Local-First Principles: a Behavioural Types Approach

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joint work with

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Tutorial at Discotec 2023
Lisbon 23 June, 2023

– Prelude –

Take-away message

To trade consistency for availability in systems of **asymmetric replicated peers**

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- machines: peers
- enforce good behaviour via behavioural typing

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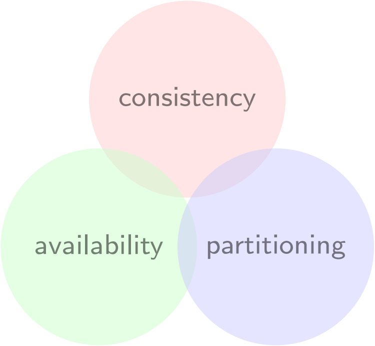
See our recent ECOOP 2023 paper
(to appear; extended version available at
`https://arxiv.org/abs/2305.04848`)

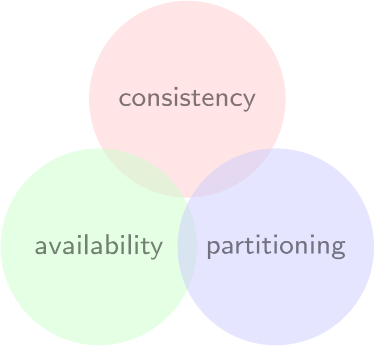
Distributed coordination



An "old" problem

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

Distributed coordination



An “old” problem

Distributed agreement
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With some “solutions”

Centralisation points
Distributed consensus
Commutative replicated data types
...

Local-first...first

Autonomy

Thou shall be autonomous
Thou shall collaborate
Thou shall recognise and embrace conflicts
Thou shall resolve conflicts
Thou shall be consistent

Some implications

- peers are not malicious
- peers can progress at all times...even under partial knowledge
- purity: inconsistencies resolved by "replaying" executions (invertible or compensatable actions)
- reliable communications

Local-First at work

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They use a mobile app to agree on a grocery list and decide who buys what.

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Eventually the lists can be merged somehow...But who's going to buy the eggs?

Plan of the talk

A motivating case study

Our formalisation

Our typing discipline

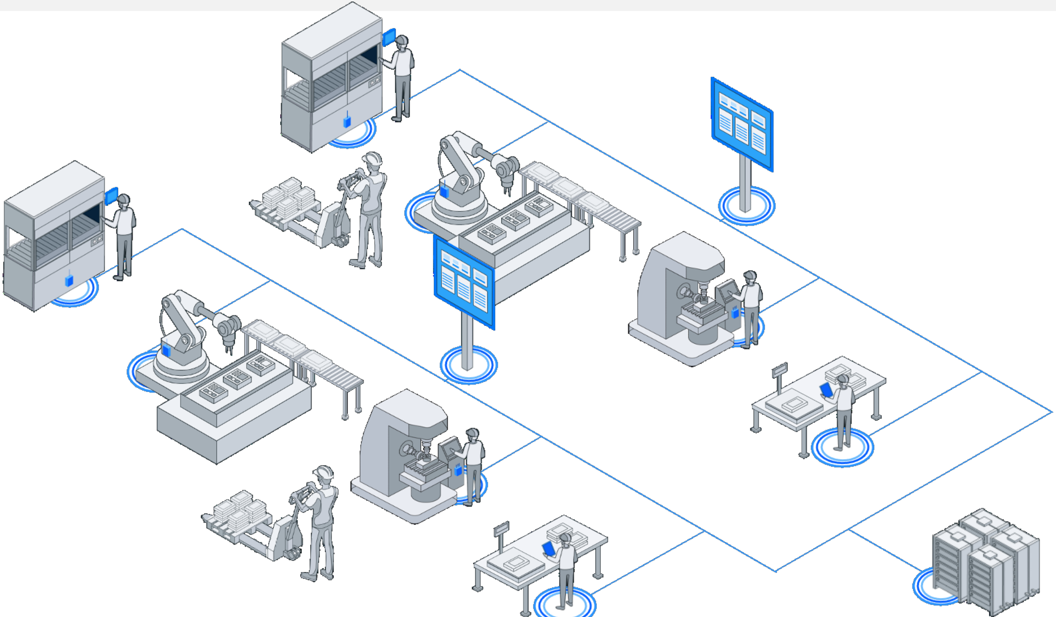
Tool support

Open issues

– Motivations –

A collaborative environment and its execution model

(the pictures are courtesy of Actyx AG)



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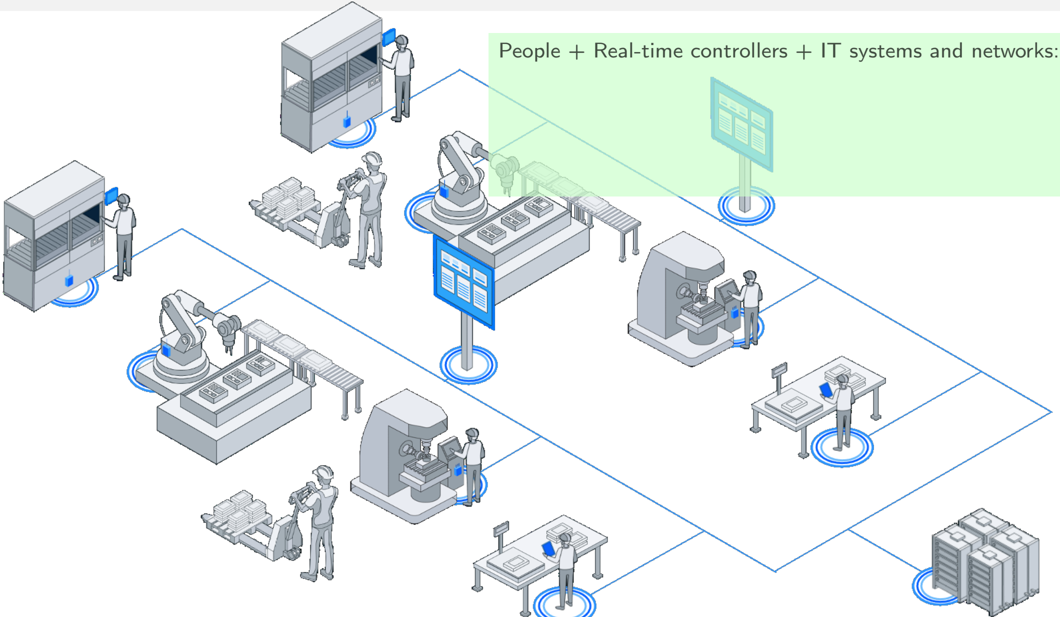

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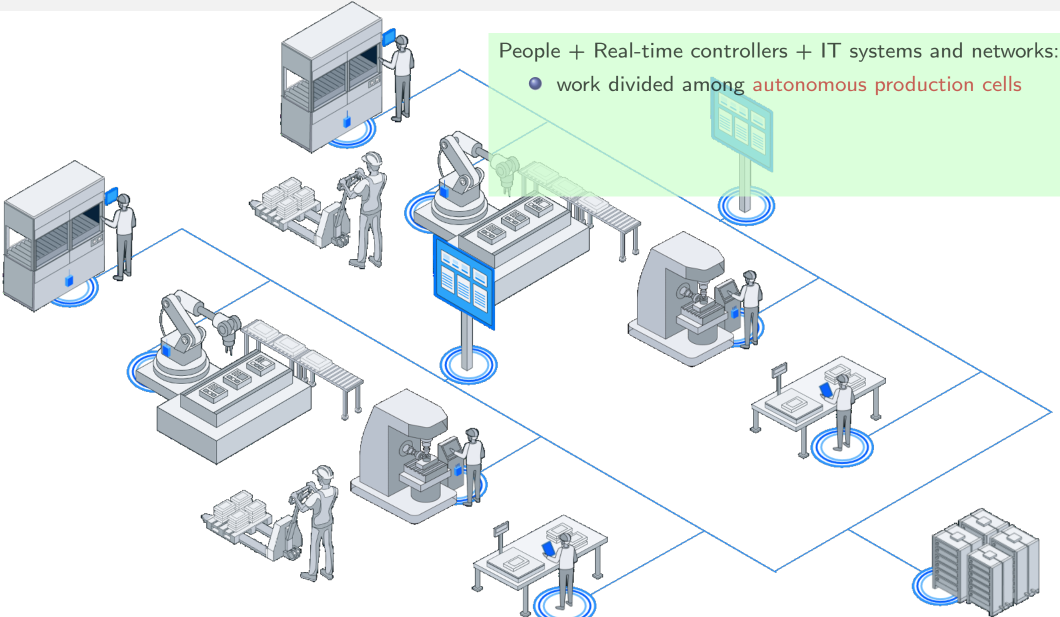

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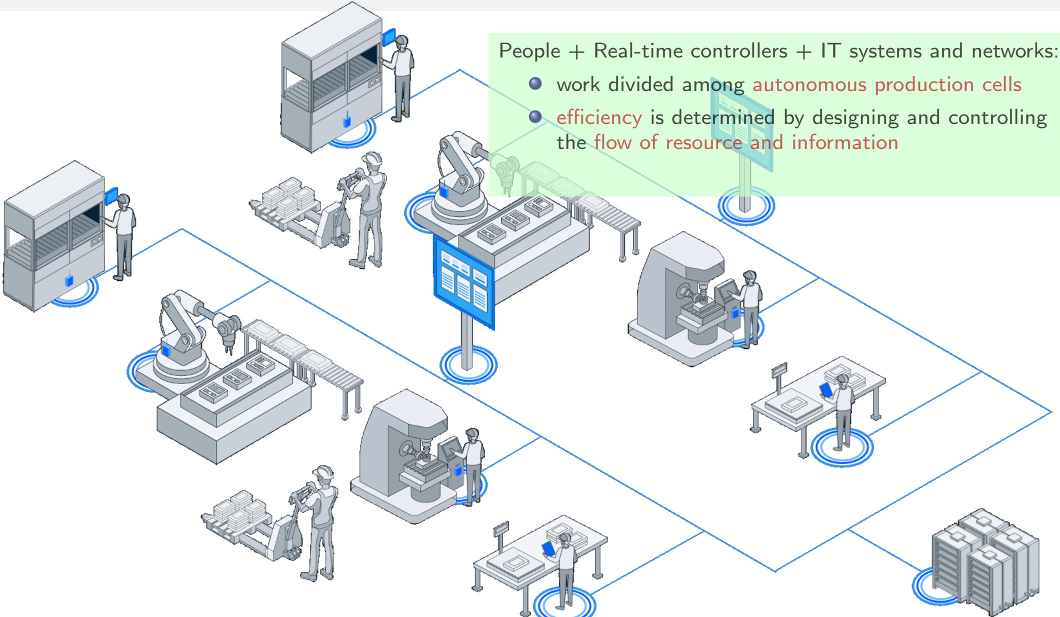

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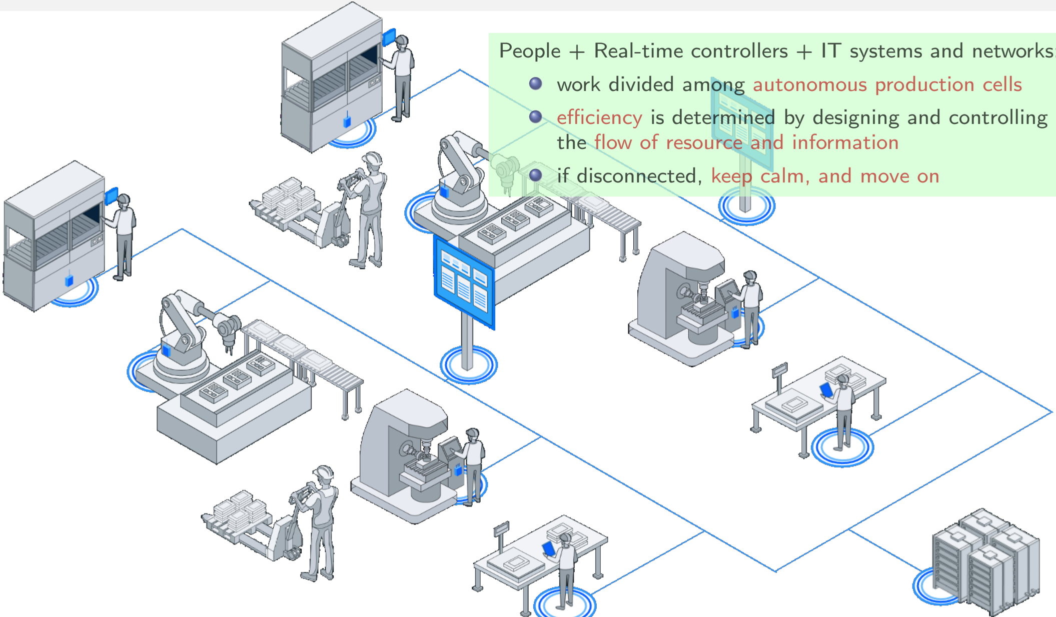

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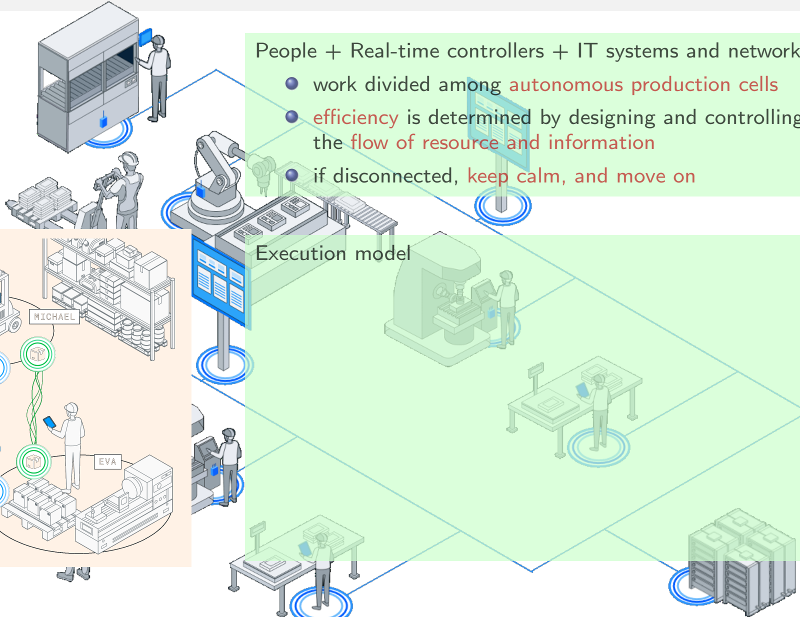

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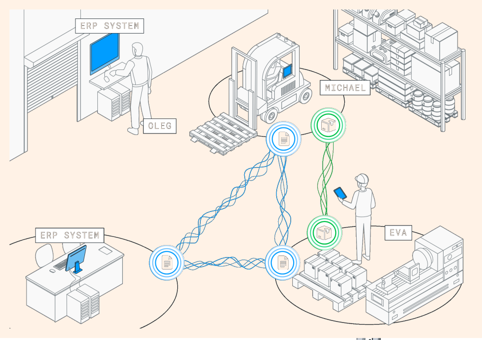

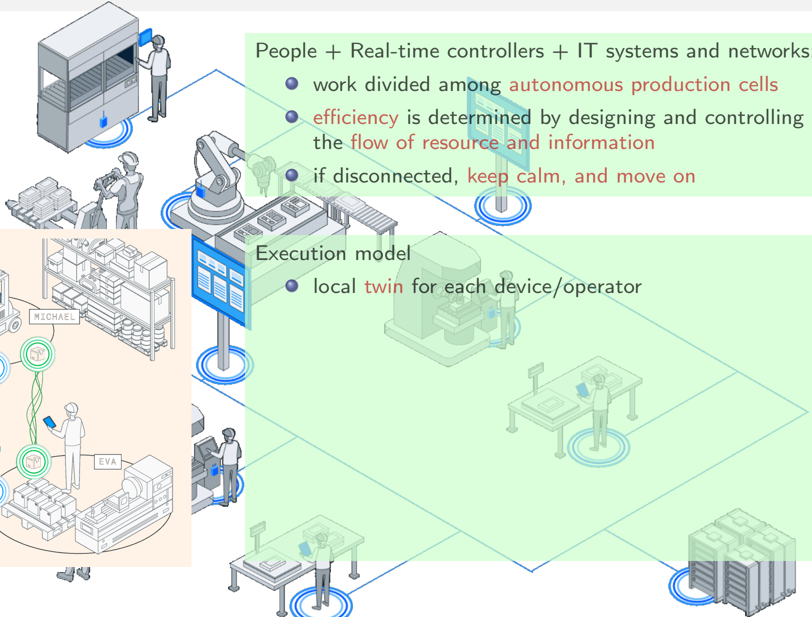

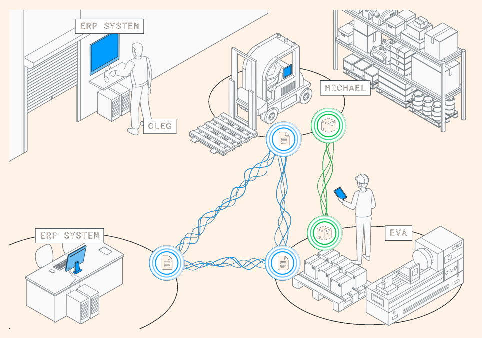

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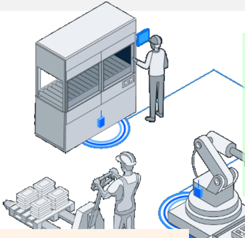

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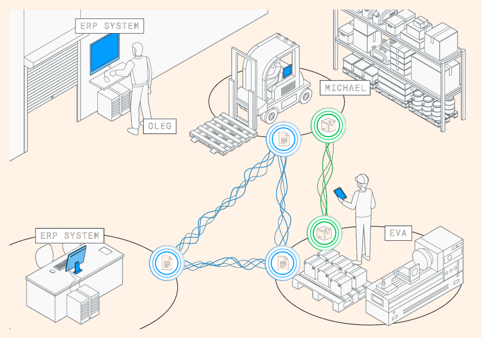

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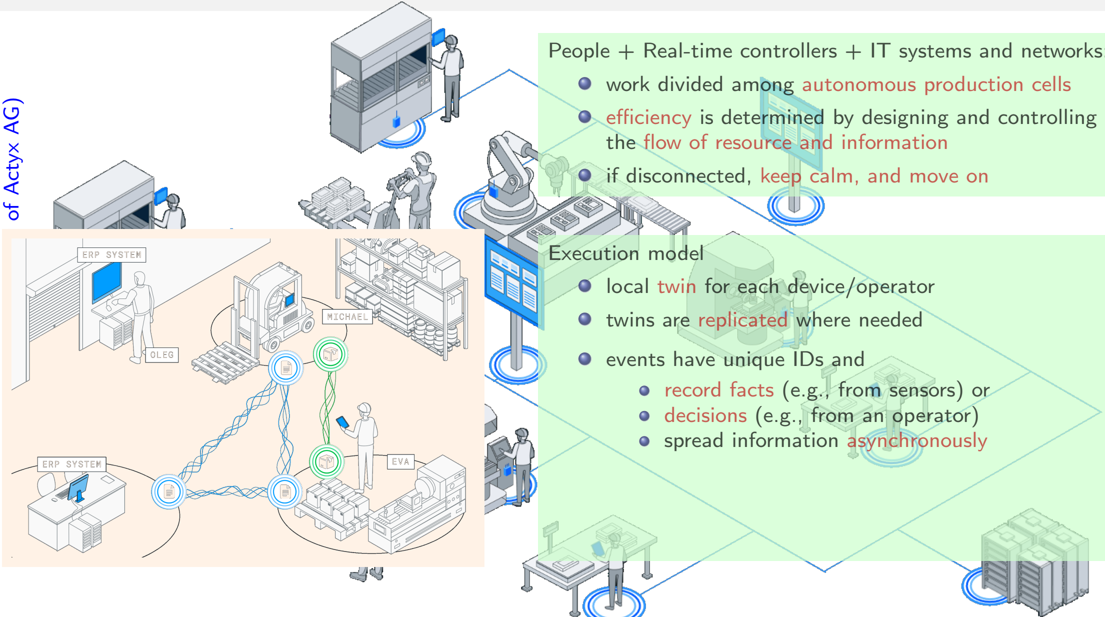

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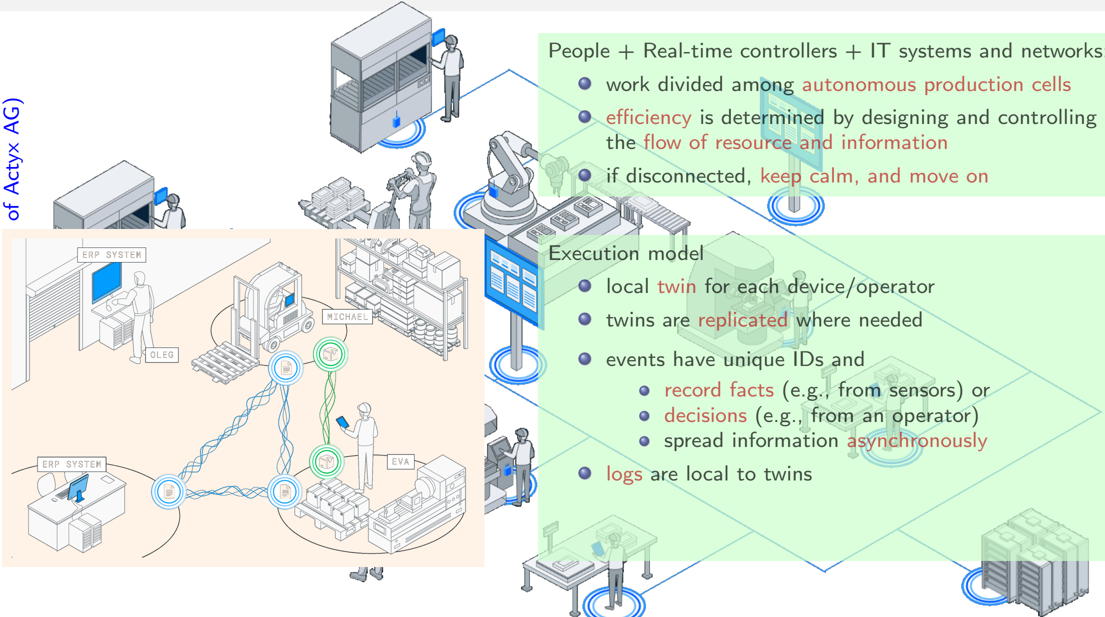

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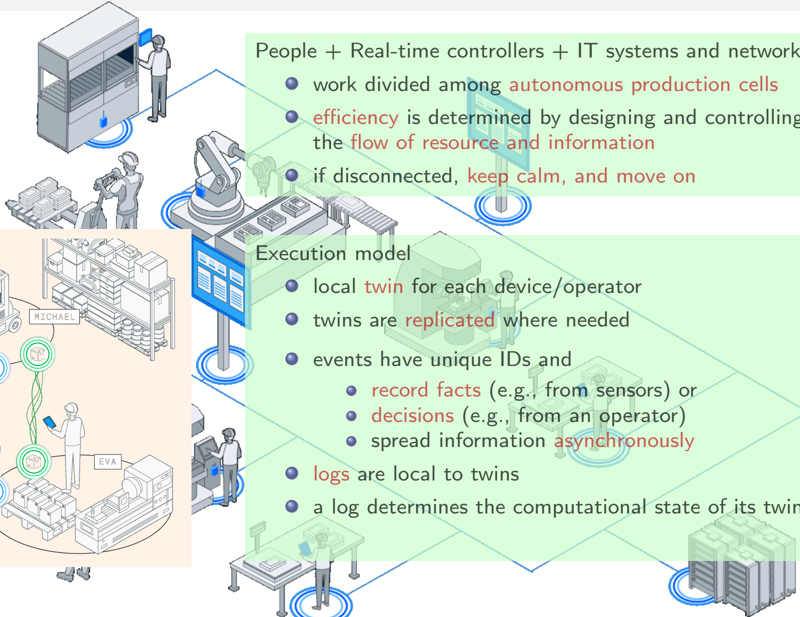

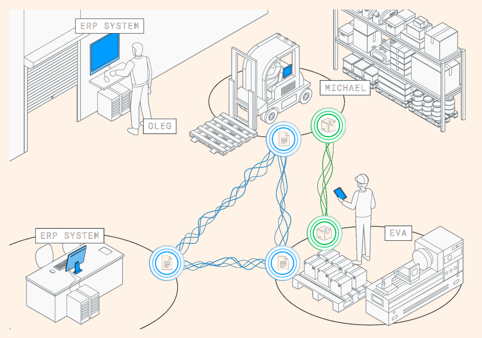

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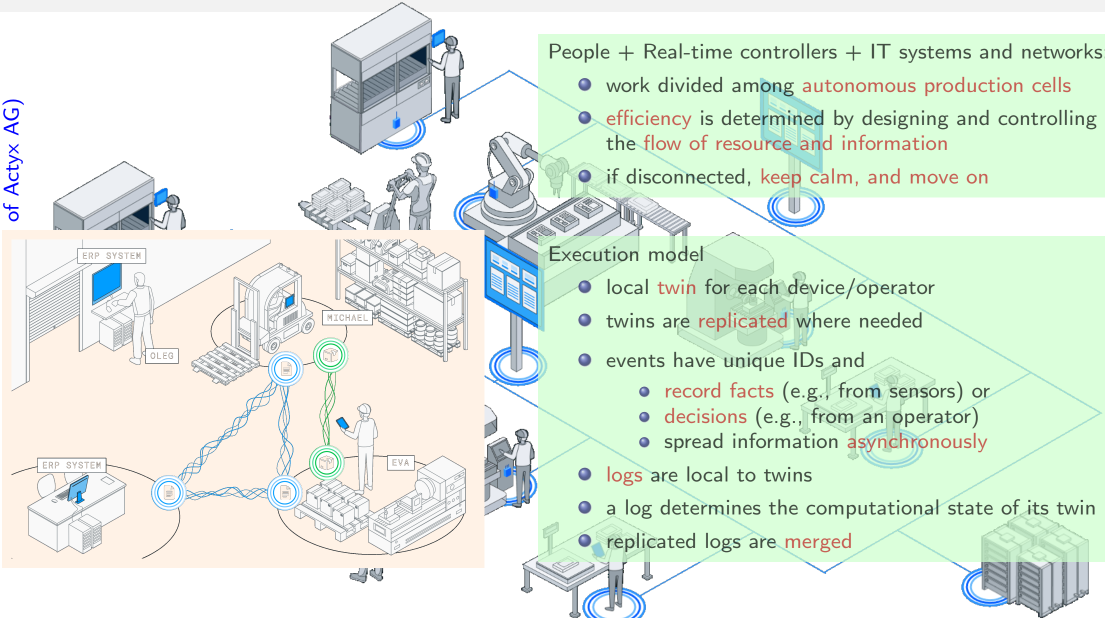

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- a log determines the computational state of its twin
- replicated logs are merged

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

Challenges

Specify application-level protocols where decisions

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Specify application-level protocols where decisions

- don't require consensus
- are based on stale local states
- yet, collaboration has to be successful

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– A formal model –

Events	e
	$src(e)$
Logs	$e_1 \cdot e_2 \ldots$

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		$src(e)$		
Logs	$\vdash$	$e_1 \cdot e_2 \ldots$	$:$	$t_1 \cdot t_2 \ldots$

Ingredients (I): events & logs

Events $\vdash$ e : t

$$src(e)$$

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

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

Ingredients (II): log shipping

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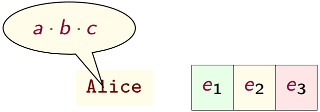

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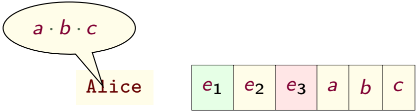

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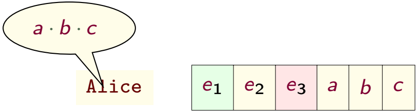
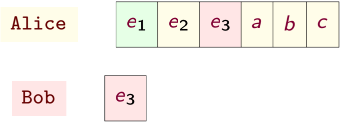


Phase II: newly emitted events are shipped to other machines



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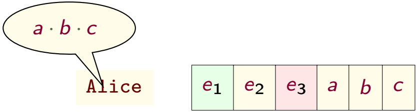

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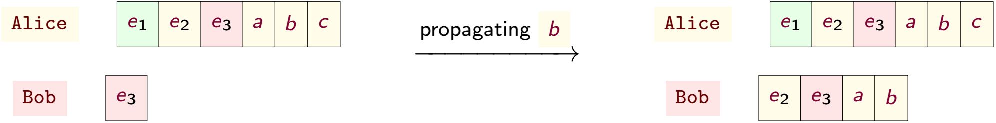

Machines

Fix a set of commands ranged over by c

Let κ range over finite maps from commands to non-empty log types

Machines

Fix a set of commands ranged over by $\mathtt{c}$

Let κ range over finite maps from commands to non-empty log types

A machine is a **regular term** of this co-inductive grammar

$$\mathtt{M} \overset{\text{co}}{::=} \kappa\cdot[\mathtt{t}_1\,?\,\mathtt{M}_1\,\&\cdots\&\,\mathtt{t}_n\,?\,\mathtt{M}_n]$$

for $i \in \{1\ldots,n\}$, the guard of the i-th branch is $\mathtt{t}_i$

An infinite tree is regular when it has finitely-many subtrees The subtrees of $\mathtt{M} = \kappa\cdot[\mathtt{t}_1\,?\,\mathtt{M}_1\,\&\cdots\&\,\mathtt{t}_n\,?\,\mathtt{M}_n]$ are $\mathtt{M}$ plus the subtrees of each $\mathtt{M}_i$

An example

Passenger $\mathtt{P}$ launches an auction for a taxi $\mathtt{T}$

$$
\begin{aligned}
\mathtt{InitialP} \quad &= \quad \mathsf{Request} \mapsto \mathsf{Requested} \cdot [\mathsf{Requested}\,?\,\mathtt{AuctionP}] \\[1em]
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&\qquad\qquad\quad \& \\
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Notation

- write $\mathtt{t}_1 ?\, \mathtt{M}_1 \,\&\, \cdots \,\&\, \mathtt{t}_n ?\, \mathtt{M}_n$ when κ is the empty function
- if $n = 0$, $\kappa \cdot 0$ abbreviates $\kappa \cdot [\mathtt{t}_1 ?\, \mathtt{M}_1 \,\&\, \cdots \,\&\, \mathtt{t}_n ?\, \mathtt{M}_n]$
- write $\&_{1 \leq i \leq n} \mathtt{l}_i ?\, \mathtt{M}_i$ in place of $\mathtt{t}_1 ?\, \mathtt{M}_1 \,\&\, \cdots \,\&\, \mathtt{t}_n ?\, \mathtt{M}_n$

Treat κ as its graph and e.g. write $\mathtt{c} / \mathtt{l} \in \kappa$ for $\kappa(\mathtt{c}) = \mathtt{l}$ or write κ as $\{\mathtt{c}_1 / \mathtt{l}_1, \ldots, \mathtt{c}_h / \mathtt{l}_h\}$ when $\kappa : \mathtt{c}_i \mapsto \mathtt{l}_i$ for $i \in \{1, \ldots h\}$

Machines as automata

A machine $\mathtt{M} = \kappa \cdot [\mathtt{t}_1 ? \mathtt{M}_1 \& \cdots \& \mathtt{t}_n ? \mathtt{M}_n]$ is an FSA where:

- κ yields command-enabling transitions
- a branch $\mathtt{t}_i ? \mathtt{M}_i$ yields a transition $\mathtt{M} \xrightarrow{\mathtt{t}_i ?} \mathtt{M}_i$ when an event of type $\mathtt{t}_i$ is consumed

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From machines to FSAs

- the states of the automaton are the subtrees of $\mathtt{M}$
- the initial state is $\mathtt{M}$ and
  - there is a self-loop transition to $\mathtt{M}$ labelled $\mathtt{c} \,/\, \mathtt{l}$ for each $\mathtt{c} \,/\, \mathtt{l} \in \kappa$
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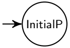
This construction yields a finite-state automaton by the regularity of $\mathtt{M}$

An example

Let's build the FSA of the machine `InitialP` on slide 18.



`InitialP` $=$

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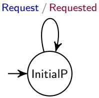

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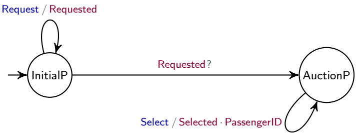

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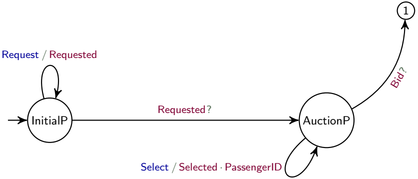
Let's build the FSA of the machine `InitialP` on slide 18.



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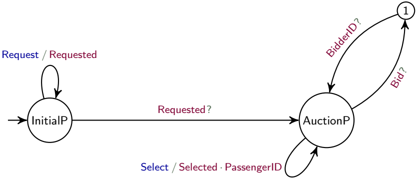

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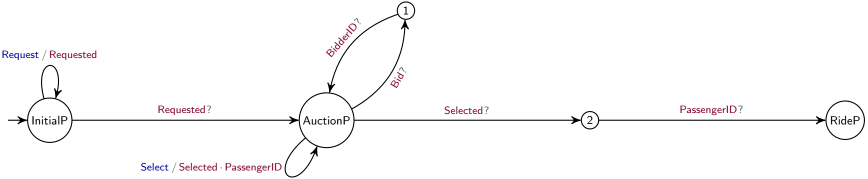

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$$\mathtt{RideP} = \cdots$$

Machines' semantics

So, think of $\mathtt{M} = \kappa \cdot [\mathtt{t}_1 ? \mathtt{M}_1 \,\&\, \cdots \,\&\, \mathtt{t}_n ? \mathtt{M}_n]$ as an FSA where transitions are

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

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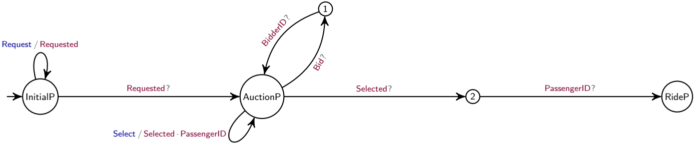
That is
after processing the events in ℓ, M reaches a state enabling $\mathtt{c}\,/\,\mathtt{l}$ then the command execution can emit ℓ' of type $\mathtt{l}$ and append it to the local log of M

An example

Take the machine `InitialP` (slide 20) with a local log $\ell = \mathit{ignoreMe} \cdot \mathit{ignoreMeToo}$ where $\not\vdash \mathit{ignoreMe} : \mathsf{Requested}$ and $\not\vdash \mathit{ignoreMeToo} : \mathsf{Requested}$



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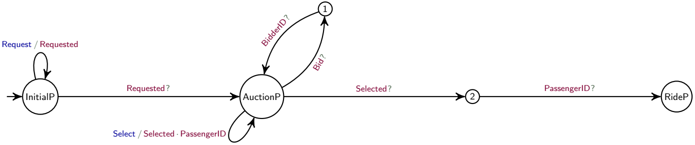

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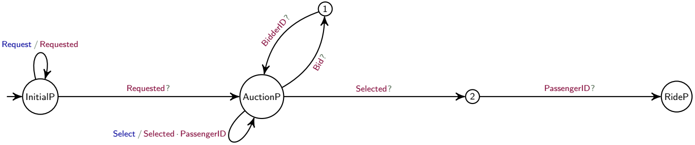

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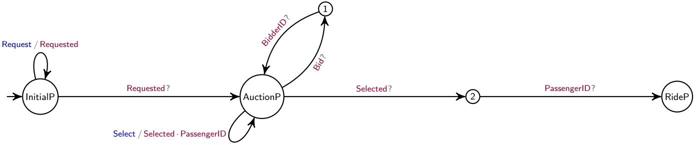

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Exercise

Calculate $\delta(\texttt{InitialP}, \ell \cdot \mathit{Requested})$

Some considerations

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We have formalised the emission of events and their consumption
We now focus on the formalisation of log shipping

Swarms

A swarm (of size n) is a pair $(\mathtt{S}, \ell)$ where

- $\mathtt{S}$ maps each index $1 \leq i \leq n$ to a pair $(\mathtt{M}_i, \ell_i)$
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Notation

$\mathtt{M}_1 \boxed{\ell_1} \mid \dots \mid \mathtt{M}_n \boxed{\ell_n} \mid \ell$

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Disclaimer

Seemingly, we've a contradiction: isn't the global log a centralisation point?

Well...no, it isn't: the global log is just a theoretical ploy!

- it abstracts away from low-level technical details for events' dispatching

Log shipping middlewares rely on timestamp mechanisms (Actyx uses Lamport's timestamps) and guarantee that events are in the same order in all the local logs

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- it abstracts away from low-level technical details for events' dispatching
- it elegantly (IOHO) models asynchrony
- it is not used in our algorithms and tools

Coherence

A swarm $\mathtt{M}_1\boxed{\ell_1} \mid \ldots \mid \mathtt{M}_n\boxed{\ell_n} \mid \ell$ is coherent if $\ell = \bigcup_{1 \le i \le n} \ell_i$ and $\ell_i \sqsubseteq \ell$ for $1 \le i \le n$

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That is
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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Hereafter, we assume coherence

Merging logs

Exercise

Recall slide 16 and consider a swarm

$$\cdots \mid \quad \texttt{Alice} \quad \boxed{e_1 \mid e_2 \mid e_3 \mid a \mid b \mid c} \quad \mid \cdots \mid \ell \qquad (1)$$

If $\ell = e_1 \cdot e_2 \cdot e_3 \cdot e$, under which condition is (1) coherent?

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If $\ell = e_1 \cdot e_2 \cdot e_3 \cdot e$, under which condition is (1) coherent?

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 [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

Semantics at work (I)

If $\mathrm{B}\boxed{b} \xrightarrow{\mathtt{c}\,/\,\mathtt{1}} \mathrm{B}\boxed{b \cdot d \cdot e}$ with $\vdash d \cdot e : \mathtt{1}$

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If $\quad \mathtt{B}\boxed{b} \xrightarrow{\mathtt{c}\,/\,\mathtt{l}} \mathtt{B}\boxed{b \cdot d \cdot e} \quad$ with $\quad \vdash d \cdot e : \mathtt{l}$

then, by [Local] $\quad \mathtt{A}\boxed{a} \mid \mathtt{B}\boxed{b} \mid \mathtt{C}\boxed{c} \mid a \cdot b \cdot c \xrightarrow{\mathtt{c}\,/\,\mathtt{l}} \mathtt{A}\boxed{a} \mid \mathtt{B}\boxed{b \cdot d \cdot e} \mid \mathtt{C}\boxed{c} \mid \ell$

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Exercise

Compute $(a \cdot b \cdot c) \bowtie (b \cdot d \cdot e)$

Semantics at work (II)

Take from slide 28

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and let's propagate some events

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Excercise

In both cases b must be shipped too. Why?
And why is event a not shipped to $\mathtt{C}$ together with the events from $\mathtt{B}$?

Plan of the talk

A motivating case study

Our formalisation

Our typing discipline

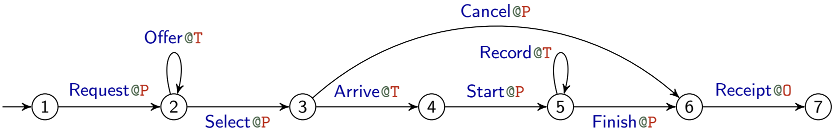
Tool support

Open issues

– Behavioural types for swarms –

A taxi service

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



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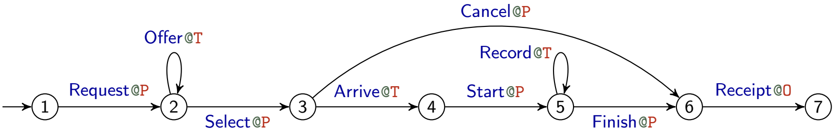

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- one passenger and one office (for simplicity)

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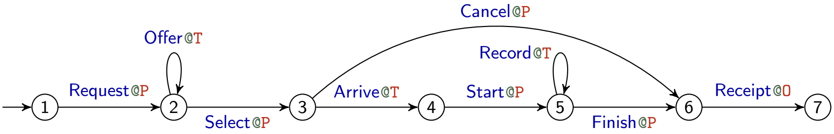

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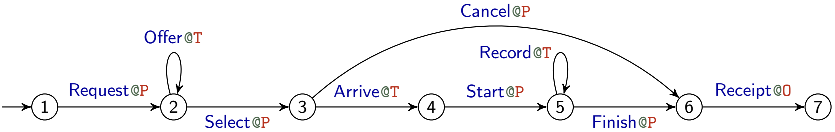
- but an arbitrary number of taxis

A taxi service

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



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)

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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Local viewpoint$_i$ ··· M_n
Local viewpoint$_n$ — spec,no code

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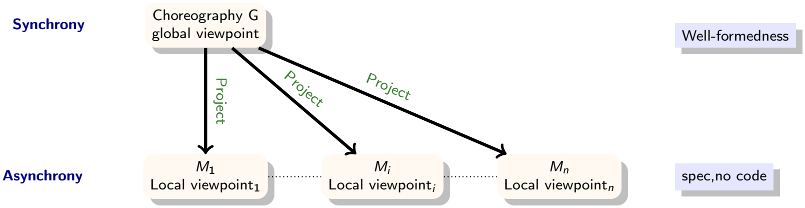

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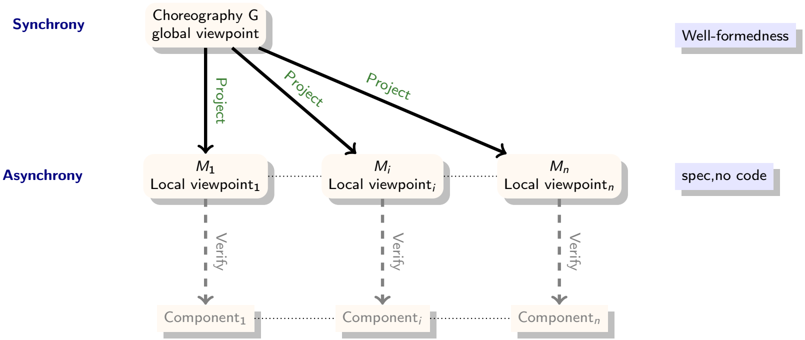

Swarm protocols: global type for local-first applications

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 32)

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

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

An example

A swarm protocol for the taxi scenario on slide 32:

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

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

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

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

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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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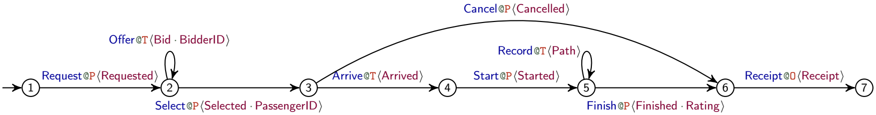
Swarm protocols as FSA

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:

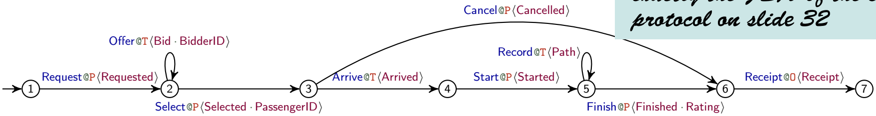
- the set of states consists of G plus the states in G_i for each $i \in \{1 \ldots, n\}$
- G is the initial state
- for each $i \in I$, G has a transition to state G_i labelled with $\mathtt{c}_i @ \mathtt{R}_i \langle \mathtt{l}_i \rangle$, written $\mathsf{G} \xrightarrow{\mathtt{c}_i \,/\, \mathtt{l}_i}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

An example



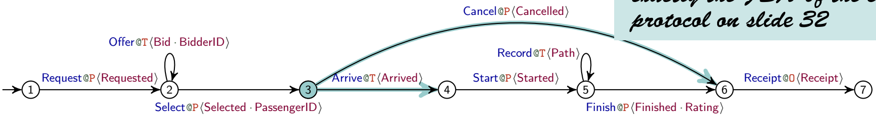
Cancel@P⟨Cancelled⟩
Offer@T⟨Bid · BidderID⟩
Record@T⟨Path⟩
Request@P⟨Requested⟩
Arrive@T⟨Arrived⟩
Start@P⟨Started⟩
Receipt@O⟨Receipt⟩
1
2
3
4
5
6
7
Select@P⟨Selected · PassengerID⟩
Finish@P⟨Finished · Rating⟩

An example



Removing log types yields exactly the FSA of the swarm protocol on slide 32

An example



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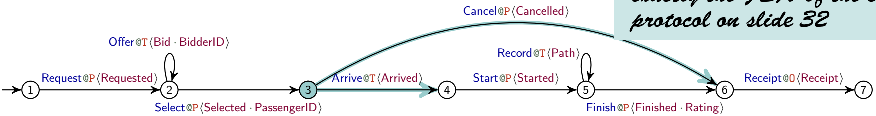
There is a race in state 3!

- the selected taxi may invoke Arrive
- **while** P loses patience and invokes Cancel

An example



Removing log types yields exactly the FSA of the swarm protocol on slide 32

There is a race in state 3!

- the selected taxi may invoke Arrive
- **while** P loses patience and invokes Cancel

This protocol violates well-formedness conditions typically imposed on behavioural types due to the race in state 3 (because it has two selectors, which is also true of states 2 and 5)

Semantics of swarm protocols

One rule only!

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

One rule only!

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

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

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

From swarm protocols to machines

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

Each machine plays one role

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

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

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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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where

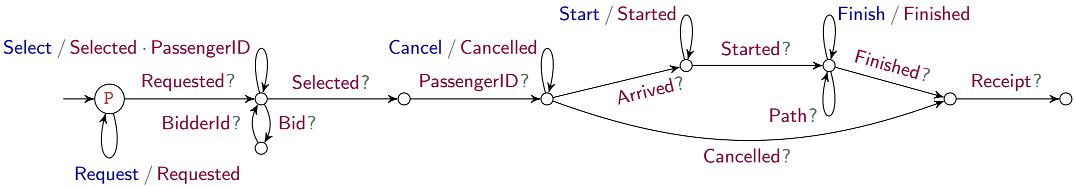
$$\kappa = \{ \mathtt{c}_i \, / \, \mathtt{l}_i \mid \mathtt{R}_i = \mathtt{R} \text{ and } i \in I \}$$

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

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

An example

A reasonable subscription for P is the total one since the passenger should be aware of all events: $\sigma(\mathtt{P})$ contains all event types



An example

Exercise

The taxi driver does not need to bother with the receipt: the subscription for $\sigma(\mathtt{T})$ consists of all messages but Receipt; give the projection of the taxi protocol on such subscription for $\mathtt{T}$.

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If we want the office to know only the details about the ride we set $\sigma(\mathtt{O}) = \{\mathsf{Started}, \mathsf{Finished}, \mathsf{Receipt}\}$

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Exercise (hard)

Is this a good idea?

Well-formedness: sufficient conditions for well-behaviour

Transitory deviations are tolerated provided that consistency is eventually recovered

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Example

T may bid after P has made their selection if the selection event T has not yet been received.

This inconsistency is temporary: when the selection event reaches T this inconsistency is recognised and resolved

Well-formedness: sufficient conditions for well-behaviour

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Example

T may bid after P has made their selection if the selection event T has not yet been received.

This inconsistency is temporary: when the selection event reaches T this inconsistency is recognised and resolved

Convention

Let's write $\mathtt{R} \in_\sigma \mathtt{G} = \sum_{i \in I} \mathtt{c}_i @ \mathtt{R}_i \langle \mathtt{l}_i \rangle \,.\, \mathtt{G}_i$ when there is $i \in I$ such that

$$\mathtt{R} = \mathtt{R}_i \quad \text{or} \quad \sigma(\mathtt{R}) \cap \mathtt{l}_i \neq \emptyset \quad \text{or} \quad \mathtt{R} \in_\sigma \mathtt{G}_i$$

and set $\mathsf{roles}(\mathtt{G}, \sigma) = \{\mathtt{R} \mid \mathtt{R} \in_\sigma \mathtt{G}\}$ and

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

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

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

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

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

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

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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 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	there is a unique subtree G' of G emitting $\mathtt{t}$ for each $\mathtt{t}$ starting a log emitted by a command in G

Some considerations

Further consequences:

- **Unspecified receptions** are just ignored according to the δ transition function of machines
- It is fine to violate **session fidelity**, provided that consistency is eventually attained

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- **Unspecified receptions** are just ignored according to the δ transition function of machines
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Care is therefore necessary

- for the definition of **correctness**
- and for the **correct realisation** of swarm protocols

Of course we appeal to projections

On correctness

$(\mathtt{S}, \ell)$ faithfully implements G if it produces only logs possibly generated by G

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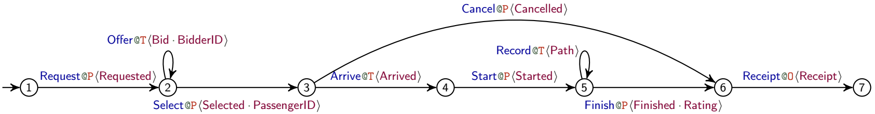
Exercise

Take the swarm $\mathtt{S} = \mathtt{P} \parallel \mathtt{T} \parallel \mathtt{O} \parallel \mathtt{T}$ implementing



(i.e., the swarm protocol G on slide 37). Check that $\mathtt{S}$ generates the log

$$\ell_{\mathsf{auc}} = \mathit{requested} \cdot \mathit{bid} \cdot \mathit{bidderID} \cdot \mathit{selected} \cdot \mathit{bid} \cdot \mathit{bidderID} \cdot \mathit{passengerID}$$

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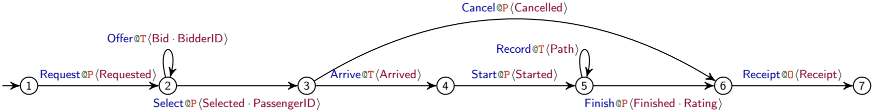

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Too strong a requirement!

Let's consider only "good enough" logs, i.e., those typeable with G's log types

Effective types

Let $\mathsf{active}(\sum_{i\in I} \mathtt{c}_i @ \mathtt{R}_i \langle \mathtt{l}_i \rangle \,.\, \mathsf{G}_i) = \bigcup_{i\in I}\{\mathtt{R}_i\}$

ℓ has effective type $\mathtt{l}$ wrt G and σ if $\mathsf{G}, \epsilon \vdash_\sigma \ell \triangleright \mathtt{l}$ is provable; where

$$\frac{}{\mathsf{G}, \epsilon \vdash_\sigma e \cdot \ell \triangleright \mathtt{t} \cdot \mathtt{l}}$$

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$$\frac{\vdash e : \mathtt{t} \in \sigma(\mathsf{roles}(\mathsf{G}, \sigma)) \qquad \mathsf{G} \xrightarrow{\mathtt{c} \,/\, \mathtt{t} \cdot \mathtt{l}'} \mathsf{G}' \qquad \mathsf{G}', \mathsf{filter}(\mathtt{l}', \sigma(\mathsf{active}(\mathsf{G}'))) \vdash_\sigma \ell \triangleright \mathtt{l}}{\mathsf{G}, \epsilon \vdash_\sigma e \cdot \ell \triangleright \mathtt{t} \cdot \mathtt{l}}$$

$$\frac{\vdash e : \mathtt{t} \qquad \mathsf{G}, \mathtt{l} \vdash_\sigma \ell \triangleright \mathtt{l}'}{\mathsf{G}, \mathtt{t} \cdot \mathtt{l} \vdash_\sigma e \cdot \ell \triangleright \mathtt{t} \cdot \mathtt{l}'}$$

Effective types

Let $\mathsf{active}(\sum_{i \in I} \mathtt{c}_i @ \mathtt{R}_i \langle \mathtt{l}_i \rangle \,.\, \mathsf{G}_i) = \bigcup_{i \in I} \{\mathtt{R}_i\}$

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$$\frac{\mathsf{G}, \mathtt{l} \vdash_\sigma \ell \triangleright \mathtt{l}' \qquad \text{none of the other rules applies}}{\mathsf{G}, \mathtt{l} \vdash_\sigma e \cdot \ell \triangleright \mathtt{l}'}$$

Effective types

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Exercise

For the swarm protocol G on slide 37, find a condition on σ so that

$$\mathsf{G}, \epsilon \vdash_\sigma \ell_{\mathsf{auc}} \triangleright \mathsf{Requested} \,.\, \mathsf{Bid} \,.\, \mathsf{BidderID} \,.\, \mathsf{Selected} \,.\, \mathsf{PassengerID}$$

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

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

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

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

On correct realisations

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

consistent if there is ℓ s.t.

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

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

On correct realisations

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

consistent if there is ℓ s.t.

$$\begin{array}{ccccc} & & & & (\mathtt{S}, \ell_1') \\ & & & \nearrow\!\!\!\nearrow & \\ (\mathtt{S}, \epsilon) & \Longrightarrow & (\mathtt{S}, \ell) & & \\ & & & \searrow\!\!\!\searrow & \\ & & & & (\mathtt{S}, \ell_2') \end{array}$$

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

On correct realisations

$(\mathtt{s},\epsilon)$ consistent if there is ℓ s.t. $(\mathtt{s},\epsilon) \Longrightarrow (\mathtt{s},\ell)$ with $\ell_1 = \ell \cdot \ell'_1$ and $\ell_2 = \ell \cdot \ell'_2$ and $\ell'_1 \cap \ell'_2 = \emptyset$

$$
\begin{array}{ccc} & & (\mathtt{s},\ell_1) \\ & \nearrow\!\!\!\nearrow & \\ (\mathtt{s},\epsilon) & & \\ & \searrow\!\!\!\searrow & \\ & & (\mathtt{s},\ell_2) \end{array}
\qquad
(\mathtt{s},\epsilon) \Longrightarrow (\mathtt{s},\ell)
\begin{array}{cc} & (\mathtt{s},\ell'_1) \\ \nearrow\!\!\!\nearrow & \\ & \\ \searrow\!\!\!\searrow & \\ & (\mathtt{s},\ell'_2) \end{array}
$$

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 $\ell^{(j)} = \ell_j \cdot \cdots \cdot \ell_1$

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 $\ell = \bigcup_{1\le i\le k} \ell_i$ 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, G denotes a σ-WF protocol

Results

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 $\ell \equiv_{\mathsf{G},\sigma} \ell'$

Lemma (Admissibility is preserved)

Let ℓ_1 and $\ell_2 \subseteq \ell_1$ be admissible logs for 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 ℓ is admissible for G

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

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

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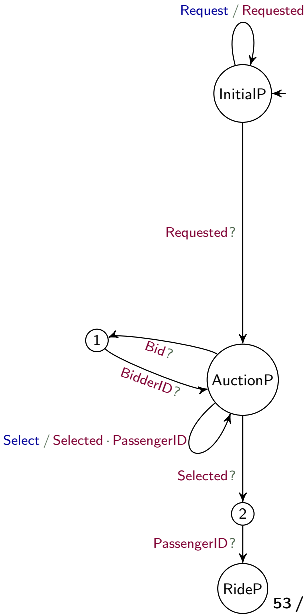
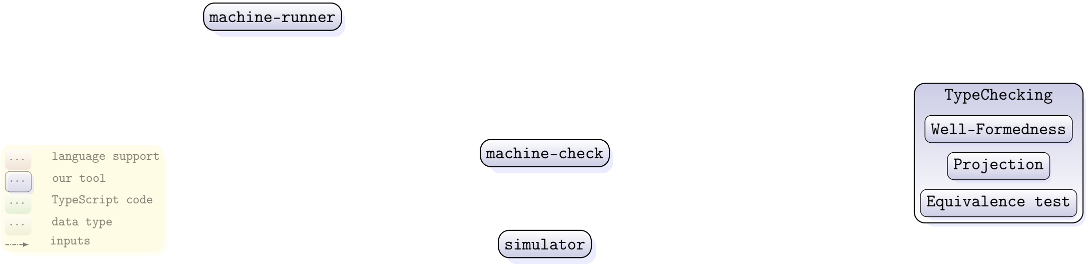
– Tooling –

```
// 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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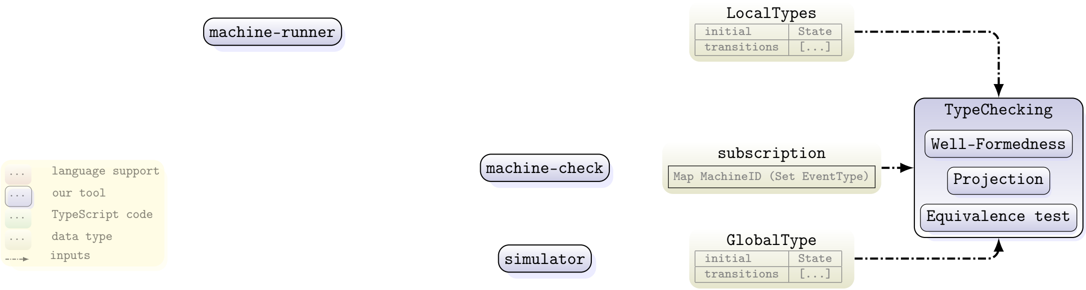

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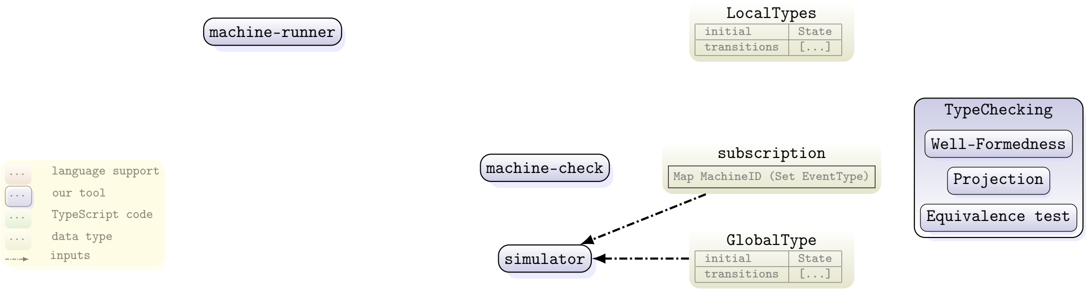

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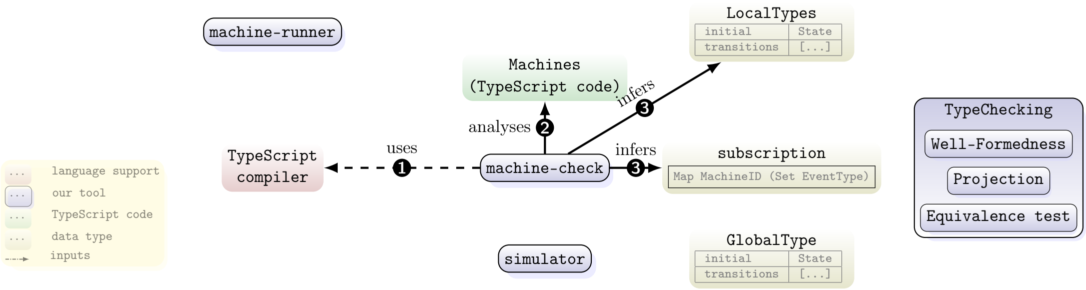

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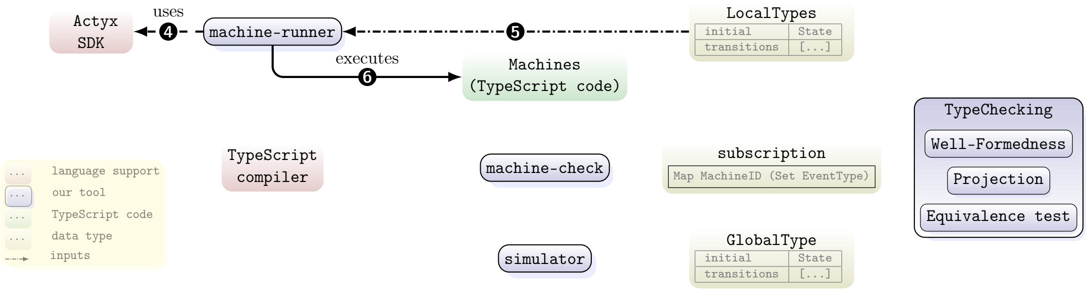

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If you want to play with our prototype?

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 –

To be continued....

There are a number of future directions to explore:

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Identify weaker conditions for well-formedness

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- Identify weaker conditions for well-formedness
- "Efficiency"

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  - Unreliable propagation

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    - Adversarial contexts

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- "Efficiency"
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- ....

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We defined an operational semantics that captures the platform of Actyx AG

We introduced behavioural types to specify and verify eventual consistency

The key idea is to trade consistency for availability: temporary inconsistency are tolerated provided that they can be resolved at some point

Thank you!

– Solutions –

Solutions to exercises

- Slide 22: $\delta(\texttt{InitialP}, \ell \cdot \mathit{Requested}) = \texttt{AuctionP}$
- Slide 26: $\mathit{src}(e) \neq \texttt{Alice}$
- Slide 28: $(a \cdot b \cdot c) \bowtie (b \cdot d \cdot e) = \{a \cdot b \cdot c \cdot d \cdot e,\ a \cdot b \cdot d \cdot c \cdot e,\ a \cdot b \cdot d \cdot e \cdot c\}$
- Slide 29: Because [prop] won't apply since e is not a sublog of the local log of $\texttt{B}$
- Slide 41: The solution of the first exercise is in our ECOOP paper. For the second exercise, the idea is not bad because with such subscription the protocol is not well-formed (work out why)
- Slide 45: Apply the operational semantics of swarms
- Slide ??: $\sigma(P) \ni \mathit{Requested}, \mathit{BidderID}, \mathit{Selected}, \mathit{PassengerID}$