTOR_ON;
await BUMPER;
emit 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

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
Inconsistent Outputs

- Problem with `MOTOR_ON` and `MOTOR_OFF`: undefined behavior with both signals present
- Can address this at host-language level
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:

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

```plaintext
[
  present BUMPER else
    emit MOTOR_ON;
    await BUMPER
  end present;
  emit MOTOR_OFF
]
```
Valued Signal for Motor Control

Option 3: Boolean valued signal

- Merge pure signals \texttt{MOTOR\_ON} and \texttt{MOTOR\_OFF} into one valued signal \texttt{MOTOR}

- Motor is switched on if every emit-statement in that instant emits true
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

```plaintext
input BUMPER;
output MOTOR combine BOOLEAN with and;
emit MOTOR(true);
await immediate BUMPER;
emit MOTOR(false);
```
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

```plaintext
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
Valued Signal for Motor Control

Option 3 contd.
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
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
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
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.