# Local-First Principles: a Behavioural Types Approach


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joint work with

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It-Matters
Lucca 11-12 July, 2023

# – Prelude –

# Take-away message

An approach to trade consistency for availability in systems of **asymmetric replicated peers**

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based on local-first's principles to (re-)gain consensus ... eventually

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- swarm protocols: systems from an abstract global viewpoint
- enforce good behaviour via behavioural typing

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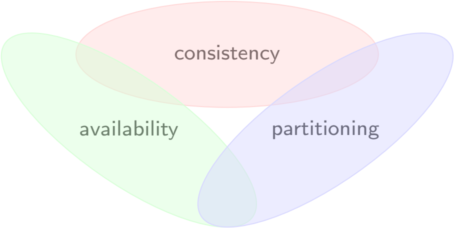
See our recent ECOOP 2023 paper
(to appear; extended version available at `https://arxiv.org/abs/2305.04848`)

# Distributed coordination




### An "old" problem

Distributed agreement
Distributed sharing
Security
Computer-assisted collaborative work
...

### With some "solutions"

Centralisation points
Consensus protocols
Commutative replicated data types
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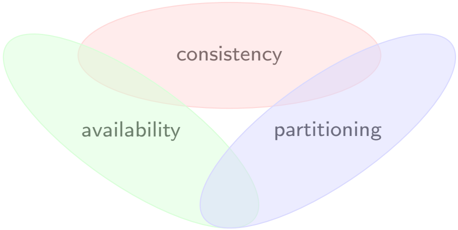
# Distributed coordination




### Availability = Money

Kohavi et al. KDD'14

- Amazon sales down 1% if 100ms delay
- Google searches down 0.2% - 0.6% if 100-400ms delay
- Bing's revenue down ∼1.5% if 250ms delay

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# A new (?) solution

**What about using local-first principles?**

Thou shall be autonomous

Thou shall collaborate

Thou shall recognise conflicts

Thou shall resolve conflicts

Thou shall be consistent

# Plan of the talk

Some motivations

Our formalisation

Our typing discipline

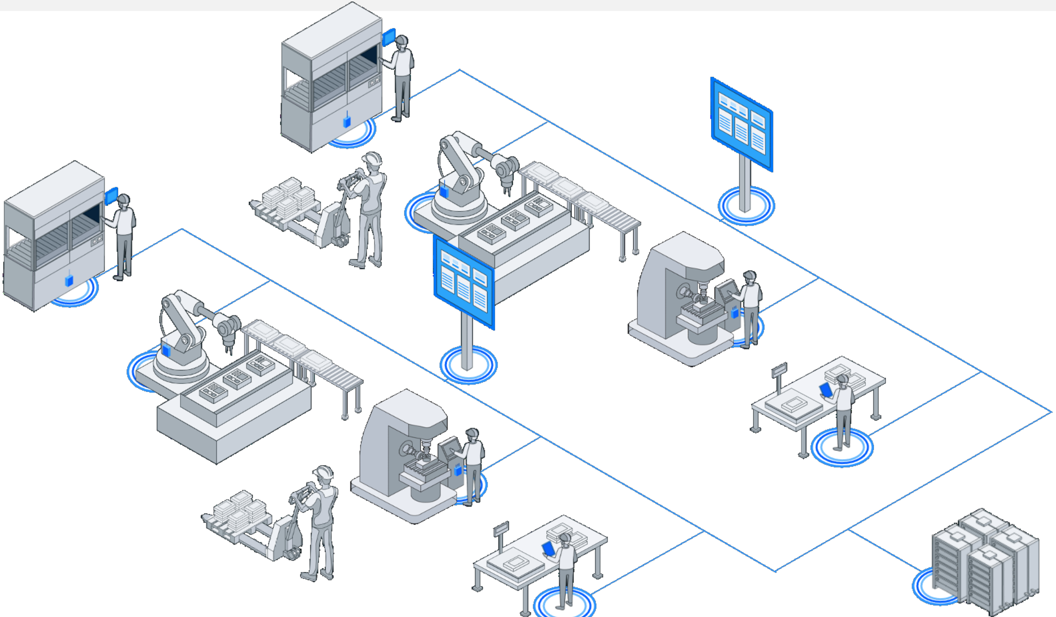
Tool support

Open issues

# – Motivations –

# A collaborative environment and its execution model

(the pictures are courtesy of Actyx AG)



# A collaborative environment and its execution model

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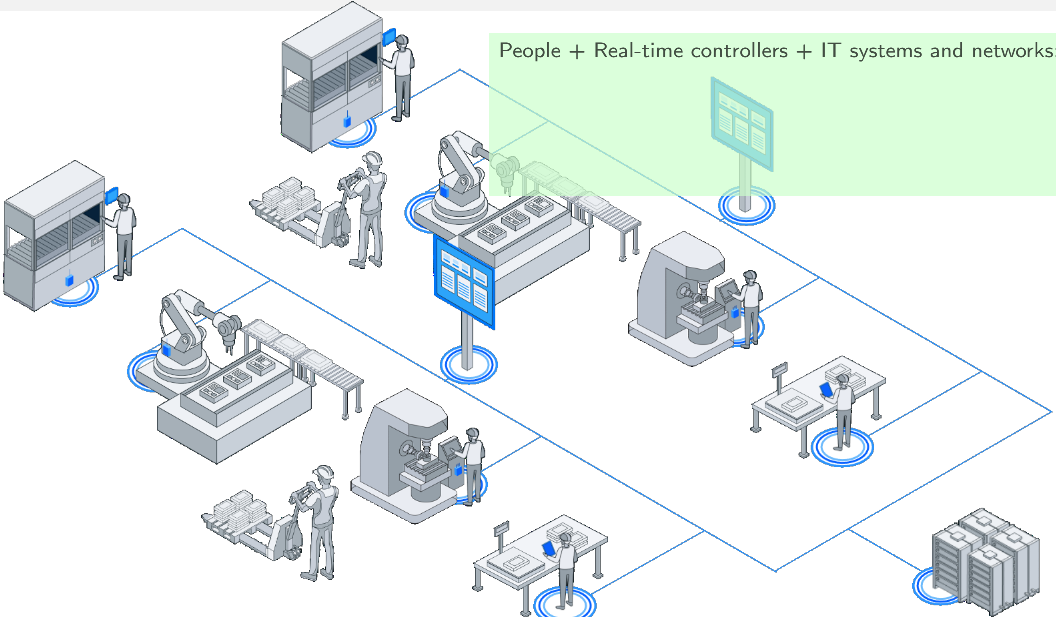
People + Real-time controllers + IT systems and networks:



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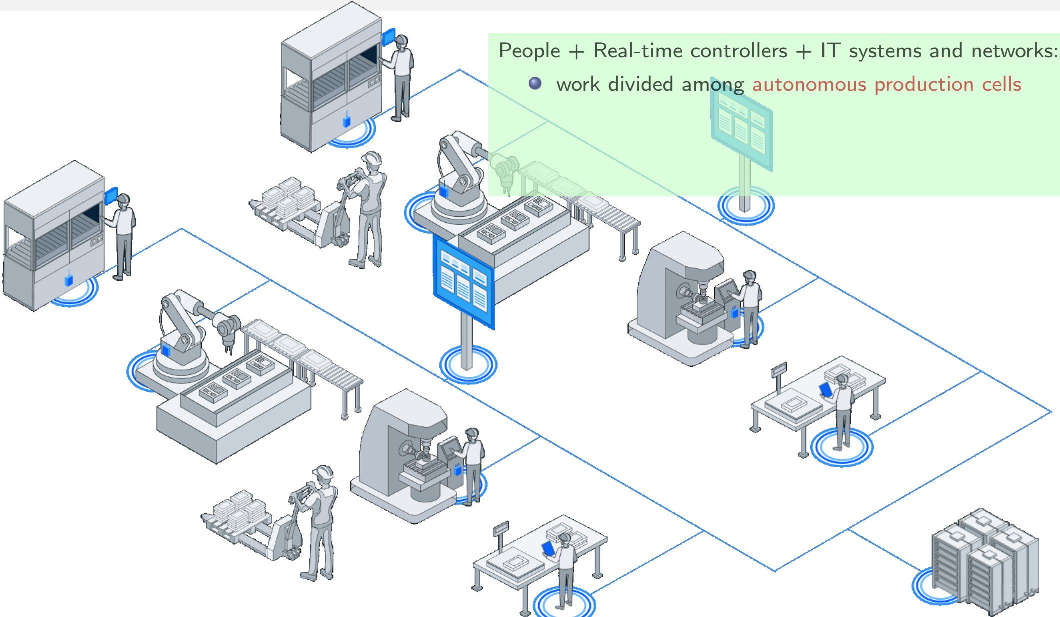

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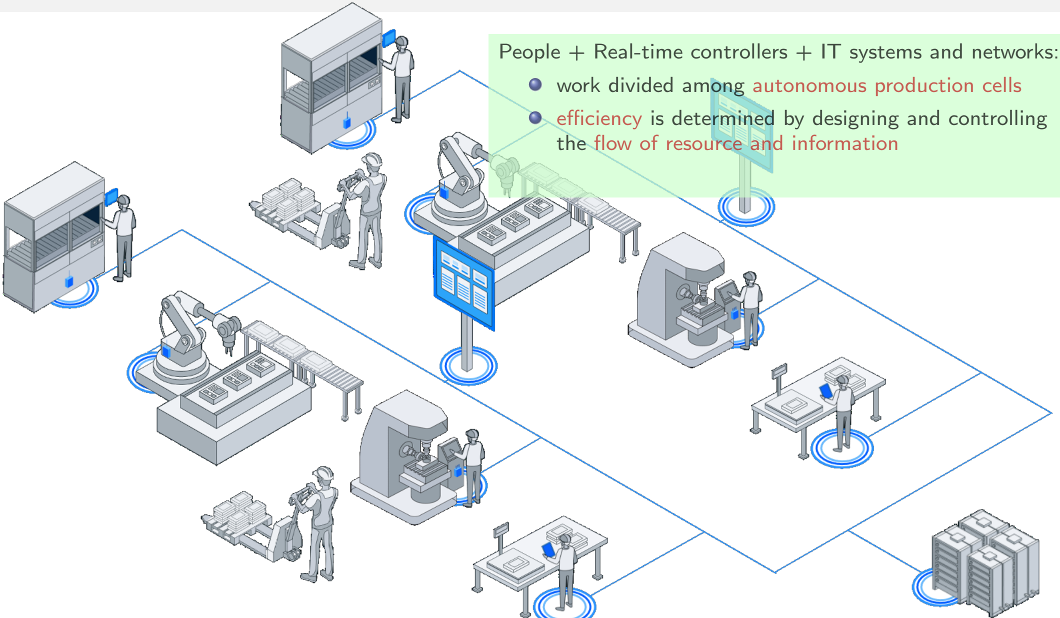

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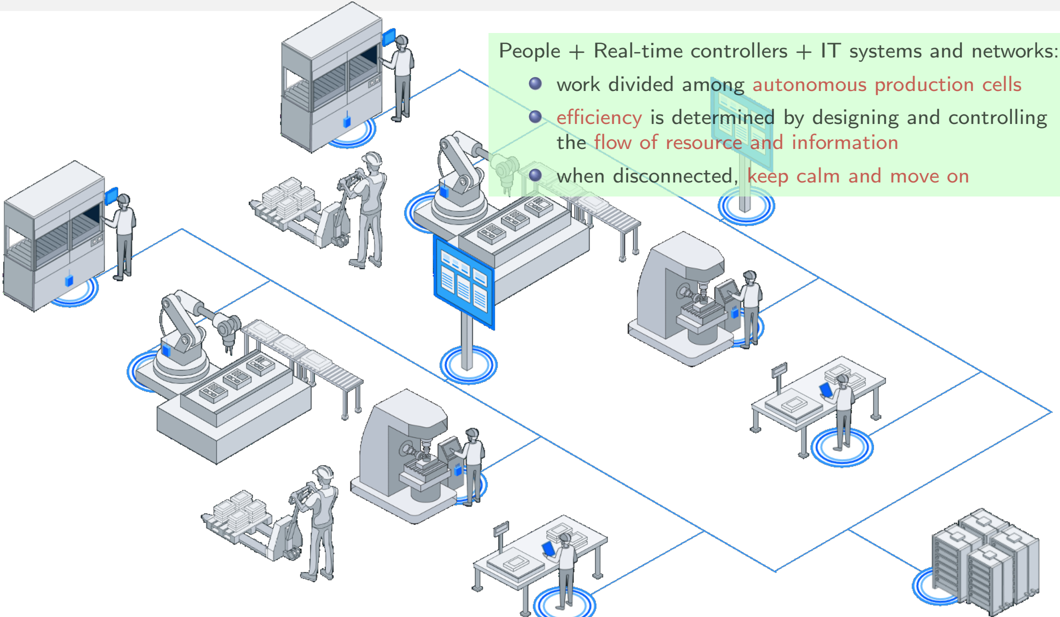

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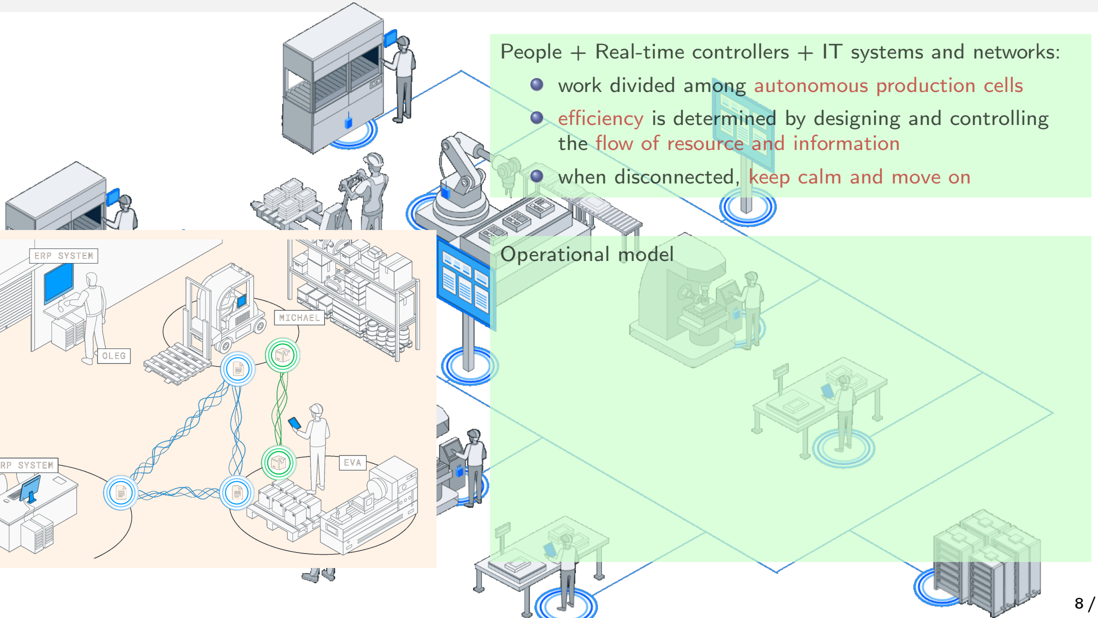

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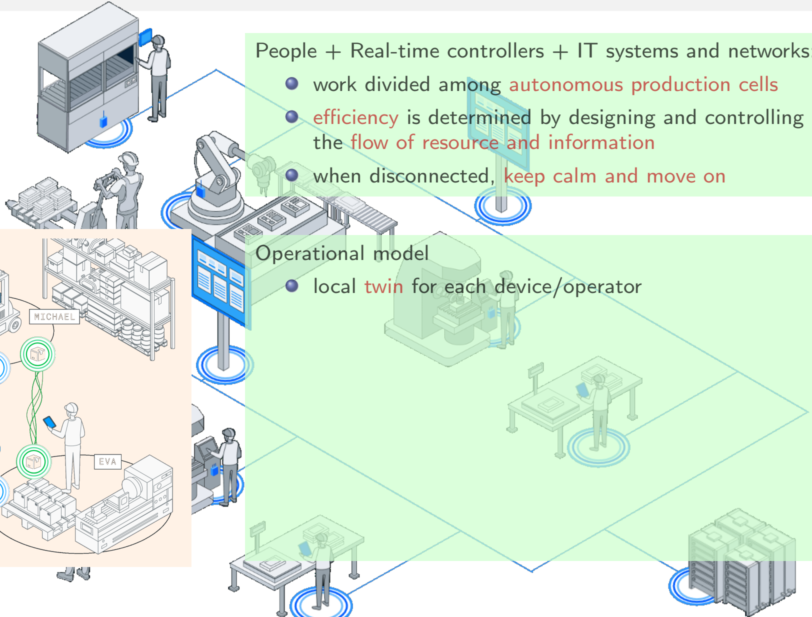

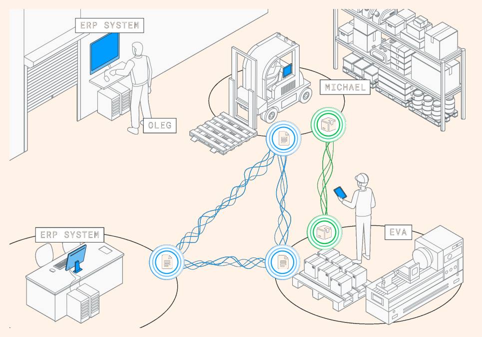


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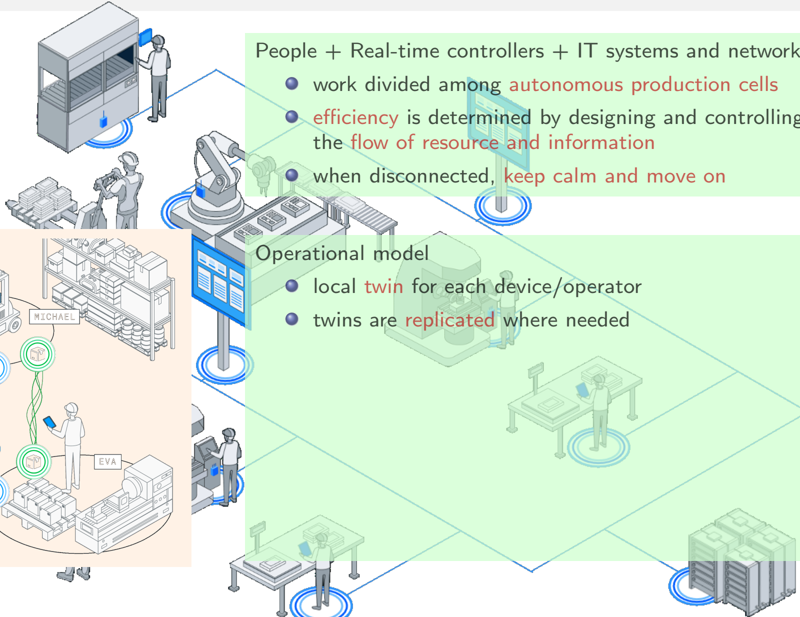

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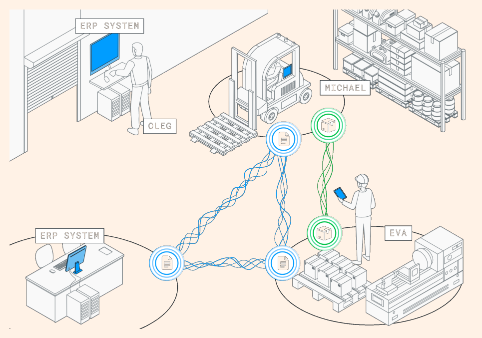


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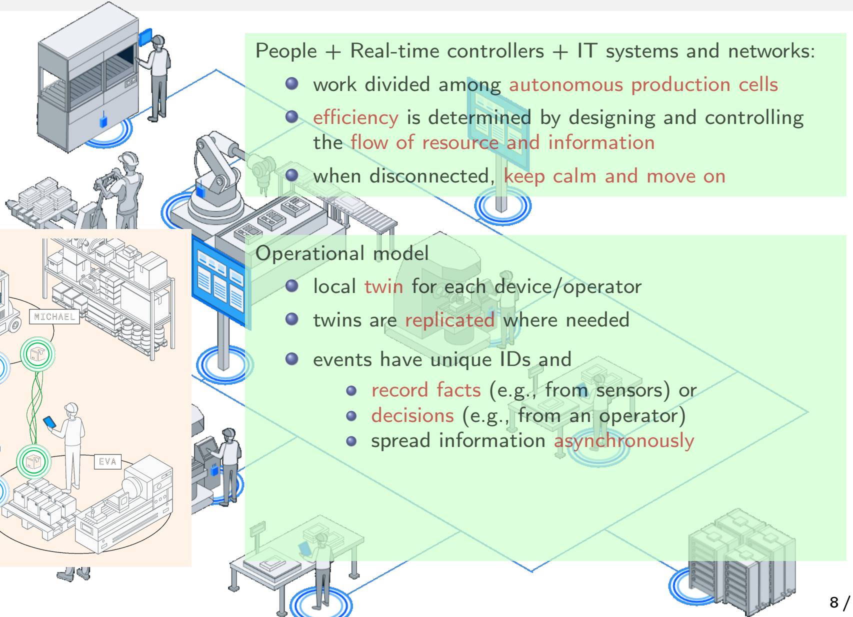

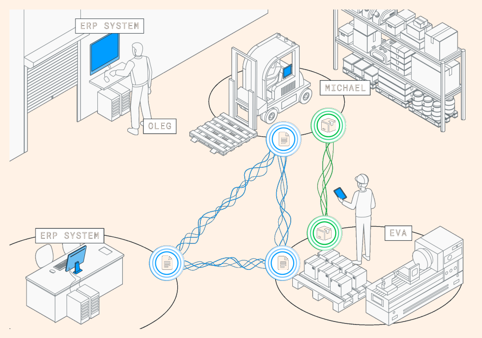


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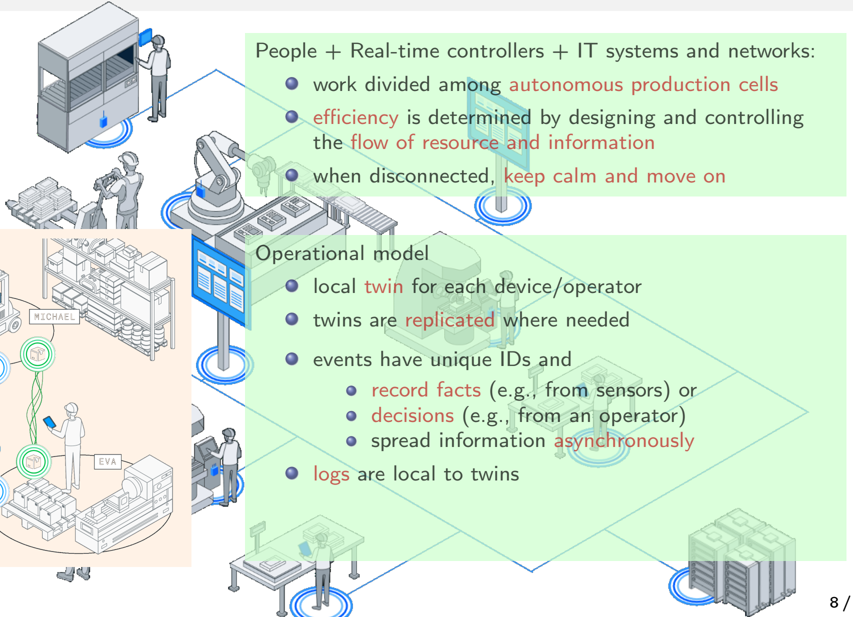

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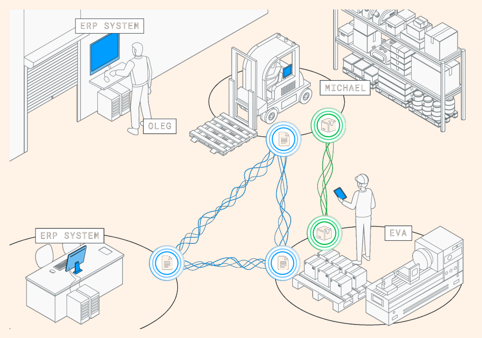


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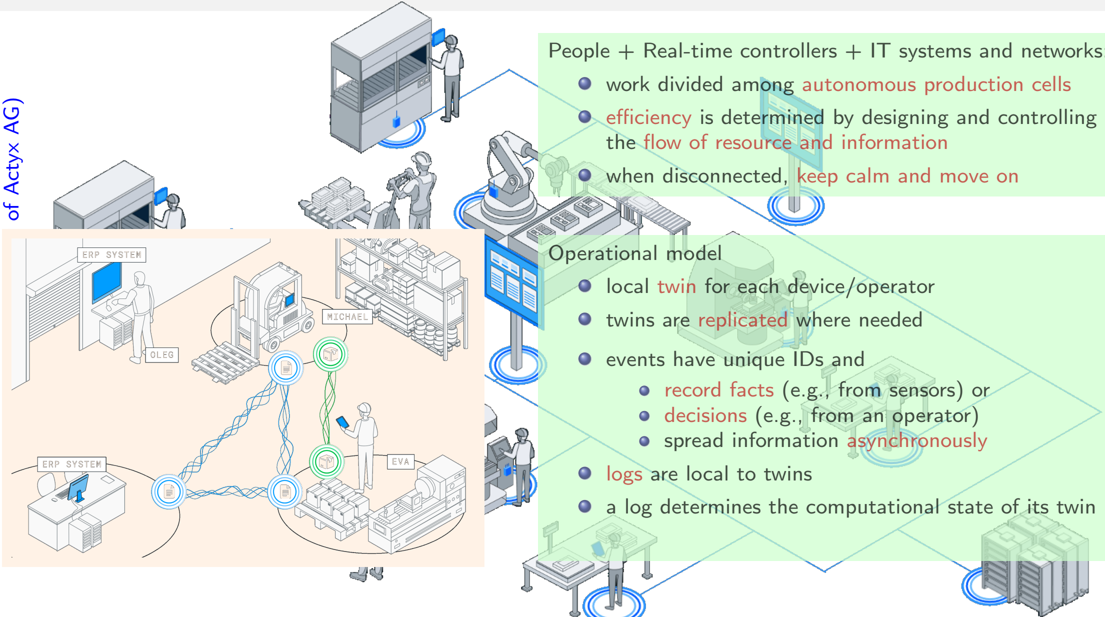


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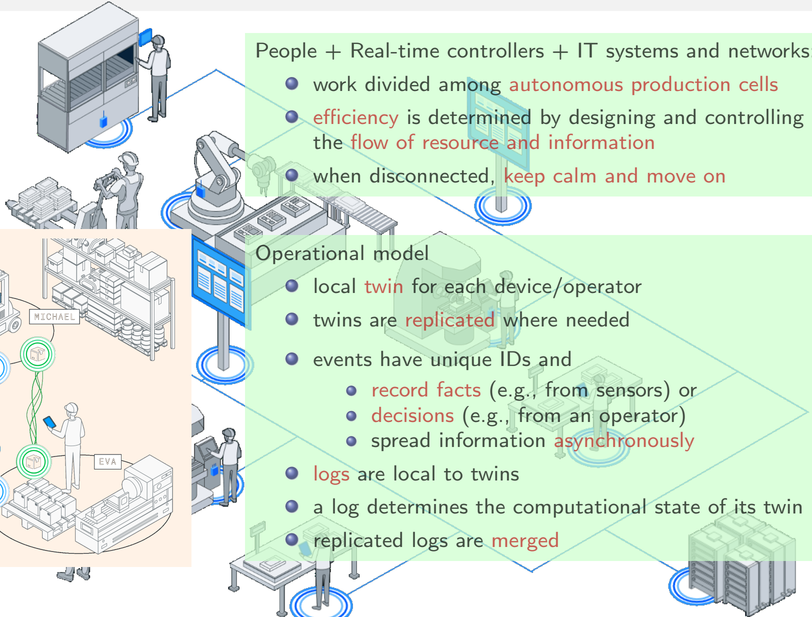

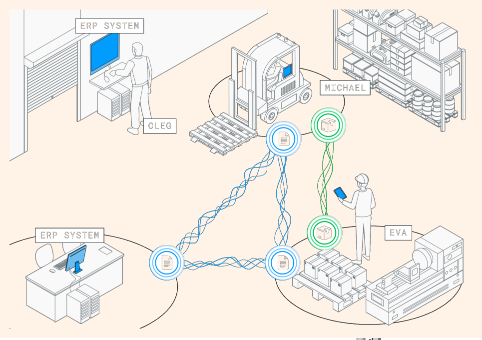


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- logs are local to twins
- a log determines the computational state of its twin
- replicated logs are merged

# A motto

execute

$+$

propagate

$+$

merge

# Other application domains / motivations

## More applications

Robots (e.g., rescue missions or space applications)

Collaborative applications (`https://automerge.org/`)

Home automation

# Other application domains / motivations

### IoT...really?

Why your fridge and mobile should go in the cloud to talk to each other?

# Other application domains / motivations

**"Anytime, anywhere..." really?**

like the AWS's outage on 25/11/2020

or almost all Google services down on 14/12/2020

DSL typical availability of 97% (& some SLA have no lower bound) checkout
`https://www.internetsociety.org/blog/2022/03/what-is-the-digital-divide`

# Other application domains / motivations

**Also, taking decisions locally**

can reduce downtime

shifts data ownership

gets rid of any centralization point...for real

# Plan of the talk

A motivating case study

Our formalisation

Our typing discipline

Tool support

Future work

# – A formal model –

# Ingredients (I): events & logs

Events $e$

Logs $e_1 \cdot e_2 \ldots$

$$\text{Events} \quad \vdash \quad e \quad : \quad t$$

$$src(e)$$

$$\text{Logs} \quad \vdash \quad e_1 \cdot e_2 \ldots \quad : \quad t_1 \cdot t_2 \ldots$$

# Ingredients (I): events & logs

Events $\vdash$ $e : \mathsf{t}$

$$src(e)$$

Logs $\vdash$ $e_1 \cdot e_2 \ldots : \mathsf{t}_1 \cdot \mathsf{t}_2 \ldots$

order induced by $\ell = e_1 \cdots e_n$ $e_i <_\ell e_j \iff i < j$

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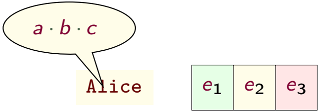

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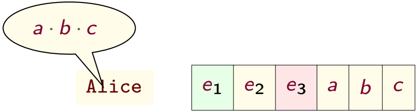

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$a \cdot b \cdot c$

| | | | | | | |
|---|---|---|---|---|---|---|
| `Alice` | $e_1$ | $e_2$ | $e_3$ | $a$ | $b$ | $c$ |

Phase II: newly emitted events are shipped to other machines

| | | | | | | |
|---|---|---|---|---|---|---|
| `Alice` | $e_1$ | $e_2$ | $e_3$ | $a$ | $b$ | $c$ |
| `Bob` | $e_3$ | | | | | |

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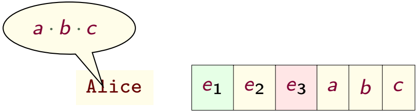


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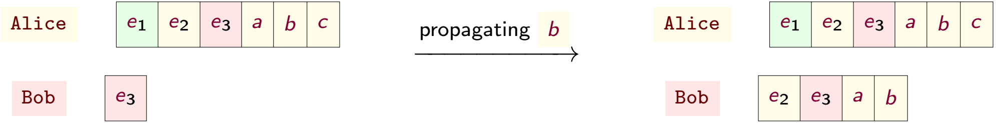
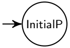


# Machines by example




`InitialP =`

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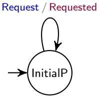


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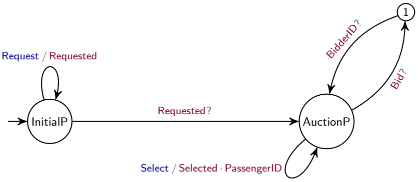


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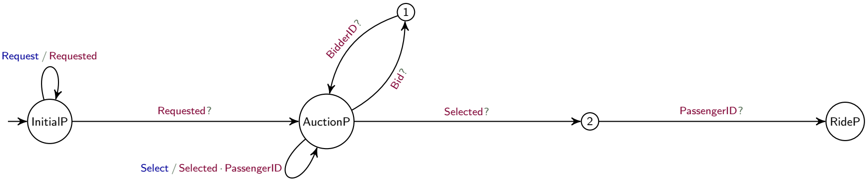


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Think of machines as emitters/consumers of events with a semantics given in terms of state transition function :

$$\delta(\mathtt{M}, \epsilon) = \mathtt{M}$$

$$\delta(\mathtt{M}, e \cdot \ell) = \begin{cases} \delta(\mathtt{M}', \ell) & \text{if } \vdash e : \mathtt{t},\ \mathtt{M} \xrightarrow{\mathtt{t}?} \mathtt{M}' \\ \delta(\mathtt{M}, \ell) & \text{otherwise} \end{cases}$$

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$$\frac{\delta(M, \ell) \xrightarrow{c\,/\,l} \delta(M, \ell) \qquad \ell' \text{ fresh} \qquad \vdash \ell' : l}{(M, \ell) \xrightarrow{c\,/\,l} (M, \ell \cdot \ell')}$$

That is
after processing the events in $\ell$, M reaches a state enabling $c\,/\,l$ then the command execution can emit $\ell'$ of type $l$ and append it to the local log of M

# Swarms

Swarms: $\mathtt{M}_1\boxed{\ell_1} \mid \ldots \mid \mathtt{M}_n\boxed{\ell_n} \mid \ell$ s.t. $\ell = \bigcup_{1\leq i\leq n} \ell_i$ and $\ell_i \sqsubseteq \ell$ for $1 \leq i \leq n$

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The propagation of newly generated events happens by merging logs:
Log merging: $\ell_1 \bowtie \ell_2 = \{\ell \mid \ell \subseteq \ell_1 \cup \ell_2 \text{ and } \ell_1 \sqsubseteq \ell \text{ and } \ell_2 \sqsubseteq \ell\}$

# Semantics of swarms

By rule [Local] below, a command's execution updates both local and global logs

$$\frac{\mathtt{S}(i) = \mathtt{M}\boxed{\ell_i} \qquad \mathtt{M}\boxed{\ell_i} \xrightarrow{\mathtt{c}\,/\,\mathtt{l}} \mathtt{M}\boxed{\ell'_i} \qquad \mathit{src}(\ell'_i \setminus \ell_i) = \{i\} \qquad \ell' \in \ell \bowtie \ell'_i}{(\mathtt{S}, \ell) \xrightarrow{\mathtt{c}\,/\,\mathtt{l}} (\mathtt{S}[i \mapsto \mathtt{M}\boxed{\ell'_i}], \ell')}\,[\text{Local}]$$

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By rule [Local] below, a command's execution updates both local and global logs

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$$\frac{\mathtt{S}(i) = \mathtt{M}\boxed{\ell_i} \qquad \ell_i \sqsubseteq \ell' \sqsubseteq \ell \qquad \ell_i \subset \ell'}{(\mathtt{S}, \ell) \xrightarrow{\tau} (\mathtt{S}[i \mapsto \mathtt{M}\boxed{\ell'}], \ell)}\,[\text{Prop}]$$

By rule [Prop] above, the propagation of events happens

- by shipping a **non-deterministically chosen** subset of events in the global log
- to a **non-deterministically chosen** machine

# Plan of the talk

A motivating case study

Our formalisation

Our typing discipline

Tool support

Future work

# – Behavioural types for swarms –

# Inspired by choreographies

## Quoting W3C:

*"[...] a contract [...] of the common ordering conditions and constraints under which messages are exchanged [...] from a global viewpoint [...]*
*Each party can then use the global definition to build and test solutions [...]*
*global specification is in turn realised by combination of the resulting local systems"*

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**Synchrony**

Choreography G
global viewpoint

**Asynchrony**

$M_1$
Local viewpoint$_1$

$M_i$
Local viewpoint$_i$

$M_n$
Local viewpoint$_n$

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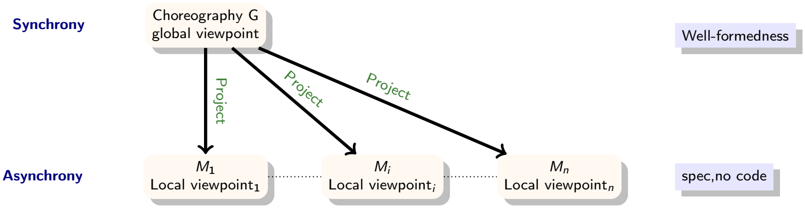

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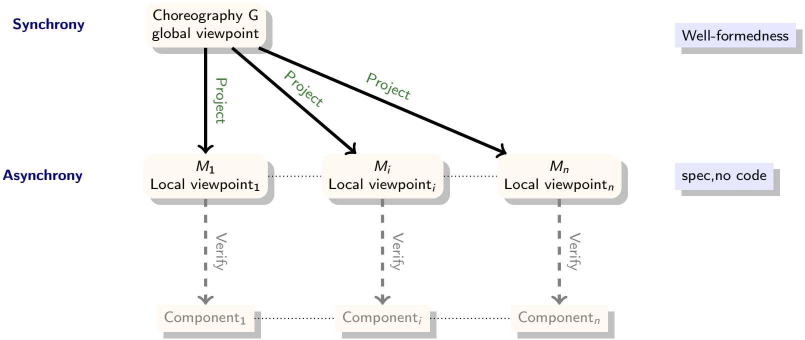
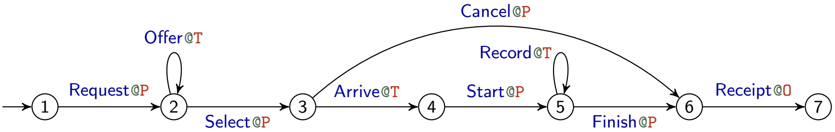


# Swarm protocols by example

An intuitive auction protocol for a passenger P to get a taxi T:



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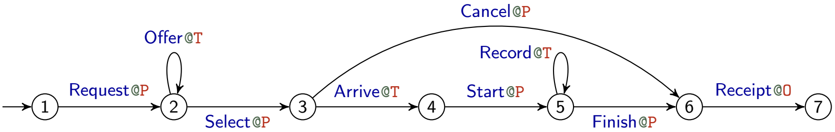


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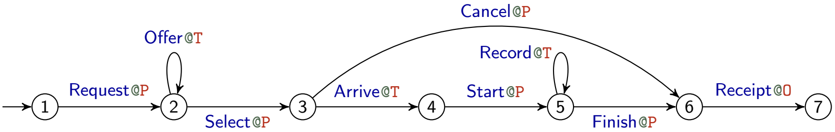


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- one passenger and one office (for simplicity)
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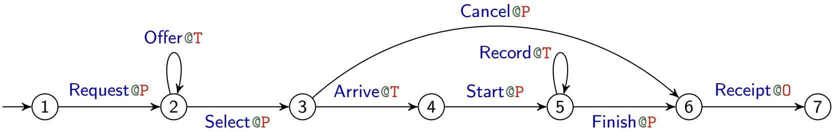


We assume

- one passenger and one office (for simplicity)
- but an arbitrary number of taxis
- a receipt is issued by the office O at the end of the ride (if any)

# Swarm protocols: global type for local-first applications

An **idealised** specification relying on **synchronous communication**

Fix a set of roles ranged over by $\mathtt{R}$ (e.g., $\mathtt{P}$, $\mathtt{T}$, and $\mathtt{O}$ on slide 31)

The syntax of swarm protocols is again given co-inductively:

$$\mathtt{G} \overset{\text{co}}{::=} \sum_{i \in I} \mathtt{c}_i @ \mathtt{R}_i \langle \mathtt{l}_i \rangle \,.\, \mathtt{G}_i \quad \Big| \quad 0 \qquad \text{where } I \text{ is a finite set (of indexes)}$$

# An example

A swarm protocol for the taxi scenario on slide 31:

$$G = \mathsf{Request}\,@\mathtt{P}\,\langle\mathsf{Requested}\rangle\,.\,G_{\mathsf{auction}}$$

$$\begin{aligned} G_{\mathsf{auction}} &= \mathsf{Offer}\,@\mathtt{T}\,\langle\mathsf{Bid}\cdot\mathsf{BidderID}\rangle\,.\,G_{\mathsf{auction}} \\ &+ \mathsf{Select}\,@\mathtt{P}\,\langle\mathsf{Selected}\cdot\mathsf{PassengerID}\rangle\,.\,G_{\mathsf{choose}} \end{aligned}$$

$$\begin{aligned} G_{\mathsf{choose}} &= \mathsf{Arrive}\,@\mathtt{T}\,\langle\mathsf{Arrived}\rangle\,.\,\mathsf{Start}\,@\mathtt{P}\,\langle\mathsf{Started}\rangle\,.\,G_{\mathsf{ride}} \\ &+ \mathsf{Cancel}\,@\mathtt{P}\,\langle\mathsf{Cancelled}\rangle\,.\,\mathsf{Receipt}\,@\mathtt{O}\,\langle\mathsf{Receipt}\rangle\,.\,0 \end{aligned}$$

$$\begin{aligned} G_{\mathsf{ride}} &= \mathsf{Record}\,@\mathtt{T}\,\langle\mathsf{Path}\rangle\,.\,G_{\mathsf{ride}} \\ &+ \mathsf{Finish}\,@\mathtt{P}\,\langle\mathsf{Finished}\cdot\mathsf{Rating}\rangle\,.\,\mathsf{Receipt}\,@\mathtt{O}\,\langle\mathsf{Receipt}\rangle\,.\,0 \end{aligned}$$

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*Note the log types in each prefixes*

$$\begin{aligned} G_{\mathsf{choose}} &= \mathsf{Arrive}@\mathtt{T}\langle \mathsf{Arrived} \rangle \,.\, \mathsf{Start}@\mathtt{P}\langle \mathsf{Started} \rangle \,.\, G_{\mathsf{ride}} \\ &+ \mathsf{Cancel}@\mathtt{P}\langle \mathsf{Cancelled} \rangle \,.\, \mathsf{Receipt}@\mathtt{O}\langle \mathsf{Receipt} \rangle \,.\, 0 \end{aligned}$$

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# Swarm protocols as FSA

Like for machines, a swarm protocols $\mathsf{G} = \sum_{i \in I} \mathtt{c}_i @ \mathtt{R}_i \langle \mathtt{l}_i \rangle \,.\, \mathsf{G}_i$ has an associated FSA:

- the set of states consists of $\mathsf{G}$ plus the states in $\mathsf{G}_i$ for each $i \in \{1 \ldots, n\}$
- $\mathsf{G}$ is the initial state
- for each $i \in I$, $\mathsf{G}$ has a transition to state $\mathsf{G}_i$ labelled with $\mathtt{c}_i @ \mathtt{R}_i \langle \mathtt{l}_i \rangle$, written $\mathsf{G} \xrightarrow{\mathtt{c}_i \,/\, \mathtt{l}_i} \mathsf{G}_i$

# Semantics of swarm protocols

**One** rule only!

$$\frac{}{(\mathsf{G}, \ell) \xrightarrow{\texttt{c}\,/\,\texttt{l}} (\mathsf{G}, \ell \qquad)}\,[\text{G-Cmd}]$$

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$$\frac{\delta(\mathsf{G}, \ell) \xrightarrow{\mathtt{c}\,/\,\mathtt{l}} \mathsf{G}'}{(\mathsf{G}, \ell) \xrightarrow{\mathtt{c}\,/\,\mathtt{l}} (\mathsf{G}, \ell \quad)}\text{[G-Cmd]}$$

where

$$\delta(\mathsf{G}, \ell) = \begin{cases} \mathsf{G} & \text{if } \ell = \epsilon \\ \delta(\mathsf{G}', \ell'') & \text{if } \mathsf{G} \xrightarrow{\mathtt{c}\,/\,\mathtt{l}} \mathsf{G}' \text{ and } \vdash \ell' : \mathtt{l} \text{ and } \ell = \ell' \cdot \ell'' \\ \bot & \text{otherwise} \end{cases}$$

*Logs to be consumed "atomically", hence $\delta(\mathsf{G}, \ell)$ may be undefined*

# Semantics of swarm protocols

**One** rule only!

$$\frac{\delta(\mathsf{G}, \ell) \xrightarrow{\mathtt{c}\,/\,\mathtt{l}} \mathsf{G}' \qquad \vdash \ell' : \mathtt{l} \qquad \ell' \text{ log of fresh events}}{(\mathsf{G}, \ell) \xrightarrow{\mathtt{c}\,/\,\mathtt{l}} (\mathsf{G}, \ell \cdot \ell')}\text{[G-Cmd]}$$

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*Logs to be consumed "atomically", hence $\delta(\mathsf{G}, \ell)$ may be undefined*

We restrict ourselves to deterministic swarm protocols that is, on different transitions from a same state

- log types start differently — log determinism
- pairs (command,role) differ — command determinism

# From swarm protocols to machines

Transitions of a swarm protocol $G$ are labelled with a role that may invoke the command

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Obtain machines by projecting G on each role

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First attempt

$$\Big(\sum_{i\in I} \mathtt{c}_i @ \mathtt{R}_i \langle \mathtt{l}_i \rangle \,.\, \mathsf{G}_i\Big) \downarrow_{\mathtt{R}} = \kappa \cdot [\&_{i\in I}\, \mathtt{l}_i ?\, \mathsf{G}_i \downarrow_{\mathtt{R}}]$$

where $\kappa = \{(\mathtt{c}_i \,/\, \mathtt{l}_i) \;\big|\; \mathtt{R}_i = \mathtt{R} \text{ and } i \in I\}$

Transitions of a swarm protocol $\mathsf{G}$ are labelled with a role that may invoke the command

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Obtain machines by projecting $\mathsf{G}$ on each role

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where $\kappa = \{(\mathtt{c}_i \,/\, \mathtt{l}_i) \mid \mathtt{R}_i = \mathtt{R} \text{ and } i \in I\}$

simple, but

- projected machines are large in all but the most trivial cases
- processing **all** events is undesirable: security and efficiency

# Another attempt

Let's subscribe to subscriptions : maps from roles to sets of event types

*In pub-sub, processes subscribe to "topics"*

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*In pub-sub, processes subscribe to "topics"*

Given $G = \sum_{i \in I} c_i@R_i\langle l_i \rangle \,.\, G_i$, the projection of $G$ on a role $R$ with respect to subscription $\sigma$ is

$$G \downarrow_{R}^{\sigma} = \kappa \cdot [\&_{j \in J}\, \mathsf{filter}(l_j, \sigma(R))\, ?\, G_j \downarrow_{R}^{\sigma}]$$

where

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Let's subscribe to subscriptions : maps from roles to sets of event types

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$$\mathsf{G} \downarrow^{\sigma}_{\mathtt{R}} = \kappa \cdot [\&_{j \in J} \, \mathsf{filter}(\mathtt{l_j}, \sigma(\mathtt{R}))\, ?\, \mathsf{G}_j \downarrow^{\sigma}_{\mathtt{R}}]$$ where

$$\kappa = \{\mathtt{c}_i \,/\, \mathtt{l}_i \mid \mathtt{R}_i = \mathtt{R} \text{ and } i \in I\}$$

$$J = \{i \in I \mid \mathsf{filter}(\mathtt{l}_i, \sigma(\mathtt{R})) \neq \epsilon\}$$

$$\mathsf{filter}(\mathtt{l}, E) = \begin{cases} \epsilon, & \text{if } \mathtt{t} = \epsilon \\ \mathtt{t} \cdot \mathsf{filter}(\mathtt{l}', E) & \text{if } \mathtt{t} \in E \text{ and } \mathtt{l} = \mathtt{t} \cdot \mathtt{l}' \\ \mathsf{filter}(\mathtt{l}, E) & \text{otherwise} \end{cases}$$

# Well-formedness

Trading consistency for availability has implications:

# Well-formedness = Causality

Trading consistency for availability has implications:

Propagation of events is non-atomic (cf. rule [Prop])

$\implies$ differences in how machines perceive the (state of the) computation

## Causality

Fix a subscription $\sigma$. For each branch $i \in I$ of $\mathsf{G} = \sum_{i \in I} \mathsf{c}_i @ \mathtt{R}_i \langle \mathtt{l}_i \rangle \,.\, \mathsf{G}_i$

*If* $\mathtt{R}$ *should have* $\mathsf{c}$ *enabled after* $\mathsf{c}'$ *then* $\sigma(\mathtt{R})$ *contains some event type emitted by* $\mathsf{c}'$

**Explicit re-enabling** $\quad \sigma(\mathtt{R}_i) \cap \mathtt{l}_i \neq \emptyset$

**Command causality** $\quad$ if $\mathtt{R}$ executes a command in $\mathsf{G}_i$

then $\sigma(\mathtt{R}) \cap \mathtt{l}_i \neq \emptyset \quad$ and $\quad \sigma(\mathtt{R}) \cap \mathtt{l}_i \supseteq \bigcup_{\mathtt{R}' \in_\sigma \mathsf{G}_i} \sigma(\mathtt{R}') \cap \mathtt{l}_i$

# Well-formedness = Causality + Determinacy

Trading consistency for availability has implications:

Propagation of events is non-atomic (cf. rule [Prop])

$\implies$ different roles may take inconsistent decisions

## Causality & Determinacy

Fix a subscription $\sigma$. For each branch $i \in I$ of $\mathsf{G} = \sum_{i \in I} \mathtt{c}_i@\mathtt{R}_i\langle \mathtt{l}_i \rangle . \mathsf{G}_i$

**Explicit re-enabling** $\sigma(\mathtt{R}_i) \cap \mathtt{l}_i \neq \emptyset$

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**Determinacy** $\mathtt{R} \in_\sigma \mathsf{G}_i \implies \mathtt{l}_i[0] \in \sigma(\mathtt{R})$

## Well-formedness = Causality + Determinacy - Confusion

Trading consistency for availability has implications:

Propagation of events is non-atomic (cf. rule [Prop])

$\implies$ branches unambiguously identified and events emitted on eventually discharged branches ignored

### Causality & Determinacy & Confusion freeness

Fix a subscription $\sigma$. For each branch $i \in I$ of $G = \sum_{i \in I} \mathtt{c}_i @ \mathtt{R}_i \langle \mathtt{l}_i \rangle . G_i$

| | |
|---|---|
| Explicit re-enabling | $\sigma(\mathtt{R}_i) \cap \mathtt{l}_i \neq \emptyset$ |
| Command causality | if $\mathtt{R}$ executes a command in $G_i$<br>then $\sigma(\mathtt{R}) \cap \mathtt{l}_i \neq \emptyset$ and $\sigma(\mathtt{R}) \cap \mathtt{l}_i \supseteq \bigcup_{\mathtt{R}' \in_\sigma G_i} \sigma(\mathtt{R}') \cap \mathtt{l}_i$ |
| Determinacy | $\mathtt{R} \in_\sigma G_i \implies \mathtt{l}_i[0] \in \sigma(\mathtt{R})$ |
| Confusion freeness | there is a unique subtree $G'$ of $G$ emitting $\mathtt{t}$<br>for each $\mathtt{t}$ starting a log emitted by a command in $G$ |

# Implementations

Write $\ell \equiv_{\mathsf{G},\sigma} \ell'$ when $\ell$ and $\ell'$ have the same effective type wrt $\mathsf{G}$ and $\sigma$.

A swarm $(\mathtt{S}, \epsilon)$ is eventually faithful to $\mathsf{G}$ and $\sigma$ if $(\mathtt{S}, \epsilon) \Longrightarrow (\mathtt{S}, \ell)$ then there is $(\mathsf{G}, \epsilon) \Longrightarrow (\mathsf{G}, \ell')$ with $\ell \equiv_{\mathsf{G},\sigma} \ell'$

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A $(\sigma, G)$-realisation is a swarm $(\mathtt{S}, \epsilon)$ of size $n$ such that, for each $1 \leq i \leq n$, there exists a role $\mathtt{R} \in \mathsf{roles}(G, \sigma)$ such that $\mathtt{S}(i) = G \downarrow^{\sigma}_{\mathtt{R}}$ $\square$

# Implementations & projections

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A swarm $(\mathtt{S}, \epsilon)$ is eventually faithful to G and $\sigma$ if $(\mathtt{S}, \epsilon) \Longrightarrow (\mathtt{S}, \ell)$ then there is $(G, \epsilon) \Longrightarrow (G, \ell')$ with $\ell \equiv_{G,\sigma} \ell'$

A $(\sigma, G)$-realisation is a swarm $(\mathtt{S}, \epsilon)$ of size $n$ such that, for each $1 \leq i \leq n$, there exists a role $\mathtt{R} \in \text{roles}(G, \sigma)$ such that $\mathtt{S}(i) = G \downarrow^{\sigma}_{\mathtt{R}}$ ▯

**Lemma (Projections of well-formed protocols are eventually faithful)**

*If* G *is a* $\sigma$*-WF protocol and* $\left(\delta(G \downarrow^{\sigma}_{\mathtt{R}}, \ell)\right) \downarrow_{\mathtt{c}\,/\,\mathtt{1}}$ *then there exists* $\ell' \equiv_{G,\sigma} \ell$ *such that* $(G, \epsilon) \Longrightarrow (G, \ell')$ *and* $\delta(G, \ell') \xrightarrow{\mathtt{c}\,/\,\mathtt{1}} G'$

# On correct realisations

$$\begin{tikzcd}[column sep=small, row sep=small] & (\mathtt{S}, \ell_1) \\ (\mathtt{S}, \epsilon) \arrow[ur, Rightarrow] \arrow[dr, Rightarrow] & \\ & (\mathtt{S}, \ell_2) \end{tikzcd}$$

consistent if there is $\ell$ s.t.

$$\begin{tikzcd}[column sep=small, row sep=small] & & & (\mathtt{S}, \ell'_1) \\ (\mathtt{S}, \epsilon) \arrow[r, Longrightarrow] & (\mathtt{S}, \ell) \arrow[urr, Rightarrow] \arrow[drr, Rightarrow] & & \\ & & & (\mathtt{S}, \ell'_2) \end{tikzcd}$$

with $\ell_1 = \ell \cdot \ell'_1$ and $\ell_2 = \ell \cdot \ell'_2$ and $\ell'_1 \cap \ell'_2 = \emptyset$

*A set of runs is consistent when its elements are pair-wise consistent*

# On correct realisations

$$\begin{array}{ccc} & & (\mathtt{s}, \ell_1) \\ & \nearrow & \\ (\mathtt{s}, \epsilon) & & \\ & \searrow & \\ & & (\mathtt{s}, \ell_2) \end{array}$$

consistent if there is $\ell$ s.t.

$$(\mathtt{s}, \epsilon) \Longrightarrow (\mathtt{s}, \ell) \begin{array}{c} \nearrow (\mathtt{s}, \ell'_1) \\ \searrow (\mathtt{s}, \ell'_2) \end{array}$$

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*A set of runs is consistent when its elements are pair-wise consistent*

**Notation**

For $(\mathtt{G}, \epsilon) \xrightarrow{\mathtt{c}_1 \,/\, \mathtt{l}_1} (\mathtt{G}, \ell_1) \xrightarrow{\mathtt{c}_2 \,/\, \mathtt{l}_2} \cdots \xrightarrow{\mathtt{c}_n \,/\, \mathtt{l}_n} (\mathtt{G}, \overbrace{\ell_1 \cdot \ell_2 \cdot \cdots \cdot \ell_n}^{=\ell})$
let $\ell^{(j)} = \ell_j \cdot \cdots \cdot \ell_1$

$$\begin{tikzcd}[row sep=small] & (\mathtt{S}, \ell_1) \\ (\mathtt{S}, \epsilon) \arrow[ur, Rightarrow] \arrow[dr, Rightarrow] & \\ & (\mathtt{S}, \ell_2) \end{tikzcd}$$

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**Notation**

For $(\mathsf{G}, \epsilon) \xrightarrow{\mathtt{c}_1 / \mathtt{l}_1} (\mathsf{G}, \ell_1) \xrightarrow{\mathtt{c}_2 / \mathtt{l}_2} \cdots \xrightarrow{\mathtt{c}_n / \mathtt{l}_n} (\mathsf{G}, \overbrace{\ell_1 \cdot \ell_2 \cdots \cdot \ell_n}^{=\ell})$
let $\ell^{(j)} = \ell_j \cdot \cdots \cdot \ell_1$

## Admissibility

A log $\ell$ is admissible for a $\sigma$-WF protocol $\mathsf{G}$ if there are consistent runs $\{(\mathsf{G}, \epsilon) \Longrightarrow (\mathsf{G}, \ell_i)\}_{1 \le i \le k}$ and a log $\ell' \in (\bowtie_{1 \le i \le k} \ell_i)$ such that $\ell = \bigcup_{1 \le i \le k} \ell_i$ and

$$\ell' \equiv_{\mathsf{G},\sigma} \ell \qquad \text{and} \qquad \ell_i^{(j)} \sqsubseteq \ell \text{ for all } 1 \le i \le k$$

Hereafter, $\mathsf{G}$ denotes a $\sigma$-WF protocol

# Results

**Lemma (Well-formedness generates any admissible log)**

*If* $\ell$ *is admissible for* $\mathsf{G}$ *then there is a log* $\ell'$ *such that* $(\mathsf{G}, \epsilon) \Longrightarrow (\mathsf{G}, \ell')$ *and* $\ell \equiv_{\mathsf{G},\sigma} \ell'$

**Lemma (Admissibility is preserved)**

*Let* $\ell_1$ *and* $\ell_2 \subseteq \ell_1$ *be admissible logs for* $\mathsf{G}$*. If* $(\mathsf{G}, \ell_2) \xrightarrow{\mathtt{c}\,/\,\mathtt{l}} (\mathsf{G}, \ell_2 \cdot \ell_3)$ *and* $\ell \in \ell_1 \bowtie (\ell_2 \cdot \ell_3)$ *then* $\ell$ *is admissible for* $\mathsf{G}$

**Theorem (Well-formed protocols generate only admissible logs)**

*If* $(\mathtt{S}, \epsilon) \Longrightarrow (\mathtt{S}', \ell)$ *for* $(\mathtt{S}, \epsilon)$ *realisation of* $\mathsf{G}$ *then* $\ell$ *is admissible for* $\mathsf{G}$

**Corollary**

*Every realisation of* $\mathsf{G}$ *is eventually faithful wrt* $\mathsf{G}$ *and* $\sigma$

# On complete realisations

**Complete realisations**

A $(\sigma, \mathtt{G})$-realisation $(\mathtt{S}, \epsilon)$ of size $n$ is complete if for all $\mathtt{R} \in \mathsf{roles}(\mathtt{G}, \sigma)$ there exists $1 \leq i \leq n$ such that $\mathtt{S}(i) = \mathtt{G} \downarrow^{\sigma}_{\mathtt{R}}$ $\square$

**Lemma (Projections reflect swarm protocols)**

*If* $(\mathtt{G}, \epsilon) \Longrightarrow (\mathtt{G}, \ell)$ *then* $\delta(\mathtt{G} \downarrow^{\sigma}_{\mathtt{R}}, \ell) = \delta(\mathtt{G}, \ell) \downarrow^{\sigma}_{\mathtt{R}}$ *for all* $\mathtt{R} \in \mathsf{roles}(\mathtt{G}, \sigma)$

**Theorem (Complete realisations reflect the protocol)**

*Let* $(\mathtt{S}, \epsilon)$ *be a complete realisation of* $\mathtt{G}$. *If* $(\mathtt{G}, \epsilon) \Longrightarrow (\mathtt{G}, \ell)$ *then there is a swarm* $\mathtt{S}'$ *such that* $(\mathtt{S}, \epsilon) \Longrightarrow (\mathtt{S}', \ell)$

# Plan of the talk

A motivating case study

Our formalisation

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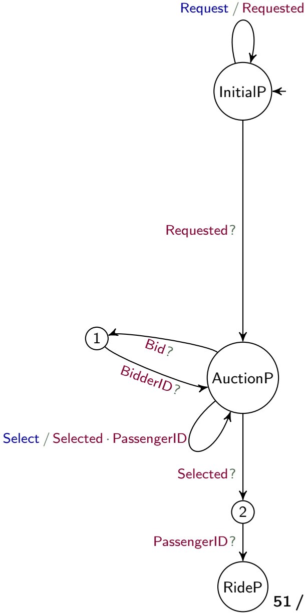
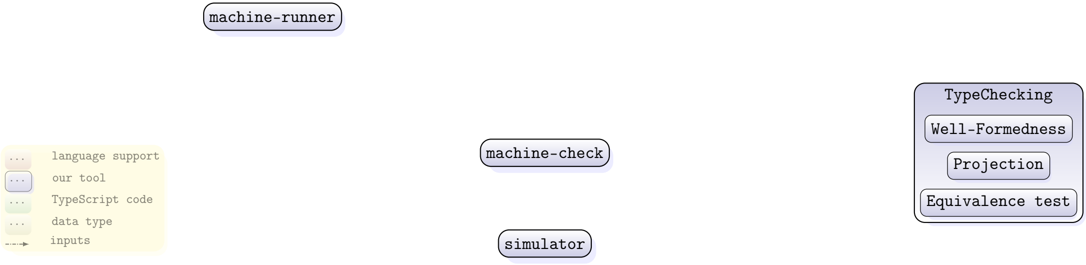
# – Tooling –

```
// analogous for other events; "type" property matches type name (checked by tool)
type Requested = { type: 'Requested'; pickup: string; dest: string }
type Events = Requested | Bid | BidderID | Selected | ...

/** Initial state for role P */
@proto('taxiRide') // decorator injects inferred protocol into runtime
export class InitialP extends State<Events> {
  constructor(public id: string) { super() }
  execRequest(pickup: string, dest: string) {
    return this.events({ type: 'Requested', pickup, dest })
  }
  onRequested(ev: Requested) {
    return new AuctionP(this.id, ev.pickup, ev.dest, [])
  }
}
@proto('taxiRide')
export class AuctionP extends State<Events> {
  constructor(public id: string, public pickup: string, public dest: string,
    public bids: BidData[]) { super() }
  onBid(ev1: Bid, ev2: BidderID) {
    const [ price, time ] = ev1
    this.bids.push({ price, time, bidderID: ev2.id })
    return this
  }
  execSelect(taxiId: string) {
    return this.events({ type: 'Selected', taxiID },
                       { type: 'PassengerID', id: this.id })
  }
  onSelected(ev: Selected, id: PassengerID) {
    return new RideP(this.id, ev.taxiID)
  }
}
@proto('taxiRide')
export class RideP extends State<Events> { ... }
```



# Architecture




- TypeChecking implements the functionalities of our typing discipline
- simulator simulates the semantics of swarm realisations
- machine-check and machine-runner integrate our framework in the Actyx platform

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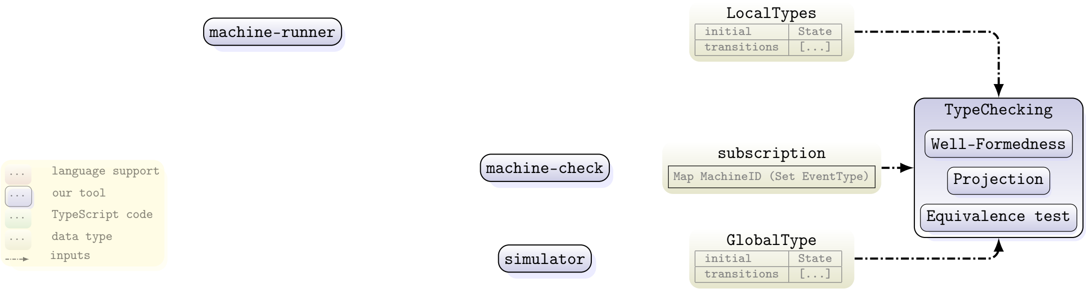


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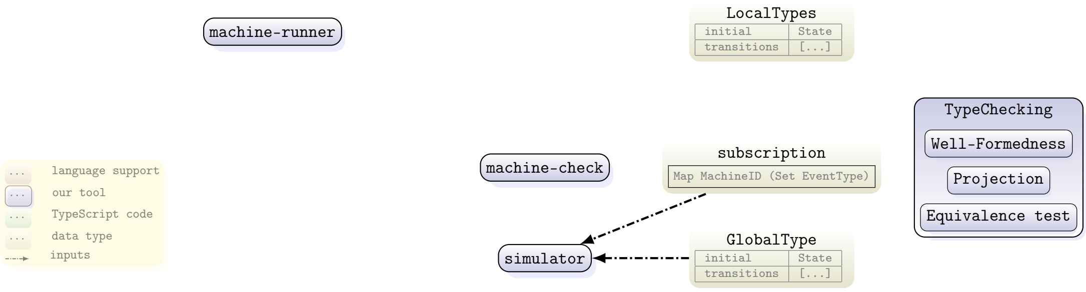


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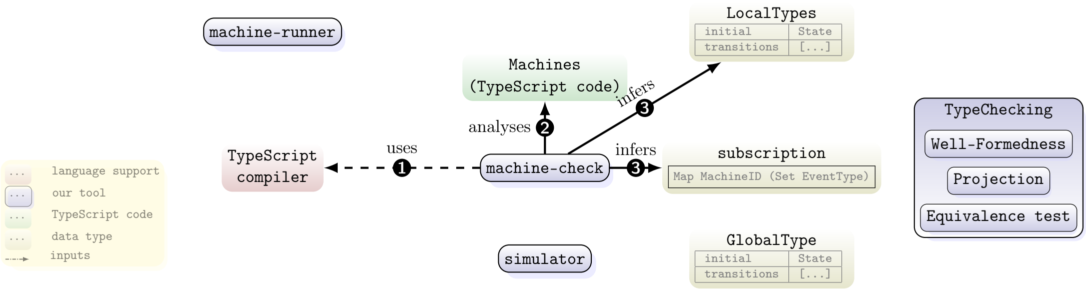


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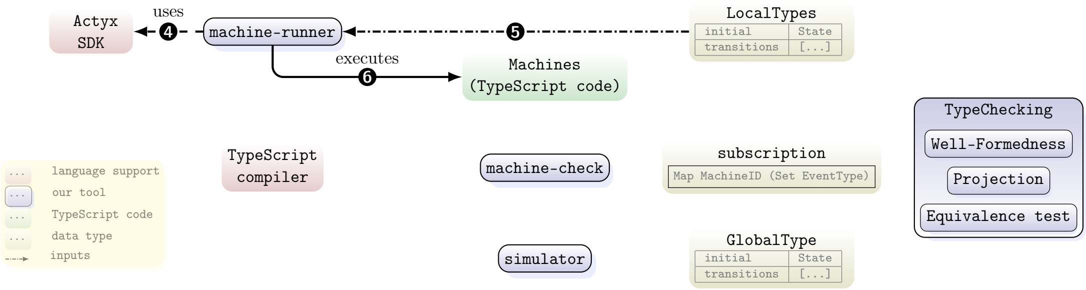


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# If you want to play with our prototype?

Have a look at

- our ECOOP artifact paper (not online yet; extended version at `https://arxiv.org/abs/2305.04848`)
- code at `https://doi.org/10.5281/zenodo.7737188`
- An ISSTA tool paper from Actyx (`https://arxiv.org/abs/2306.09068`)

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# – Epilogue –

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A formal semantics that faithfully captures Actyx's platform

and behavioural types to specify and verify eventual consensus

*Thank you!*