Behavioural Specifications and Quantitative Techniques

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Challenges and Perspectives of Formal Methods for Trustworthy Software
PhD seminars series

IMT SCUOLA ALTI STUDI LUCCA

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Plan of the talk

An overview of results

- Resource-awareness
- Probabilities
- Time

in behavioural specifications (mainly, behavioural types)

Some open problems

– Resource Awareness –

Das, Hoffmann, Pfenning: [LICS'18]
Work Analysis with Resource-Aware Session types

Static derivation of worst-case bounds on work for communication

$$S, T \ ::= \ V \ \mid \ \oplus\{l_i^{q_i} : S\} \ \mid \ \&\{l_i^{q_i} : S\} \ \mid \ S \overset{q}{\multimap} T \ \mid \ S \overset{q}{\otimes} T \ \mid \ \mathbf{1}^q$$

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Theorem (Soundness)

WF processes don't "generate" energy

Theorem (Progress)

WF processes get stuck only if they correctly terminate
(direct conseguence of progress in SILL [Toninho, Caires, Pfenning: ESOP'13])

Case studies

Das, Balzar, Hoffmann, Pfenning, Santurkar: Resource-Aware STs for digital contracts [CSF'21]

Nomos: DSL to account for requirements of digital contracts

Session-typing discipline for resource-analysis

- linearity to prevent duplication/deletion of assets
- type reconstruction to automatically infer resource bounds
- amortized resource analysis to control resource usage

Theorem

Type preservation & progress

Evaluation on case studies

Verify the system-wide QoS properties of a distributed system given the QoS of its components

Lopez Pombo, Martinez-Suñé, Tuosto: [ICTAC'23] A Dynamic Temporal Logic for QoS in Choreographic Models

Verify the system-wide QoS properties of a distributed system given the QoS of its components

QL logic

$$\begin{array}{rcl} \Phi & ::= & \top \\ & | & \psi \\ & | & \neg\Phi \\ & | & \Phi \vee \Phi \\ & | & \Phi \; \mathsf{U}^{\mathsf{G}} \Phi \end{array}$$

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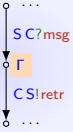
QoS CFSMs



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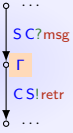

QoS Specs

$$\begin{array}{rcl} \Sigma & = & \langle \{0,1\} \cup \mathsf{Q}, \\ & & \{+,\cdot\} \cup \{\oplus^{\mathsf{a}}\}_{\mathsf{a}\in\mathsf{Q}}, \\ & & < \\ & & \rangle \\ \Gamma & = & \Gamma_{\mathrm{RCF}} \cup \Gamma' \end{array}$$

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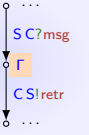

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Bounded MC

```
1  qUntil(Φ1, G, Φ2, S, π, π′, π″):
2      if L[π″] ∈ L̂[G] and qModels(Φ2, S, π, π′π″) then
3          return true
4      else if not qModels(Φ1, S, π, π′π″) then
5          return false
6      else
7          Let ⇝ q be the transition such that π′π″ ⇝ q ∈ prf(π)
             (takes the first transition in π if π′π″ = ϵ,
             and it is not defined if π′π″ = π)
8          if π′π″ = π or L[π″ ⇝ q] ∉ L[G] then
9              return false
10         else
11             return qUntil(Φ1, G, Φ2, S, π, π′, π″ ⇝ q)
```

now implemented in **ChorGram**

– Probabilities –

$$
\begin{array}{lcll}
G & ::= & \sum_{i\in I} q \to_{\delta_i} q' : k\langle S_i\rangle.G_i & (probValues)\\
 & \mid & q \to_1 q' : k\langle T@p\rangle.G & (delegation)\\
 & \mid & \sum_{i\in I} q \to_{\delta_i} q' : k\langle l_i : G_i\rangle & (probBranching)\\
 & \mid & G, G & (parallel)\\
 & \mid & \mu\, t.G & (recursive)\\
 & \mid & t & (variable)\\
 & \mid & \mathtt{end} & (end)\\
S & ::= & \mathtt{bool} \mid \mathtt{nat}\cdots & (valuetypes)
\end{array}
$$

Theorem (Soundness)

Well-formed processes do not have "proabability errors"

In WOLLIC'22 things get simpler using results in
[Darda, Hu, Scalas, and Yoshida:ECOOP'22]

Inverso, Melgratti, Padovani, Trubiani, Tuosto: Probabilistic Analysis of Binary Sessions [Concur'20]

Reasoning about session termination ... probabilistically

$$S, T \overset{\text{co}}{::=} \circ \mid \bullet \mid ?t.S \mid !t.S \mid S \oplus^{p} T \mid S \,\&^{p}\, T$$

success

prob. choice

technical convenience

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success — prob. choice — technical convenience

Session Types $\mapsto$ Discrete-Time Markov Chains

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- *(Possibly diverging) well-typed processes respects (the probabilities in) their type*
- *Well-typed processes are deadlock-free*
- *Type preservation*

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[Burló, Francalanza, Scalas, Trubiani, Tuosto:SCP'21] defines a probabilistic monitoring discipline

Dal Lago, Giusti [Concur'22]
On Session Typing, Probabilistic Time, and cryptographic experiments

Binary session types to model cryptographic experiments

- Extend [Caires, Pfenning: Concur'10] with
  - probabilistic choice
  - polytime functions
- this yields a model of cryptographic protocols

Theorem (Soundness)

Subject reduction & progress holds for well typed processes

Theorem (Confluence)

Well typed processes are confluent

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Theorem (Soundness)

Subject reduction & progress holds for well typed processes

Theorem (Confluence)

Well typed processes are confluent

Silent steps converge to a same probability distribution

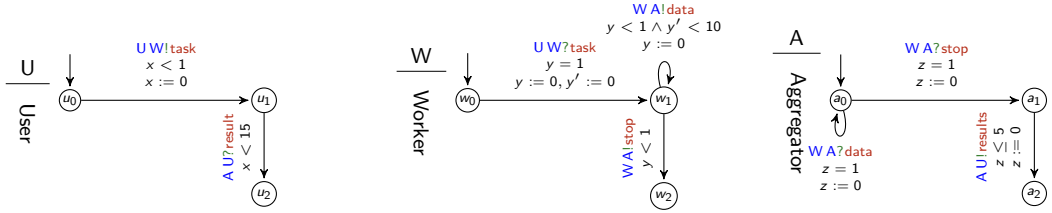
Das, Wang, Hoffman: [PoPL'23] Probabilistic Resource Aware Session Types

Resource analysis of probabilistic systems via probabilistic binary session types

- Probabilistic binary session types to derive expected cost bounds of message-passing systems (exteding [LICS'18])
- The proposed calculus features both non-deterministic and probabilistic choices
- The typing discipline ensures type preservation, progress, and probability consistency
- NomosPro is implemented and extensively evaluated

– Time –

An example borrowed from [Bocchi, Lange, Yoshida:Concur'15]:



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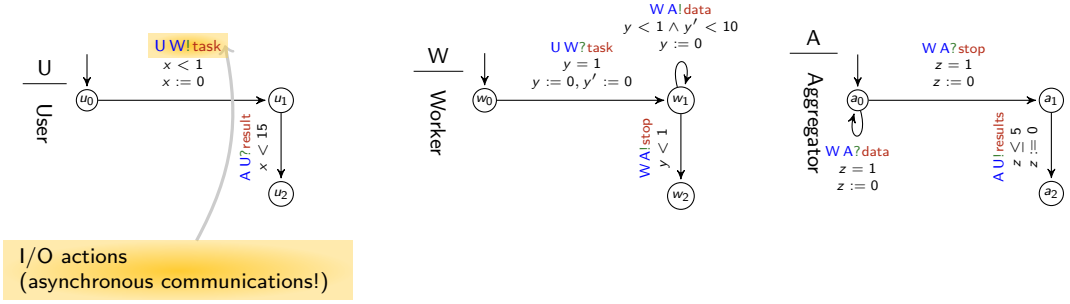

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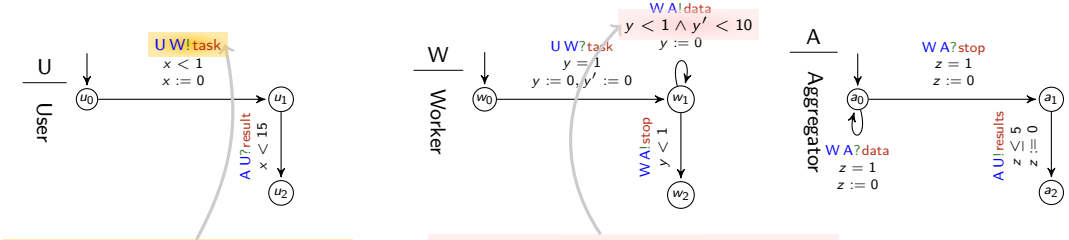

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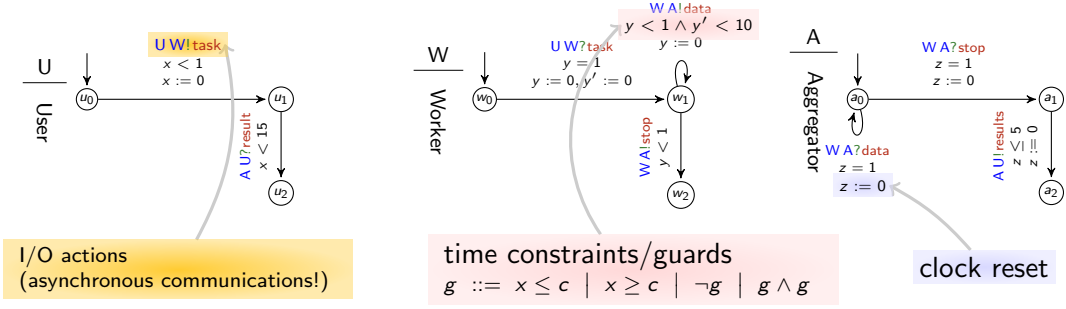

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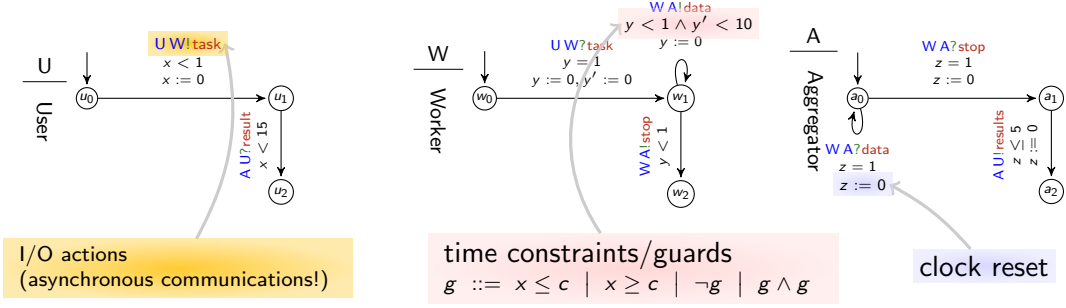
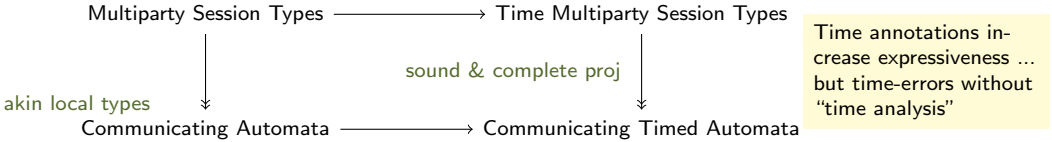


Evaluations

$\nu : x \mapsto r$ where $r \in \Re^{\geq 0}$

Bocchi, Yang, Yoshida [Concur'14]
Timed Multiparty Session Types



Theorem (Soundness)

Well-typed processes respect timing

Theorem (Progress)

$$\textit{Feasibility} + \textit{Wait-Freedom} \implies \textit{time progress of typed processes}$$

where

Feasibility	=	*Partial timed executions can be completed*
Wait-Freedom	=	*if senders respect their timing then receivers do not have to wait*

CFSM/timed automata $\longrightarrow$ Communicating Timed Automata

Sound membership decision procedure
- safety = deadlock freedom + no orphan messages
- eventual reception
- progress
- no-zenoness

Theorem (Soundness)

If S is a multiparty-compatible system then

- *S is safe and*
- *S is timed bisimilar to its projection*

Toolchain for timed interactions

- define timed protocols in **Scribble**
- check for feasibility and wait-freedom
- projections
- derive monitors to check timing constraints

The binary (synchronous) case is interesting too!

Duality does not yield compatibility (i.e., deadlock-freedom)

- is compatibility decidable in timed session types?
- can compliant timed counterpart be found?

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Theorem (Reduction)

Timed compliance can be (algorithmically) reduced to model-check deadlock-freedom in timed automata ($\Longrightarrow$ decidability of timed compliance)

Theorem (Characterisation of evaluations)

The set of evaluations of a timed session type admitting a compliant timed session type is effectively computable
($\Longrightarrow$ canonical compliant timed session types are computable)

Theorem (Decidability of Subtyping)

Subtyping is decidable in timed session types

Synchronous compliance $\not\Longrightarrow$ Asynchronous compliance
The implication holds if firable inputs are not delayed
This result generated interesting new stuff:

- Refinements of Communicating Timed Automata (aking to timed session types) that do not introduce deadlocks/livelocks are simulated by abstract systems [Bartoletti, Bocchi, Murgia:Concur'18]
- Generalisation of duality & compliance based on urgent semantics [Bocchi, Murgia, Vasconcelos, Yoshida:ESOP'19]

Binary asynchronous session types with LTL-like modalities

- $\circ A$ inhabited by process of the form delay;P (P behaves as A after a time unit!)
- $\Box A$ = "always ready to do A"
- $\Diamond A$ = "eventually ready to do A"

This give a generic framework for cost analysis

Well-typed processes enjoy progress & type preservation

The cost model can be parameterised

Extend mixed sessions [Vasconcelos et al.: ESOP'20] to allow mixed choice in timed session types

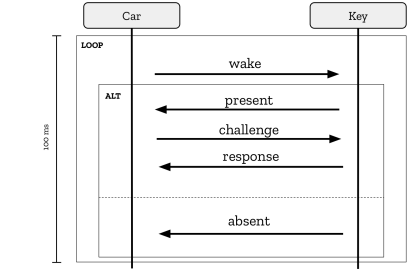
Theorem (Progress)

Well-typed systems have progress

This framework assume urgent input [Murgia:ICE'18,JLAMP'19]

Irachi, Chuang, Hu, Ziarek [OOPSLA'23]
Validating IoT Devices with Range-based session types

Grant Iraci, Cheng-En Chuang, Raymond Hu, and Lukasz Ziarek



- Synchronous binary session types to reason about rates
- Simple extension: periodic recursion

Mind the rates!

$\omega_n t.!m.t \not\sim \omega_n t.!m.!m.t$

Theorem (Soundness)

Well-typed systems do not have rate-errors

– Open Problems –

Resource	Probabilities	Time
• Cost analysis for QoS • Data Dependent QoS	• Relative Expressiveness • Rates	• (Inter)action duration • challenges in CPS • asynchronous subtyping • relativity
tooling	from binary to multiparty	unification

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Can we use [Bocchi, Honda, Yoshida, Tuosto:Concur'10]?

– Thank you! –

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