A formal microstep semantics for Esterel

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Goal: a formally proven compilation scheme for Esterel

- Esterel, a synchronous imperative language
  - Synchronous: execution happens in instants
  - Imperative: instructions, not equations ($\neq$ Lustre)
- Formal verification of the compilation scheme
  - Based on a web book by Gérard Berry

    [The Constructive Semantics of Pure Esterel]
  - Modular compilation (SOS)
  - In Coq
- Restrictions
  - Compilation towards digital circuits
  - No data: Pure Esterel v.5
  - No reincarnation

    future work . . .

“Hello world!” in Esterel: ABRO

Specification:

- As soon as signals *A* and *B* are received, emit *O*
- Restart whenever *R* is received

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halt
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```
halt               := loop pause end
awimm $s$          := trap $T$ in
                          loop [if $s$ then exit $T^2$ else pause end] end
abort $p$ when $s$ := trap $T$ in
                          loop [if $s$ then exit $T^2$ else pause end] end
                        ||
                          [$p$ ; exit $T^2$]
```

Esterel Syntax (instructions)

$p, q :=$	`nothing`		
	`pause`		
	`exit` T^k	k is an index	
	`trap` T `in` p `end`		
	`emit` s		
	`if` s `then` p `else` q `end`		$s\,?\,p\,,\,q$
	`suspend` p `when` s		
	p ; q		
	p || q		
	`loop` p `end`		
	`signal` s `in` p `end`		$p\backslash s$

+ derived constructions (macros)

What Type of Semantics?

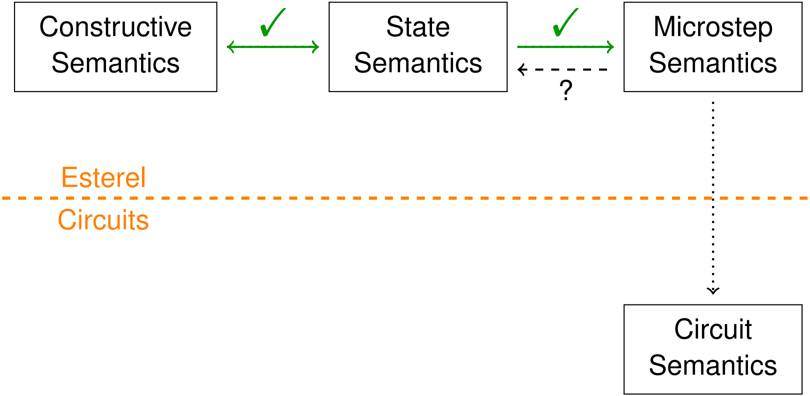
Structural Operational Semantics (SOS)

- Mathematical definition through rewriting
  - Structural: follows the program structure
  - Operational: one transition = one instant
- Shape of the rules: $p \xrightarrow[E]{E', k} p'$
  - Inputs E
  - outputs E'
  - Return code k 0 = done, 1 = pausing, 2+ = traps

Some remarks:

- E and E' map to each signal its status:
  present $(+)$ absent (–) unknown $(\perp)$
- signals in E and E' are “unrelated”

Chain of Esterel Semantics



Constructive Semantics

✓

State Semantics

✓

?

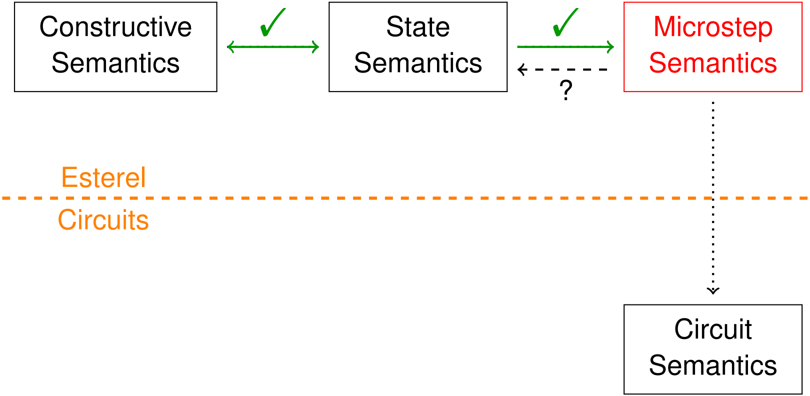
Microstep Semantics

Esterel

Circuits

Circuit Semantics

Chain of Esterel Semantics



Let’s Enter the Instant: Microsteps Semantics

State Semantics

- Perfect correspondence with circuits between instants
- Computation of local signals in 2 steps — Must/Can

Microstep Semantics

- Explain computation within one instant
  $\rightsquigarrow$ be (almost) as precise as logical gates
- Get rid of Must/Can
- No E' nor k: too low-level
- Focus on control: keep E — less wires

Limitations

- No reincarnation thus no loop

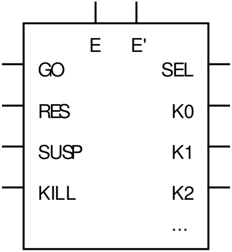
Intuition of the Microstep Semantics

- Inspiration = Scott semantics on circuit
  - Increase information in wires
  - Restricted to within one instant ⇝ never cross a `pause`

- Objective: connection with the state semantics

$$\begin{tikzcd}
\overline{p} \arrow[rr, two heads, "{E', k}", "E"'] \arrow[d, dashed] & & \overline{p'} \\
\text{◪}\ p\ \circ \arrow[rr, "E"', "*" {pos=1}] & & \text{◪}\ p'\ \bullet_k \arrow[u, dashed]
\end{tikzcd}$$

Intuition for microstates



According to the circuit translation:

Go/Resume transfer control

Suspend freeze state

Kill prevent activation of `pauses`

Sel propagate activation

Ki propagate termination and traps

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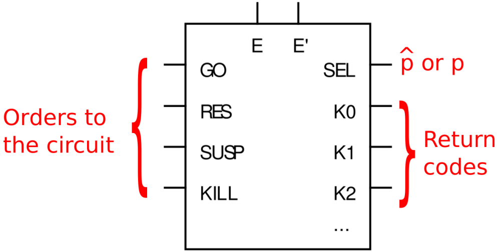

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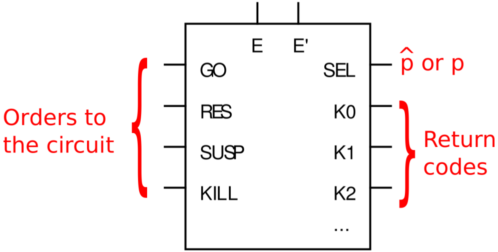

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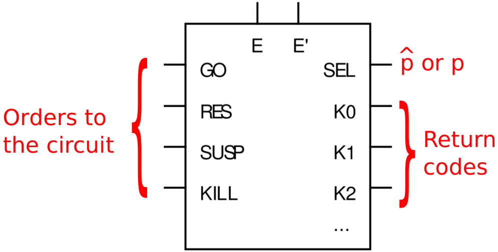

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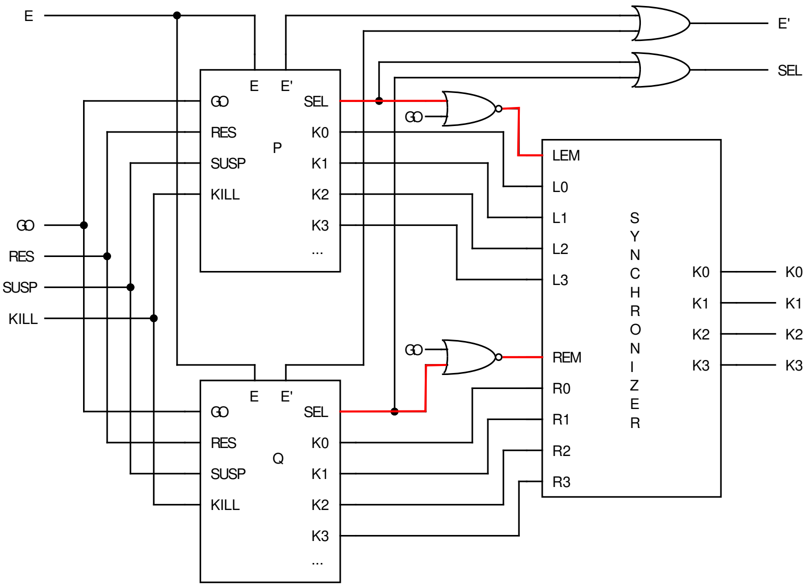
Sel is used inside the synchronizer for *p* | | *q*!

The synchronizer of $p \;||\; q$



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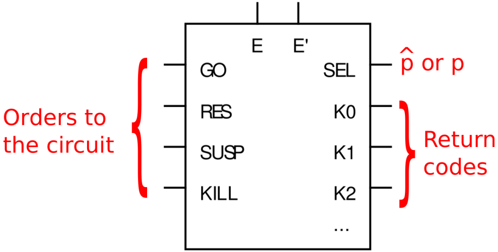

Orders to the circuit

$\hat{p}$ or p

Return codes

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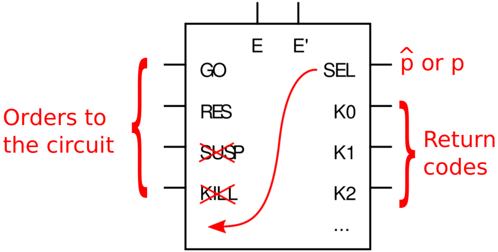

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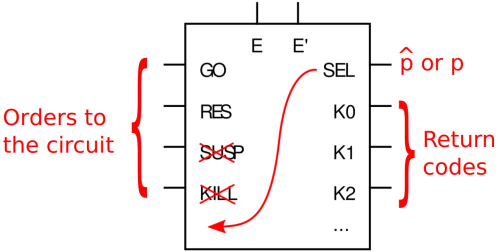

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Definition of Microstates

Microstate: ◪ p ◐

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Inputs: □, □, ■, ■

- □ = start fresh
- ■ = resume
- □ = don’t start
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Outputs: $\bullet_k, \circ_K$
"1-hot" encoding
of return codes

- $\bullet_k$: Must
  k-th wire is 1
- $\circ_K$: Can
  no wire is 1
  wires $\in K$ are $\perp$

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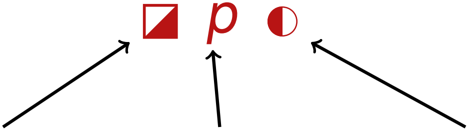

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Program p

- Inert
- ◪ / ◐ in subterms

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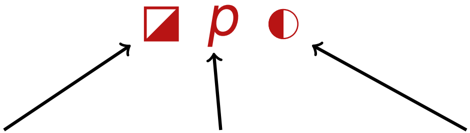

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Scott order $\leq$

- Inputs: ◪ $\leq$ ◪ composant-wise
- Outputs:

$$
\begin{aligned}
\circ_K \leq \circ_L \quad &:= \quad L \subseteq K \\
\circ_K \leq \bullet_k \quad &:= \quad k \in K \\
\bullet_k \leq \bullet_l \quad &:= \quad k = l
\end{aligned}
$$

Definition of Microsteps

Microstep: $$\text{◪}\ p\ \text{◐} \xrightarrow[E]{} \text{◪}\ p'\ \text{◐}'$$

- Update ◪ and ◐ until reaching max info
  - Inputs: all components $\neq \bot$
  - Outputs: $●_k$ or $○_\varnothing$
- Too small to have E', k
  - no return code (k encoded inside ◐)
  - s emitted iff ◪ `emit` s $●_0$

    $\leadsto$ Must/Can replaced by reading the microstate
- Connection with the state semantics:

$$\begin{tikzcd}
\overline{p} \arrow[r, two heads, "{E', k}", "E"'] \arrow[d, dashed, "\texttt{from\_cmd} \ / \ \texttt{from\_state}"'] & \overline{p'} \\
\text{◪}\ p\ ○_K \arrow[r, "E"', "*"] & \text{◪}\ p'\ ●_k \arrow[u, dashed, "\texttt{to\_term}"']
\end{tikzcd}$$

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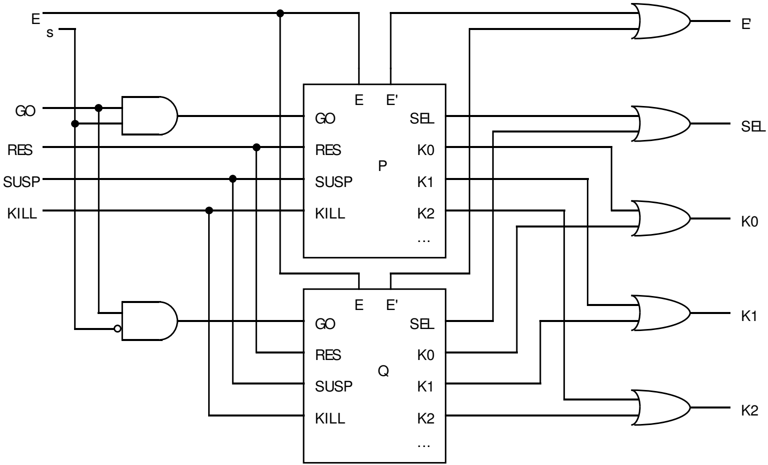
◪\ p\ ○_K \arrow[r, "E"', "*"] & ◪\ p'\ ●_k \arrow[u, dashed, "\begin{array}{l}\texttt{to\_term} \\ \text{Susp/Kill done here}\end{array}"']
\end{tikzcd}$$

Microstep Rules for then

Circuit Translation for $s ? p , q$

`if` s `then` P `else` Q `end`



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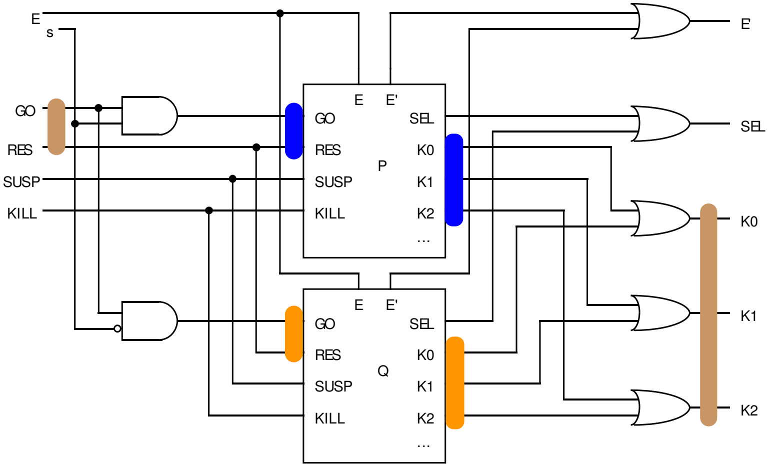

Microstep Rules for then

◪ = Input ◐ = Output

$$\frac{s^b \in E \qquad (\mathrm{Go}\,\text{◪}) < (\mathrm{Go}\,\text{◪}) \wedge b \qquad \text{◪} = \text{◪}[\mathrm{Go} \leftarrow (\mathrm{Go}\,\text{◪}) \wedge b]}{\text{◪}(s\,?\,(\text{◪}p\text{◐})\,,\,(\text{◪}q\text{◐}))\text{◐} \xrightarrow[E]{} \text{◪}(s\,?\,(\text{◪}p\text{◐})\,,\,(\text{◪}q\text{◐}))\text{◐}}$$

$$\frac{\text{◪}p\text{◐} \xrightarrow[E]{} \text{◪}p'\text{◐}}{\text{◪}(s\,?\,(\text{◪}p\text{◐})\,,\,(\text{◪}q\text{◐}))\text{◐} \xrightarrow[E]{} \text{◪}(s\,?\,(\text{◪}p'\text{◐})\,,\,(\text{◪}q\text{◐}))\text{◐}}$$

$$\frac{\text{◐} < (\text{◐} \vee \text{◐})}{\text{◪}(s\,?\,(\text{◪}p\text{◐})\,,\,(\text{◪}q\text{◐}))\text{◐} \xrightarrow[E]{} \text{◪}(s\,?\,(\text{◪}p\text{◐})\,,\,(\text{◪}q\text{◐}))(\text{◐} \vee \text{◐})}$$

The Return of ABRO: First Instant

```
loop
  abort
        awimm A
     ||
       awimm B
    ;
    (emit O ;
     halt)
  when R
end
```

$E_1 = \{ A^-, B^+, R^-, O^\perp \}$

The Return of ABRO: First Instant

□ : Sel^{-}

```
□ loop
    □ abort
        □ { □ [     (□ awimm $A$  $\bigcirc_{\{0,1\}}$)
                 ||
                    (□ awimm $B$ $\bigcirc_{\{0,1\}}$)
              ] $\bigcirc_{\{0,1\}}$ ;
            □ [ (□ emit $O$ $\bigcirc_{\{0\}}$) ;
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                ||
                     (□ awimm B ○_{0,1})
              ] ○_{0,1} ;
            □ [ (□ emit O ○_{0}) ;
                (□ halt ○_{1})
              ] ○_{1}
          } ○_{1}
    when R  ○_{0,1}
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            🟥 [ (□ emit $O$ $\bigcirc_{\{0\}}$) ;
                (□ halt $\bigcirc_{\{1\}}$)
              ] $\bigcirc_{\{1\}}$
          } $\bigcirc_{\{1\}}$
    when $R$ $\bigcirc_{\{1\}}$
  end $\bigcirc_{\{1\}}$
```

```
loop
  abort
        awimm $A$
     ||
       awimm $B$
     ;
     (emit $O$ ;
      halt)
  when $R$
end
```

$$E_1 = \{\, \mathrm{A}^-, \mathrm{B}^+, \mathrm{R}^-, \mathrm{O}^\perp \,\}$$

The Return of ABRO: First Instant

□ : Sel$^-$ 🟩 : Sel$^-$, Go$^+$ 🟥 : Sel$^-$, Go$^-$

```
🟩 loop
    🟩 abort
        🟩 { 🟩 [     (🟩 awimm A ●1)
                   ||
                     (□ awimm B ○{0,1})
                 ] ○{1} ;
              🟥 [ (🟥 emit O ○{0}) ;
                  (□ halt ○{1})
                 ] ○{1}
           } ○{1}
      when R  ○{1}
   end ○{1}
```

```
loop
  abort
        awimm A
     ||
       awimm B
     ;
     (emit O ;
      halt)
  when R
end
```

$E_1 = \{ \mathrm{A}^-, \mathrm{B}^+, \mathrm{R}^-, \mathrm{O}^\perp \}$

The Return of ABRO: First Instant

□ : Sel^- 🟩 : $\text{Sel}^-, \text{Go}^+$ 🟥 : $\text{Sel}^-, \text{Go}^-$

```
🟩 loop
    🟩 abort
        🟩 { 🟩 [     (🟩 awimm A ●_1)
                   ||
                     (□ awimm B ○_{0,1})
                ] ○_{1} ;
              🟥 [ (🟥 emit O ○_∅) ;
                   (□ halt ○_{1})
                ] ○_{1}
           } ○_{1}
      when R  ○_{1}
   end ○_{1}
```

```
loop
  abort
        awimm A
     ||
       awimm B
     ;
     (emit O ;
      halt)
  when R
end
```

$$E_1 = \{\, A^-, B^+, R^-, O^\perp \,\}$$

The Return of ABRO: First Instant

□ : Sel$^-$ □ : Sel$^-$, Go$^+$ □ : Sel$^-$, Go$^-$

```
□ loop
   □ abort
      □ { □ [     (□ awimm A $\bullet_1$)
                 ||
                  (□ awimm B $\circ_{\{0,1\}}$)
              ] $\circ_{\{1\}}$ ;
            □ [ (□ emit O $\circ_\varnothing$) ;
                (□ halt $\circ_{\{1\}}$)
              ] $\circ_{\{1\}}$
        } $\circ_{\{1\}}$
     when R $\circ_{\{1\}}$
  end $\circ_{\{1\}}$
```

```
loop
  abort
        awimm A
     ||
       awimm B
     ;
     (emit O ;
      halt)
  when R
end
```

$E_1 = \{ A^-, B^+, R^-, O^\perp \}$

The Return of ABRO: First Instant

□ : Sel$^-$ 🟩 : Sel$^-$, Go$^+$ 🟥 : Sel$^-$, Go$^-$

```
🟩 loop
    🟩 abort
        🟩 { 🟩 [     (🟩 awimm $A$ $\bullet_1$)
                  ||
                     (□ awimm $B$ $\bigcirc_{\{0,1\}}$)
               ] $\bigcirc_{\{1\}}$ ;
             🟥 [ (🟥 emit $O$ $\bigcirc_{\varnothing}$) ;
                 (🟥 halt $\bigcirc_{\varnothing}$)
               ] $\bigcirc_{\{1\}}$
           } $\bigcirc_{\{1\}}$
      when $R$ $\bigcirc_{\{1\}}$
  end $\bigcirc_{\{1\}}$
```

E_1 = { A$^-$, B$^+$, R$^-$, O$^\perp$ }

```
loop
  abort
        awimm A
     ||
        awimm B
     ;
     (emit O ;
      halt)
  when R
end
```

The Return of ABRO: First Instant

□ : Sel^- 🟩 : $\mathrm{Sel}^-, \mathrm{Go}^+$ 🟥 : $\mathrm{Sel}^-, \mathrm{Go}^-$

```
🟩 loop
     🟩 abort
          🟩 { 🟩 [      (🟩 awimm A $\bullet_1$)
                    ||
                       (□ awimm B $\bigcirc_{\{0,1\}}$)
                 ] $\bigcirc_{\{1\}}$ ;
               🟥 [ (🟥 emit O $\bigcirc_{\emptyset}$) ;
                    (🟥 halt $\bigcirc_{\emptyset}$)
                 ] $\bigcirc_{\emptyset}$
             } $\bigcirc_{\{1\}}$
      when R $\bigcirc_{\{1\}}$
  end $\bigcirc_{\{1\}}$
```

```
loop
  abort
        awimm A
     ||
        awimm B
     ;
     (emit O ;
      halt)
  when R
end
```

$$E_1 = \{\, A^-, B^+, R^-, O^\perp \,\}$$

The Return of ABRO: First Instant

□ : Sel$^-$ 🟩 : Sel$^-$, Go$^+$ 🟥 : Sel$^-$, Go$^-$

```
🟩 loop
    🟩 abort
        🟩 { 🟩 [     (🟩 awimm $A$ $\bullet_1$)
                   ||
                     (🟩 awimm $B$ $\bigcirc_{\{0,1\}}$)
               ] $\bigcirc_{\{1\}}$ ;
               🟥 [ (🟥 emit $O$ $\bigcirc_{\emptyset}$) ;
                   (🟥 halt $\bigcirc_{\emptyset}$)
               ] $\bigcirc_{\emptyset}$
           } $\bigcirc_{\{1\}}$
      when $R$ $\bigcirc_{\{1\}}$
  end $\bigcirc_{\{1\}}$
```

```
loop
  abort
        awimm A
    ||
       awimm B
    ;
    (emit O ;
     halt)
  when R
end
```

$E_1 = \{\ \mathrm{A}^-, \mathrm{B}^+, \mathrm{R}^-, \mathrm{O}^\perp\ \}$

The Return of ABRO: First Instant

□ : Sel$^-$ 🟩 : Sel$^-$, Go$^+$ 🟥 : Sel$^-$, Go$^-$

```
🟩 loop
   🟩 abort
      🟩 { 🟩 [     (🟩 awimm A ●_1)
                 ||
                   (🟩 awimm B ●_0)
               ] ○_{1} ;
             🟥 [ (🟥 emit O ○_∅) ;
                  (🟥 halt ○_∅)
               ] ○_∅
         } ○_{1}
      when R  ○_{1}
   end ○_{1}
```

$E_1 = \{ \mathrm{A}^-, \mathrm{B}^+, \mathrm{R}^-, \mathrm{O}^\perp \}$

```
loop
  abort
        awimm A
     ||
       awimm B
     ;
     (emit O ;
      halt)
  when R
end
```

The Return of ABRO: First Instant

□ : Sel$^-$ 🟩 : Sel$^-$, Go$^+$ 🟥 : Sel$^-$, Go$^-$

```
🟩 loop
    🟩 abort
        🟩 { 🟩 [     (🟩 awimm $A$ $\bullet_1$)
                  ||
                    (🟩 awimm $B$ $\bullet_0$)
                ]$\bullet_1$ ;
              🟥 [ (🟥 emit $O$ $\bigcirc_\varnothing$) ;
                   (🟥 halt $\bigcirc_\varnothing$)
                ] $\bigcirc_\varnothing$
           } $\bigcirc_{\{1\}}$
      when $R$  $\bigcirc_{\{1\}}$
  end $\bigcirc_{\{1\}}$
```

```
loop
  abort
        awimm A
    ||
       awimm B
    ;
    (emit O ;
     halt)
  when R
end
```

$E_1 = \{ A^-, B^+, R^-, O^\perp \}$

The Return of ABRO: First Instant

□ : Sel^- 🟩 : $\mathrm{Sel}^-, \mathrm{Go}^+$ 🟥 : $\mathrm{Sel}^-, \mathrm{Go}^-$

```
🟩 loop
    🟩 abort
        🟩 { 🟩 [     (🟩 awimm $A$ $\bullet_1$)
                   ||
                     (🟩 awimm $B$ $\bullet_0$)
                 ]$\bullet_1$ ;
               🟥 [ (🟥 emit $O$ $\circ_\varnothing$) ;
                    (🟥 halt $\circ_\varnothing$)
                 ] $\circ_\varnothing$
           } $\bullet_1$
      when $R$ $\circ_{\{1\}}$
   end $\circ_{\{1\}}$
```

```
loop
  abort
        awimm $A$
    ||
        awimm $B$
    ;
    (emit $O$ ;
     halt)
  when $R$
end
```

$$E_1 = \{\, \mathrm{A}^-, \mathrm{B}^+, \mathrm{R}^-, \mathrm{O}^\perp \,\}$$

The Return of ABRO: First Instant

□ : Sel^- 🟩 : $\text{Sel}^-, \text{Go}^+$ 🟥 : $\text{Sel}^-, \text{Go}^-$

```
🟩 loop
   🟩 abort
      🟩 { 🟩 [     (🟩 awimm $A$ $\bullet_1$)
                 ||
                   (🟩 awimm $B$ $\bullet_0$)
             ]$\bullet_1$ ;
           🟥 [ (🟥 emit $O$ $\circ_\varnothing$) ;
                (🟥 halt $\circ_\varnothing$)
              ] $\circ_\varnothing$
         } $\bullet_1$
      when $R$ $\bullet_1$
   end $\circ_{\{1\}}$
```

```
loop
  abort
        awimm A
     ||
       awimm B
     ;
     (emit O ;
      halt)
  when R
end
```

$E_1 = \{\, \text{A}^-, \text{B}^+, \text{R}^-, \text{O}^\perp \,\}$

The Return of ABRO: First Instant

□ : Sel$^-$ 🟩 : Sel$^-$, Go$^+$ 🟥 : Sel$^-$, Go$^-$

```
🟩 loop
   🟩 abort
      🟩 { 🟩 [     (🟩 awimm A ●_1)
                 ||
                  (🟩 awimm B ●_0)
               ]●_1 ;
            🟥 [ (🟥 emit O ○_∅) ;
                 (🟥 halt ○_∅)
               ] ○_∅
         } ●_1
     when R ●_1
  end ●_1
```

```
loop
  abort
        awimm A
    ||
       awimm B
    ;
    (emit O ;
     halt)
  when R
end
```

$E_1 = \{ A^-, B^+, R^-, O^\perp \}$

The Return of ABRO: First Instant

□ : Sel$^-$ 🟩 : Sel$^-$, Go$^+$ 🟥 : Sel$^-$, Go$^-$

```
🟩 loop
   🟩 abort
      🟩 { 🟩 [      (🟩 awimm $A$ $\bullet_1$)
                  ||
                    (🟩 awimm $B$ $\bullet_0$)
             ]$\bullet_1$ ;
           🟥 [ (🟥 emit $O$ $\circ_\varnothing$) ;
                (🟥 halt $\circ_\varnothing$)
             ] $\circ_\varnothing$
         } $\bullet_1$
     when $R$ $\bullet_1$
  end $\bullet_1$
```

```
loop
  abort
        awimm A
    ||
        awimm B
    ;
    (emit O ;
     halt)
  when R
end
```

$$E_1 = \{\ \mathrm{A}^-, \mathrm{B}^+, \mathrm{R}^-, \mathrm{O}^\perp\ \}$$

$$E_1' = \{\ \mathrm{A}^-, \mathrm{B}^-, \mathrm{R}^-, \mathrm{O}^\perp\ \}$$

The Return of ABRO: First Instant

□ : Sel$^-$ 🟩 : Sel$^-$, Go$^+$ 🟥 : Sel$^-$, Go$^-$

```
🟩 loop
    🟩 abort
        🟩 { 🟩 [     (🟩 awimm $A$ $\bullet_1$)
                   ||
                     (🟩 awimm $B$ $\bullet_0$)
               ]$\bullet_1$ ;
             🟥 [ (🟥 emit $O$ $\circ_\varnothing$) ;
                  (🟥 halt $\circ_\varnothing$)
               ] $\circ_\varnothing$
           } $\bullet_1$
      when $R$ $\bullet_1$
  end $\bullet_1$
```

```
loop
  abort
        awimm $A$
     ||
       awimm $B$
     ;
     (emit $O$ ;
      halt)
  when $R$
end
```

$$E_1 = \{\ A^-, B^+, R^-, O^\perp\ \}$$
$$E'_1 = \{\ A^-, B^-, R^-, O^-\ \}$$

The Return of ABRO: First Instant

□ : Sel^- □ : $\text{Sel}^-, \text{Go}^+$ □ : $\text{Sel}^-, \text{Go}^-$

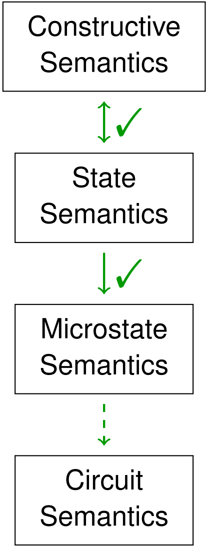
```
□ loop
    □ abort
        □ { □ [     (□ awimm $A$ $\bullet_1$)
                   ||
                     (□ awimm $B$ $\bullet_0$)
              ]$\bullet_1$ ;
              □ [ (□ emit $O$ $\circ_\varnothing$) ;
                  (□ halt $\circ_\varnothing$)
              ] $\circ_\varnothing$
          } $\bullet_1$
    when $R$ $\bullet_1$
  end $\bullet_1$
```

```
loop
  abort
        $\widehat{\texttt{awimm}}$ $A$
     ||
        awimm $B$
     ;
     (emit $O$ ;
      halt)
  $\widehat{\texttt{when}}$ $R$
end
```

$E_1 = \{\, \text{A}^-, \text{B}^+, \text{R}^-, \text{O}^\perp \,\}$

$E_1' = \{\, \text{A}^-, \text{B}^-, \text{R}^-, \text{O}^- \,\}$

Final Overview of Esterel Semantics



Constructive Semantics

↕ ✓

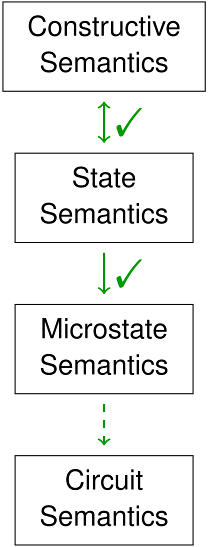
State Semantics

↓ ✓

Microstate Semantics

Circuit Semantics

Final Overview of Esterel Semantics



Constructive Semantics

↕ ✓

State Semantics

↓ ✓

Microstate Semantics

Circuit Semantics

⊕ usual PL semantics
⊕ few rules (14)
⊖ rewrites the program

⊕ execution by marking
⊕ link with stables states of circuits
⊖ two types of rules (14 + 15)

⊕ low-level local semantics
⊕ no more Can/Must
⊖ lots of rules (52)
⊖ no loops (because no reincarnation)

⊕ few rules (18)
⊕ insensitive to reincarnation
⊖ big terms