Local Reasoning for Reconfigurable Distributed Systems

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[1] With support from Dr. Marius Bozga

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Hoare Logic

Verification

If C is a program, then we specify assertions P and Q and prove:

$$\{\ P\ \}\ C\ \{\ Q\ \}.$$

Separation Logic

- Extension of Hoare Logic

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BIP

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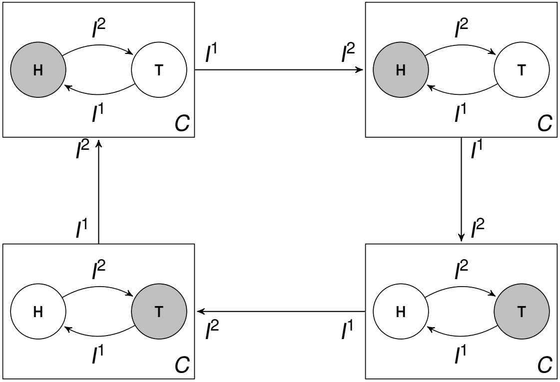
- *Interactions* connect ports of components

Token Ring



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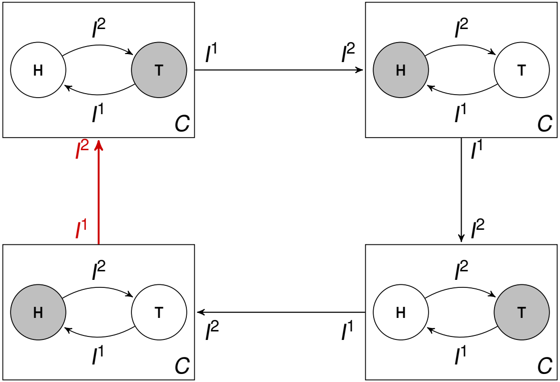

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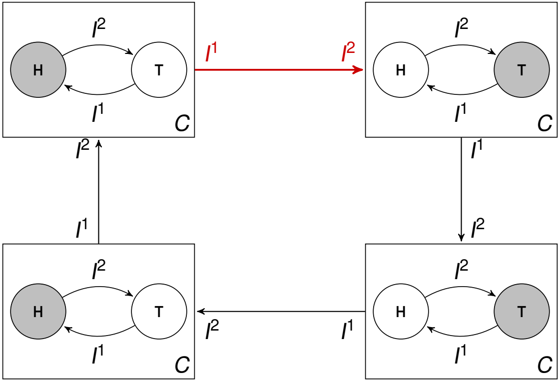

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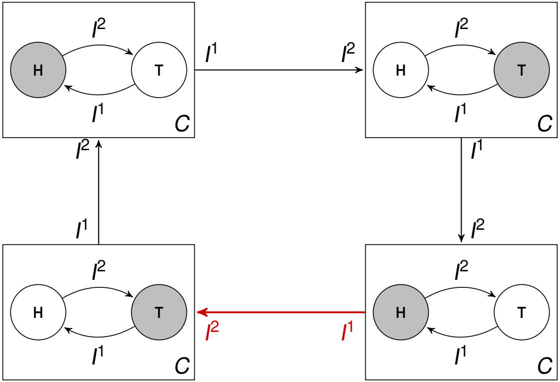

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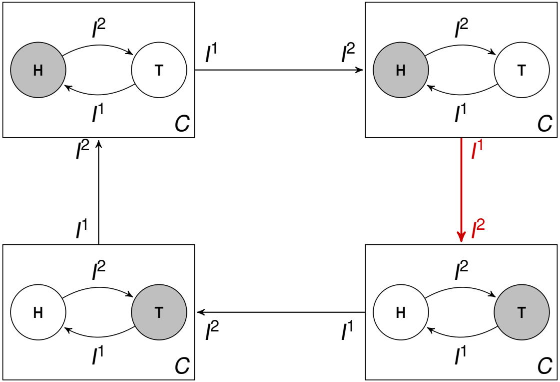
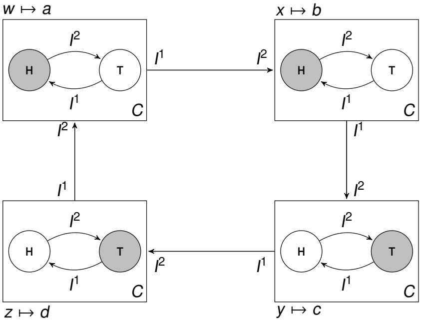


Verification of Reconfiguration Programs




```
with  I(x,y) ∗ C(y) ∗ I(y,z) ∧ state(y,T)  do
   disconnect(I,y,z);
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   delete(C,y);
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```

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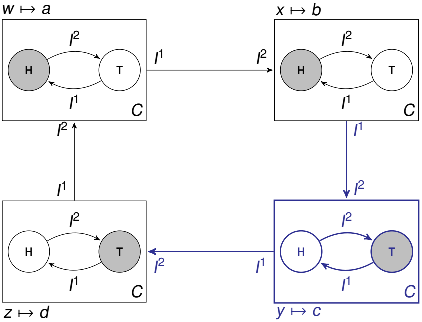


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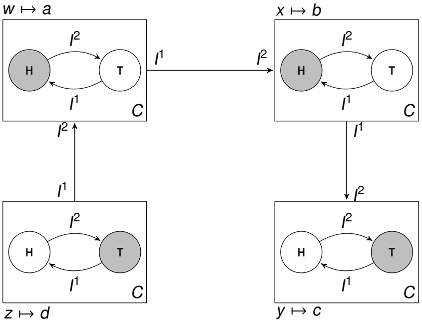


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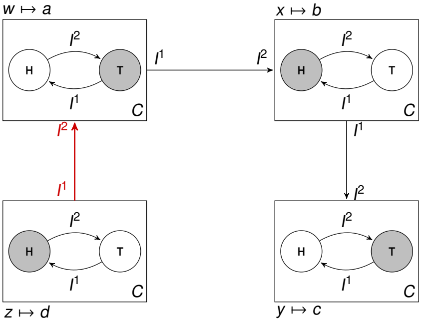


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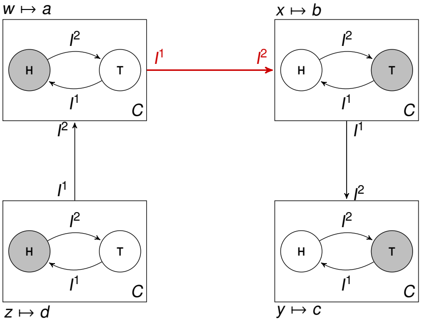


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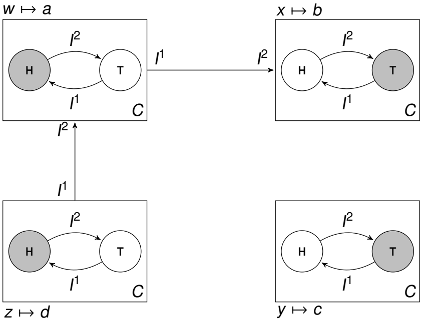


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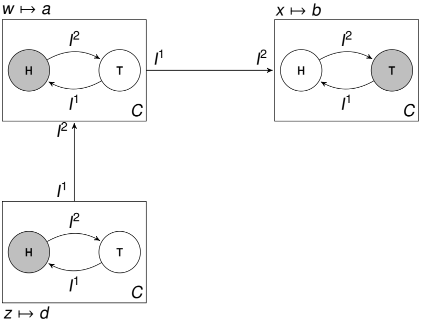

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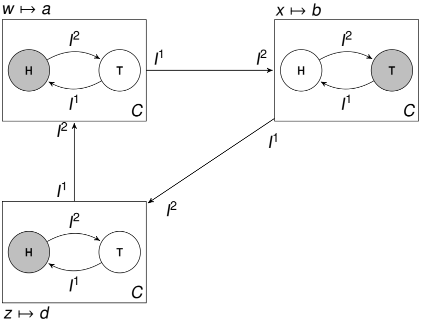


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To verify reconfiguration programs using Hoare logic, we need to

- define *BIP Configurations*,
- define *Separation Logic* on BIP configurations,
- define *Reconfiguration Language*, and
- specify inference rules and prove their soundness.

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Signature

Definition

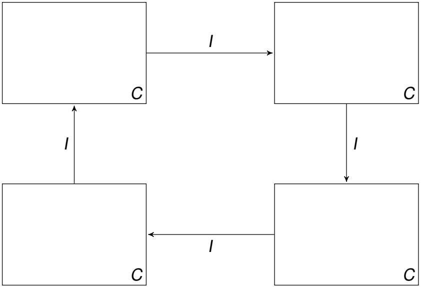
The *signature* of a BIP system is

$$\langle\, \mathcal{C}, \mathcal{I} \,\rangle = \langle\, C_1, \ldots, C_n, I_1, \ldots, I_m \,\rangle,$$

where

- $\mathcal{C} = \{C_1, \ldots, C_n\}$ is a finite set of component symbols with arity 1, and
- $\mathcal{I} = \{I_1, \ldots, I_m\}$ is a finite set of interaction symbols with arity $\alpha(I_j) \geq 2$ for each $I_j \in I$.

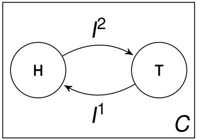
Signature



Token Ring

- Only one component type C and one interaction type I with arity $\alpha(I) = 2$.
- The signature is $\langle\ C, I\ \rangle$.

Components



Definition

The *component type* $C_i \in C$ is associated to

$$(\mathbb{S}_i, \mathbb{P}_i, s_i^0, \rightsquigarrow_i),$$

where

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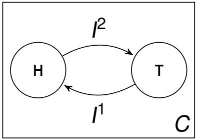

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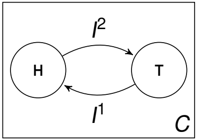

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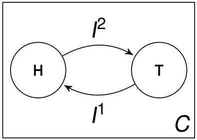

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- $\rightsquigarrow_i \subseteq \mathbb{S}_i \times \mathbb{P}_i \times \mathbb{S}_i$ is a finite set of transition rules.

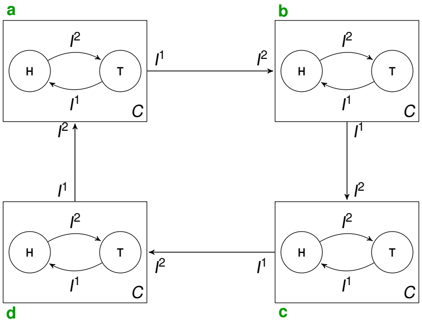
BIP System

Definition

A *BIP system* is $\mathfrak{S} := \langle\, C_1^{\mathfrak{S}}, \ldots, C_n^{\mathfrak{S}}, I_1^{\mathfrak{S}}, \ldots, I_m^{\mathfrak{S}} \,\rangle$, where

- $C_i^{\mathfrak{S}} \subseteq \mathcal{U}$, $1 \leq i \leq n$, are relations over the universe $\mathcal{U}$ with arity 1, and
- $I_j^{\mathfrak{S}} \subseteq \mathcal{U}^{\alpha(j)}$, $1 \leq j \leq m$, are relations over the universe $\mathcal{U}$ with arity $\alpha(j)$.

Token Ring as BIP System



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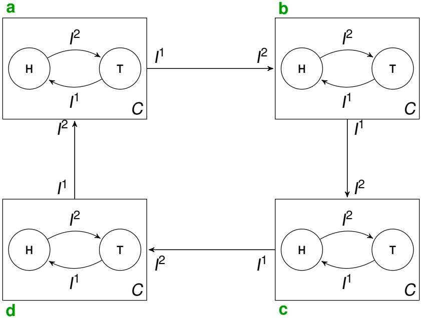

This system can be written as

$$\mathfrak{S} = \langle\ C^{\mathfrak{S}} = \{a, b, c, d\}, I^{\mathfrak{S}} = \{(a, b), (b, c), (c, d), (d, a)\}\ \rangle$$

for pairwise distinct elements $a, b, c, d \in \mathcal{U}$.

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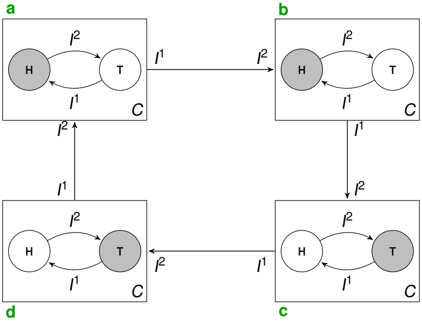

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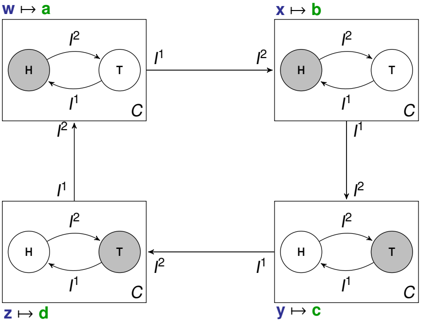

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BIP Configurations

Definition

Let $\mathbb{S} = \bigcup_{i=1}^{n} \mathbb{S}_i$. A *state snapshot* is a function

$$\varsigma : \mathcal{U} \times C \to \mathbb{S},$$

where $\varsigma(u, C_i) \in \mathbb{S}_i$ for every $1 \leq i \leq n$.

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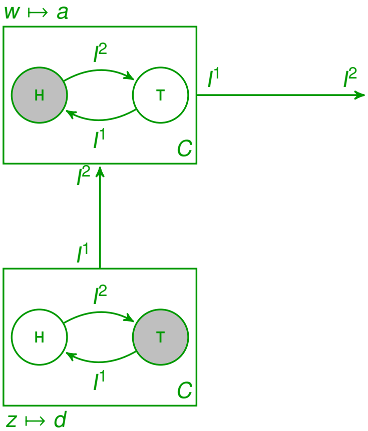
Definition

A *BIP Configuration* is a triple $(\mathfrak{S}, \varsigma, \nu)$, where

- $\mathfrak{S}$ is a BIP system,
- ς is a state snapshot, and
- $\nu : \mathcal{V} \rightarrow \mathcal{U}$ maps each variable to an element in the universe.

Set of configurations $\Sigma_{\langle\, C, \mathcal{I}\,\rangle}$.

Separation Algebra



$$(\mathfrak{S}_0, \varsigma, \nu)$$

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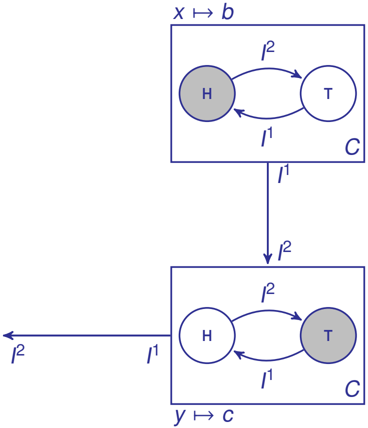
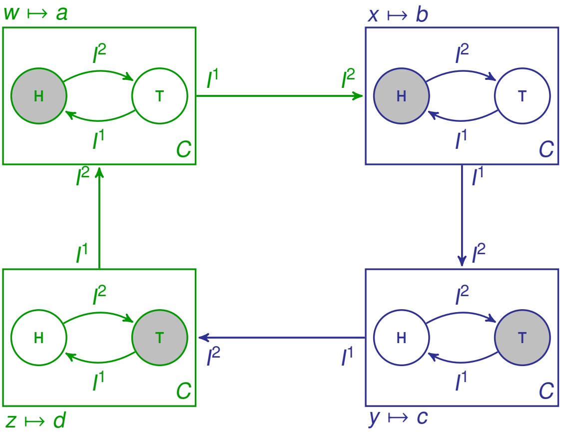


$$(\mathfrak{S}_1, \varsigma, \nu)$$

Separation Algebra



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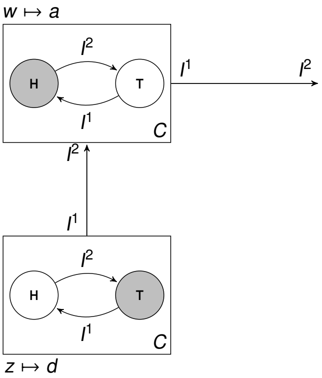
Behavioral Semantics



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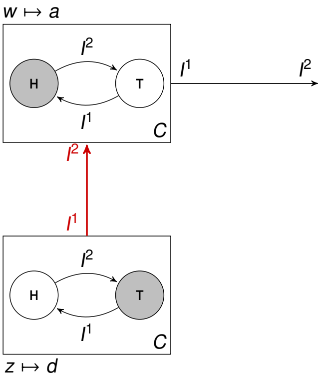

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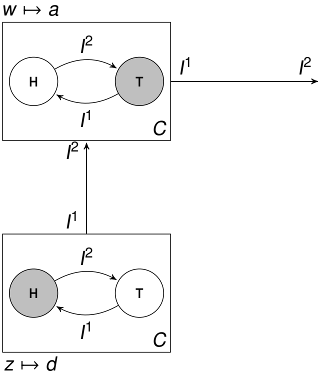

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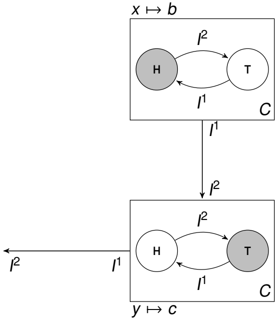
Separation Logic on BIP

$$\phi ::= \mathtt{emp} \mid C_i(x) \mid I_j(x_1, \ldots, x_{\alpha(j)}) \mid \mathsf{state}(x, s) \mid A(t_1, \ldots, t_{\alpha(A)}) \mid \mathtt{true} \mid \neg\phi \mid \phi * \psi \mid \phi \wedge \psi \mid \exists x.\phi,$$

Semantics of Separation Logic on BIP



$$(\mathfrak{S}, \varsigma, \nu) \models C(x) * I(x, y) * C(y) * I(y, z)$$

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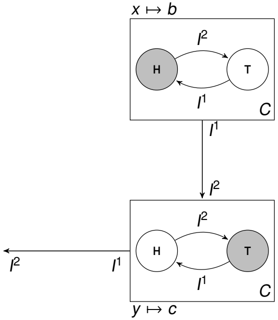

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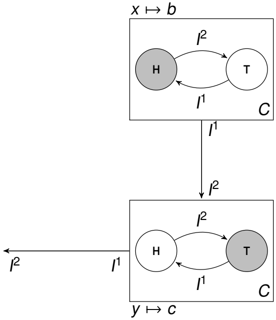

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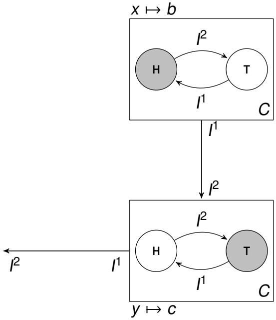

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$$(\mathfrak{S}, \varsigma, \nu) \models C(x) * I(x, y) * \mathtt{true} \wedge \mathrm{state}(x, \textsc{h}) \wedge \mathrm{state}(y, \textsc{t})$$

Inductive Predicates

$$\mathsf{chain}(x, x) \leftarrow \mathtt{emp},$$
$$\mathsf{chain}(x, z) \leftarrow \exists y \;.\; C(x) * I(x, y) * \mathsf{chain}(y, z)$$

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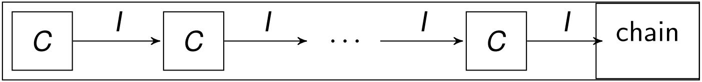

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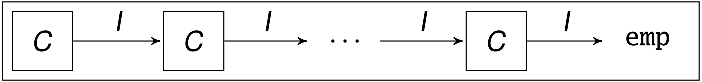

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Reconfiguration Language on BIP

$$
\begin{aligned}
\ell \ ::= \ & \texttt{new}(C_i, x) \mid \texttt{delete}(C_i, x) \mid \texttt{connect}(I_j, x_1, \ldots, x_{\alpha(j)}) \mid \\
& \texttt{disconnect}(I_j, x_1, \ldots, x_{\alpha(j)}) \mid \texttt{skip} \mid \\
& \texttt{when}\ \phi\ \texttt{do}\ \ell \mid \texttt{with}\ \psi\ \texttt{do}\ \ell \mid \ell; \ell' \mid \ell + \ell' \mid \ell^*
\end{aligned}
$$

Hoare Triple

Hoare Triple

For $P, Q \in \mathsf{SL}^{\mathsf{BIP}}_{\mathcal{R}}\langle\, \mathcal{C}, \mathcal{I}\,\rangle$, $\ell \in \mathcal{L}\langle\, \mathcal{C}, \mathcal{I}\,\rangle$:

$$\{\, P \,\}\ \ell\ \{\, Q \,\}.$$

Valid Hoare Triple

For all $(\mathfrak{S}, \varsigma, \nu) \in \Sigma_{\langle\, \mathcal{C}, \mathcal{I}\,\rangle}$

$$(\mathfrak{S}, \varsigma, \nu) \models P \quad \text{implies} \quad (\mathfrak{S}', \varsigma', \nu') \models Q$$

for all $(\mathfrak{S}', \varsigma', \nu') \in [\![\ell]\!](\mathfrak{S}, \varsigma, \nu)$.

Semantics of Reconfiguration Language on BIP

- $\texttt{new}(C_i, x)$
  $\Rightarrow \{ \texttt{emp} \} \; \texttt{new}(C_i, x) \; \{ C_i(x) \wedge \mathsf{state}(x, s_i^0) \}$

Semantics of Reconfiguration Language on BIP

- $\texttt{new}(C_i, x)$
  $\Rightarrow \{\ \texttt{emp}\ \}\ \texttt{new}(C_i, x)\ \{\ C_i(x) \wedge \mathsf{state}(x, s_i^0)\ \}$
- $\texttt{delete}(C_i, x)$
  $\Rightarrow \{\ C_i(x)\ \}\ \texttt{delete}(C_i, x)\ \{\ \texttt{emp}\ \}$

Semantics of Reconfiguration Language on BIP

- $\texttt{new}(C_i, x)$
  $\Rightarrow \{\ \texttt{emp}\ \}\ \texttt{new}(C_i, x)\ \{\ C_i(x) \wedge \mathsf{state}(x, s_i^0)\ \}$
- $\texttt{delete}(C_i, x)$
  $\Rightarrow \{\ C_i(x)\ \}\ \texttt{delete}(C_i, x)\ \{\ \texttt{emp}\ \}$
- $\texttt{connect}(I_j, x, y)$
  $\Rightarrow \{\ \texttt{emp}\ \}\ \texttt{connect}(I_j, x_1, \ldots, x_{\alpha(j)})\ \{\ I_j(x_1, \ldots, x_{\alpha(j)})\ \}$

Semantics of Reconfiguration Language on BIP

- $\texttt{new}(C_i, x)$
  $\Rightarrow \{ \text{ emp } \} \ \texttt{new}(C_i, x) \ \{ \ C_i(x) \wedge \text{state}(x, s_i^0) \ \}$
- $\texttt{delete}(C_i, x)$
  $\Rightarrow \{ \ C_i(x) \ \} \ \texttt{delete}(C_i, x) \ \{ \text{ emp } \}$
- $\texttt{connect}(I_j, x, y)$
  $\Rightarrow \{ \text{ emp } \} \ \texttt{connect}(I_j, x_1, \ldots, x_{\alpha(j)}) \ \{ \ I_j(x_1, \ldots, x_{\alpha(j)}) \ \}$
- $\texttt{disconnect}(I_j, x, y)$
  $\Rightarrow \{I_j(x_1, ..., x_{\alpha(j)})\} \ \texttt{disconnect}(I_j, x_1, ..., x_{\alpha(j)}) \ \{\text{emp}\}$

Semantics of Reconfiguration Language on BIP

- $\texttt{new}(C_i, x)$
  $\Rightarrow \{\text{ emp }\}\ \texttt{new}(C_i, x)\ \{\ C_i(x) \wedge \text{state}(x, s_i^0)\ \}$
- $\texttt{delete}(C_i, x)$
  $\Rightarrow \{\ C_i(x)\ \}\ \texttt{delete}(C_i, x)\ \{\text{ emp }\}$
- $\texttt{connect}(I_j, x, y)$
  $\Rightarrow \{\text{ emp }\}\ \texttt{connect}(I_j, x_1, \ldots, x_{\alpha(j)})\ \{\ I_j(x_1, \ldots, x_{\alpha(j)})\ \}$
- $\texttt{disconnect}(I_j, x, y)$
  $\Rightarrow \{I_j(x_1, ..., x_{\alpha(j)})\}\ \texttt{disconnect}(I_j, x_1, ..., x_{\alpha(j)})\ \{\text{emp}\}$
- $\texttt{skip}$
  $\Rightarrow \{\ P\ \}\ \texttt{skip}\ \{\ P\ \}$

Semantics of Reconfiguration Language on BIP

- when ϕ do ℓ

$$\Rightarrow \frac{\{\ P \wedge \phi\ \}\ \ell\ \{\ Q\ \}}{\{\ P\ \}\ \texttt{when}\ \phi\ \texttt{do}\ \ell\ \{\ Q\ \}}$$

Semantics of Reconfiguration Language on BIP

- $\texttt{when}\ \phi\ \texttt{do}\ \ell$

$$\Rightarrow \frac{\{\ P \wedge \phi\ \}\ \ell\ \{\ Q\ \}}{\{\ P\ \}\ \texttt{when}\ \phi\ \texttt{do}\ \ell\ \{\ Q\ \}}$$

- $\texttt{with}\ \psi\ \texttt{do}\ \ell$

$$\Rightarrow \frac{\{\ \exists y_1, \ldots, y_i.\ P \wedge \psi[x_1/y_1, \ldots, x_i/y_i] * \texttt{true}\ \}\ \ell\ \{\ Q\ \}}{\{\ P\ \}\ \texttt{with}\ \psi\ \texttt{do}\ \ell\ \{\ Q\ \},}$$

where $\{x_1, \ldots, x_i\} \subseteq \mathrm{fv}(\psi)$ and $y_1, \ldots, y_n \in \mathcal{V}$,

Structural Reconfiguration Rules

$$\frac{\{\ P\ \}\ \ell_0\ \{\ P'\ \} \qquad \{\ P'\ \}\ \mathtt{havoc}\ \{\ Q'\ \} \qquad \{\ Q'\ \}\ \ell_1\ \{\ Q\ \}}{\{\ P\ \}\ \ell_0; \ell_1\ \{\ Q\ \}},$$

Structural Reconfiguration Rules

$$\frac{\{\ P\ \}\ \ell_0\ \{\ P'\ \} \qquad \{\ P'\ \}\ \mathtt{havoc}\ \{\ Q'\ \} \qquad \{\ Q'\ \}\ \ell_1\ \{\ Q\ \}}{\{\ P\ \}\ \ell_0;\ell_1\ \{\ Q\ \}},$$

$$\frac{\{\ P\ \}\ \ell_0\ \{\ Q\ \} \qquad \{\ P\ \}\ \ell_1\ \{\ Q\ \}}{\{\ P\ \}\ \ell_0 + \ell_1\ \{\ Q\ \}},$$

Structural Reconfiguration Rules

$$\frac{\{\,P\,\}\ \ell_0\ \{\,P'\,\} \qquad \{\,P'\,\}\ \mathtt{havoc}\ \{\,Q'\,\} \qquad \{\,Q'\,\}\ \ell_1\ \{\,Q\,\}}{\{\,P\,\}\ \ell_0;\ell_1\ \{\,Q\,\}},$$

$$\frac{\{\,P\,\}\ \ell_0\ \{\,Q\,\} \qquad \{\,P\,\}\ \ell_1\ \{\,Q\,\}}{\{\,P\,\}\ \ell_0+\ell_1\ \{\,Q\,\}}, \qquad \frac{\{\,P\,\}\ \ell\ \{\,P\,\} \qquad \{\,P\,\}\ \mathtt{havoc}\ \{\,P\,\}}{\{\,P\,\}\ \ell^*\ \{\,P\,\}},$$

Frame Rule

$$\frac{\{\ P\ \}\ \ell\ \{\ Q\ \}}{\{\ P * F\ \}\ \ell\ \{\ Q * F\ \}}$$

where

- $\mathrm{Modifies}(\ell) \cap \mathrm{fv}(F) = \emptyset$,
- ℓ does not contain `with` ψ `do`, sequential composition, and the Kleene operator.

Frame Rule

$$\frac{\{\ P\ \}\ \ell\ \{\ Q\ \}}{\{\ P * F\ \}\ \ell\ \{\ Q * F\ \}}$$

where

- $\mathrm{Modifies}(\ell) \cap \mathrm{fv}(F) = \emptyset$,
- ℓ does not contain `with` ψ `do`, sequential composition, and the Kleene operator.

Theorem

The reconfiguration rules are sound.

Table of Contents

Havoc Triple

Havoc Triple

For $P, Q \in \mathrm{SL}_{\mathcal{R}}^{\mathrm{BIP}}\langle\, \mathcal{C}, \mathcal{I}\,\rangle$ and L is language over alphabet Σ:

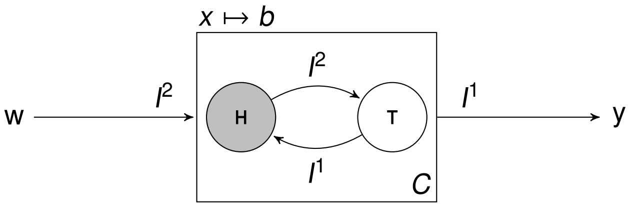
$$\{\, P \,\}\ L\ \{\, Q \,\}.$$

Valid Havoc Triple

For all $(\mathfrak{S}, \varsigma, \nu), (\mathfrak{S}, \varsigma', \nu) \in \Sigma_{\langle\, \mathcal{C}, \mathcal{I}\,\rangle}$

> $(\mathfrak{S}, \varsigma, \nu) \models P$ *and* $(\mathfrak{S}, \varsigma, \nu) \overset{w}{\rightsquigarrow}_o (\mathfrak{S}, \varsigma', \nu)$ *for some* $w \in L$ *implies* $(\mathfrak{S}, \varsigma', \nu) \models Q$.

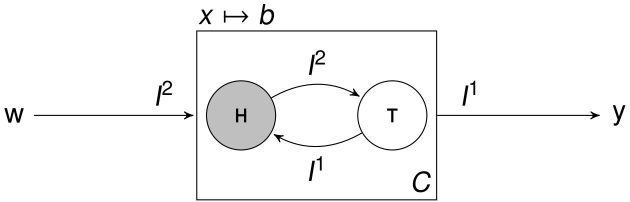
Examples of Havoc Triples



$$P := I(w, x) * C(x) * I(x, y)$$

$$\{\ P \wedge \text{state}(x, \text{H})\ \}\ \ I(w, x)\ \ \{\ P \wedge \text{state}(x, \text{T})\ \}$$

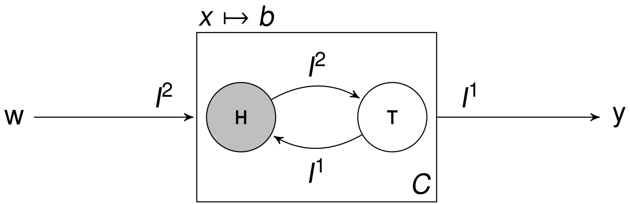
Examples of Havoc Triples



$$P := I(w, x) * C(x) * I(x, y)$$

$$\{\ P \wedge \text{state}(x, \text{H})\ \}\ \ I(w, x)\ \ \{\ P \wedge \text{state}(x, \text{T})\ \}$$
$$\{\ P \wedge \text{state}(x, \text{H})\ \}\ \ I(x, y)\ \ \{\ \texttt{false}\ \}$$

Examples of Havoc Triples



$$P := I(w,x) * C(x) * I(x,y)$$

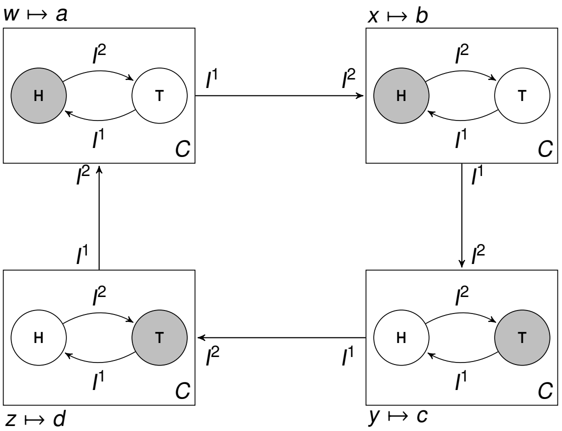
$$\{\ P \wedge \mathrm{state}(x, \textsc{h})\ \}\ \ I(w,x)\ \ \{\ P \wedge \mathrm{state}(x, \textsc{t})\ \}$$
$$\{\ P \wedge \mathrm{state}(x, \textsc{h})\ \}\ \ I(x,y)\ \ \{\ \mathtt{false}\ \}$$
$$\{\ P \wedge \mathrm{state}(x, \textsc{h})\ \}\ \ (I(w,x) \cdot I(x,y))^*\ \ \{\ P \wedge \mathrm{state}(x, \textsc{h})\ \}$$

Selection of Havoc Rules

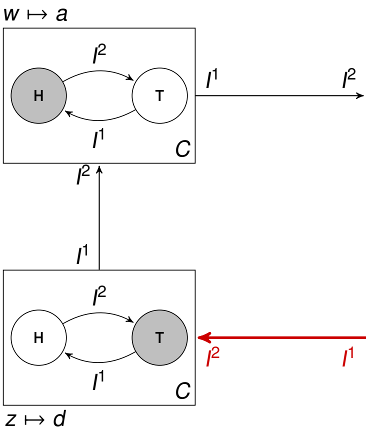
$$\frac{}{\{\ P\ \}\ \epsilon\ \{\ P\ \}}\ (\epsilon) \qquad \frac{\{\ P\ \}\ L_1\ \{\ Q\ \} \qquad \{\ Q\ \}\ L_2\ \{\ R\ \}}{\{\ P\ \}\ L_1 \cdot L_2\ \{\ R\ \}}\ (\cdot)$$

$$\frac{\{\ P\ \}\ L_1\ \{\ Q\ \} \qquad \{\ P\ \}\ L_2\ \{\ Q\ \}}{\{\ P\ \}\ L_1 \cup L_2\ \{\ R\ \}}\ (\cup) \qquad \frac{\{\ P\ \}\ L\ \{\ P\ \}}{\{\ P\ \}\ L^*\ \{\ P\ \}}\ (*)$$

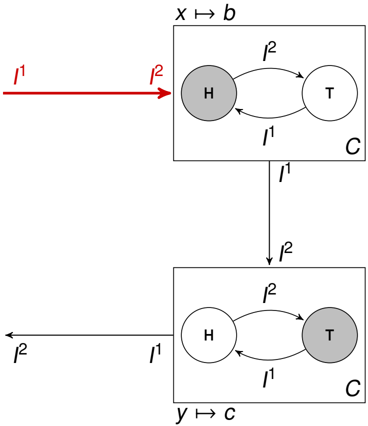
Frontier



Frontier



Frontier



Composition Rule

$$\frac{\{\, P_1 * \mathcal{F}\ (P_1, P_2)\}\ L_1\ \{\, Q_1 * \mathcal{F}\ (P_1, P_2)\} \qquad \{\, P_2 * \mathcal{F}\ (P_2, P_1)\}\ L_2\ \{\, Q_2 * \mathcal{F}\ (P_2, P_1)\}}{\{\, P_1 * P_2\,\}\ L_1 \bowtie L_2\ \{\, Q_1 * Q_2\,\}}\ (\bowtie)$$

Composition Rule

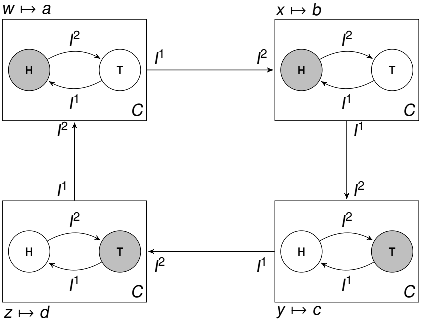
$$\frac{\{\ P_1 * \mathcal{F}\ (P_1, P_2)\}\ L_1\ \{\ Q_1 * \mathcal{F}\ (P_1, P_2)\} \quad \{\ P_2 * \mathcal{F}\ (P_2, P_1)\}\ L_2\ \{\ Q_2 * \mathcal{F}\ (P_2, P_1)\}}{\{\ P_1 * P_2\ \}\ L_1 \bowtie L_2\ \{\ Q_1 * Q_2\ \}}\ (\bowtie)$$

Theorem

The havoc rules are sound.

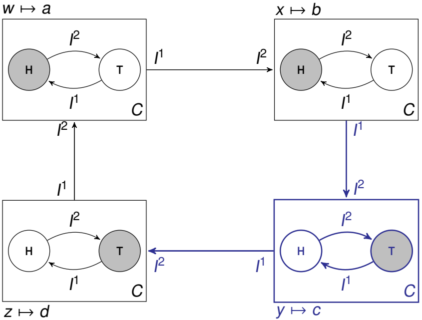
Table of Contents

Application on Token Ring




```
with I(x,y) ∗ C(y) ∗ I(y,z) ∧ state(y,T) do
    disconnect(I,y,z);
    disconnect(I,x,y);
    delete(C,y);
    connect(I,x,z)
```

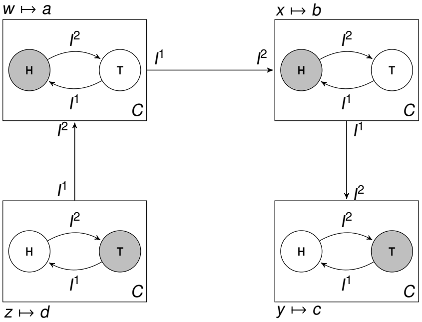
Application on Token Ring



with $l(x,y) * C(y) * l(y,z) \wedge \mathrm{state}(y,\mathrm{T})$ **do**

```
    disconnect(I,y,z);
    disconnect(I,x,y);
    delete(C,y);
    connect(I,x,z)
```

Application on Token Ring



with $I(x,y) * C(y) * I(y,z) \wedge \text{state}(y, \mathrm{T})$ **do**

```
  disconnect(I,y,z);
  disconnect(I,x,y);
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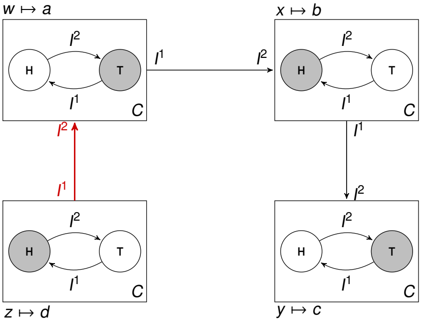
Application on Token Ring

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with I(x,y) * C(y) * I(y,z) ∧ state(y, T) do
    disconnect(I,y,z);
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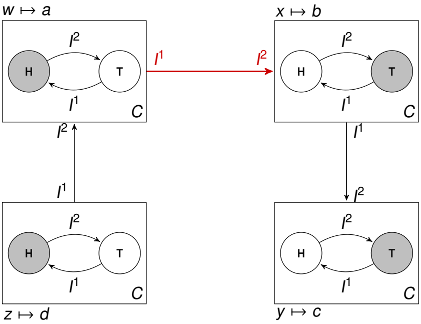


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with I(x,y) * C(y) * I(y,z) ∧ state(y,T) do
    disconnect(I,y,z);
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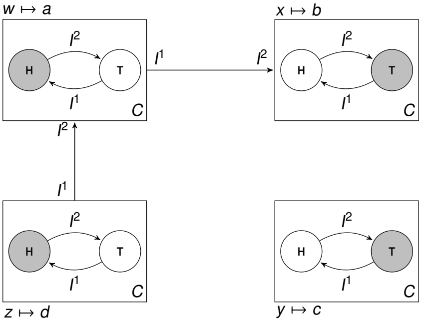


```
with I(x, y) ∗ C(y) ∗ I(y, z) ∧ state(y, T) do
   disconnect(I,y,z);
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   delete(C,y);
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```

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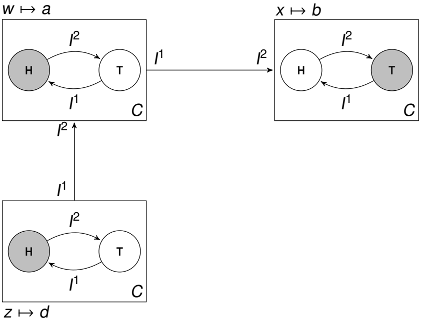

with $I(x, y) * C(y) * I(y, z) \wedge \mathrm{state}(y, \mathrm{T})$ **do**

```
   disconnect(I,y,z);
   disconnect(I,x,y);
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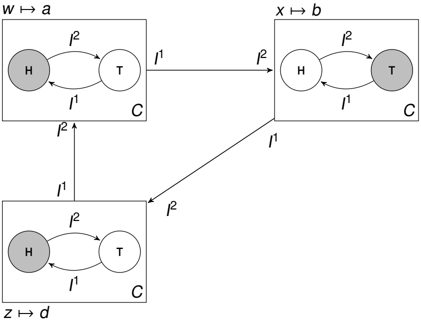
```

Application on Token Ring




```
with I(x,y) ∗ C(y) ∗ I(y,z) ∧ state(y,T) do
   disconnect(I,y,z);
   disconnect(I,x,y);
   delete(C,y);
   connect(I,x,z)
```

Correctness of Reconfiguration Program

Theorem

The reconfiguration program $P_{\texttt{delete}}$ is correct, meaning that

$$\{\ \mathsf{token\_ring}^{\top}(a)\ \}\ P_{\texttt{delete}}\ \{\ \mathsf{token\_ring}(a)\ \}.$$

Correctness of Reconfiguration Program

$F := [\mathsf{chain}^*(z, x, h-1, t) \wedge \mathsf{state}(x, \text{н})] \vee [\mathsf{chain}^*(z, x, h, t-1) \wedge \mathsf{state}(x, \text{т})]$

$\{ \mathsf{token\_ring}^{\text{T}}(a) \}$
$\{ \exists x, y, z.\ \ C(x) * I(x,y) * C(y) * I(y,z) * F \wedge \mathsf{state}(y, \text{т}) \}$
with $I(x,y) * C(y) * I(y,z) \wedge \mathsf{state}(y, \text{т})$ **do**

```
disconnect(I,y,z)
```

$\{ C(x) * I(x,y) * C(y) * F \wedge \mathsf{state}(y, \text{т}) \}$

```
havoc
```

$\{ C(x) * I(x,y) * C(y) * F \wedge \mathsf{state}(y, \text{т}) \}$

```
disconnect(I,x,y)
```

$\{ C(x) * C(y) * F \wedge \mathsf{state}(y, \text{т}) \}$

```
havoc
```

$\{ C(x) * C(y) * F \wedge \mathsf{state}(y, \text{т}) \}$

```
delete(C,y)
```

$\{ C(x) * F \}$

```
havoc
```

$\{ C(x) * F \}$

```
connect(I,x,z)
```

$\{ C(x) * I(x,z) * F \}$
$\{ \mathsf{token\_ring}(x) \}$

Conlusion

Achievements

- BIP Configurations
- Separation Logic on BIP
- Reconfiguration Language on BIP
- Inference rules
- Correctness of reconfiguration programs on token rings $\rightarrow$ the resulting configuration is still deadlock-free

Future Work

- Completeness of inference rules
- Apply on *dining philosophers* problem
- Proof correctness of reconfiguration programs for other systems
- Automatize proofs

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