Compilation Correctness from Event Structure Based Weak Memory Model

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July 24, 2019

Weak memory models of Programming Languages

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Easier to reason about

Weak memory models of Programming Languages

stronger

Easier to reason about

weaker

More efficient target code

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More optimizations allowed

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More optimizations allowed

C11 memory model is too weak

Out-Of-Thin-Air (OOTA) behaviours

$$\begin{array}{rcl} a & := & [x]; \\ [y] & := & 1; \end{array} \;\Bigg\|\; \begin{array}{rcl} b & := & [y]; \\ [x] & := & 1 \end{array}$$

$$\begin{array}{rcl} a & := & [x]; \\ [y] & := & 1 + a - a; \end{array} \;\Bigg\|\; \begin{array}{rcl} b & := & [y]; \\ [x] & := & 1 + b - b; \end{array}$$

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Out-Of-Thin-Air (OOTA) behaviours

$$a = 1 \quad b = 1 \; ?$$

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$$\begin{array}{lcl|lcl} a & := & [x]; & b & := & [y]; \\ [y] & := & 1; & [x] & := & 1 \end{array}$$

instruction reordering

$$\begin{array}{lcl|lcl} a & := & [x]; & b & := & [y]; \\ [y] & := & 1 + a - a; & [x] & := & 1 + b - b; \end{array}$$

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compiler optimisation & instruction reordering

$$\begin{array}{rcl} a & := & [x]; \\ [y] & := & a; \end{array} \;\Bigg\|\; \begin{array}{rcl} b & := & [y]; \\ [x] & := & b; \end{array}$$

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Out-Of-Thin-Air (OOTA) behaviours

$$a = 1 \quad b = 1 \text{ ?}$$

$\begin{array}{lcl} a & := & [x]; \\ [y] & := & 1; \end{array} \;\Big\|\; \begin{array}{lcl} b & := & [y]; \\ [x] & := & 1 \end{array}$	instruction reordering	✓
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Out-Of-Thin-Air (OOTA) behaviours

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Out-Of-Thin-Air (OOTA) behaviours

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out-of-thin-air behaviour ✗

C11 **allows** this execution for all three programs !

C11 is Declarative (Axiomatic) Memory Model

$$
\begin{array}{l} a \ := \ [x]; \\ [y] \ := \ a; \end{array}
\;\left\|\;
\begin{array}{l} b \ := \ [y]; \\ [x] \ := \ b; \end{array}\right.
$$

C11 is Declarative (Axiomatic) Memory Model

$$
\begin{array}{lcl|l}
a \; := \; [x]; & \Big\| & b \; := \; [y]; \\
[y] \; := \; a; & & [x] \; := \; b;
\end{array}
$$

1. $G^{\mathtt{pre}} \triangleq \langle \mathtt{E}, \mathtt{po} \rangle$

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a & := & [x]; \\
[y] & := & a;
\end{array}
\;\Bigg\|\;
\begin{array}{lcl}
b & := & [y]; \\
[x] & := & b;
\end{array}
$$

1. $G^{\mathtt{pre}} \triangleq \langle \mathtt{E}, \mathtt{po} \rangle$

$$
\left\{
\begin{array}{cccc}
\mathtt{R}(x,0) & \mathtt{R}(y,0) & \mathtt{R}(x,1) & \mathtt{R}(y,1) \\
\downarrow & \downarrow & \downarrow & \downarrow \\
\mathtt{W}(y,0) & \mathtt{W}(x,0) & \mathtt{W}(y,1) & \mathtt{W}(x,1) \\
 & & \ldots & \\
\mathtt{R}(x,42) & \mathtt{R}(y,42) & \mathtt{R}(x,43) & \mathtt{R}(y,43) \\
\downarrow & \downarrow & \downarrow & \downarrow \\
\mathtt{W}(y,42) & \mathtt{W}(x,42) & \mathtt{W}(y,43) & \mathtt{W}(x,43) \\
 & & \ldots &
\end{array}
\right\}
$$

C11 is Declarative (Axiomatic) Memory Model

$$\begin{array}{lcl} a & := & [x]; \\ [y] & := & a; \end{array} \;\Bigg\|\; \begin{array}{lcl} b & := & [y]; \\ [x] & := & b; \end{array}$$

1. $G^{\mathtt{pre}} \triangleq \langle \mathtt{E}, \mathtt{po} \rangle$
2. $G \triangleq \langle \mathtt{E}, \mathtt{po}, \mathtt{rf}, \mathtt{mo} \rangle$

$$\left\{ \begin{array}{cccc} \mathtt{R}(x,0) \;\; \mathtt{R}(y,0) & & \mathtt{R}(x,1) \;\; \mathtt{R}(y,1) \\ \downarrow \qquad\quad \downarrow & & \downarrow \qquad\quad \downarrow \\ \mathtt{W}(y,0) \;\; \mathtt{W}(x,0) & & \mathtt{W}(y,1) \;\; \mathtt{W}(x,1) \\ & \ldots & \\ \mathtt{R}(x,42) \;\; \mathtt{R}(y,42) & & \mathtt{R}(x,43) \;\; \mathtt{R}(y,43) \\ \downarrow \qquad\quad \downarrow & & \downarrow \qquad\quad \downarrow \\ \mathtt{W}(y,42) \;\; \mathtt{W}(x,42) & & \mathtt{W}(y,43) \;\; \mathtt{W}(x,43) \\ & \ldots & \end{array} \right\}$$

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a & := & [x]; & b & := & [y]; \\
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$$

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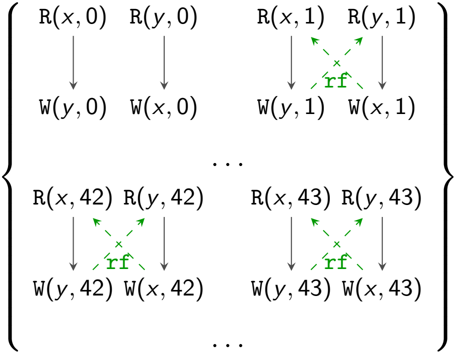

C11 is Declarative (Axiomatic) Memory Model

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\begin{array}{lcl||lcl}
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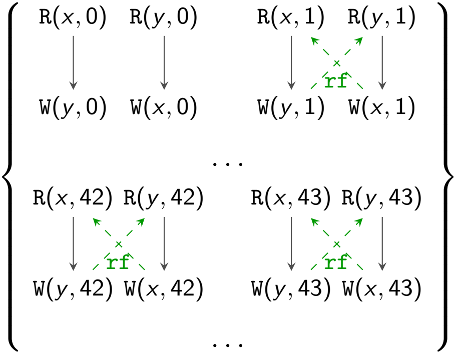
\end{array}
$$

1. $G^{\mathtt{pre}} \triangleq \langle \mathtt{E}, \mathtt{po} \rangle$
2. $G \triangleq \langle \mathtt{E}, \mathtt{po}, \mathtt{rf}, \mathtt{mo} \rangle$
3. $\mathtt{isCons}_{\mathtt{C11}}(G)$



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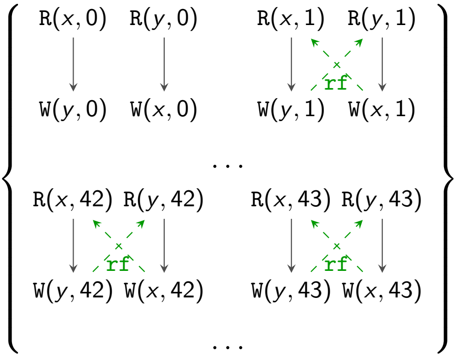
3. $\texttt{isCons}_{\texttt{C11}}(G)$

   $\wedge$

   $\texttt{po} \cup \texttt{rf}$ is acyclic



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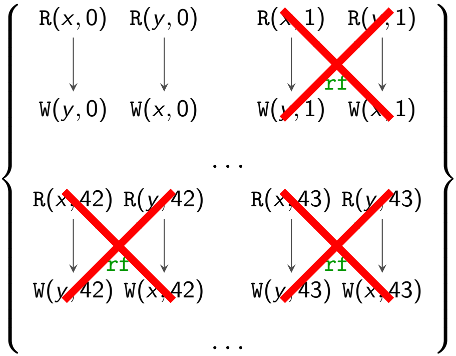

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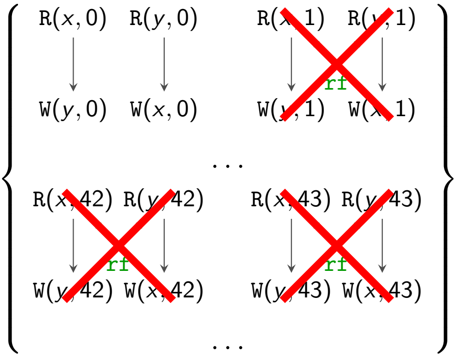

WeakestMO — Memory Model Based on Event Structures

[Chakraborty et al. 2019]

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\begin{array}{l} a \ := \ [x]; \\ [y] \ := \ 1 + a - a; \end{array}
\;\Bigg|\Bigg|\;
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WeakestMO — Memory Model Based on Event Structures

[Chakraborty et al. 2019]

$$\begin{array}{l} a := [x]; \\ [y] := 1 + a - a; \end{array} \quad \Bigg|\Bigg| \quad \begin{array}{l} b := [y]; \\ [x] := 1 + b - b; \end{array}$$

$\mathtt{R}(x, 0)$

WeakestMO — Memory Model Based on Event Structures

[Chakraborty et al. 2019]

$$\begin{array}{l} \overrightarrow{a} := [x]; \\ \underrightarrow{[y]} := 1 + a - a; \end{array} \;\Big|\Big|\; \begin{array}{l} \overrightarrow{b} := [y]; \\ [x] := 1 + b - b; \end{array}$$

$$\begin{array}{c} \mathtt{R}(x, 0) \\ \downarrow \\ \mathtt{W}(y, 1) \end{array}$$

WeakestMO — Memory Model Based on Event Structures

[Chakraborty et al. 2019]

$$
\begin{array}{l}
a := [x]; \\
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\end{array}
\;\Bigg\|\;
\begin{array}{l}
b := [y]; \\
{[x]} := 1 + b - b;
\end{array}
$$

$$
\begin{tikzcd}
\mathtt{R}(x,0) \arrow[d] & & \mathtt{R}(y,1) \\
\mathtt{W}(y,1) \arrow[urr, dashed, "\mathtt{jf}"] & &
\end{tikzcd}
$$

WeakestMO — Memory Model Based on Event Structures

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\begin{array}{l}
a \;:=\; [x]; \\
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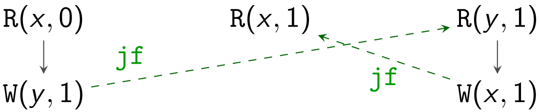

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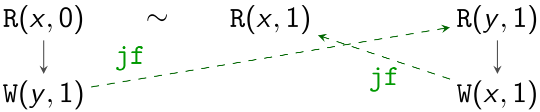

WeakestMO — Memory Model Based on Event Structures

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\ \Bigg|\Bigg| \
\begin{array}{l} b \ := \ [y]; \\ [x] \ := \ 1 + b - b; \end{array}
$$

$$
\begin{tikzcd}
\mathtt{R}(x,0) \arrow[d] & \sim & \mathtt{R}(x,1) \arrow[d] & \mathtt{R}(y,1) \arrow[d] \\
\mathtt{W}(y,1) \arrow[urrr, dashed, "\mathtt{jf}"] & \sim & \mathtt{W}(y,1) & \mathtt{W}(x,1) \arrow[ul, dashed, "\mathtt{jf}"']
\end{tikzcd}
$$

WeakestMO — Memory Model Based on Event Structures

[Chakraborty et al. 2019]

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\begin{array}{l} a \;:=\; [x]; \\ [y] \;:=\; 1 + a - a; \end{array}
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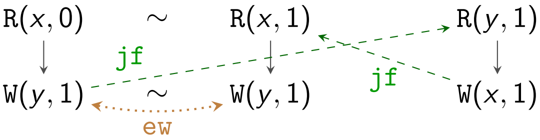

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b := [y]; \\
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\end{array}
$$

$$
\begin{tikzcd}
\mathtt{R}(x,0) \arrow[r, phantom, "\sim"] \arrow[d] & \mathtt{R}(x,1) \arrow[d] & \mathtt{R}(y,1) \arrow[r, phantom, "\sim"] \arrow[d] & \mathtt{R}(y,0) \\
\mathtt{W}(y,1) \arrow[r, phantom, "\sim"] \arrow[r, dotted, leftrightarrow, bend right, "\mathtt{ew}"'] \arrow[urr, dashed, "\mathtt{jf}"] & \mathtt{W}(y,1) & \mathtt{W}(x,1) \arrow[ul, dashed, "\mathtt{jf}"'] &
\end{tikzcd}
$$

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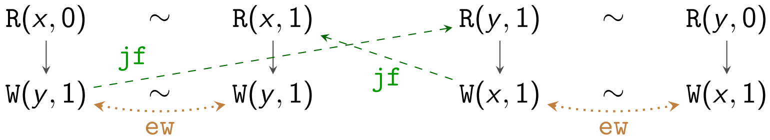
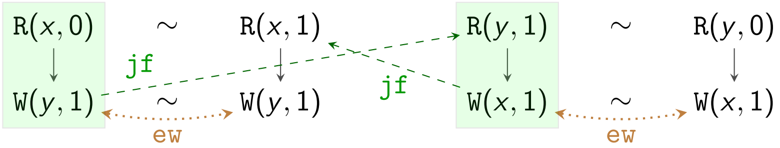


WeakestMO — Memory Model Based on Event Structures

[Chakraborty et al. 2019]

$$\begin{array}{lcl|l} a &:=& [x]; & b := [y]; \\ [y] &:=& 1 + a - a; & [x] := 1 + b - b; \end{array} \qquad S \triangleright \boxed{G_1}$$



WeakestMO — Memory Model Based on Event Structures

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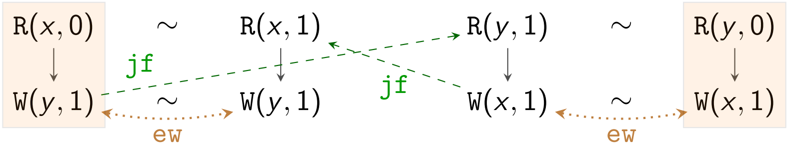
$$\begin{array}{l} a := [x]; \\ [y] := 1 + a - a; \end{array} \;\Big\|\; \begin{array}{l} b := [y]; \\ [x] := 1 + b - b; \end{array}$$

$S \triangleright G_1 \qquad S \triangleright G_2$



WeakestMO — Memory Model Based on Event Structures

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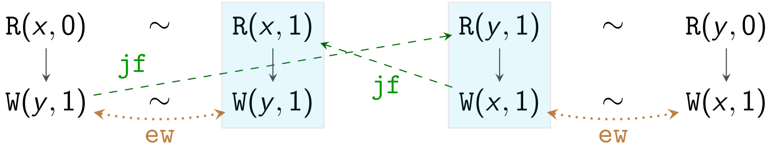
$$\begin{array}{l} a \;:=\; [x]; \\ [y] \;:=\; 1 + a - a; \end{array} \;\Bigg|\Bigg|\; \begin{array}{l} b \;:=\; [y]; \\ [x] \;:=\; 1 + b - b; \end{array}$$

$S \triangleright \boxed{G_1}$ $S \triangleright \boxed{G_2}$

$S \triangleright \boxed{G_3}$



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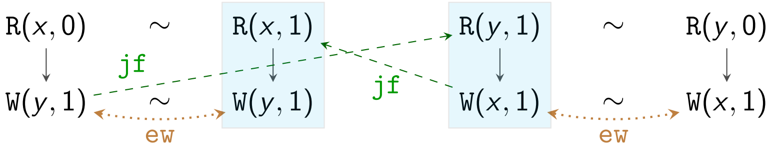
$S \triangleright G_1$ $\quad S \triangleright G_2$

$S \triangleright G_3$



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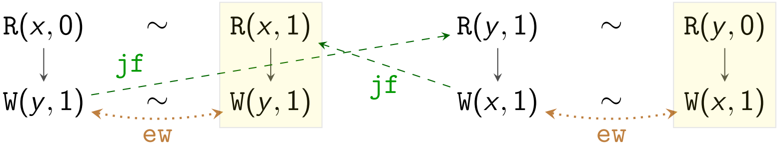
\quad\Big|\Big|\quad
\begin{array}{l} b \;:=\; [y]; \\ [x] \;:=\; 1 + b - b; \end{array}
$$

$S \rhd G_1$ $\quad S \rhd G_2$

$S \rhd G_3$ $\quad S \rhd G_4$



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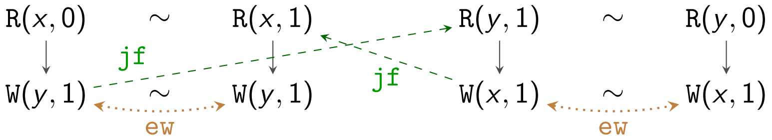
$S \triangleright G_1 \qquad S \triangleright G_2$

$S \triangleright G_3 \qquad S \triangleright G_4$



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WeakestMO — Memory Model Based on Event Structures

[Chakraborty et al. 2019]

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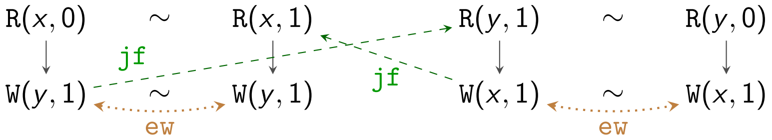

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$\mathtt{R}(x, 0)$

WeakestMO — Memory Model Based on Event Structures

[Chakraborty et al. 2019]

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$S \triangleright G_1$ $\quad S \triangleright G_2$

$S \triangleright G_3$ $\quad S \triangleright G_4$

$$\begin{tikzcd}
\mathtt{R}(x,0) \arrow[d] \arrow[r, phantom, "\sim"] & \mathtt{R}(x,1) \arrow[d] & \mathtt{R}(y,1) \arrow[d] \arrow[r, phantom, "\sim"] & \mathtt{R}(y,0) \arrow[d] \\
\mathtt{W}(y,1) \arrow[urr, dashed, "\mathtt{jf}"] \arrow[r, dotted, leftrightarrow, "\mathtt{ew}"'] & \mathtt{W}(y,1) & \mathtt{W}(x,1) \arrow[ul, dashed, "\mathtt{jf}"'] \arrow[r, dotted, leftrightarrow, "\mathtt{ew}"'] & \mathtt{W}(x,1)
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\mathtt{W}(y,0) \arrow[urr, dashed, "\mathtt{jf}"] & &
\end{tikzcd}$$

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\mathtt{W}(y,1) \arrow[rrrru, dashed, "\mathtt{jf}"] \arrow[rr, phantom, "\sim"] \arrow[rr, dotted, leftrightarrow, bend right, "\mathtt{ew}"'] & & \mathtt{W}(y,1) & & \mathtt{W}(x,1) \arrow[llu, dashed, "\mathtt{jf}"] \arrow[rr, phantom, "\sim"] \arrow[rr, dotted, leftrightarrow, bend right, "\mathtt{ew}"'] & & \mathtt{W}(x,1)
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WeakestMO — Memory Model Based on Event Structures

[Chakraborty et al. 2019]

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$$

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$S \triangleright G_3$ $S \triangleright G_4$

$$
\begin{tikzcd}
\mathtt{R}(x,0) \arrow[d] \arrow[r, phantom, "\sim"] & \mathtt{R}(x,1) \arrow[d] & \mathtt{R}(y,1) \arrow[d] \arrow[r, phantom, "\sim"] & \mathtt{R}(y,0) \arrow[d] \\
\mathtt{W}(y,1) \arrow[urr, dashed, "\mathtt{jf}"] \arrow[r, phantom, "\sim"] \arrow[r, dotted, bend right, leftrightarrow, "\mathtt{ew}"'] & \mathtt{W}(y,1) & \mathtt{W}(x,1) \arrow[ul, dashed, "\mathtt{jf}"] \arrow[r, phantom, "\sim"] \arrow[r, dotted, bend right, leftrightarrow, "\mathtt{ew}"'] & \mathtt{W}(x,1)
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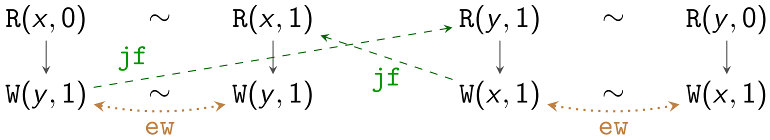

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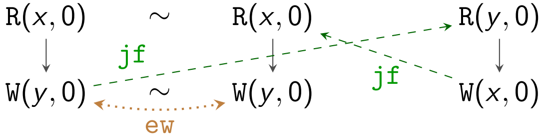

WeakestMO — Memory Model Based on Event Structures

[Chakraborty et al. 2019]

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\begin{array}{l}
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\end{array}
\;\Big\|\;
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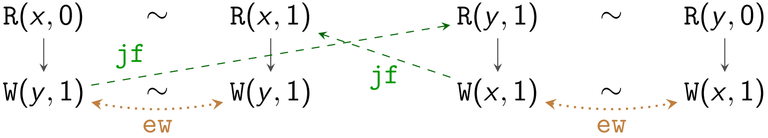
$$

$S \rhd G_1 \qquad S \rhd G_2$

$S \rhd G_3 \qquad S \rhd G_4$



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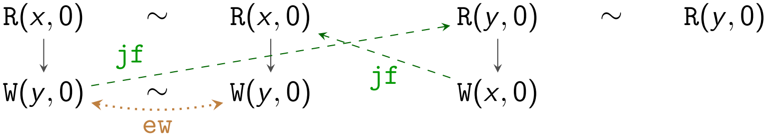

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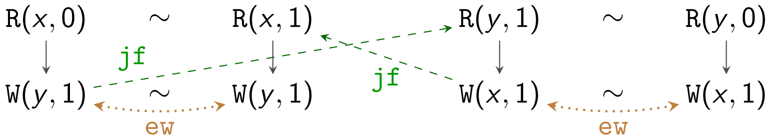

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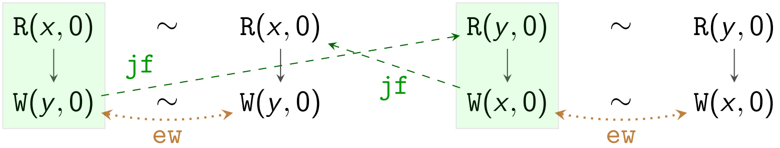

WeakestMO — Memory Model Based on Event Structures

[Chakraborty et al. 2019]

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\begin{array}{lcl||lcl}
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$$

$S \triangleright \boxed{G_1}$ $S \triangleright \boxed{G_2}$

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\begin{tikzcd}
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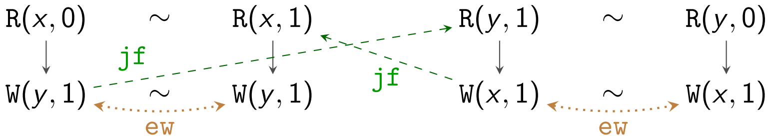

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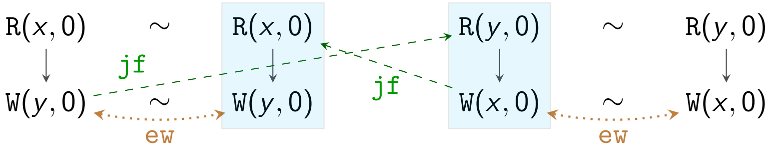

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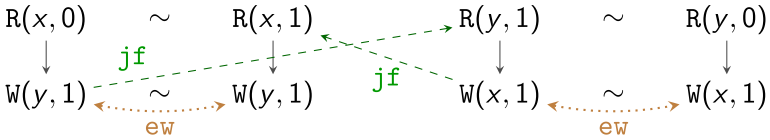

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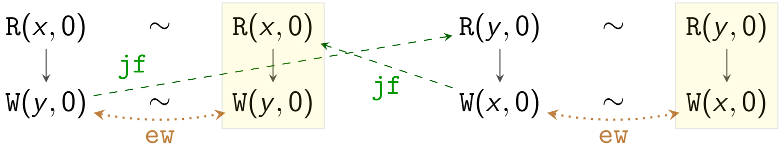

Compilation Correctness

WeakestMO

[Chakraborty et al. 2019]

x86-TSO

[Alglave et al. 2014]

ARMv7

[Alglave et al. 2014]

ARMv8

[Pulte et al. 2018]

RISC-V

POWER

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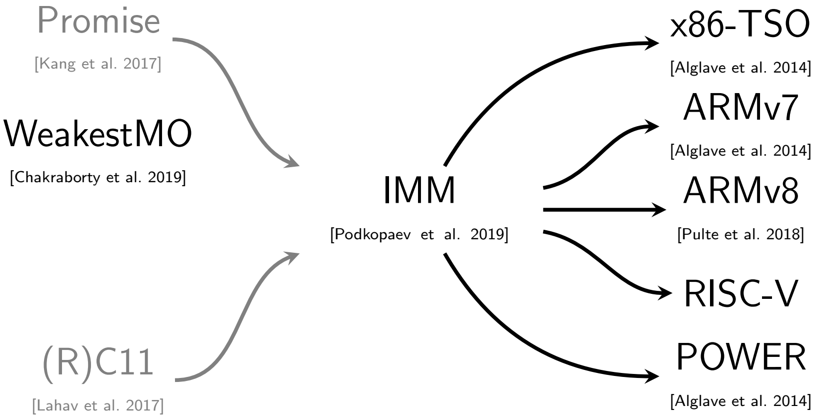

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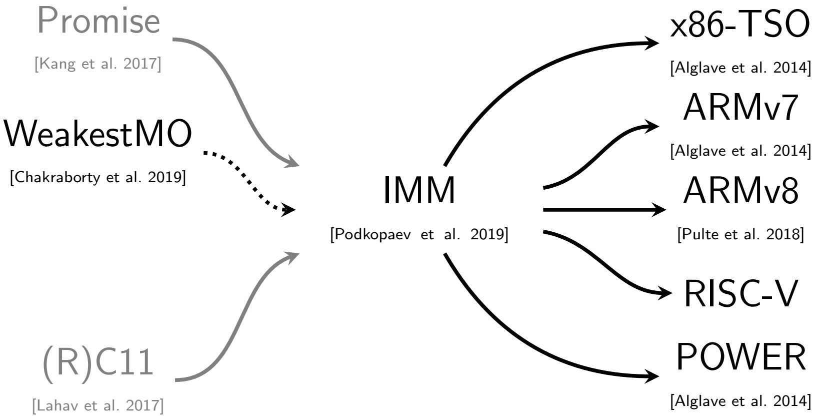

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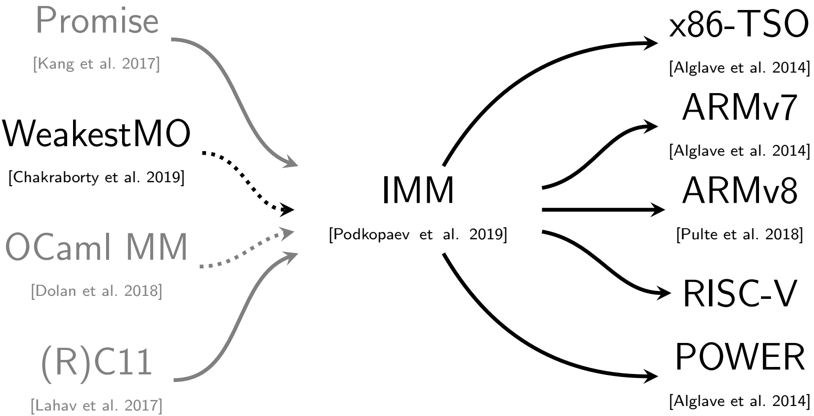

Compilation Correctness

Theorem

$\forall P.\ \forall G \in [\![P]\!]_{\texttt{IMM}}.\ \exists S.\ S_{\texttt{init}} \longrightarrow^{*} S\ \wedge\ S \rhd G$

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Compilation Correctness

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$G \vdash \langle C_0, I_0 \rangle \longrightarrow^{*} \langle C_n, I_n \rangle$ — **traversal** of G

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$\mathcal{R}(G, \langle C_i, I_i \rangle, S_i, X_i)$ — **simulation** relation

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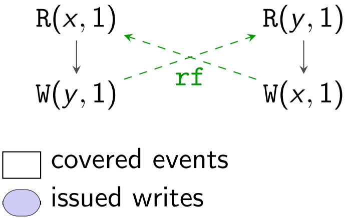
$S_i \rhd X_i$ — **candidate** execution

$$\begin{tikzcd} \langle C_0, I_0 \rangle \arrow[r, dashed, no head, "\mathcal{R}"] & \langle S_{\texttt{init}}, X_{\texttt{init}} \rangle \\ \langle C_n, I_n \rangle \arrow[r, dashed, no head, "\mathcal{R}"] & \langle S_n, X_n \equiv G \rangle \end{tikzcd}$$

$$\begin{tikzcd} \langle C_i, I_i \rangle \arrow[r, dashed, no head, "\mathcal{R}"] \arrow[d] & \langle S_i, X_i \rangle \arrow[d, "*"] \\ \langle C_{i+1}, I_{i+1} \rangle \arrow[r, dashed, no head, "\mathcal{R}"] & \langle S_{i+1}, X_{i+1} \rangle \end{tikzcd}$$

Traversal

$$\begin{array}{lcl||lcl} a & := & [x]; & b & := & [y]; \\ [y] & := & 1; & [x] & := & 1; \end{array}$$



$\langle C, I \rangle$ — traversal configuration

C — covered events

$dom(G.\mathtt{po}; [C]) \subseteq C$

$dom(G.\mathtt{rf}; [C]) \subseteq I$

$G.\mathtt{W} \cap C \subseteq I$

I — issued writes

$dom(G.\mathtt{rf}\mathrm{e}; G.\mathtt{ppo}; [I]) \subseteq I$

plus some other constraints related to fences and rel/acq/sc accesses

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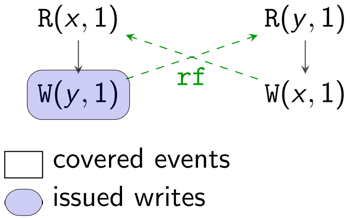

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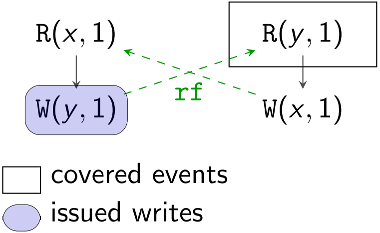

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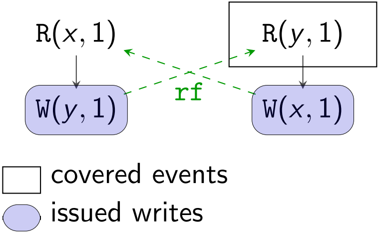

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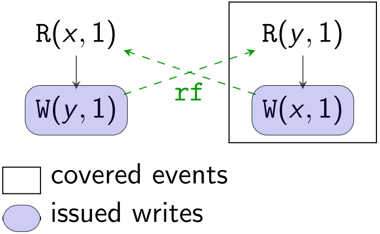

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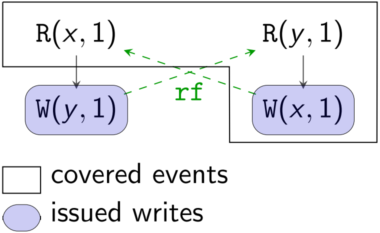

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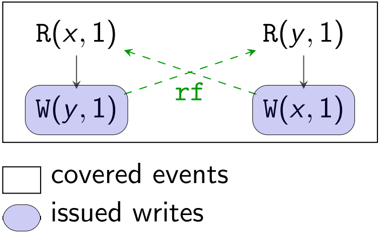

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Simulation

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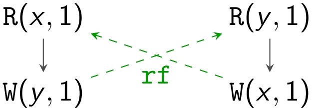

Simulation step:

1. Certify
2. Modify Candidate

covered events

issued writes

$S \triangleright X$ — candidate

$X^{\texttt{cert}} \subseteq S.\mathtt{E}$ — certificate

Simulation

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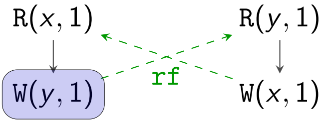

Simulation step:

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covered events

issued writes

$S \rhd \boxed{X}$ — candidate

$\boxed{X^{\texttt{cert}}} \subseteq S.\mathtt{E}$ — certificate

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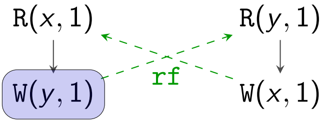

covered events

issued writes

Simulation step:

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$\mathtt{R}(x, 0)$

$S \triangleright X$ — candidate

$X^{\mathtt{cert}} \subseteq S.\mathtt{E}$ — certificate

Simulation

$a := [x];$	$\Vert$	$b := [y];$
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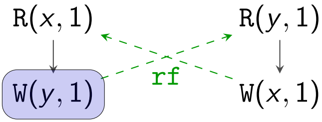

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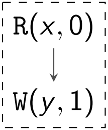

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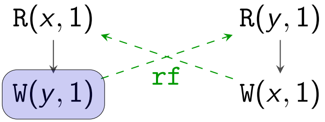

Simulation step:

1. Certify
2. Modify Candidate

$\square$ covered events

issued writes

$$\begin{tikzcd} \mathtt{R}(x, 0) \arrow[d] \\ \mathtt{W}(y, 1) \end{tikzcd}$$

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Simulation

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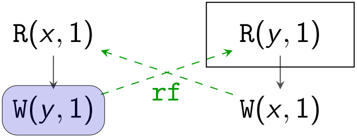

covered events

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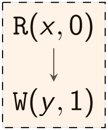

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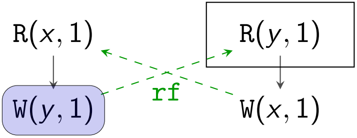

covered events

issued writes

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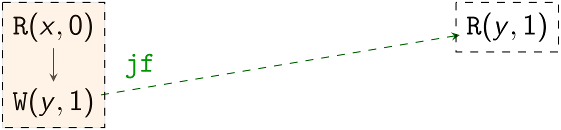

$S \triangleright X$ — candidate

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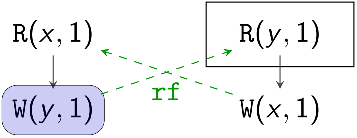
Simulation

$a := [x];$	$\parallel$	$b := [y];$
$[y] := 1;$	$\parallel$	$[x] := 1;$



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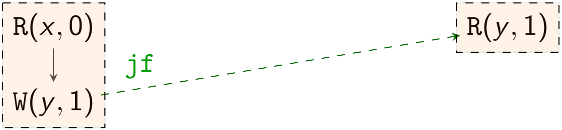

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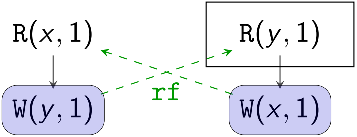

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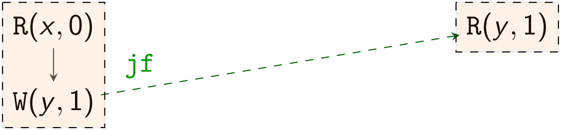

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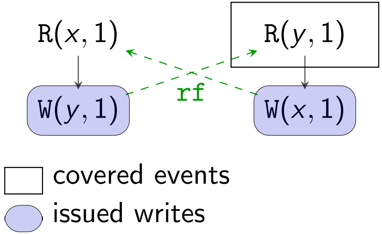

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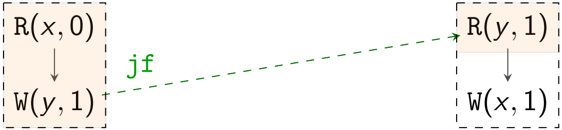

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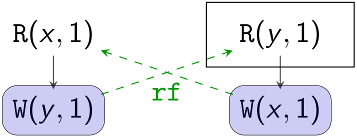

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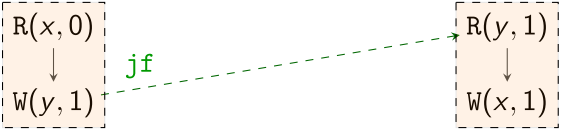

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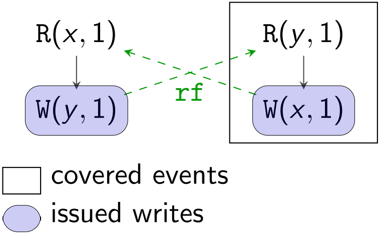

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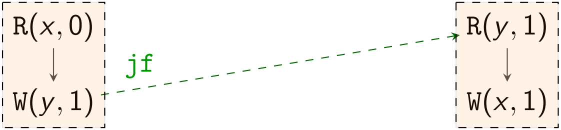

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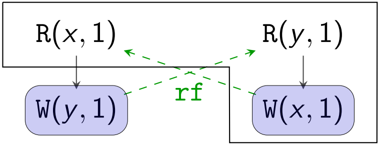

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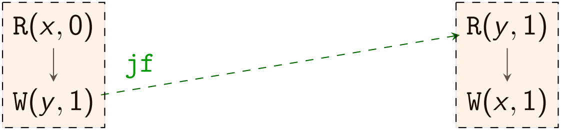

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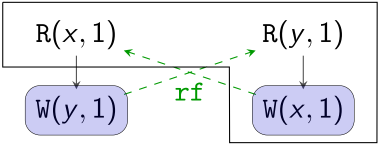

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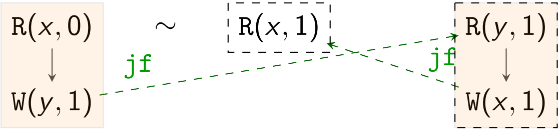

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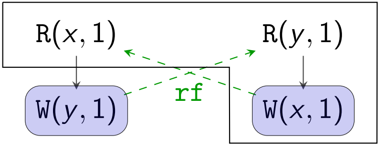

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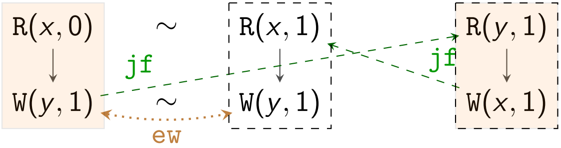

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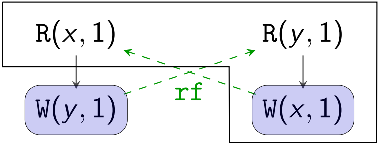

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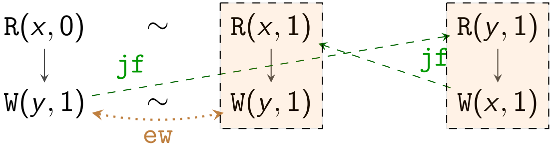

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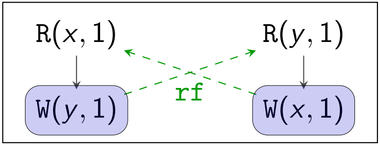

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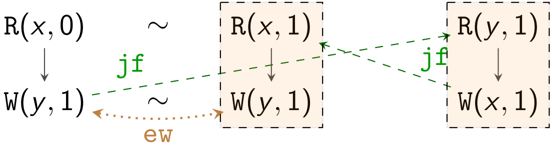

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Conclusion

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- C11 Memory model permits out-of-thin-air (OOTA) behaviours

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Conclusion

- C11 Memory model permits out-of-thin-air (OOTA) behaviours
- WeakestMO is a new model based on event structures that solves OOTA problem
- Our work — mechanization of this model and the compilation correctness theorem

References I

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