

# Preventing Glitches and Short Circuits in High-Level Self-Timed Chip Specifications

Stephen Longfield   **Brittany Nkounkou**   Rajit Manohar   Ross Tate

Cornell University

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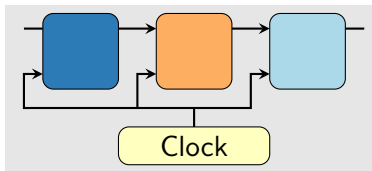
Ross Tate

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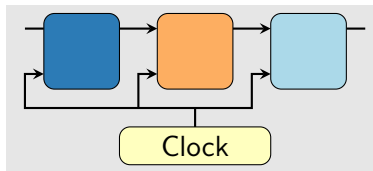




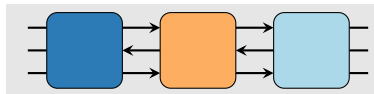
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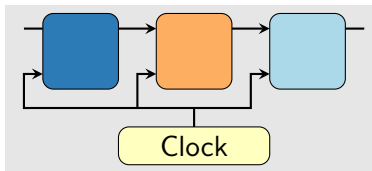
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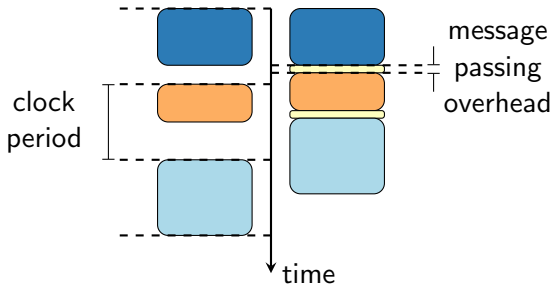
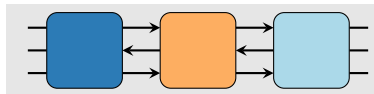
Self-Timed



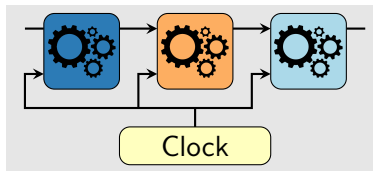
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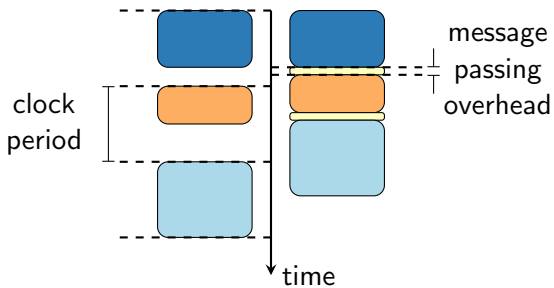
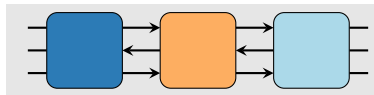
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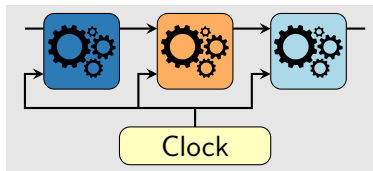
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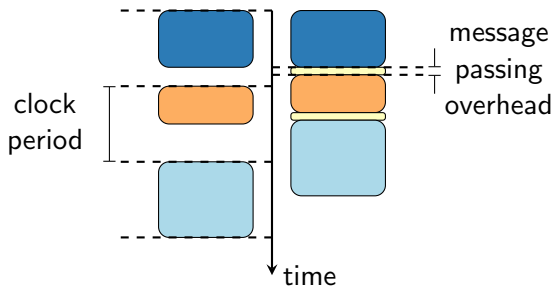
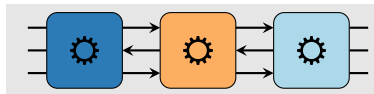
## Self-Timed



## Clocked

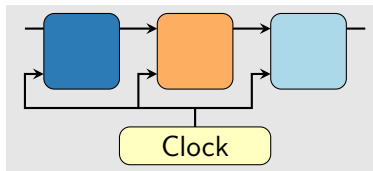


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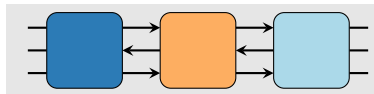




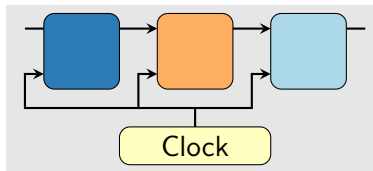
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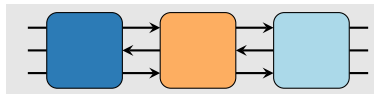
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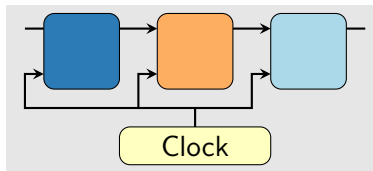
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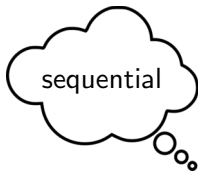
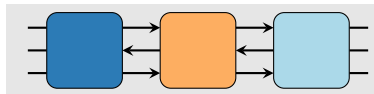
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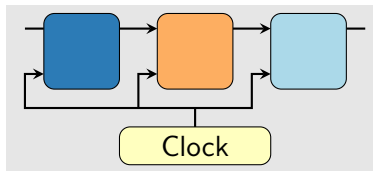
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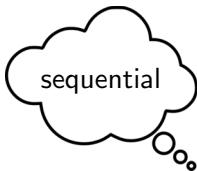
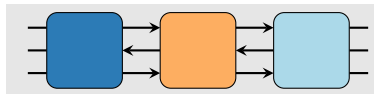
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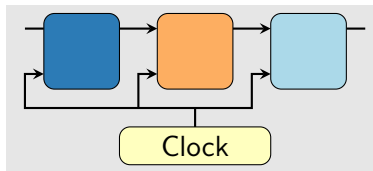
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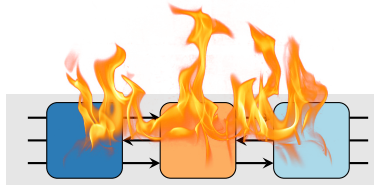
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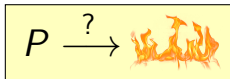


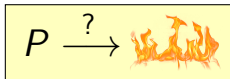
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Self-Timed







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# Communicating Hardware Processes (CHP)

# Communicating Hardware Processes (CHP)

Channel A

# Communicating Hardware Processes (CHP)

Channel  $A$

Program  $P ::=$

# Communicating Hardware Processes (CHP)

Channel  $A$

Program  $P ::= A!$

# Communicating Hardware Processes (CHP)

Channel  $A$

Program  $P ::= A! \mid A?$

# Communicating Hardware Processes (CHP)

Channel  $A$

Program  $P ::= A! \mid A?$   
 $\mid P; P$

# Communicating Hardware Processes (CHP)

Channel  $A$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P$

# Communicating Hardware Processes (CHP)

Channel  $A$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P$



# Communicating Hardware Processes (CHP)

Channel  $A$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip}$

# Communicating Hardware Processes (CHP)

Channel  $A$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---

# Communicating Hardware Processes (CHP)

Channel  $A$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---

$P; P' \parallel Q; Q'$

# Communicating Hardware Processes (CHP)

Channel  $A$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---

$P; P' \parallel Q; Q'$   
↑            ↑

# Communicating Hardware Processes (CHP)

Channel  $A$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---

$P; A!; P' \parallel Q; A?; Q'$

# Communicating Hardware Processes (CHP)

Channel  $A$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---

$P; A!; P' \parallel Q; A?; Q' \longrightarrow \dots$

# Communicating Hardware Processes (CHP)

Channel  $A$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---

$P; A!; P' \parallel Q; A?; Q' \longrightarrow \dots \longrightarrow A!; P' \parallel A?; Q'$

# Communicating Hardware Processes (CHP)

Channel  $A$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---

$$P; A!; P' \parallel Q; A?; Q' \longrightarrow \dots \longrightarrow A!; P' \parallel A?; Q' \longrightarrow P' \parallel Q'$$



# Communicating Hardware Processes (CHP)

Channel  $A$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---

$P; A!; P' \parallel Q; A?; Q' \longrightarrow \dots \longrightarrow A!; P' \parallel A?; Q' \longrightarrow P' \parallel Q'$

**ideal:**  $A!; P \parallel A?; Q \longrightarrow P \parallel Q$

# Communicating Hardware Processes (CHP)

Channel  $A$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---

$$P; A!; P' \parallel Q; A?; Q' \longrightarrow \dots \longrightarrow A!; P' \parallel A?; Q' \longrightarrow P' \parallel Q'$$

**ideal:**  $A!; P \parallel A?; Q \longrightarrow P \parallel Q$

$(A! \parallel A?) \parallel (A! \parallel A?)$

# Communicating Hardware Processes (CHP)

Channel  $A$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---

$P; A!; P' \parallel Q; A?; Q' \longrightarrow \dots \longrightarrow A!; P' \parallel A?; Q' \longrightarrow P' \parallel Q'$

**ideal:**  $A!; P \parallel A?; Q \longrightarrow P \parallel Q$

$(A! \parallel A?) \parallel (A! \parallel A?) \longrightarrow$  

# Communicating Hardware Processes (CHP)

Channel  $A$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---

# Communicating Hardware Processes (CHP)

Channel  $A$  ::=  $\langle \bar{A}, \hat{A} \rangle$

Program  $P$  ::=  $A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---

# Communicating Hardware Processes (CHP)

Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

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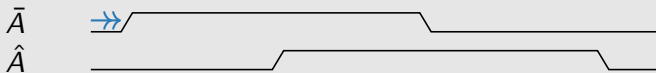


# Communicating Hardware Processes (CHP)

Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

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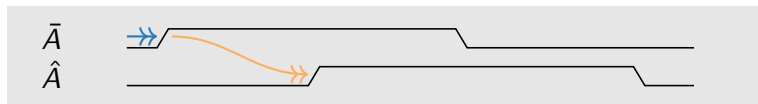


# Communicating Hardware Processes (CHP)

Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

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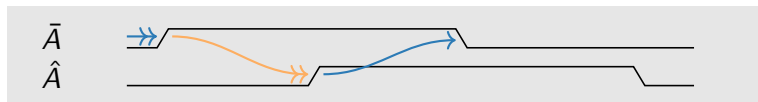


# Communicating Hardware Processes (CHP)

Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

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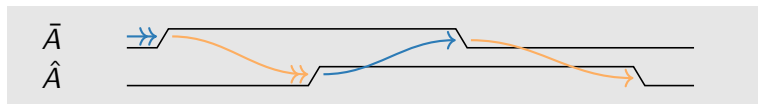


# Communicating Hardware Processes (CHP)

Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

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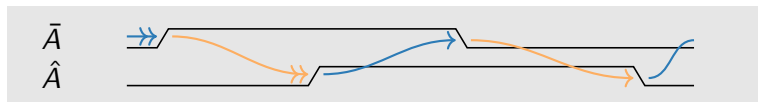


# Communicating Hardware Processes (CHP)

Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A?$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

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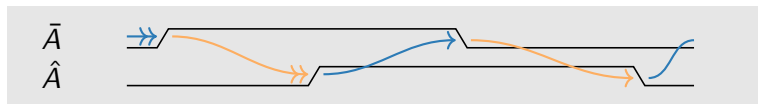


# Communicating Hardware Processes (CHP)

Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A? \mid A_i$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

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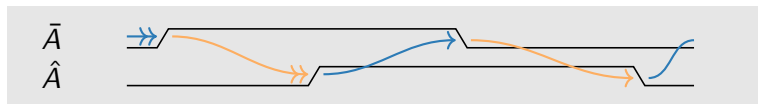


# Communicating Hardware Processes (CHP)

Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A? \mid A_i \mid A_{\bar{i}}$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

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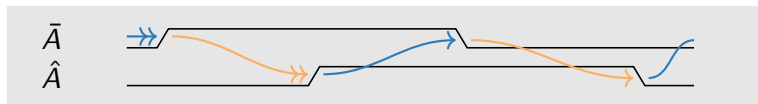


# Communicating Hardware Processes (CHP)

Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A? \mid A_i \mid A_{\bar{i}}$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

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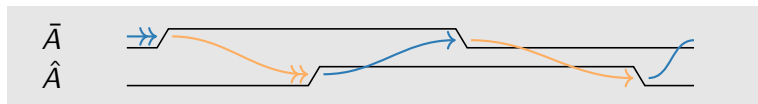
**ideal:**

# Communicating Hardware Processes (CHP)

Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A? \mid A_i \mid A_{\bar{i}}$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

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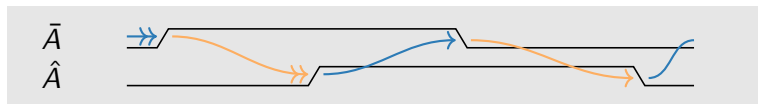
**ideal:**  $A! \parallel A?$

# Communicating Hardware Processes (CHP)

Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A? \mid A_i \mid A_{\bar{i}}$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---



**ideal:**  $A! \parallel A? \longrightarrow A_i \parallel A?$

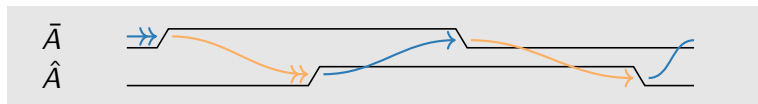


# Communicating Hardware Processes (CHP)

Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A? \mid A_i \mid A_{\bar{i}}$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

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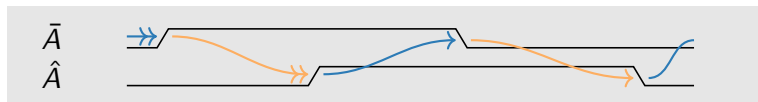
**ideal:**  $A! \parallel A? \longrightarrow A_i \parallel A_{\bar{i}}$

# Communicating Hardware Processes (CHP)

Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A? \mid A_i \mid A_{\bar{i}}$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---



**ideal:**  $A! \parallel A? \longrightarrow A_i \parallel A? \longrightarrow A_i \parallel A_{\bar{i}} \longrightarrow \text{skip} \parallel A_{\bar{i}}$

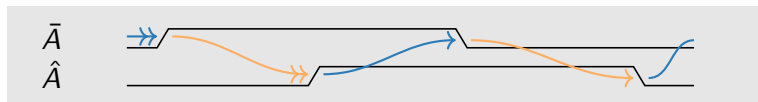


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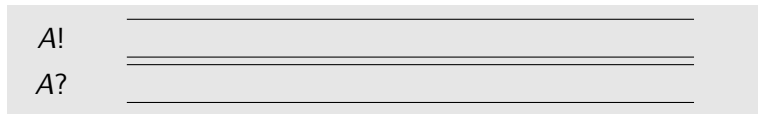
Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A? \mid A_i \mid A_{\bar{i}}$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---



**ideal:**  $A! \parallel A? \rightarrow A_i \parallel A? \rightarrow A_i \parallel A_{\bar{i}} \rightarrow \text{skip} \parallel A_{\bar{i}} \rightarrow \text{skip} \parallel \text{skip}$

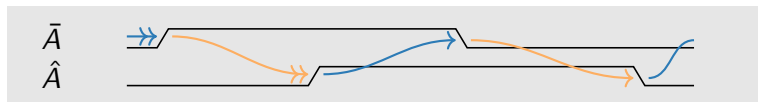


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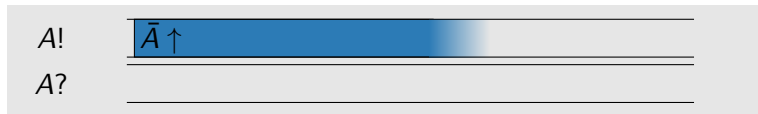
Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A? \mid A_i \mid A_i$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---



**ideal:**  $A! \parallel A? \rightarrow A_i \parallel A? \rightarrow A_i \parallel A_i \rightarrow \text{skip} \parallel A_i \rightarrow \text{skip} \parallel \text{skip}$

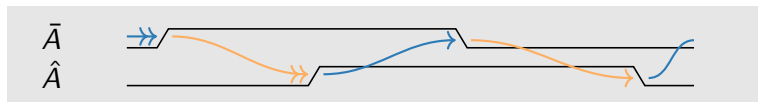


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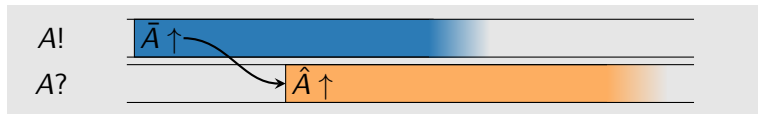
Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A? \mid A_i \mid A_i$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---



**ideal:**  $A! \parallel A? \longrightarrow A_i \parallel A? \longrightarrow A_i \parallel A_i \longrightarrow \text{skip} \parallel A_i \longrightarrow \text{skip} \parallel \text{skip}$

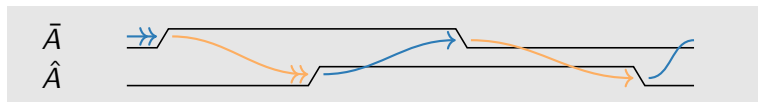


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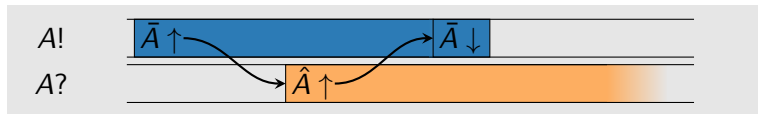
Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A? \mid A_i \mid A_i$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---



**ideal:**  $A! \parallel A? \longrightarrow A_i \parallel A? \longrightarrow A_i \parallel A_i \longrightarrow \text{skip} \parallel A_i \longrightarrow \text{skip} \parallel \text{skip}$

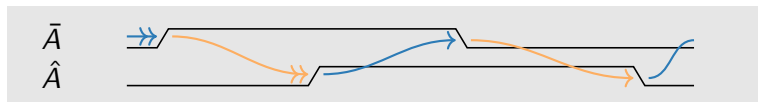


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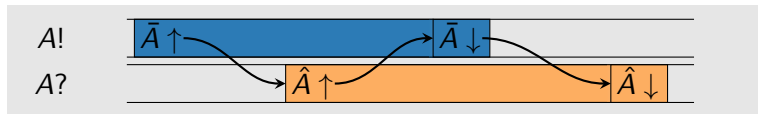
Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A? \mid A_i \mid A_i$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---



**ideal:**  $A! \parallel A? \longrightarrow A_i \parallel A? \longrightarrow A_i \parallel A_i \longrightarrow \text{skip} \parallel A_i \longrightarrow \text{skip} \parallel \text{skip}$

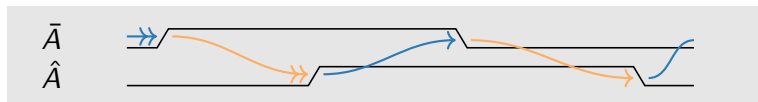




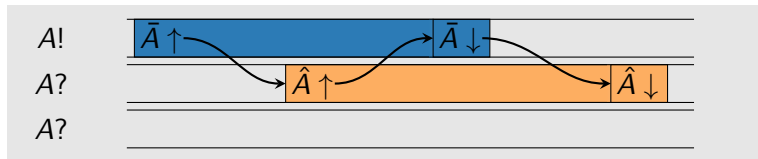
# Communicating Hardware Processes (CHP)

Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A? \mid A_i \mid A_i$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$



**ideal:**  $A! \parallel A? \longrightarrow A_i \parallel A? \longrightarrow A_i \parallel A_i \longrightarrow \text{skip} \parallel A_i \longrightarrow \text{skip} \parallel \text{skip}$

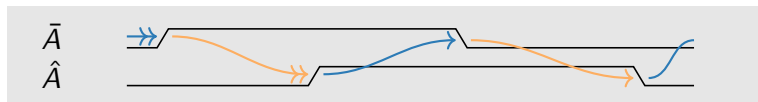


# Communicating Hardware Processes (CHP)

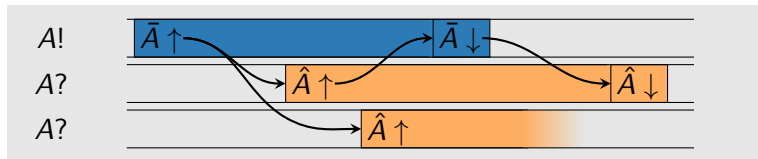
Channel  $A := \langle \bar{A}, \hat{A} \rangle$

Program  $P ::= A! \mid A? \mid A_i \mid A_{\bar{i}}$   
 $\mid P; P \mid P \parallel P \mid *P \mid \text{skip} \mid \dots$

---



**ideal:**  $A! \parallel A? \rightarrow A_i \parallel A? \rightarrow A_i \parallel A_{\bar{i}} \rightarrow \text{skip} \parallel A_{\bar{i}} \rightarrow \text{skip} \parallel \text{skip}$

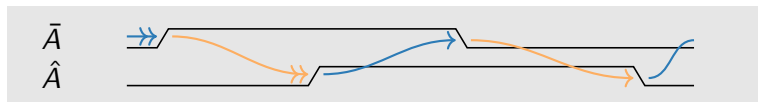


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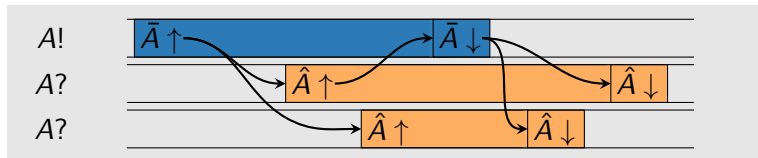
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**ideal:**  $A! \parallel A? \rightarrow A_i \parallel A? \rightarrow A_i \parallel A_{\bar{i}} \rightarrow \text{skip} \parallel A_{\bar{i}} \rightarrow \text{skip} \parallel \text{skip}$

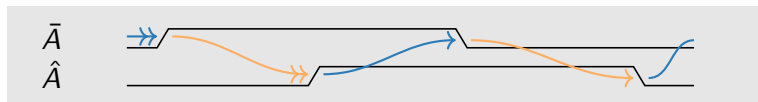


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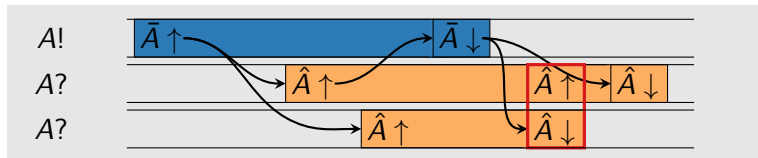
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**ideal:**  $A! \parallel A? \longrightarrow A_i \parallel A? \longrightarrow A_i \parallel A_{\bar{i}} \longrightarrow \text{skip} \parallel A_{\bar{i}} \longrightarrow \text{skip} \parallel \text{skip}$



**Short Circuit**





# CHP State Semantics

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$\langle P, \sigma \rangle \longrightarrow_s \langle P', \sigma' \rangle$  or **error**

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$$\langle A!, \sigma \rangle \longrightarrow_s$$

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$$\sigma(\hat{A}) = 0$$

---

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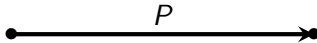
$$\frac{\sigma(\bar{A}) = 0 \quad \sigma(\hat{A}) > 1}{\langle A_i, \sigma \rangle \longrightarrow_s \mathbf{error}}$$

...

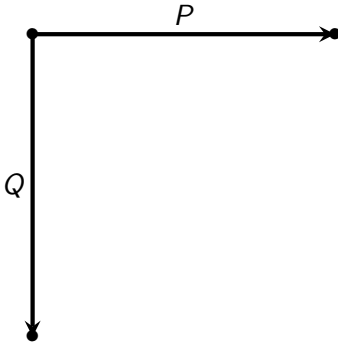
$$\langle P, \sigma_0 \rangle \xrightarrow{?}_s^* \mathbf{error}$$

$\langle P \parallel Q \parallel R, \sigma_0 \rangle \xrightarrow{?}_s^* \mathbf{error}$

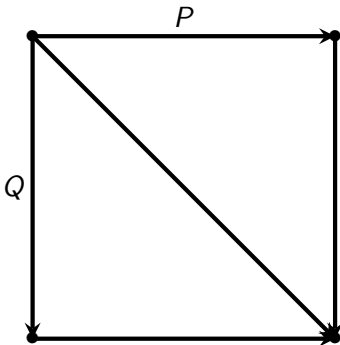
$\langle P \parallel Q \parallel R, \sigma_0 \rangle \xrightarrow{?}_s^* \text{error}$



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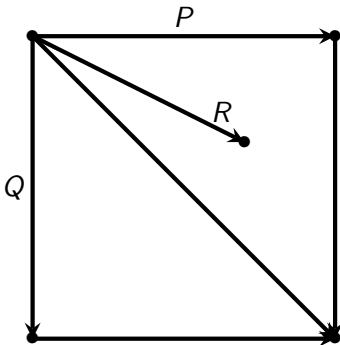


$$\langle P \parallel Q \parallel R, \sigma_0 \rangle \xrightarrow{?}_s^* \text{error}$$

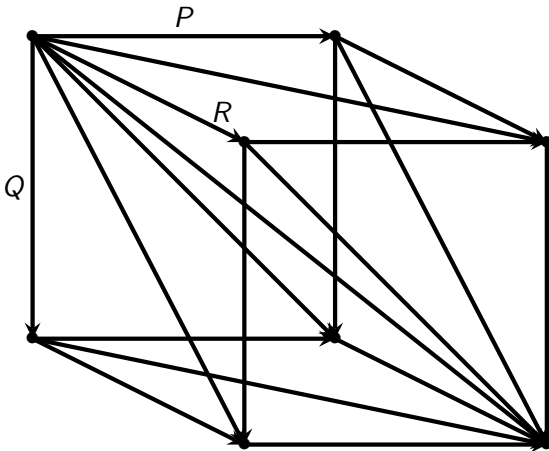




$$\langle P \parallel Q \parallel R, \sigma_0 \rangle \xrightarrow{?}_s^* \text{error}$$



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$\langle P \parallel Q \parallel R, \sigma_0 \rangle \xrightarrow{?}_s^* \mathbf{error}$

$\langle P \parallel Q \parallel R, \sigma_0 \rangle \xrightarrow{?}_s^* \mathbf{error}$

$P$

$$\langle P \parallel Q \parallel R, \sigma_0 \rangle \xrightarrow{?}_s^* \text{error}$$

$P$

$Q$

$$\langle P \parallel Q \parallel R, \sigma_0 \rangle \xrightarrow{?}_s^* \text{error}$$

*P*

*Q*

*R*

$\langle P \parallel Q \parallel R, \sigma_0 \rangle \xrightarrow{?}_s^* \text{error}$

$P$

$Q$

$R$



$\langle P \parallel Q \parallel R, \sigma_0 \rangle \xrightarrow{?}_s^* \text{error}$



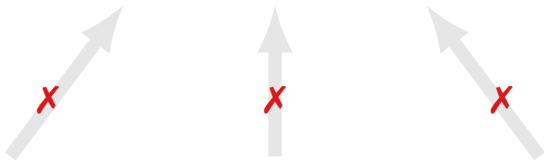
$\langle P, \sigma \rangle \xrightarrow{s} \dots$

$\langle Q, \sigma \rangle \xrightarrow{s} \dots$

$\langle R, \sigma \rangle \xrightarrow{s} \dots$



$\langle P \parallel Q \parallel R, \sigma_0 \rangle \xrightarrow{?}_s^* \text{error}$



$\langle P, \sigma \rangle \rightarrow_s \dots$

$\langle Q, \sigma \rangle \rightarrow_s \dots$

$\langle R, \sigma \rangle \rightarrow_s \dots$



# CHP Trace Semantics

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$$P \xrightarrow{L} P'$$

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Label  $L$

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Label  $L ::= \text{idle}$

# CHP Trace Semantics

$$P \xrightarrow{L} P'$$

Label  $L ::= \text{idle} \mid S$

# CHP Trace Semantics

$$P \xrightarrow{L} P'$$

Label  $L ::= \text{idle} \mid S \mid L \parallel L$



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$$P \xrightarrow{L} P'$$

Label  $L ::= \text{idle} \mid S \mid L \parallel L \mid \dots$

Step  $S ::= M_!^A \mid M_?^A$

# CHP Trace Semantics

$$P \xrightarrow{L} P'$$

Label  $L ::= \text{idle} \mid S \mid L \parallel L \mid \dots$

Step  $S ::= M_!^A \mid M_?^A$

Move  $M ::= \text{start} \mid \text{use} \mid \text{finish}$

# CHP Trace Semantics

$$P \xrightarrow{L} P'$$

Label  $L ::= \text{idle} \mid S \mid L \parallel L \mid \dots$

Step  $S ::= M_i^A \mid M_j^A$

Move  $M ::= \text{start} \mid \text{use} \mid \text{finish}$

$$\frac{\cdot}{A! \xrightarrow{\text{start}_i^A} A_i}$$

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Label  $L ::= \text{idle} \mid S \mid L \parallel L \mid \dots$

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Label  $L ::= \text{idle} \mid S \mid L \parallel L \mid \dots$

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$$\frac{\cdot}{A! \xrightarrow{\text{idle}} A!}$$

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$$\frac{\cdot}{A! \xrightarrow{\text{idle}} A!}$$

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$$\frac{\cdot}{A? \xrightarrow{\text{idle}} A?}$$

$$\frac{\cdot}{A? \xrightarrow{\text{start}_j^A} A_j}$$

$$\frac{\cdot}{A_i \xrightarrow{\text{use}_i^A} A_i}$$

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Label  $L ::= \text{idle} \mid S \mid L \parallel L \mid \dots$

Step  $S ::= M_i^A \mid M_j^A$

Move  $M ::= \text{start} \mid \text{use} \mid \text{finish}$

$$\frac{\cdot}{A! \xrightarrow{\text{idle}} A!}$$

$$\frac{\cdot}{A! \xrightarrow{\text{start}_i^A} A_i}$$

$$\frac{\cdot}{A? \xrightarrow{\text{idle}} A?}$$

$$\frac{\cdot}{A? \xrightarrow{\text{start}_j^A} A_j}$$

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$$\frac{\cdot}{A_i \xrightarrow{\text{finish}_i^A} \text{skip}}$$

$$\frac{\cdot}{A_j \xrightarrow{\text{use}_j^A} A_j}$$

$$\frac{\cdot}{A_j \xrightarrow{\text{finish}_j^A} \text{skip}}$$

$$\frac{P \xrightarrow{L} P' \quad Q \xrightarrow{K} Q'}{P \parallel Q \xrightarrow{L \parallel K} P' \parallel Q'}$$

# CHP Trace Semantics

$$P \xrightarrow{L} P'$$

Label  $L ::= \text{idle} \mid S \mid L \parallel L \mid \dots$

Step  $S ::= M_i^A \mid M_j^A$

Move  $M ::= \text{start} \mid \text{use} \mid \text{finish}$

$$\frac{\cdot}{A! \xrightarrow{\text{idle}} A!}$$

$$\frac{\cdot}{A! \xrightarrow{\text{start}_i^A} A_i}$$

$$\frac{\cdot}{A? \xrightarrow{\text{idle}} A?}$$

$$\frac{\cdot}{A? \xrightarrow{\text{start}_j^A} A_j}$$

$$\frac{\cdot}{A_i \xrightarrow{\text{use}_i^A} A_i}$$

$$\frac{\cdot}{A_i \xrightarrow{\text{finish}_i^A} \text{skip}}$$

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**compliant**( $L$ ) := traversable in hardware

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$$A_i \parallel A_j \xrightarrow{\text{use}_i^A \parallel \text{finish}_j^A} A_i \parallel \text{skip}$$

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$$A_i \parallel A_j \xrightarrow{\text{use}_i^A \parallel \text{finish}_j^A} A_i \parallel \text{skip}$$

$\neg \text{compliant}(\text{use}_i^A \parallel \text{finish}_j^A)$

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$$\frac{P \xrightarrow{L} P' \quad \text{compliant}(L) \quad \neg \text{interferant}(L)}{P \longrightarrow_t P'}$$

$$\frac{P \xrightarrow{L} P' \quad \text{compliant}(L) \quad \text{interferant}(L) \vee \dots}{P \longrightarrow_t \text{error}}$$

---

$$A_i \parallel A_j \xrightarrow{\text{finish}_?^A \parallel \text{use}_?^A} \text{skip} \parallel A_j$$



# CHP Trace Semantics

**compliant**( $L$ ) := traversable in hardware

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---



# Semantics Equivalence

$$\langle P, \sigma_0 \rangle \xrightarrow{s}^* \text{error} \iff P \xrightarrow{t}^* \text{error}$$



# Inferable Effect System

$$P \xrightarrow{?}_t^* \text{error}$$



# Inferable Effect System

$$P \xrightarrow{?}_t^* \text{error}$$

$P$

$\varepsilon P$

---



# Inferable Effect System

$$P \xrightarrow{?}_t^* \text{error}$$

$$\frac{P}{\varepsilon P}$$

A!





# Inferable Effect System



$$P \xrightarrow{?}_t^* \text{error}$$

$$\frac{P \qquad \varepsilon_P}{A! \quad A! \xrightarrow{\text{start}_i^A} A_j \xrightarrow{\text{finish}_i^A} \text{skip}}$$

# Inferable Effect System



$$P \xrightarrow{?}_t^* \text{error}$$

$$\frac{P \quad \text{idle} \quad \text{use}_i^A \quad \text{idle}}{A! \quad \text{start}_i^A \quad A_j \quad \text{finish}_i^A \quad \text{skip}} \quad \varepsilon P$$

# Inferable Effect System



$$P \xrightarrow{?}_t^* \text{error}$$

$$\frac{P \qquad \varepsilon_P}{A! \quad A! \xrightarrow{\text{start}_1^A} A_i \xrightarrow{\text{finish}_1^A} \text{skip}}$$

# Inferable Effect System



$$P \xrightarrow{?}_t^* \text{error}$$

$$\frac{P \qquad \varepsilon_P}{A! \quad A! \xrightarrow{\text{start}_1^A} A_i \xrightarrow{\text{finish}_1^A} \text{skip}}$$
$$A? \quad A? \xrightarrow{\text{start}_?^A} A_i \xrightarrow{\text{finish}_?^A} \text{skip}$$

# Inferable Effect System



$$P \xrightarrow{?}_t^* \text{error}$$

$P$	$\varepsilon P$
$A!$	$A! \xrightarrow{\text{start}_!^A} A_i \xrightarrow{\text{finish}_!^A} \text{skip}$
$A?$	$A? \xrightarrow{\text{start}_?^A} A_i \xrightarrow{\text{finish}_?^A} \text{skip}$
$P; P'$	$\varepsilon P \xrightarrow{\text{idle}} \varepsilon P'$
$P \parallel P'$	$\varepsilon P \times \varepsilon P'$
$*P$	$\varepsilon P \xrightarrow{\text{idle}} \varepsilon P$
...	

# Inferable Effect System


$$P \parallel Q \parallel R \xrightarrow{?}_t^* \text{error}$$

$P$	$\varepsilon_P$
$A!$	$A! \xrightarrow{\text{start}_!^A} A_i \xrightarrow{\text{finish}_!^A} \text{skip}$
$A?$	$A? \xrightarrow{\text{start}_?^A} A_i \xrightarrow{\text{finish}_?^A} \text{skip}$
$P; P'$	$\varepsilon_P \xrightarrow{\text{idle}} \varepsilon_{P'}$
$P \parallel P'$	$\varepsilon_P \times \varepsilon_{P'}$
$*P$	$\varepsilon_P \xrightarrow{\text{idle}} \varepsilon_P$
...	

# Inferable Effect System

$$(I?; A!) \parallel (A?; B!) \parallel (B?; O!) \xrightarrow{?}^*_t \mathbf{error}$$

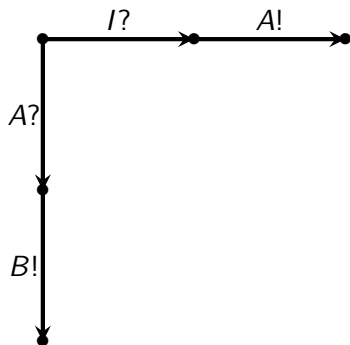
# Inferable Effect System

$$(I?; A!) \parallel (A?; B!) \parallel (B?; O!) \xrightarrow{?}_t^* \mathbf{error}$$



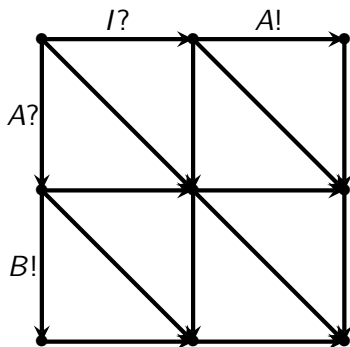

# Inferable Effect System

$(I?; A!) \parallel (A?; B!) \parallel (B?; O!) \xrightarrow{?}_t^* \mathbf{error}$



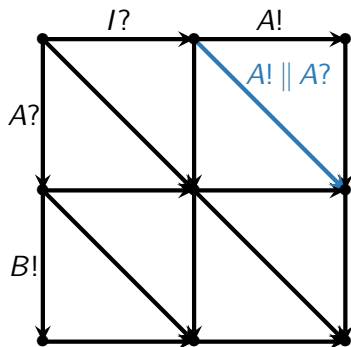
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$(I?; A!) \parallel (A?; B!) \parallel (B?; O!) \xrightarrow{?}_t^* \mathbf{error}$



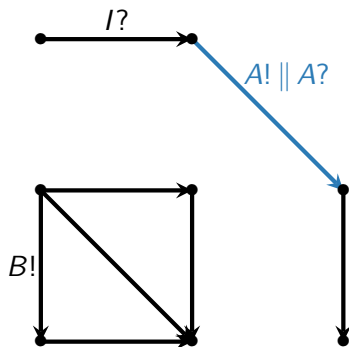
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$(I?; A!) \parallel (A?; B!) \parallel (B?; O!) \xrightarrow{?}_t^* \text{error}$



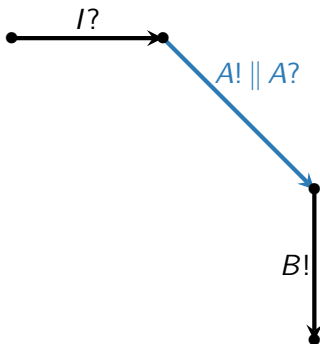
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$(I?; A!) \parallel (A?; B!) \parallel (B?; O!) \xrightarrow{?}_t^* \mathbf{error}$



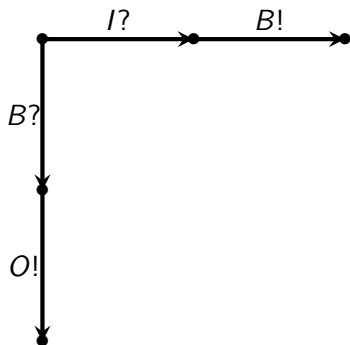
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$(I?; A!) \parallel (A?; B!) \parallel (B?; O!) \xrightarrow{?}_t^* \mathbf{error}$



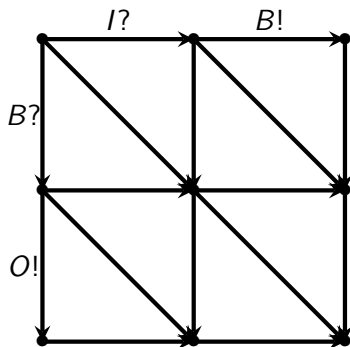
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# Inferable Effect System

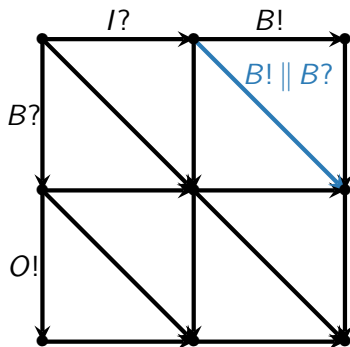
$(I?; A!) \parallel (A?; B!) \parallel (B?; O!) \xrightarrow{?}_t^* \mathbf{error}$





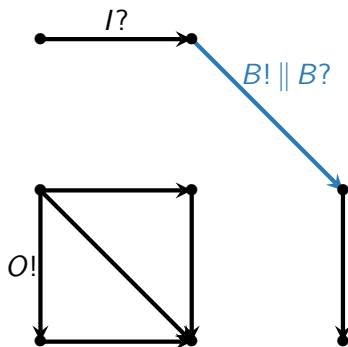
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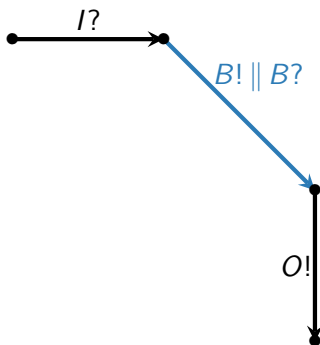
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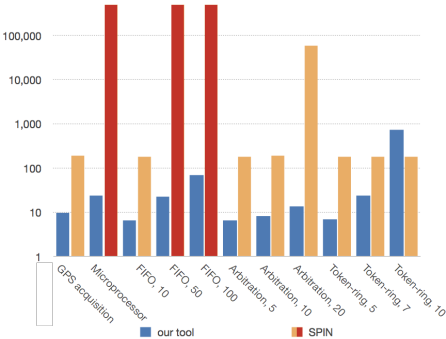
3 states vs. 27 states



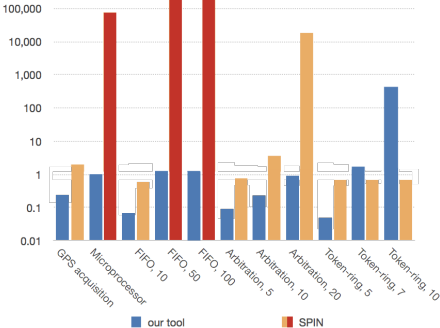
# Performance Evaluation

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### RAM (MB)



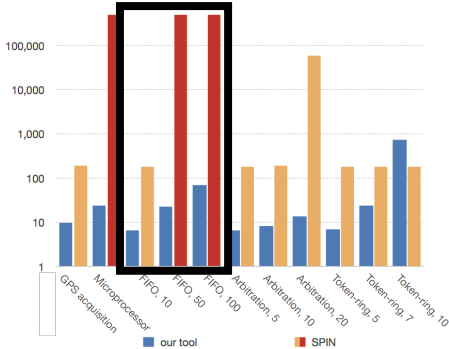
### Time (s)



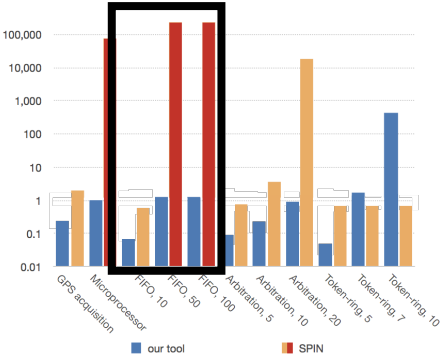


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RAM (MB)

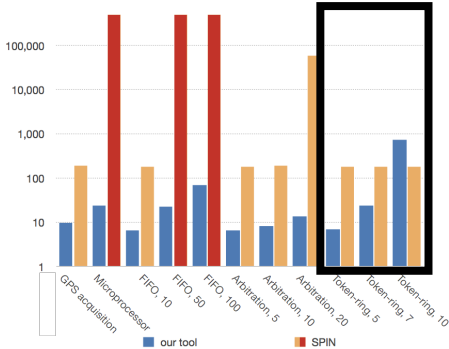


Time (s)

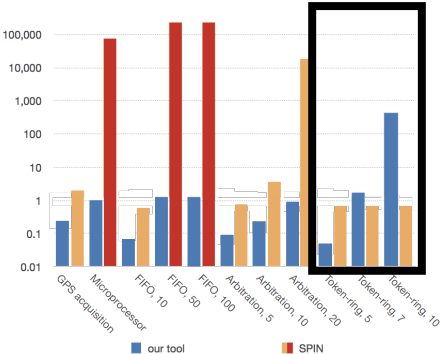


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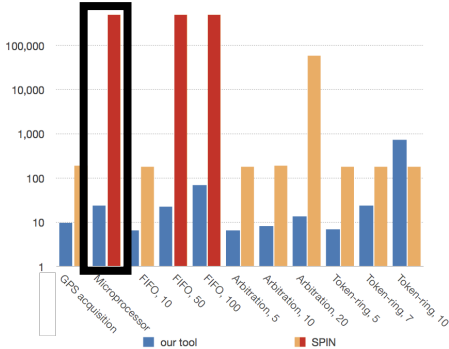


Time (s)

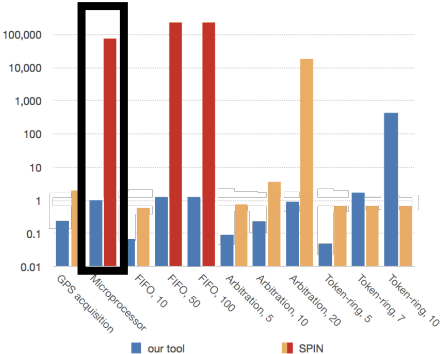


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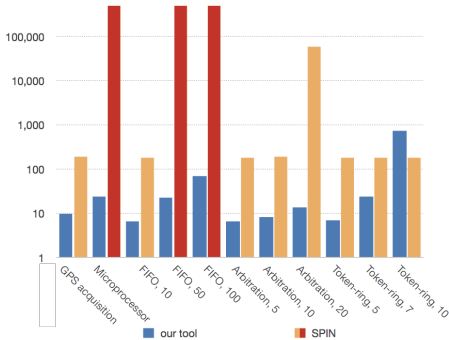


Time (s)

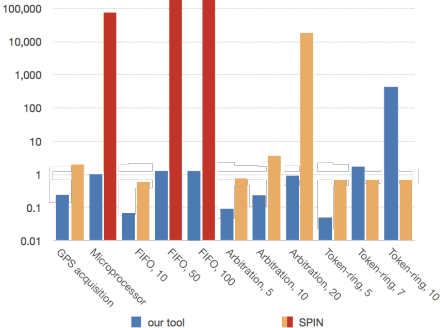


# Performance Evaluation

RAM (MB)



Time (s)





# Conclusion

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- CHP Trace Semantics

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- ✓ CHP Trace Semantics
- ✓ Inferable Effect System



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- explore other aspects of CHP design process

Thank you! Questions?

