Behavioural Types and Local-First Principles for Swarms
Swarming up with local-first principles

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Joint work with

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APM @ Turin
17 Aprile, 2026

Take-away message

Realising fully distributed computation is challenging

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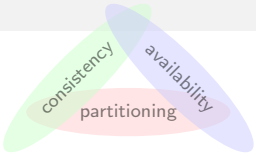

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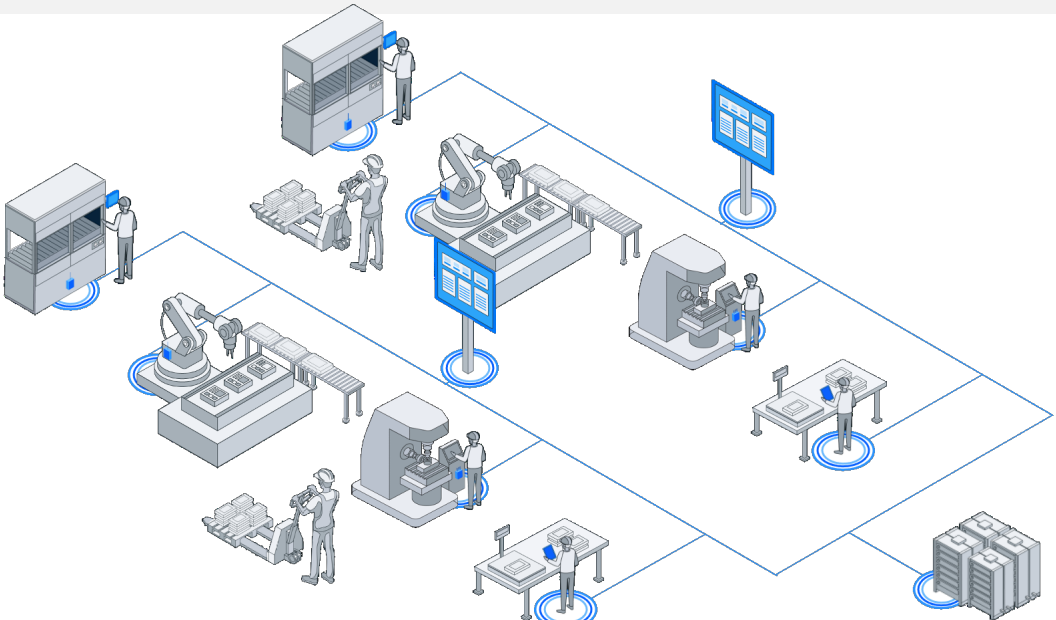
  - "standard" behavioural types "work" but, they're partial to C
  - conflict-free replicated data types work, but hard to be found
- So, let's go coordination-free
  - swarm protocols are global specs of swarms
  - allow speculative progress and tolerate inconsistencies
  - to be taken care of eventually

– Context –

An execution model for a collaborative environment



(the pictures are courtesy of Actyx AG)

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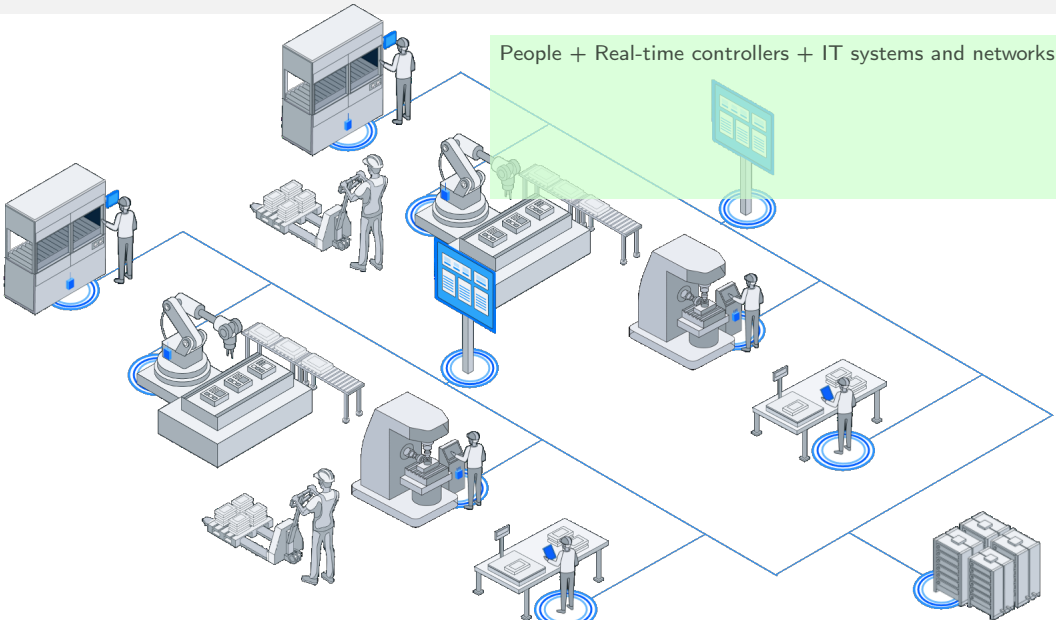

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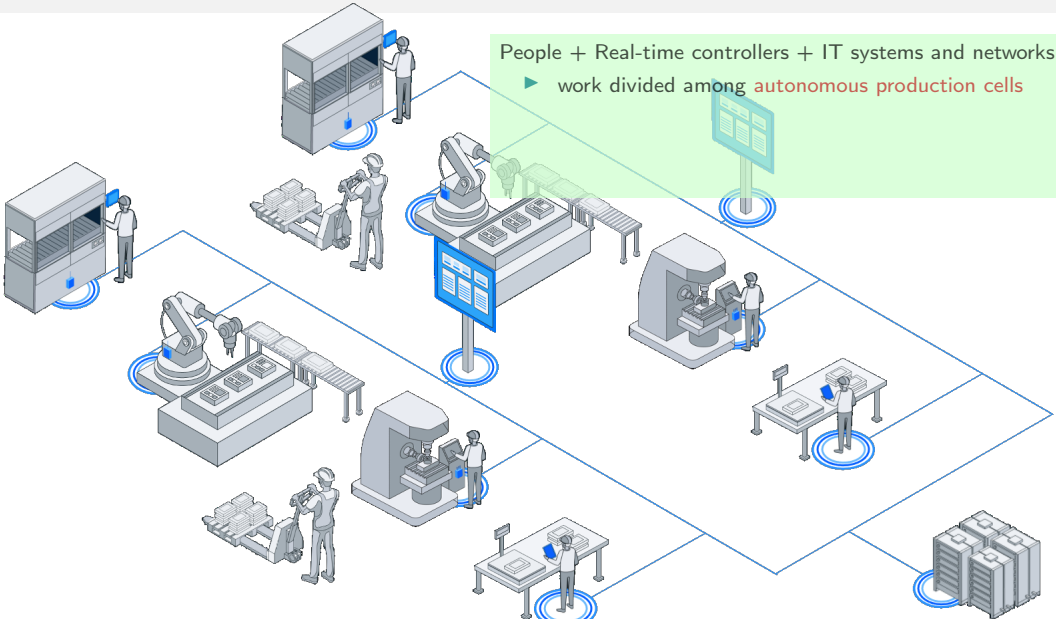

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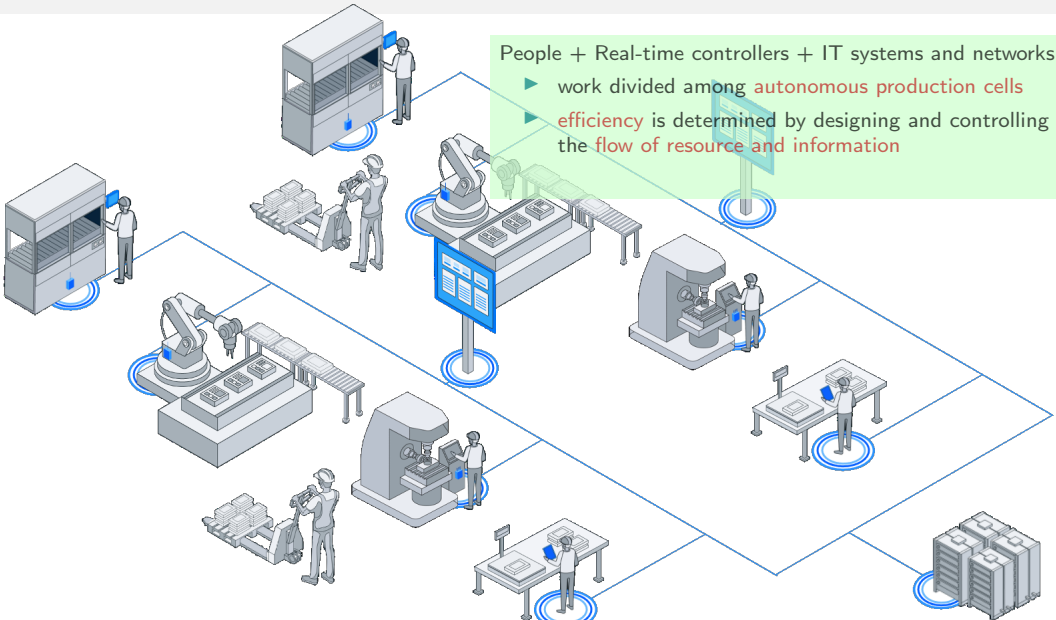

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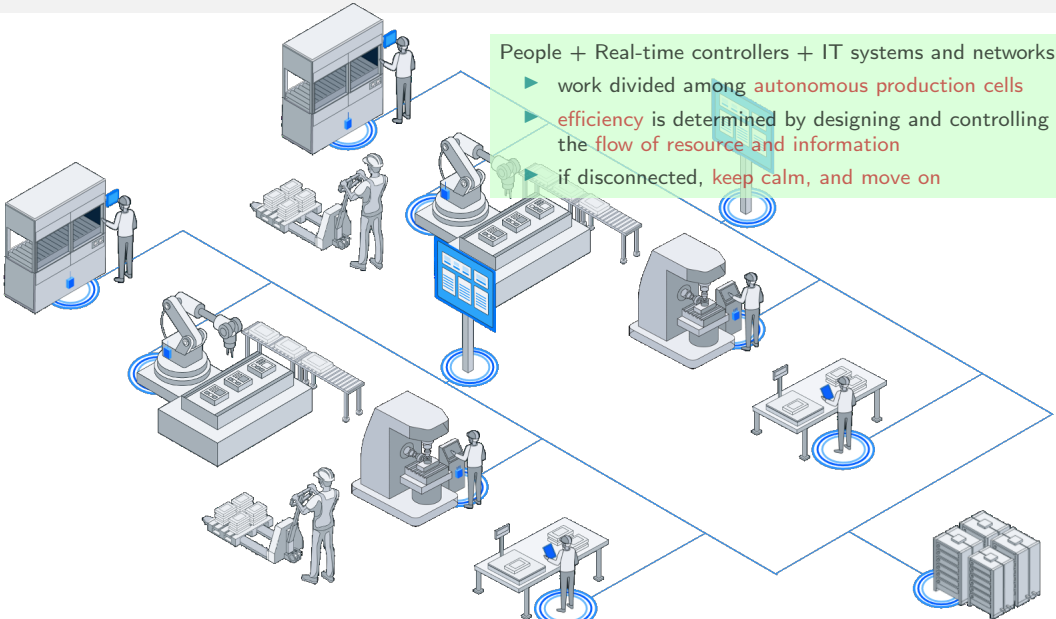

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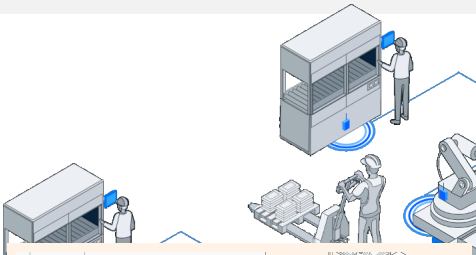

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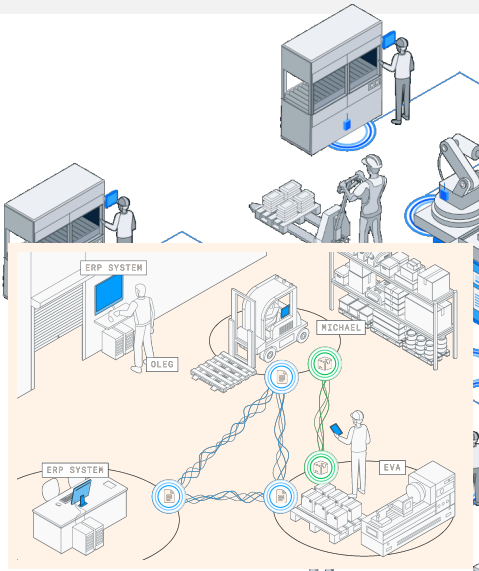

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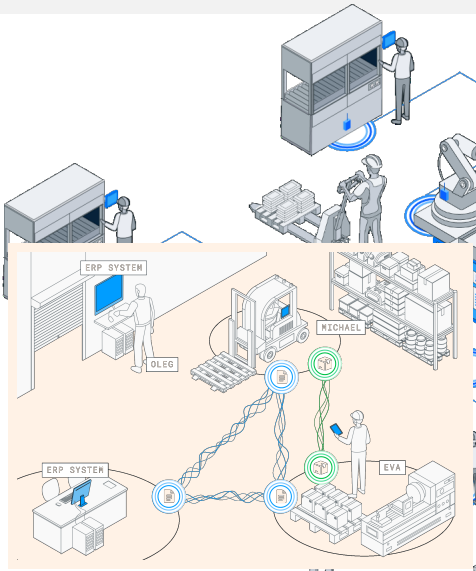

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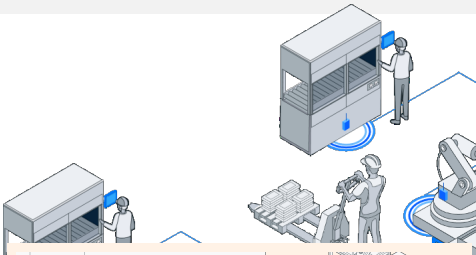

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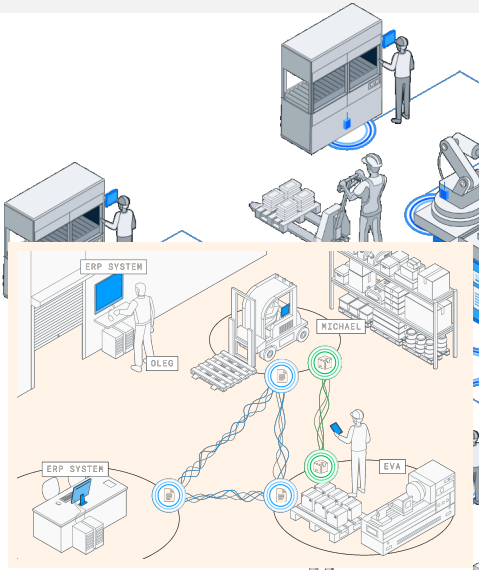

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- logs are local to twins
  - a log $\equiv$ computational state of its twin
  - replicated logs are merged

Some motivations

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really?

- "Anytime, anywhere..."
  - like during the AWS's outage on 25/11/2020
  - or almost all Google services down on 14/12/2020
  - DSL typical availability of 97%
    - acutally, some SLA have no lower bound [What Is the Digital Divide?]

Stop having your head in the clouds

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Local-first principles

- Thou shalt be available
- Thou shalt be autonomous
- Thou shalt be collaborative
- Thou shalt recognise and embrace conflicts
- Thou shalt resolve conflicts and get consistency eventually

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Challenges in specifying protocols where decisions

- don't require consensus
- are based on stale local states
- yet, "work"

Our proposal

We define behavioural specs that

- feature
  - pub-subscribe (instead point-to-point)
  - (generalised) choices
  - arbitrary (and variable) number of instances
- trade "continuous" consistency for availability
  - price: "old" properties (eg session fidelity) are lost
  - gain: eventual-consistency & flexiblity (eg roles can have multiple instances)

design (well)

+

project

+

run

Classic behavioural specs

design (well)
+
project
+
run

LF approach

execute
+
propagate
+
merge

– Swarms and Swarm Protocols –

Ingredients (I): events & logs

Events e

$src(e)$

Logs $e_1 \cdot e_2 \ldots$

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Events $\vdash e : t$

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

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

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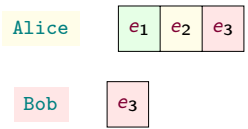

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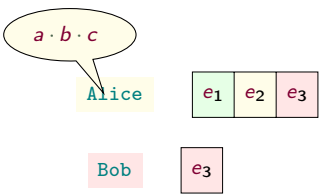

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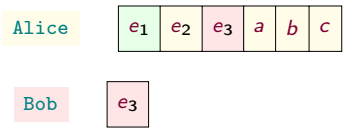

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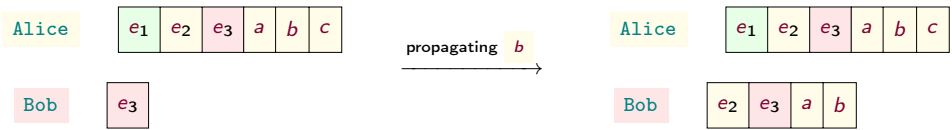

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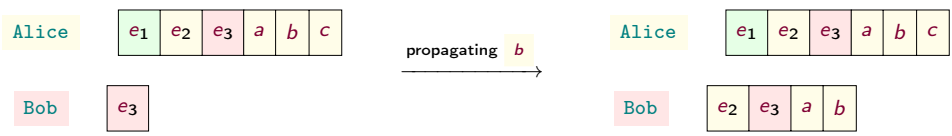

a is shipped too!

Machines by example

Let's build a machine `InitialP` for coordinating a taxi service.


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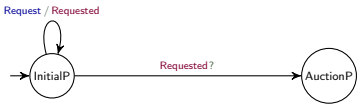

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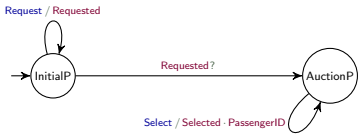

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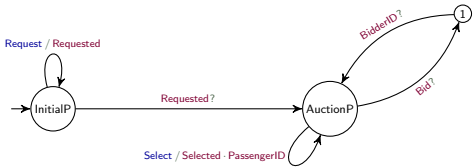

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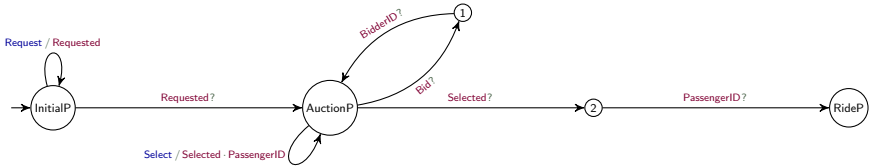

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\texttt{RideP} &= \cdots
\end{aligned}
$$

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 emitting/consuming events according to its transitions:

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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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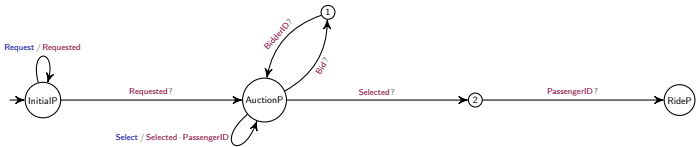
after processing the events in ℓ, $\mathtt{M}$ reaches a state enabling $\mathtt{c}\,/\,\mathtt{1}$ then the command execution can emit ℓ' of type $\mathtt{1}$ and append it to the local log of $\mathtt{M}$

An example

Take the machine `InitialP` (slide 12) 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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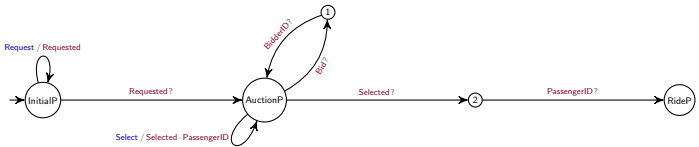

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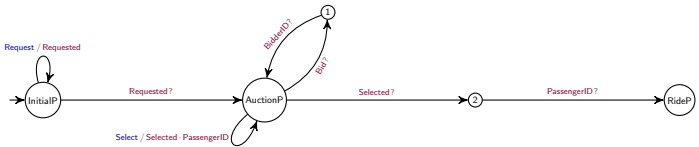

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- $(\texttt{InitialP}, \ell) \xrightarrow{\text{Request / Requested}} (\texttt{InitialP}, \ell \cdot \mathit{Requested})$
  with $\vdash \mathit{Requested} : \mathrm{Request}$ and $\mathit{src}(\mathit{Requested}) = \mathtt{P}$

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The environment triggers commands: swarms are inherently non-deterministic!

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The environment triggers commands: swarms are inherently non-deterministic!

We have formalised the emission of events and their consumption

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

Coherence

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

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where $\ell_i \sqsubseteq \ell$ is the sublog relation defined as

- $\ell_i \subseteq \ell$ and $<_{\ell_i} \subseteq <_\ell$ and

That is
all events of ℓ_i appear in the same order in ℓ

- $e <_\ell e'$, $src(e) = src(e')$ and $e' \in \ell_1 \implies e \in \ell_i$

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Hereafter, we assume coherence

Semantics by example

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

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By rule [Prop] we can propagate a non-deterministically a chosen sublog of $b \cdot d \cdot e$

Semantics by example

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

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Let's propagate $d \cdot e$ $\mathtt{A}\boxed{a} \mid \mathtt{B}\boxed{b \cdot d \cdot e} \mid \mathtt{C}\boxed{c} \mid \ell \xrightarrow{\tau} \mathtt{A}\boxed{b \cdot a \cdot d \cdot e} \mid \mathtt{B}\boxed{b \cdot d \cdot e} \mid \mathtt{C}\boxed{c} \mid \ell$

$\mathtt{A}\boxed{a} \mid \mathtt{B}\boxed{b \cdot d \cdot e} \mid \mathtt{C}\boxed{b \cdot d \cdot e \cdot c} \mid \ell \xleftarrow{\tau}$

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

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

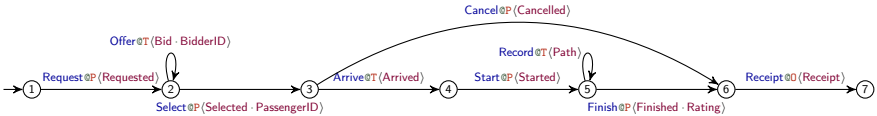
– Behavioural Types for Swarms –

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 $i \in \underline{n}$
- 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⟩
Select@P⟨Selected · PassengerID⟩
Finish@P⟨Finished · Rating⟩
1
2
3
4
5
6
7

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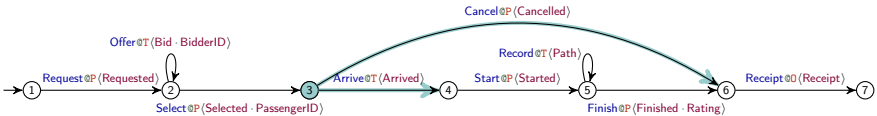

There is a race in state 3!

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

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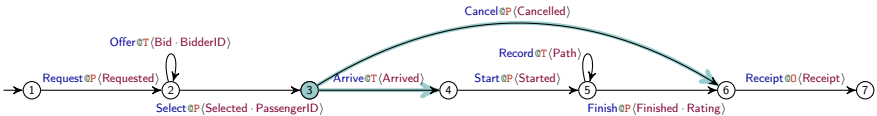

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This protocol violates well-formedness conditions typically imposed on behavioural types due to the race in state 3 (because it has two selectors, which is also true of states 2 and 5)

Semantics of swarm protocols

One rule only!

$$\frac{}{(\mathsf{G}, \ell) \xrightarrow{\mathtt{c}\,/\,\mathtt{1}} (\mathsf{G}, \ell \quad)}\ \text{[G-Cmd]}$$

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$$\frac{\delta(\mathsf{G}, \ell) \xrightarrow{\mathtt{c}\,/\,\mathtt{1}} \mathsf{G}'}{(\mathsf{G}, \ell) \xrightarrow{\mathtt{c}\,/\,\mathtt{1}} (\mathsf{G}, \ell \quad)} \text{[G-Cmd]}$$

where

$$\delta(\mathsf{G}, \ell) = \begin{cases} \mathsf{G} & \text{if } \ell = \epsilon \\ \delta(\mathsf{G}', \ell'') & \text{if } \mathsf{G} \xrightarrow{\mathtt{c}\,/\,\mathtt{1}} \mathsf{G}' \text{ and } \vdash \ell' : \mathtt{1} \text{ and } \ell = \ell' \cdot \ell'' \\ \bot & \text{otherwise} \end{cases}$$

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

Semantics of swarm protocols

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$$\frac{\delta(\mathsf{G},\ell) \xrightarrow{\mathtt{c}\,/\,\mathtt{1}} \mathsf{G}' \qquad \vdash \ell' : \mathtt{1} \qquad \ell' \text{ log of fresh events}}{(\mathsf{G},\ell) \xrightarrow{\mathtt{c}\,/\,\mathtt{1}} (\mathsf{G},\ell\cdot\ell')}\text{[G-Cmd]}$$

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Semantics of swarm protocols

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

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

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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 event types: maps from roles to sets of event types

In pub-sub, processes subscribe to "topics"

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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

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

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projection of G on a role R with respect to subscription σ is

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

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

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

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

Well-formedness: 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 decision 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

Trading consistency for availability has implications:

Well-formedness = Causality

Trading consistency for availability has implications:

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

$\Longrightarrow$ 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 a command enabled after $\mathtt{c}_i$ then $\sigma(\mathtt{R})$ contains some event type emitted by $\mathtt{c}_i$

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

Command causality 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])

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

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Determinacy	$\mathtt{R} \in_\sigma \mathtt{G}_i \implies \mathtt{l}_i[0] \in \sigma(\mathtt{R})$
Confusion freeness	there is a unique subtree $\mathtt{G}'$ of $\mathtt{G}$ emitting $\mathtt{t}$ for each $\mathtt{t}$ starting a log emitted by a command in $\mathtt{G}$

– 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)
  }
}
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```
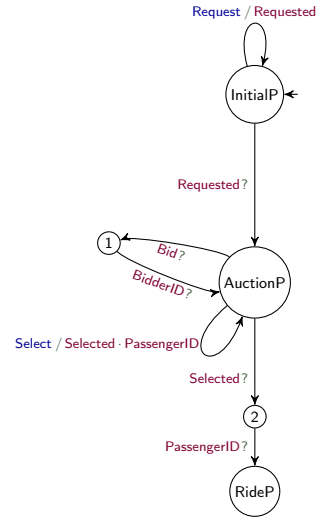
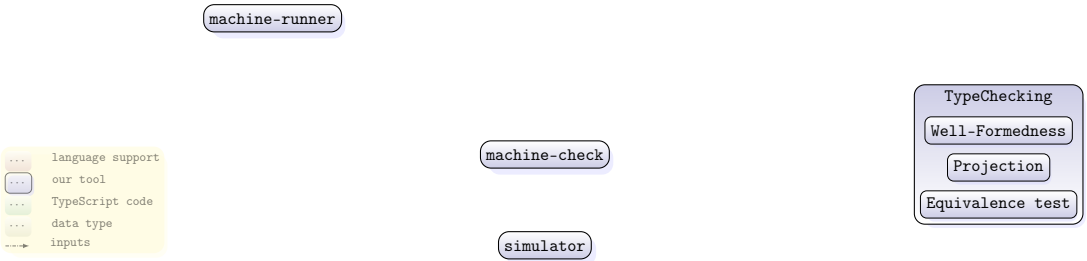



Architecture [2]



- `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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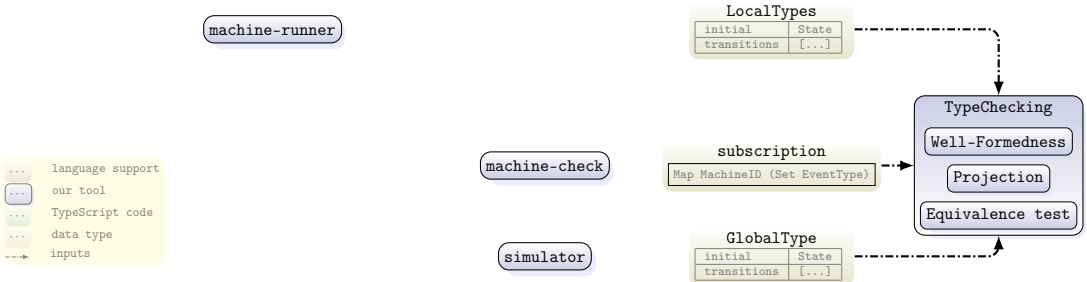

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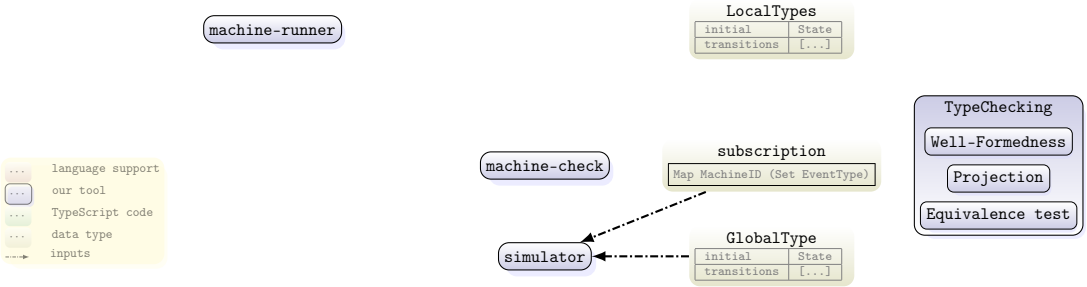

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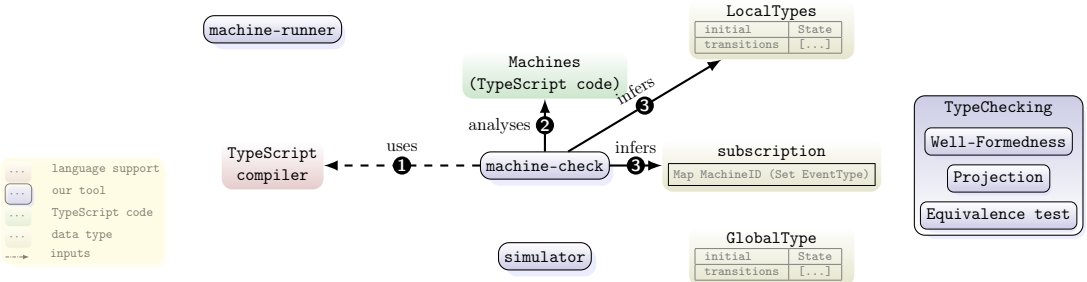

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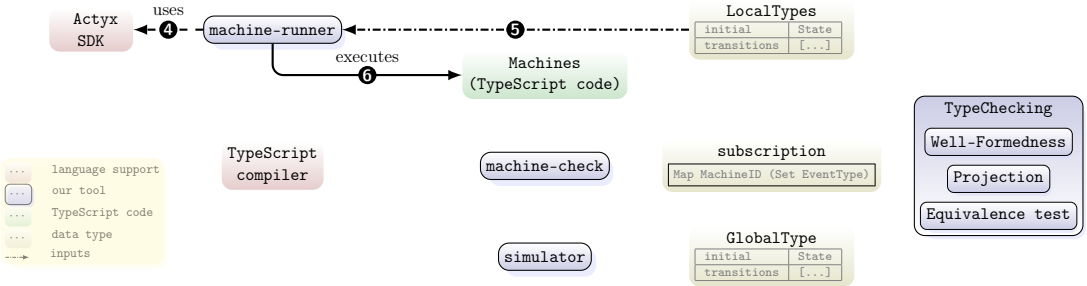

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– Wrapping up –

Summary & ongoing/future work

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What did we glance at

Summary & ongoing/future work

What did we glance at

- A choreographic approach based on behavioural types
  - Supporting local-first principles
  - Inspired (and usable) in an industrial platform
  - Addressing non-standard properties
  - in a non-standard way

Summary & ongoing/future work

What did we glance at

- A choreographic approach based on behavioural types
  - Supporting local-first principles
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- eventual consistency...fine...but how long should we wait for?

Thank you!

References I

[1] Roland Kuhn, Hernán C. Melgratti, and Emilio Tuosto. **Behavioural types for local-first software.** In Karim Ali and Guido Salvaneschi, editors, *37th European Conference on Object-Oriented Programming, ECOOP 2023, July 17-21, 2023, Seattle, Washington, United States*, volume 263 of *LIPIcs*, pages 15:1–15:28. Schloss Dagstuhl - Leibniz-Zentrum für Informatik, 2023.

[2] Roland Kuhn, Hernán C. Melgratti, and Emilio Tuosto. **Behavioural types for local-first software (artifact).** *Dagstuhl Artifacts Ser.*, 9(2):14:1–14:5, 2023.