

# Permission-based separation logic for message-passing concurrency

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[  
joint work with  
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]

# Overview

- Introduction - starting point O'Hearn/Reynolds
- Good ideas from there and criticism
- Message-passing paradigm
- Deterministic concurrency (as resources)
- Our two-stage approach
- Our language and Effect system
- Subj. Red and Confluence
- Our Logic - satis. (Exists) and seq rules
- Soundness - exists to for all via stability
- Example - parallel mergesort

# Introduction

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Resource access control and locality of reasoning are emerging as important concepts for this latter task. This talk represents our first efforts at understanding these in a message-passing concurrency setting.

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$$\frac{\{(P * R) \wedge B\} C \{Q * R\}}{\{P\} \text{ with } r \text{ when } B \text{ do } C \text{ endwith } \{Q\}}$$

$R$  is the “resource invariant” - all shared state expressed here.

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The reasoning about ownership of the resource gets tied together with reasoning about data. The state of the concurrency protocol is codified using particular data values.

In many cases, the intended concurrent control flow is clear and inferrable from the code without the need for such codification. e.g. Producer/Consumer problem.

This is partly a problem of the concurrency model used - no signalling!

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Inferring the control flow can be easier. This should help with analysis.

Idea : leverage such inference to isolate the reasoning about (transfer of) ownership of resources from reasoning about data flow.

Step One : Analyse the control flow

Step Two : Prove data manipulation is correct

# Our target setting (for starters):

Simple value-passing calculus:

- asynchronous messages

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Driving example:

- parallel mergesort

# Reasoning about message-passing

Traditionally,

Equivalences:  $P \approx \text{SPEC}$

Temporal/Modal Logics:  $P \models F$

Hoare-like logics:  $\{ \text{state} \} P \{ \text{state}' \}$

(Typed) Static analyses:  $\Delta \vdash P : \text{eff}$

We intend to exploit the latter two approaches by first using an effect system to analyse the concurrency control, and then using local Hoare reasoning to talk about data.

# Step 1: Control Flow

# Determinism via resource access control

The main (only) source of non-determinism in message-passing systems is the race for synchronisation on a channel:

$$a?x.P \parallel a?y.Q \parallel a!v$$

Here there is a competition to receive a value on a given channel.

Similarly for

$$a?x.P \parallel a!v \parallel a!w$$

So we could easily delimit deterministic processes by using linear channels.

This would rule out a large class of interesting processes - e.g. Producer/Consumers, or parallel mergesort

# Determinism again

Consider the following process:

$$a!v \parallel d!w \parallel a?x.d?y.(b!\langle \rangle \parallel a!x + y) \parallel b?z'.a?z.c!z$$

This uses channel 'a' non-linearly yet is deterministic.

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The diagram illustrates the non-linear use of channel 'a'. It shows two arrows originating from the 'a' in the first process term 'a!v'. One arrow points to the 'a' in the input prefix 'a?x' of the third process term, and the other points to the 'a' in the output prefix 'a!x + y' of the same third process term. Similarly, two arrows originate from the 'd' in the second process term 'd!w'. One arrow points to the 'd' in the input prefix 'd?y' of the third process term, and the other points to the 'd' in the output prefix 'd!x + y' of the same third process term. This visualizes how the same channel 'a' is used in multiple contexts within a single process, yet the overall process remains deterministic.


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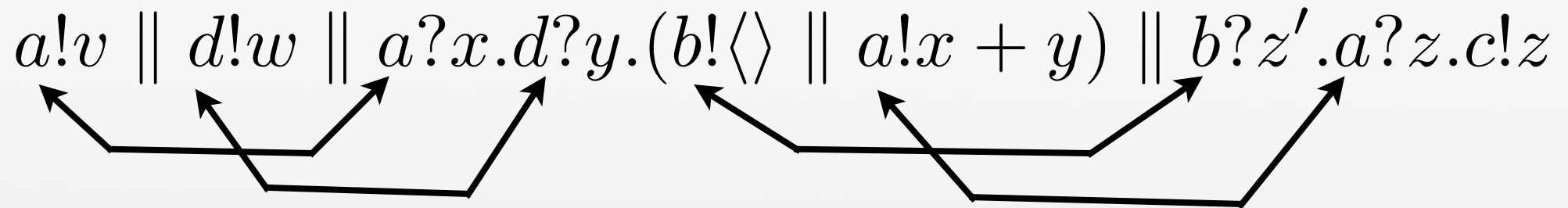


The diagram illustrates the non-linear use of channel 'a' in the process expression. It shows two arrows originating from a common point below the expression. One arrow points to the output action  $a!v$  on the far left. The other arrow points to the input action  $a?x$  in the third component of the parallel composition. This visualizes that the output of channel 'a' is used as an input to another process, creating a non-linear dependency.

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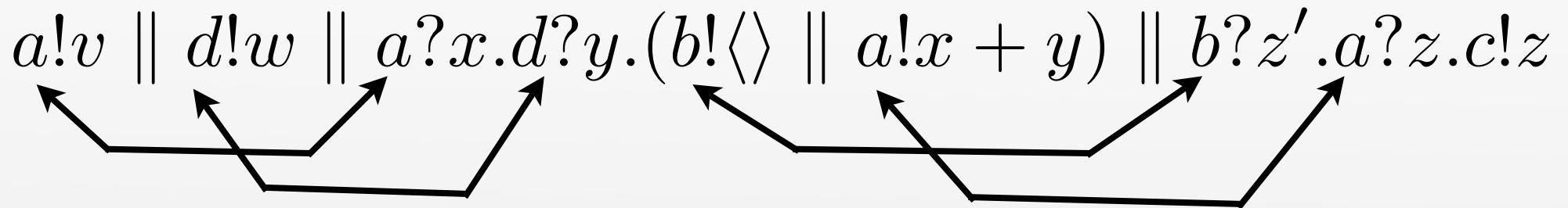
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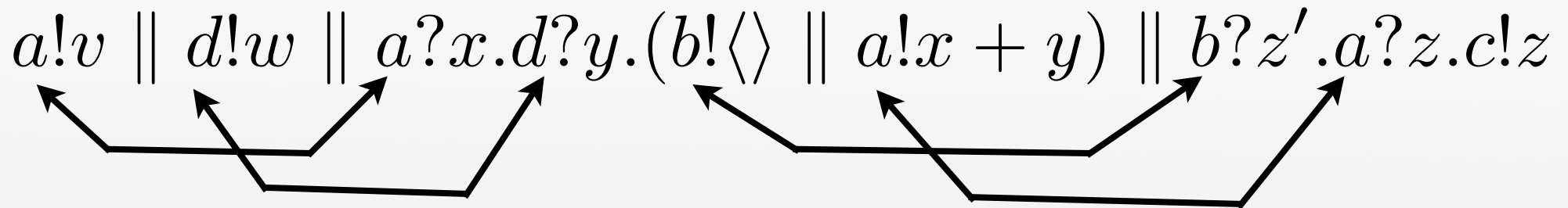


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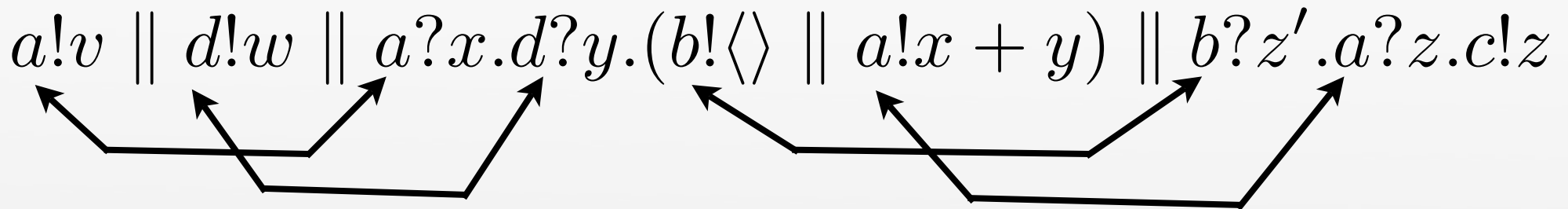
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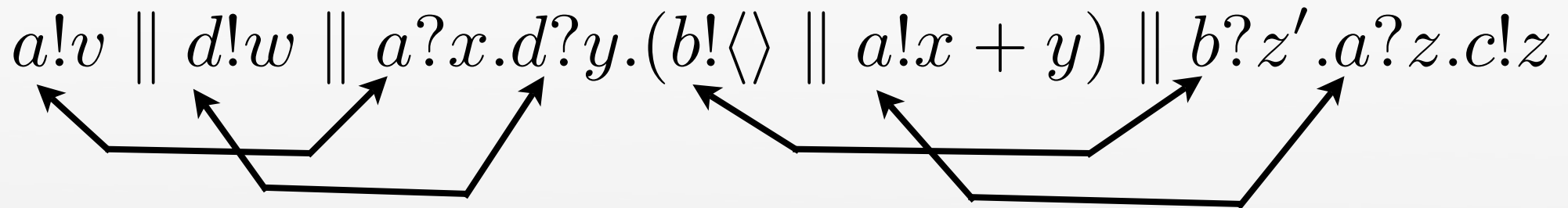
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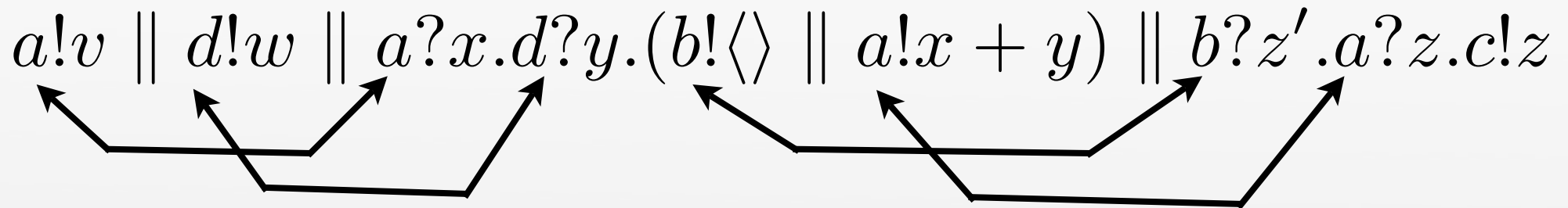
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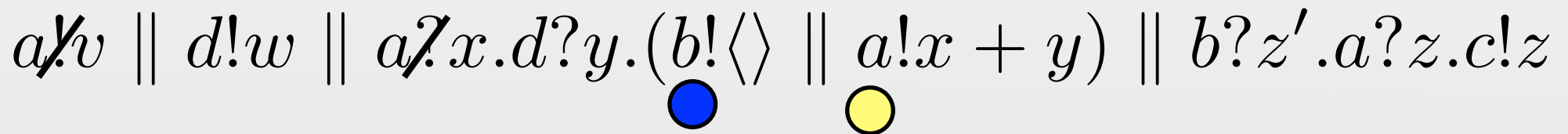
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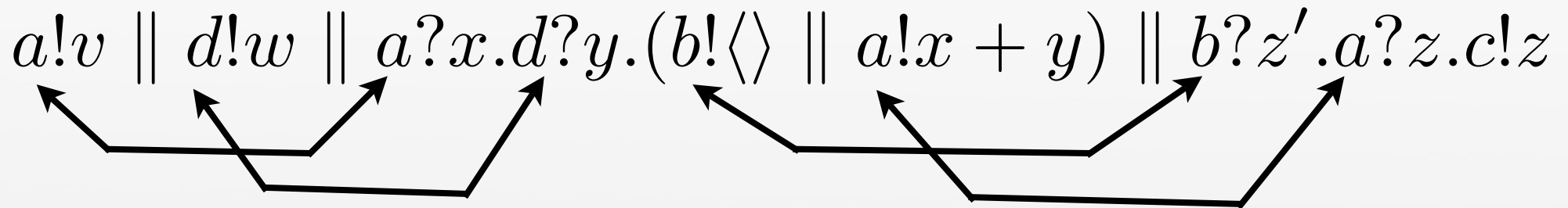
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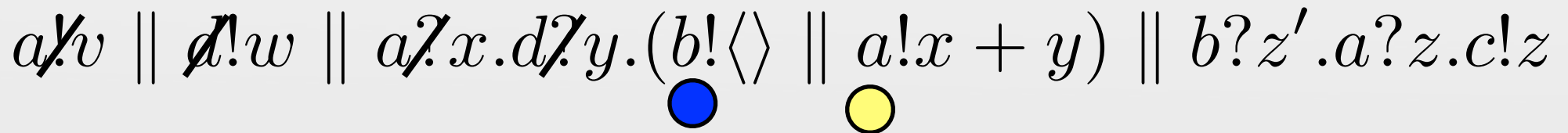
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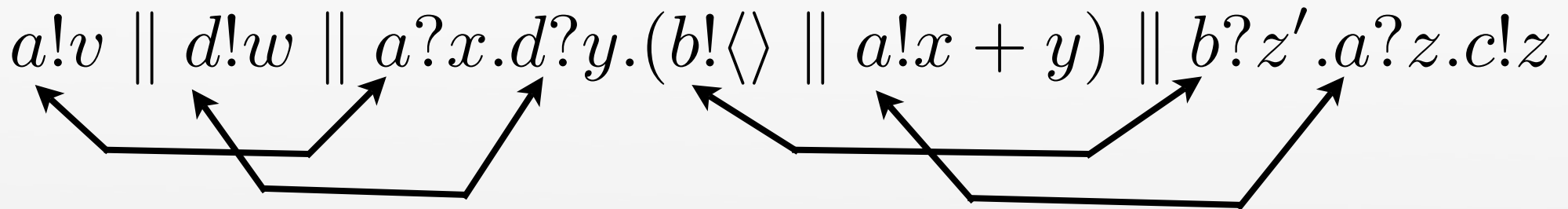
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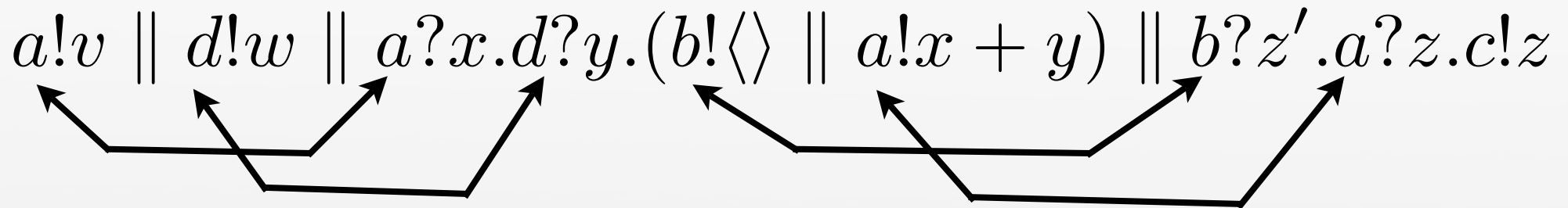
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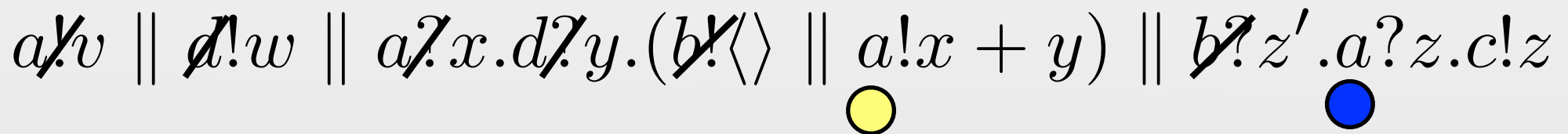
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The channel is used linearly at any given snapshot in time.

# An analysis of determinism

We check to see whether processes can be assigned linear permissions.

Permissions can be transfered implicitly through communication.

Exactly which permissions will be transfered during each communication is a parameter to the analysis :

$\Gamma$  is a map from channels to sets of permissions -  $c \mapsto \{a! , b? \}$

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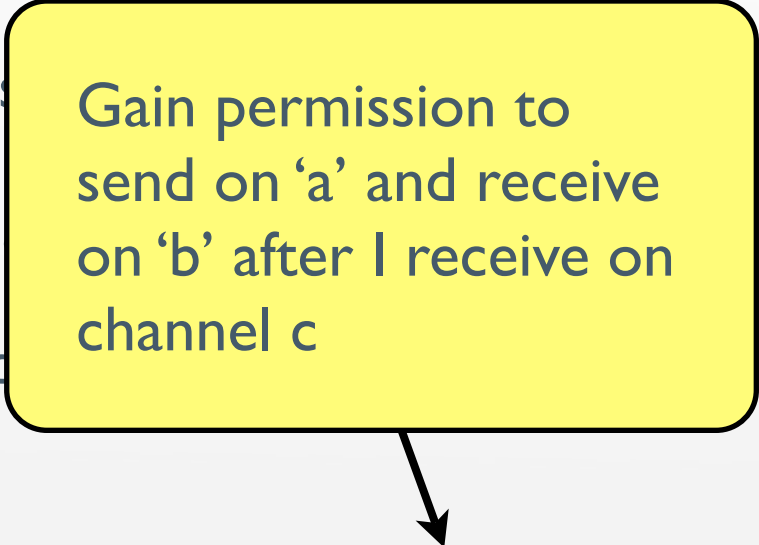
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Gain permission to  
send on 'a' and receive  
on 'b' after I receive on  
channel c



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We think of  $\Gamma$  as representing the intended control flow of the process. It acts as an assertion regarding control which must be checked. This is in accord with O'Hearn's tenet that

*“Ownership is in the eye of the asserter”*

# Our simple calculus

Grammar:

$$e ::= v \mid x \mid e + e \mid \dots \qquad v ::= 0 \mid 1 \mid 2$$

$$\begin{array}{lcl} P, Q & ::= & a!e \mid a?x.P \\ & & \mid \text{if } e \leq e' \text{ then } P \text{ else } Q \\ & & \mid \text{rec } X.P \mid X \\ & & \mid \text{nil} \mid P \parallel Q \mid (\text{new } a)P \end{array}$$

With obvious reduction rules including:

$$\frac{e \Downarrow v}{a!e \parallel a?x.P \rightarrow P[v/x]}$$

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Rule for par

$$\frac{\Gamma \vdash P : \epsilon \quad \Gamma \vdash Q : \epsilon'}{\Gamma \vdash P \parallel Q : \epsilon \oplus \epsilon'}$$

## Example

$$Pr = \text{rec } X.(p?().s?().(c!\langle \rangle \parallel X))$$

$$Con = \text{rec } X.(c?().s?().(p!\langle \rangle \parallel X))$$

$$\Gamma =$$

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# Properties of effect system

Proposition (subject reduction) :

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Proposition (confluence) :

$\Gamma \vdash P : \epsilon$  and  $P \rightarrow P_1$  and  $P \rightarrow P_2$  implies  
 $P_1 \equiv P_2$  or  $P_1 \rightarrow P_3$  and  $P_2 \rightarrow P_3$  for some  $P_3$

# Step 2: Proof System

# Logic

$$\phi, \varphi ::= \text{emp} \mid a\langle v \rangle \mid \phi \triangleright \phi \mid \phi * \phi$$

The  $a\langle v \rangle$  formulas represent outputs on the wire -  
analogous to memory locations

Satisfaction is defined by:

$\Gamma \triangleright P \models \text{emp}$	iff	<i>always</i>
$\Gamma \triangleright P \models a\langle v \rangle$	iff	$P \equiv a!e \parallel P'$ where $e \Downarrow v$
$\Gamma \triangleright P \models \phi \triangleright \psi$	iff	$\forall Q. \Gamma \triangleright Q \models \phi, \Gamma \vdash Q \perp P$ implies $\Gamma \triangleright P \parallel Q \models \psi$
$\Gamma \triangleright P \models \phi_1 * \phi_2$	iff	$\exists P_1, P_2. P \equiv P_1 \parallel P_2$ and $\Gamma \triangleright P_1 \models \phi_1, \Gamma \triangleright P_2 \models \phi_2$
$\Gamma \triangleright P \models \phi$	iff	$\exists Q. P \rightarrow^* Q, \Gamma \triangleright Q \models \phi$



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Separate permissions needed

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Satisfaction is defined by:

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$\Gamma \triangleright P \models a\langle v \rangle$	iff	$P \equiv a!e \parallel P'$ where $e \Downarrow v$
$\Gamma \triangleright P \models \phi \triangleright \psi$	iff	$\forall Q. \Gamma \triangleright Q \models \phi, \Gamma \vdash Q \perp P$ implies $\Gamma \triangleright P \parallel Q \models \psi$
$\Gamma \triangleright P \models \phi_1 * \phi_2$	iff	$\exists P_1, P_2. P \equiv P_1 \parallel P_2$ and $\Gamma \triangleright P_1 \models \phi_1, \Gamma \triangleright P_2 \models \phi_2$
$\Gamma \triangleright P \models \phi$	iff	$\exists Q. P \rightarrow^* Q, \Gamma \triangleright Q \models \phi$

Separate permissions needed

# Sequent rules

Sequents are interpreted as follows:

$$\Gamma \models \{\phi\}P\{\psi\} \stackrel{def}{=} \Gamma \vdash Q \perp P, \quad \Gamma \triangleright Q \models \phi$$

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The actual form of sequents is  $\Gamma, b \vdash \{\phi\} P \{\phi\}$  with  $b$  boolean

# Soundness

Theorem:

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This interpretation is not conventional and fairly weak - but recall that we are working with a class of confluent processes. One path is much the same as any other.

We make use of this fact to lift soundness to an 'all paths' interpretation.

# Satisfaction preservation

We'd like to prove

Proposition:

$$\Gamma \triangleright P \models \phi, \quad P \rightarrow^* Q \text{ implies } \Gamma \triangleright Q \models \phi$$

But unfortunately, this is not true for all formulas:

$$\phi = a\langle v \rangle * (a\langle v \rangle \triangleright b\langle v \rangle)$$

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However, if we rule out adjoints and check that  $P$  does not require 'input-permissions' specified by  $\Phi$ , then the above proposition holds.

# Example - parallel mergesort

$$\mathbf{srt}(X)_{i,j} \triangleq \begin{cases} X! & i = j \\ (\text{new } c_1, c_2) & i < j, \\ \left( \mathbf{srt}(c_1)_{i,m} \parallel \mathbf{srt}(c_2)_{m+1,j} \right) & m = \frac{j-i}{2} \\ \parallel c_1?.c_2?.\mathbf{mrg}(X)_{i,m+1,j} \end{cases} \quad \mathbf{shft}(X)_{i,j} \triangleq \begin{cases} X! & i = j \\ a_{j-1}?x. & \\ \left( \mathbf{shft}(X)_{i,j-1} \right) & i < j \\ \parallel a_j!x \end{cases}$$

$$\mathbf{mrg}(X)_{i,m,j} \triangleq \begin{cases} X! & i = m \vee m = j + 1 \\ a_i?x.a_m?y.\text{if } x \leq y \text{ then } (a_i!x \parallel a_m!y \parallel \mathbf{mrg}(X)_{i+1,m,j}) & \\ \text{else } \left( a_i!y. \parallel (\text{new } b) \left( \mathbf{shft}(b)_{i+1,m} \parallel \right. \right. & i < m \leq j \\ \left. \left. b?. \left( a_{i+1}!x \right. \right. \right. & \\ \left. \left. \parallel \mathbf{mrg}(X)_{i+1,m+1,j} \right) \right) & \end{cases}$$

The arrays are represented using a collection of outputs:

$$a_1!v_1 \parallel a_2!v_2 \parallel \cdots \parallel a_n!v_n$$

# Example specified

$$\begin{aligned}
 A_i^j \langle \vec{v}_i^j \rangle &\triangleq \begin{cases} \mathbf{emp} & i > j \\ a_i \langle v_i \rangle * A_{i+1}^j \langle \vec{v}_{i+1}^j \rangle & i \leq j \end{cases} & \vec{u}_i^j - v &\stackrel{\text{def}}{=} \begin{cases} \vec{u}_i^{m-1} \vec{u}_{m+1}^j & \text{if } \vec{u}_i^j = \vec{u}_i^{m-1} v \vec{u}_{m+1}^j \\ \text{undefined} & \text{otherwise} \end{cases} \\
 v \leq \vec{u}_i^j &\stackrel{\text{def}}{=} \forall i \leq k \leq j. v \leq u_k & v \in \vec{u}_i^j &\stackrel{\text{def}}{=} \exists i \leq m \leq j. \vec{u}_i^j = \vec{u}_i^{m-1} v \vec{u}_{m+1}^j \\
 \vec{v}_i^j \doteq \vec{u}_i^j &\stackrel{\text{def}}{=} v_i \in \vec{u}_i^j \wedge \vec{v}_{i+1}^j \doteq (\vec{u}_i^j - v) & \mathbf{srt}(\vec{v}_i^j) &\stackrel{\text{def}}{=} v_i \leq \vec{v}_{i+1}^j \wedge \mathbf{srt}(\vec{v}_{i+1}^j)
 \end{aligned}$$

We can derive the sequent by building a proof tree by induction over the indices:

$$\{A_i^j \langle \vec{v}_i^j \rangle\} \quad \mathbf{Srt}(b)_{i,j} \quad \{b \langle \rangle * A_i^j \langle \vec{u}_i^j \rangle\}$$

where

$$\underline{(\vec{v}_i^j \doteq \vec{w}_i^j) \wedge (\vec{w}_i^j \doteq \vec{u}_i^j) \wedge \mathbf{srt}(\vec{w}_i^{m-1}) \wedge \mathbf{srt}(\vec{w}_m^j) \wedge \mathbf{srt}(\vec{u}_i^j)}$$

# Other related work

Hennesy Milner Logic for CCS (Stirling)

Hennesy Milner Logic for the Pi-calculus (Dam)

Modal logics for Typed Pi-calculus (Berger+)

Rely-Guarantee Separation Logic (Feng+, Vafeiadis+)

Permission accounting in Separation Logic (Bornat+)

Compositional  
proof systems -  
path blow-up

Need to study  
this further

Could be very  
useful model  
for extensions

# Conclusions

We proposed a two-step analysis for local reasoning about message-passing concurrency:

- Effect analysis of deterministic flow

- Local Hoare logic for reasoning about data

Plenty more work to do to strengthen the class of programs we address

- controlled introduction of interference and racy-programs

- name-passing (a la pi-calculus)

- lots more examples

Thank You