Behavioural Types for Local-First Software

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joint work with

Roland Kuhn @ Actyx and Hernán Melgratti @ UBA

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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using local-first's principles to establish eventual consensus

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- swarm $=$ (machines $+$ local logs) $*$ imaginary global log
- swarm protocols: systems from an abstract global viewpoint
- enforce good behaviour via behavioural typing

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See our recent ECOOP 2023 paper
(`https://drops.dagstuhl.de/opus/frontdoor.php?source_opus=18208`;
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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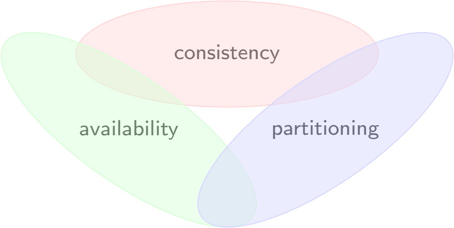


Availability = Money

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

With some "solutions"

Centralisation points
Consensus protocols
Commutative replicated data types
...

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

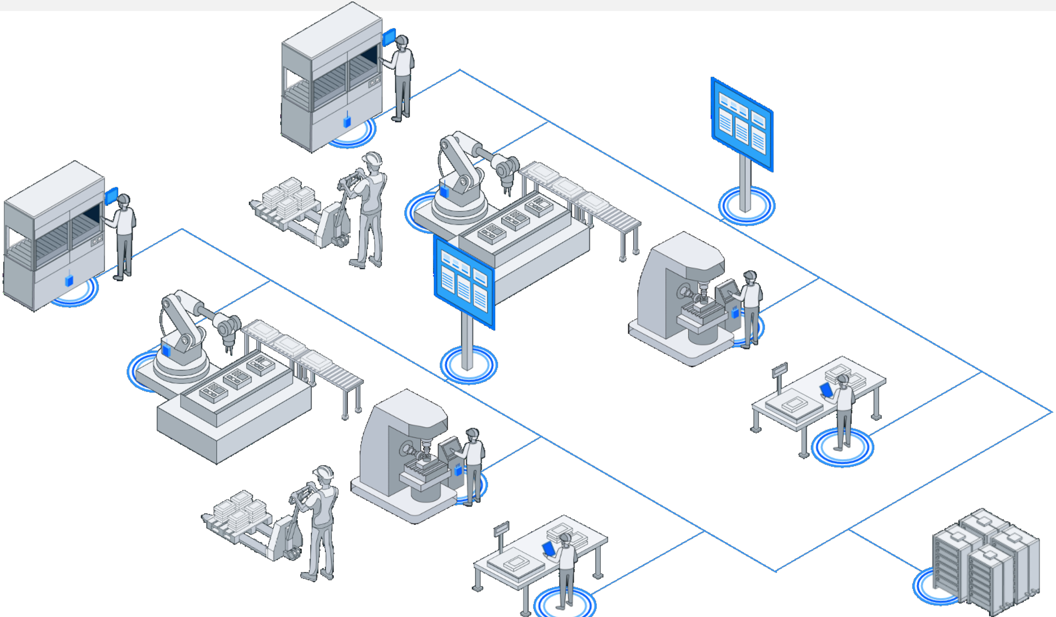
Tool support

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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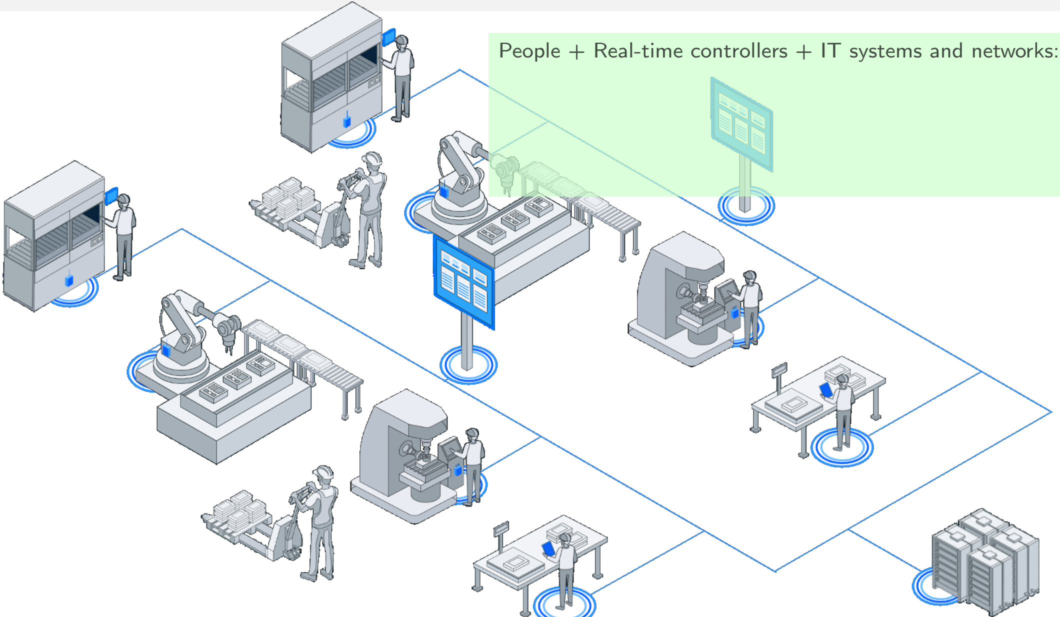

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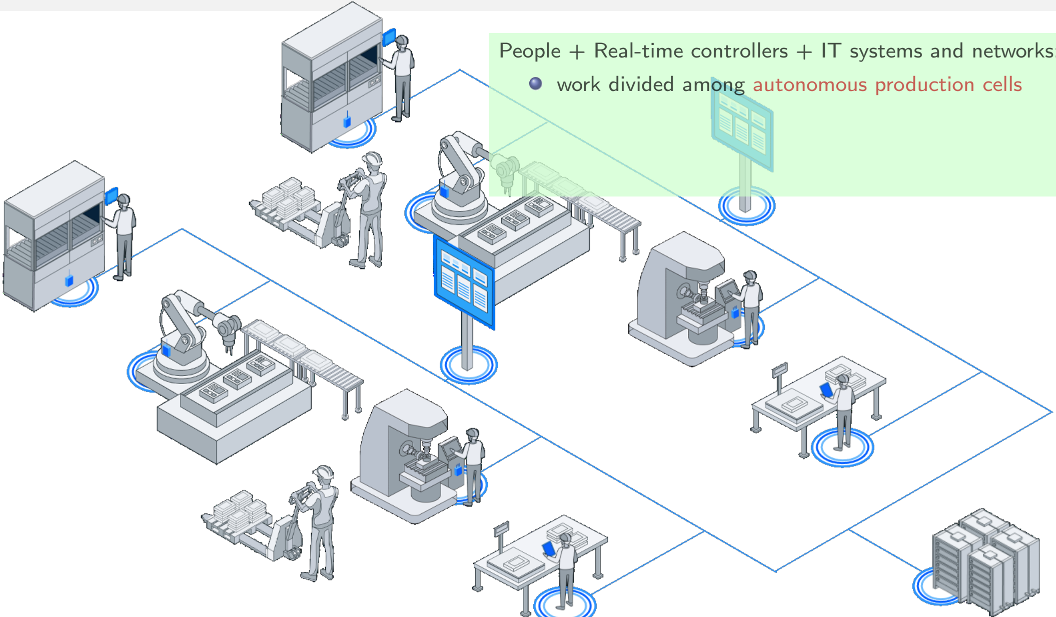

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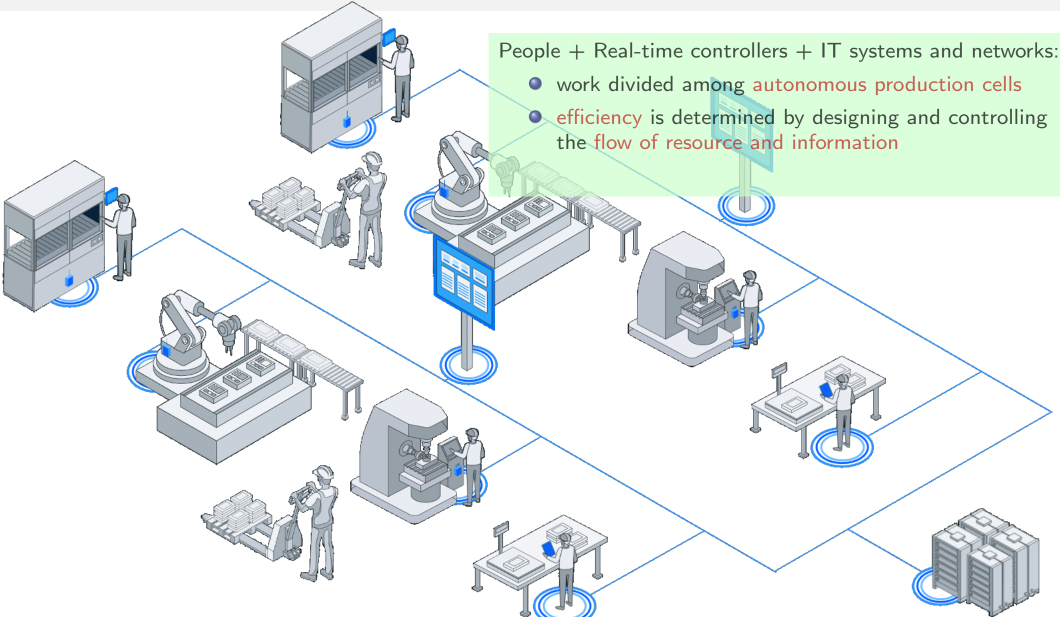

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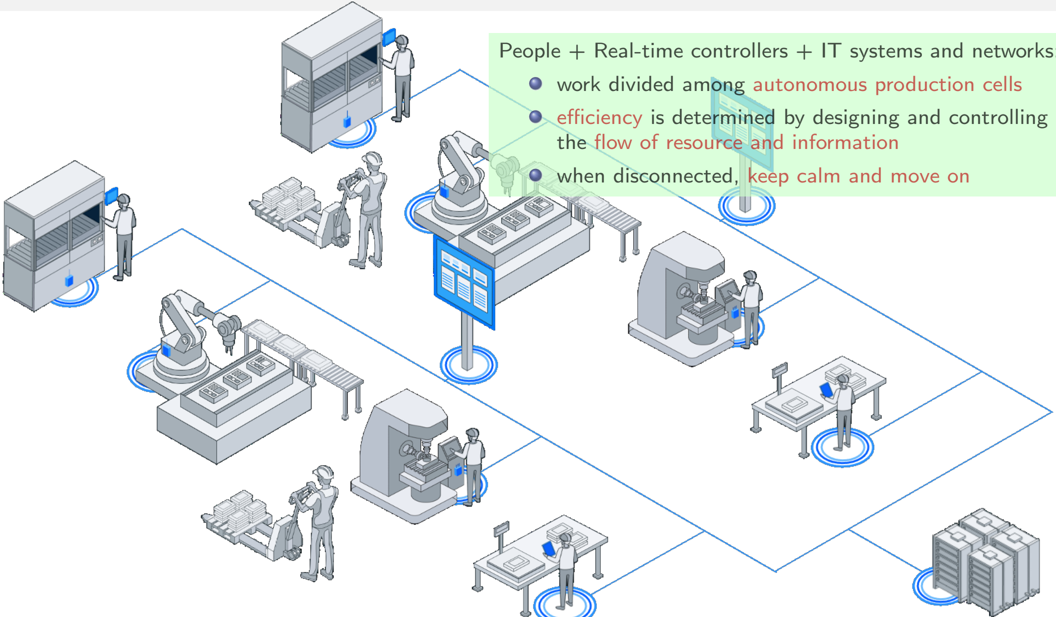

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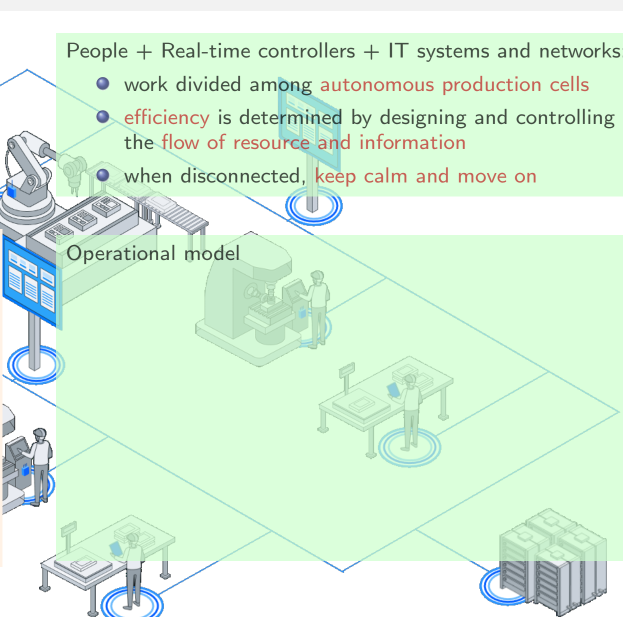

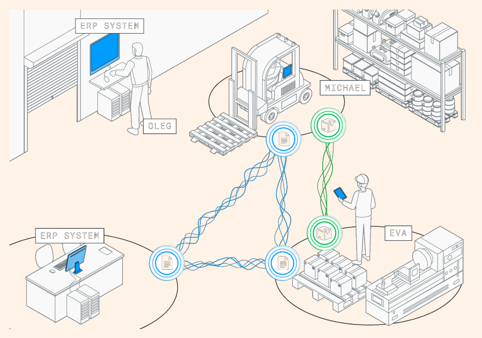

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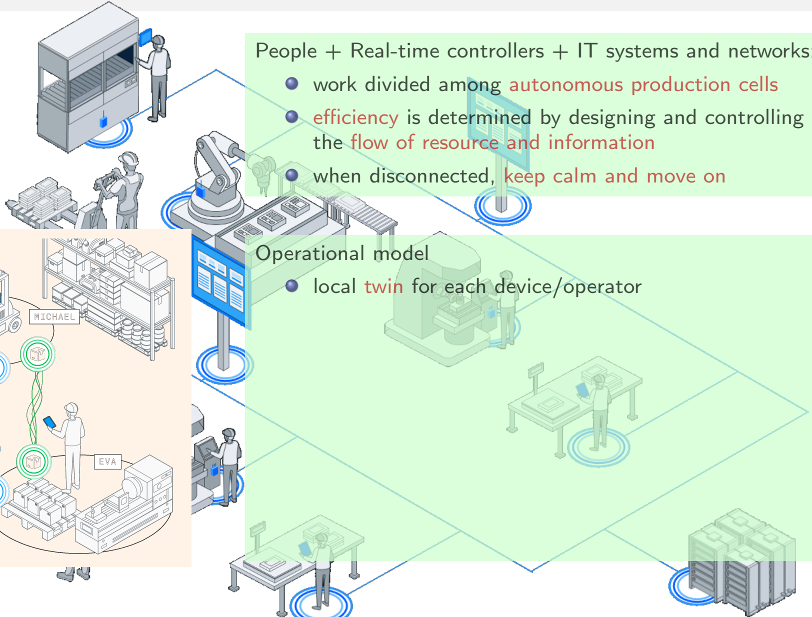

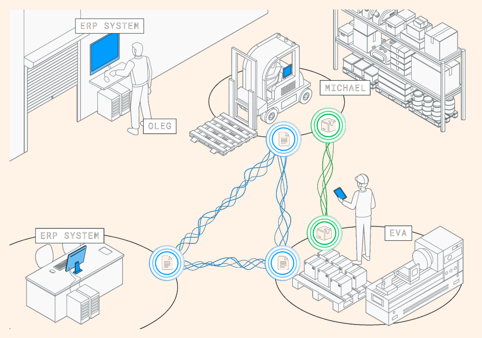

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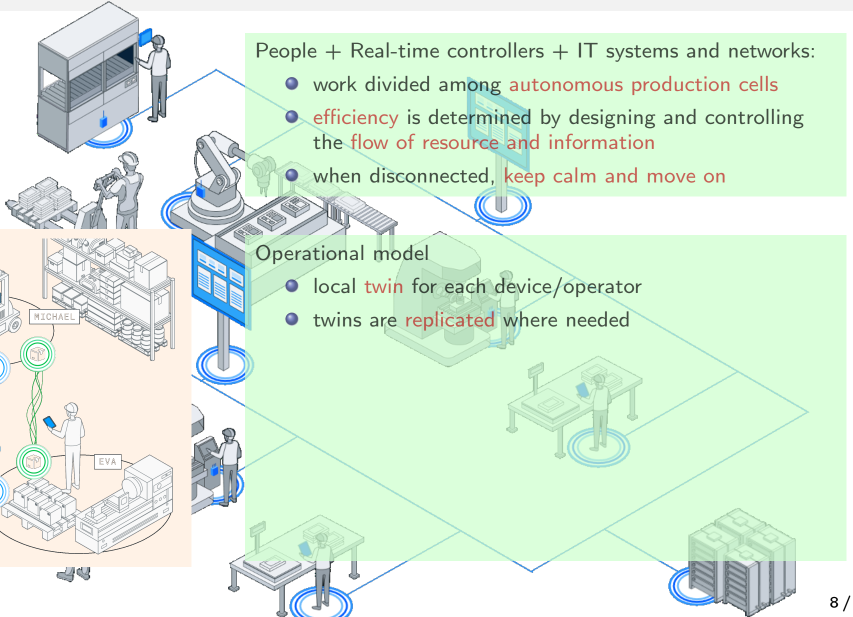

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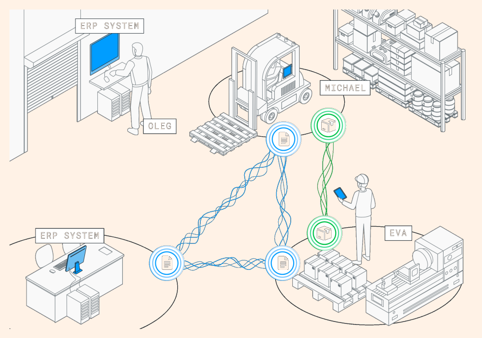

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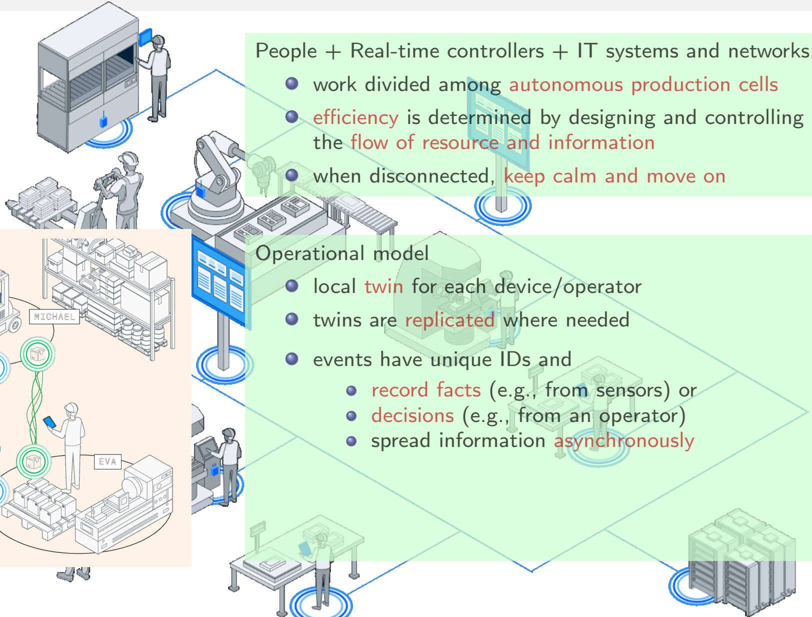

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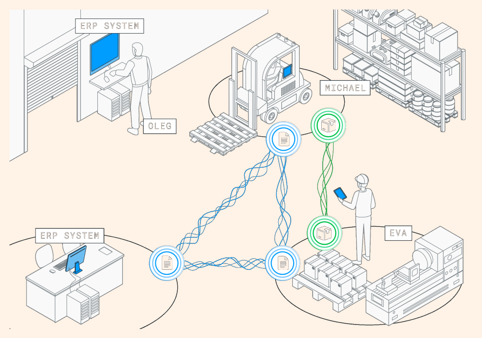

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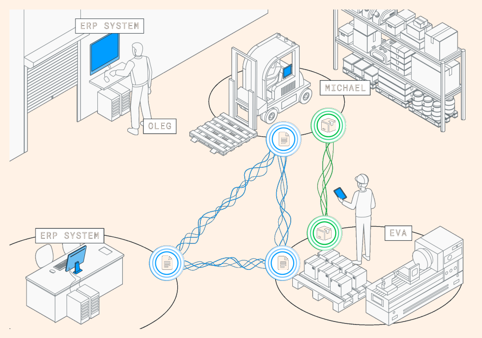

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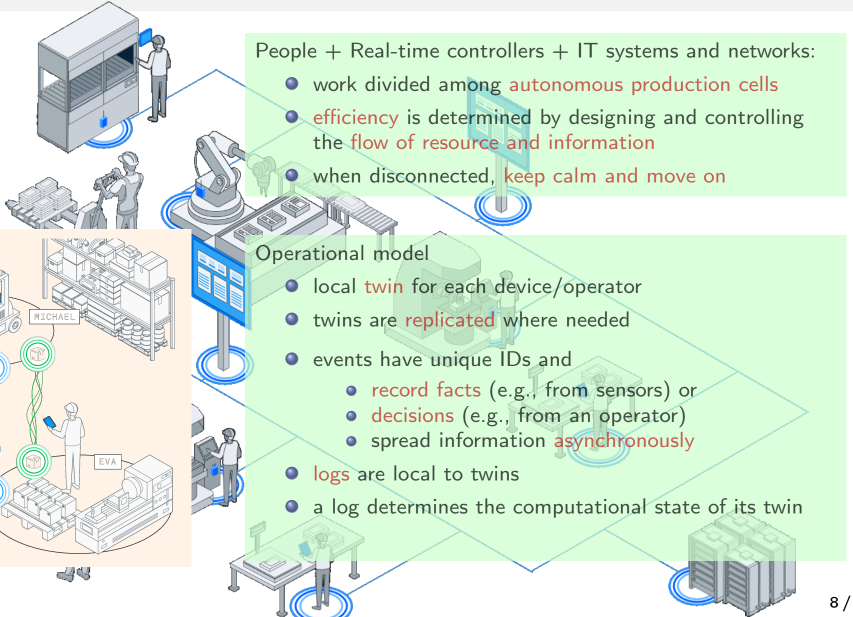

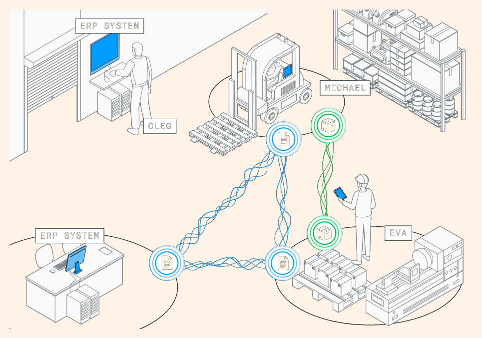

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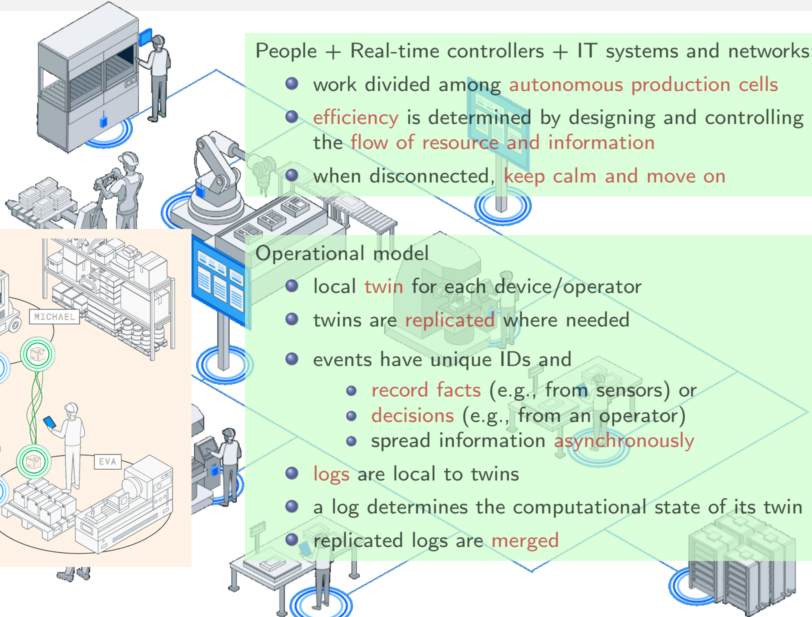

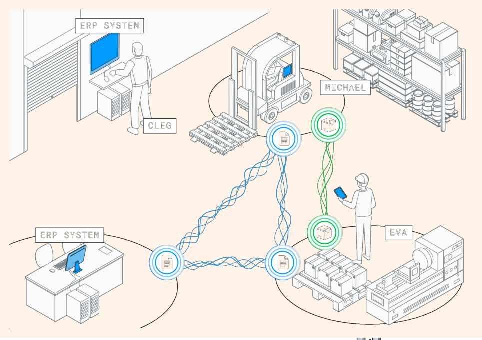

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- logs are local to twins
- a log determines the computational state of its twin
- replicated logs are merged

```
while true:
    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 $e_1 \cdot e_2 \ldots$

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Events $\vdash$ e : t

$$src(e)$$

Logs $\vdash$ $e_1 \cdot e_2 \ldots$: $t_1 \cdot t_2 \ldots$

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

$$src(e)$$

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

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

Ingredients (II): log shipping

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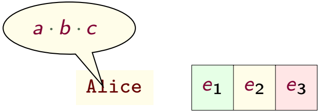

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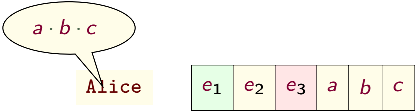

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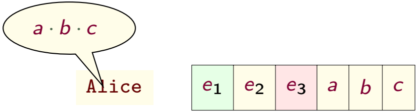
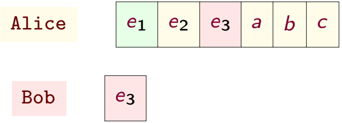


Phase II: newly emitted events are shipped to other machines



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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

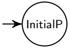
`Bob` e_3

$\xrightarrow{\text{propagating } b}$

`Alice` e_1 e_2 e_3 a b c

`Bob` e_2 e_3 a b

Machines by example



`InitialP` $=$

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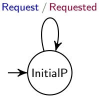

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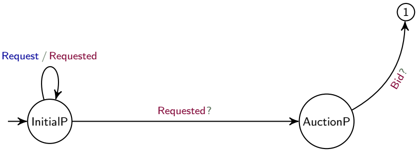

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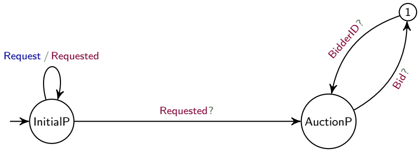

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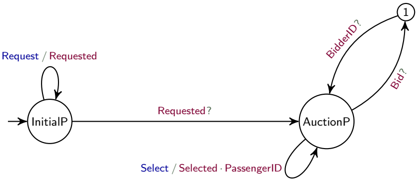

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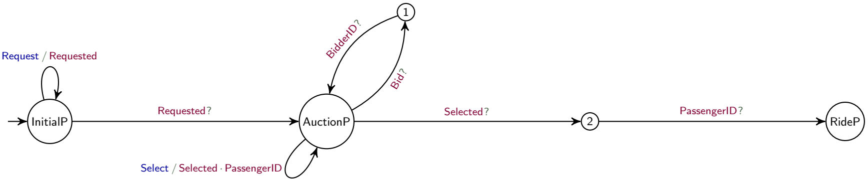

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$$\texttt{RideP} \quad = \quad \cdots$$

Machines, formally

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

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

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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all events of ℓ_1 appear in the same order in ℓ_2

- $e <_{\ell_2} e'$, $src(e) = src(e')$ and $e' \in \ell_1 \implies e \in \ell_1$

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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

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

Semantics of swarms

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

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

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

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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spec,no code

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Well-formedness

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spec,no code

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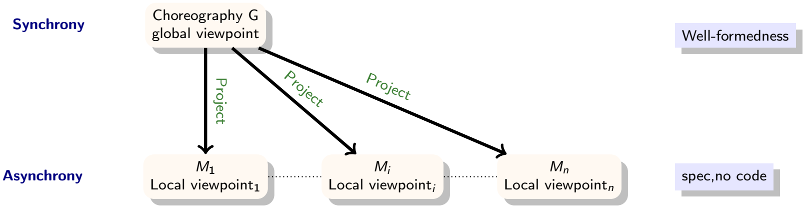
Quoting W3C:

> *"[...] 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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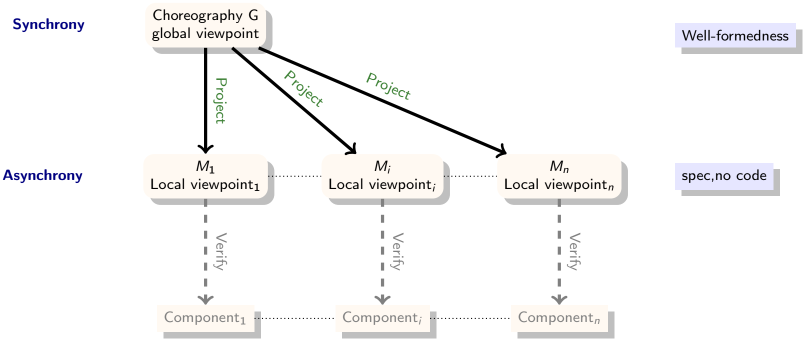
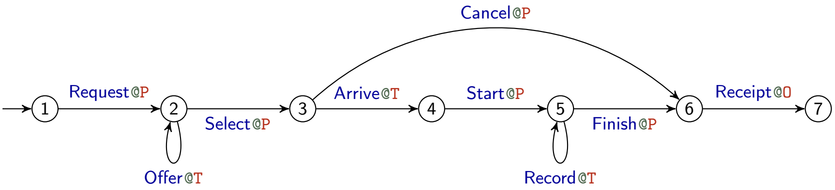


Swarm protocols by example

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



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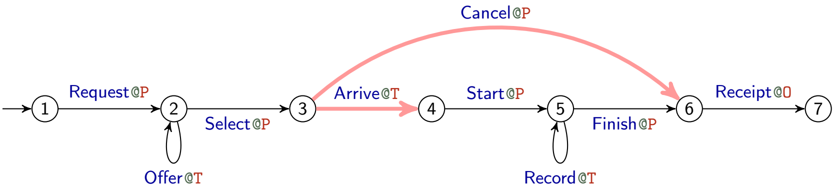

Swarm protocols: global type for local-first applications

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:

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

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

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

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

An example

A swarm protocol for the taxi scenario on slide 31:

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

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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 G plus the states in G_i for each $i \in \{1 \ldots, n\}$
- G is the initial state
- for each $i \in I$, G has a transition to state 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!

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

Semantics of swarm protocols

One rule only!

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

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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Each machine plays one role

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Obtain machines by projecting G on each role

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Obtain machines by projecting G on each role

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

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

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

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"

Another attempt

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

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 σ is

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

where

Another attempt

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

In pub-sub, processes subscribe to "topics"

Given $\mathsf{G} = \sum_{i \in I} \mathtt{c}_i @ \mathtt{R}_i \langle \mathtt{l}_i \rangle \,.\, \mathsf{G}_i$, the
projection of G on a role $\mathtt{R}$ with respect to subscription σ is

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

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

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

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

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 σ. 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* c *enabled after* c' *then* $\sigma(\mathtt{R})$ *contains some event type emitted by* 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 G_i

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

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

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

Well-formedness = Causality + Determinacy - Confusion

Trading consistency for availability has implications:

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

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

Causality & Determinacy & Confusion freeness

Fix a subscription σ. 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	$\sigma(\mathtt{R}_i) \cap \mathtt{l}_i \neq \emptyset$
Command causality	if $\mathtt{R}$ executes a command in G_i then $\sigma(\mathtt{R}) \cap \mathtt{l}_i \neq \emptyset$ and $\sigma(\mathtt{R}) \cap \mathtt{l}_i \supseteq \bigcup_{\mathtt{R}' \in_\sigma \mathsf{G}_i} \sigma(\mathtt{R}') \cap \mathtt{l}_i$
Determinacy	$\mathtt{R} \in_\sigma \mathsf{G}_i \implies \mathtt{l}_i[0] \in \sigma(\mathtt{R})$
Confusion freeness	for each $\mathtt{t}$ starting a log emitted by a command in G there is a unique state G' reachable from G which emits $\mathtt{t}$

Implementations

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

A swarm $(\mathtt{S}, \epsilon)$ is eventually faithful to G and σ 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 (σ, G)-realisation is a swarm $(\mathtt{S}, \epsilon)$ such that, for each $i \in \operatorname{dom} \mathtt{S}$, there exists a role $\mathtt{R} \in \mathsf{roles}(\mathsf{G}, \sigma)$ such that $\mathtt{S}(i) = \mathsf{G} \downarrow^{\sigma}_{\mathtt{R}}$ $\square$

Implementations & projections

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

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

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

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

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

On correct realisations

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

consistent if there is ℓ s.t.

$$\begin{tikzcd}[row sep=small] & & (\mathtt{s}, \ell'_1) \\ (\mathtt{s}, \epsilon) \arrow[r, Rightarrow] & (\mathtt{s}, \ell) \arrow[ur, Rightarrow] \arrow[dr, Rightarrow] & \\ & & (\mathtt{s}, \ell'_2) \end{tikzcd}$$

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 ℓ s.t. $(\mathtt{S}, \epsilon) \Longrightarrow (\mathtt{S}, \ell)$ $\begin{array}{l} \nearrow (\mathtt{S}, \ell'_1) \\ \searrow (\mathtt{S}, \ell'_2) \end{array}$ 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

Notation

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

On correct realisations

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

consistent if there is ℓ s.t. $(\mathtt{s}, \epsilon) \Longrightarrow (\mathtt{s}, \ell)$ $\begin{array}{c} (\mathtt{s}, \ell_1') \\ \nearrow\!\!\!\!\nearrow \\ \\ \searrow\!\!\!\!\searrow \\ (\mathtt{s}, \ell_2') \end{array}$ 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

Notation

For $(\mathsf{G}, \epsilon) \xrightarrow{\mathtt{c_1} / \mathtt{l_1}} (\mathsf{G}, \ell_1) \xrightarrow{\mathtt{c_2} / \mathtt{l_2}} \cdots \xrightarrow{\mathtt{c}_n / \mathtt{l}_n} (\mathsf{G}, \overbrace{\ell_1 \cdot \ell_2 \cdot \cdots \cdot \ell_n}^{=\ell})$
let $\ell^{(j)} = \ell_1 \cdot \cdots \cdot \ell_j$

Admissibility

A log ℓ is admissible for a σ-WF protocol 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

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

Results

Let G be well-formed; a realisation is a swarm whose components are projections of G

Lemma (Well-formedness generates any admissible log)

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

Theorem (Well-formed protocols generate only admissible logs)

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

Corollary

Every realisation of G is eventually faithful wrt G and σ

Theorem (Full realisations are complete)

If $\mathtt{S}$ is a full realisation of G and $(\mathsf{G}, \epsilon) \Longrightarrow (\mathsf{G}, \ell')$ then there is $\mathtt{S}'$ s.t. $(\mathtt{S}, \epsilon) \Longrightarrow (\mathtt{S}', \ell)$

Plan of the talk

A motivating case study

Our formalisation

Our typing discipline

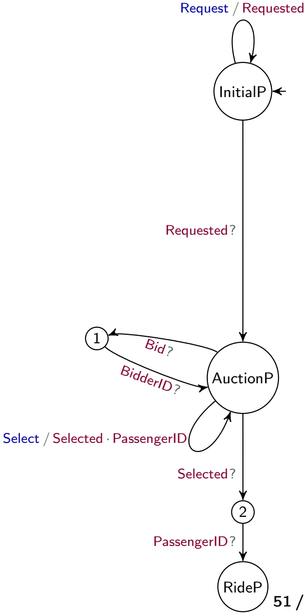
Tool support

Future work

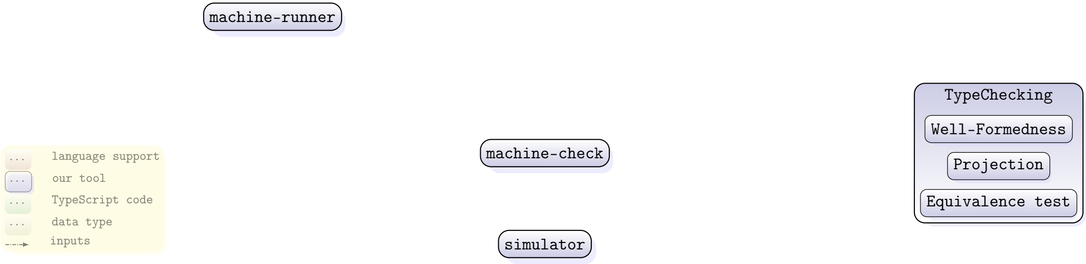
– Tooling –

```
// 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> { ... }
```

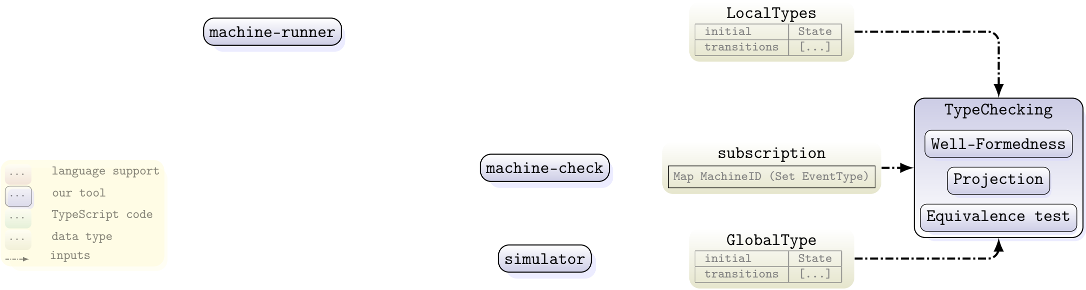


Architecture



- 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

Architecture



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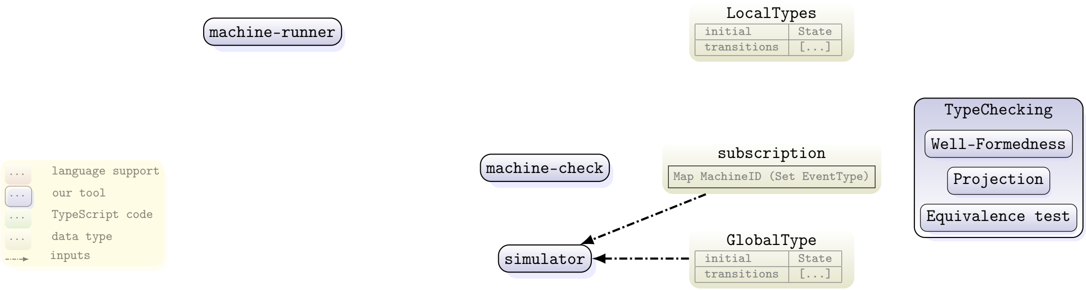

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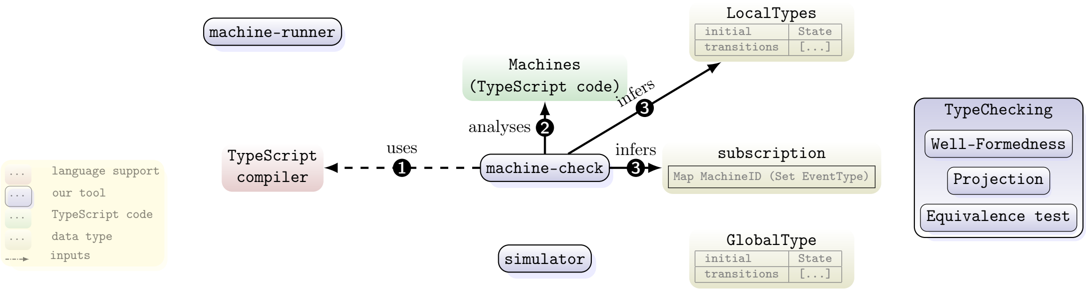

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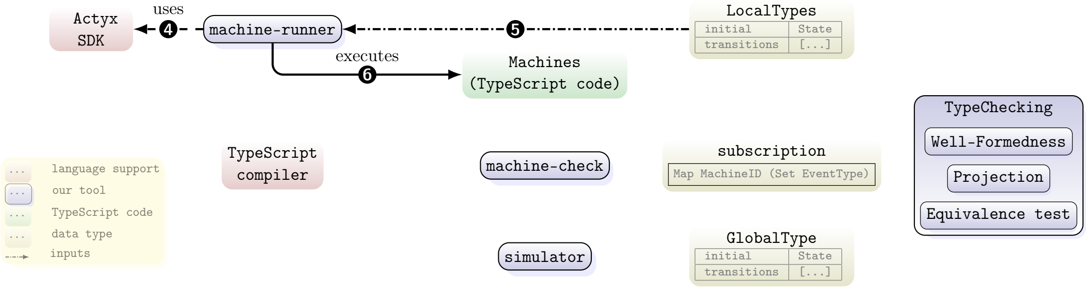

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If you want to play with our prototype?

Have a look at

- our ECOOP artifact paper (https://drops.dagstuhl.de/opus/volltexte/2023/18254/)
- code at https://doi.org/10.5281/zenodo.7737188
- An ISSTA tool paper from Actyx (https://arxiv.org/abs/2306.09068)

Plan of the talk

A motivating case study

Our formalisation

Our typing discipline

Tool support

Future work

– Epilogue –

To be continued....

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and behavioural types to specify and verify eventual consensus

Thank you!

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If you rerun the document (without altering it) this surplus page will go away, becau
LaTeX now knows how many pages to expect for this document.