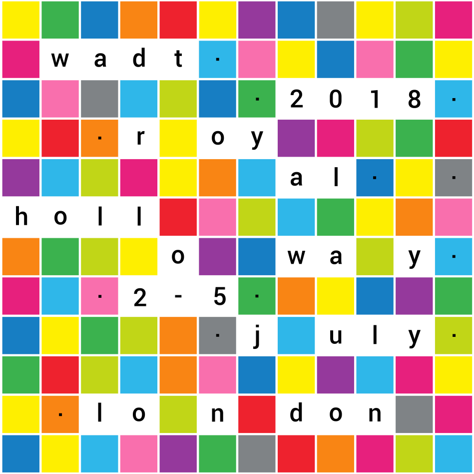
An algebraic semantics and logic for Actor Networks

José Fiadeiro   Ionuţ Ţuţu
Antónia Lopes   Dusko Pavlovic

Royal Holloway University of London, UK
University of Lisbon, Portugal
University of Hawaii, USA

Logic, Algebra and Category Theory

Melbourne, 2018



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18 May 2018

early registration deadline
1 June 2018

invited speakers
Artur d'Avila Garcez, UK
Rolf Hennicker, Germany
Kai-Uwe Kühnberger, Germany
Fernando Orejas, Spain

Under the auspices of IFIP WG 1.3

ROYAL HOLLOWAY UNIVERSITY OF LONDON

This talk

- Algebra (Milner's bigraphs)
- Modal logics (one more for the zoo)
- Institutions (behind the scenes)
- Applications (cyber-physical systems)

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The grand challenge

The design task for ubiquitous systems is all the harder because they will be at least an order of magnitude larger than present-day software systems, and even these have often been rendered inscrutable by repeated ad hoc adaptation. Yet ubiquitous systems are expected to adapt themselves without going offline (since we shall depend upon their continuous operation). It is therefore a compelling scientific challenge to understand them well enough to gain confidence in their performance.

Robin Milner
Grand Challenges for Computing Research
by the UK Computing Research Committee.

Actor Networks

- a new modelling framework for cyber-physical system protocols
- addresses networks whose components are no longer limited to programs but can include humans or physical artefacts as actors
- should be understood in the wider sense of Latour's theory

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Actors are cyber-physical entities that have shared agency.

people, objects, locations

Actors interact through channels that account for

- observations of an actor of another,
- control of an actor on another,
- movement of an actor inside another.

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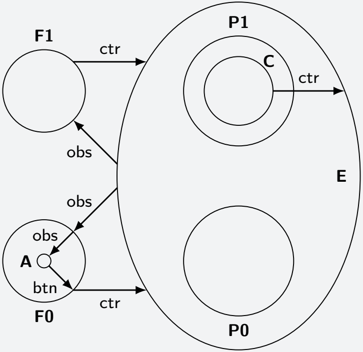

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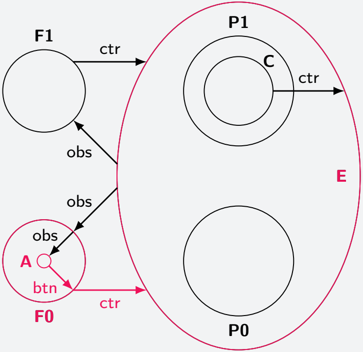

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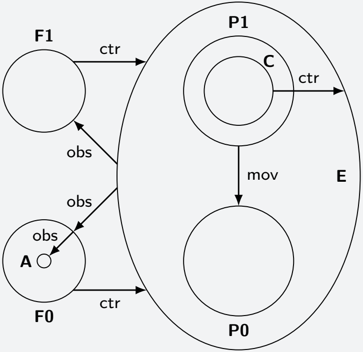

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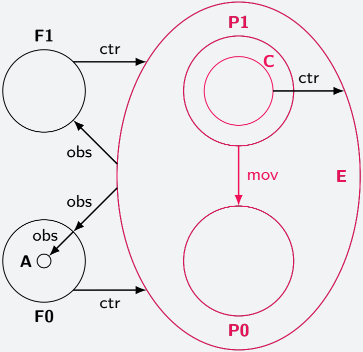

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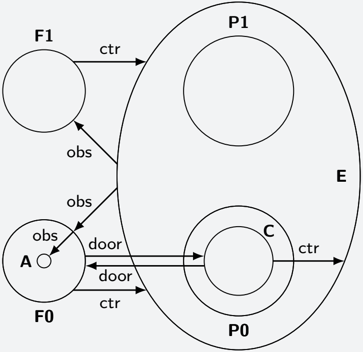

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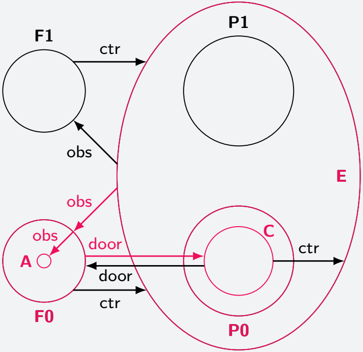

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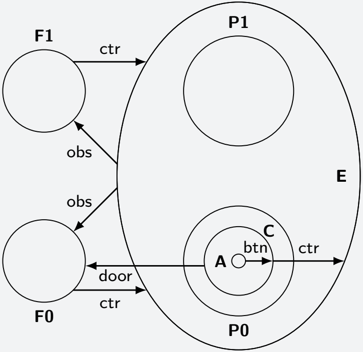

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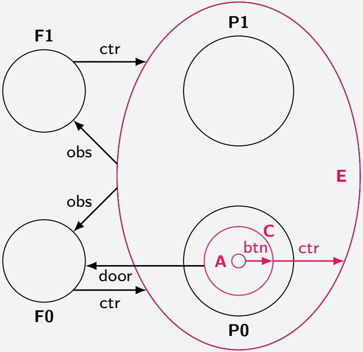

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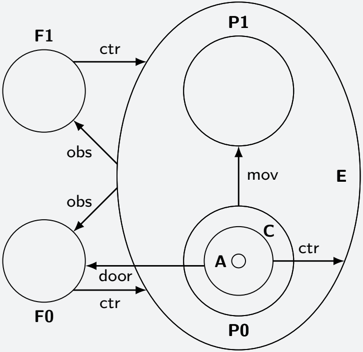

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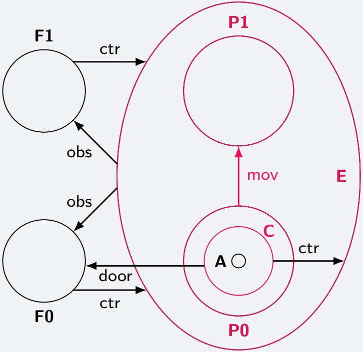

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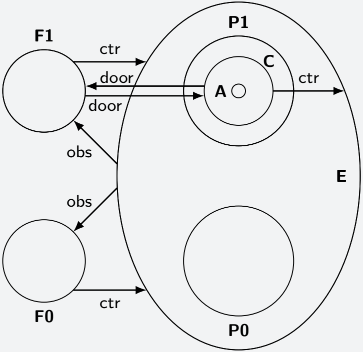

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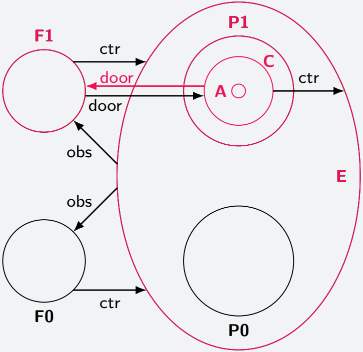

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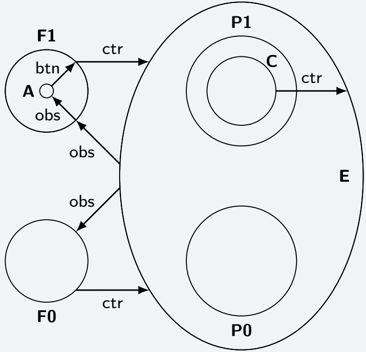
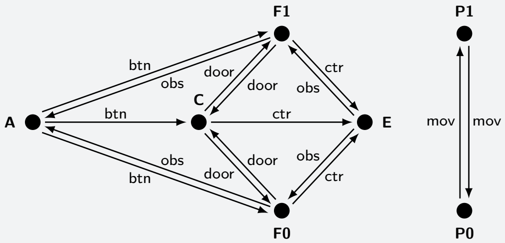


Schemas, Structures, and States

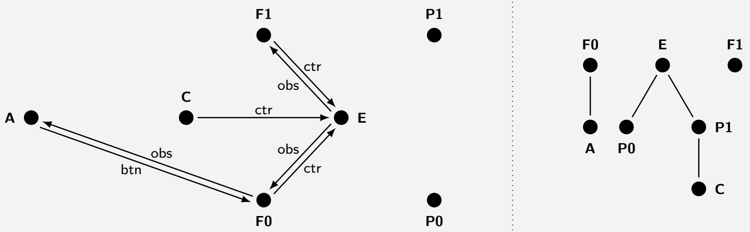
Definition (Schema). A *schema* $\mathcal{A}$ consists of:

- a finite directed graph $\mathcal{G} = \langle \mathcal{N}, \mathcal{C}, \delta, \rho \rangle$,
- a partially ordered set $\mathcal{T}$ of *channel types*,
- a function $\tau \colon \mathcal{C} \to 2^{\mathcal{T}}$ that assigns a non-empty upper set of channel types to every channel, and
- a set $\mathcal{P}$ of *propositional symbols*.



Definition (Structure). A *structure* for $\mathcal{A}$ is a pair $\mathcal{S} = \langle \mathcal{H}, \mathcal{F} \rangle$ where:

- $\mathcal{H}$ is a subgraph of $\mathcal{G}_{\mathcal{A}}$, and
- $\mathcal{F}$ is a forest over $\mathcal{N}_{\mathcal{H}}$, meaning that every node n has either none or a unique parent, denoted $\mathcal{F}(n)$.



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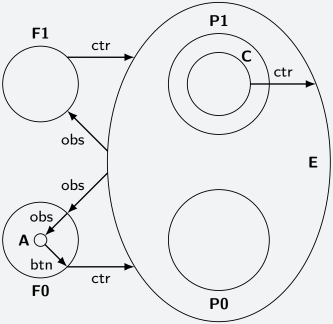
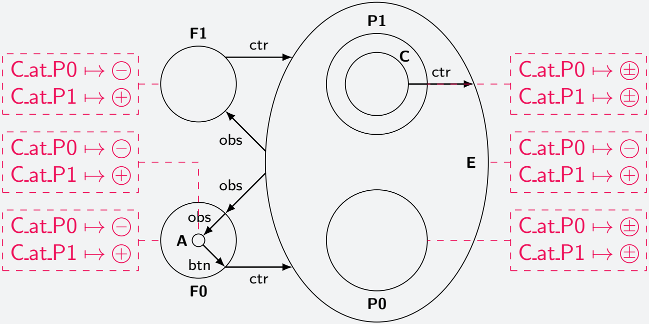


Schemas, Structures, and States

Definition (State). A *state* of an ANt schema $\mathcal{A}$ consists of

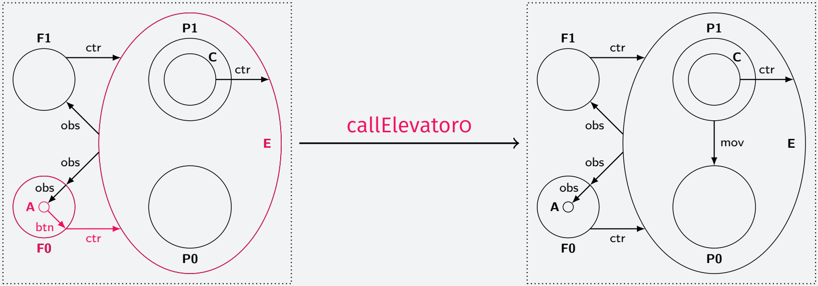
- a structure $\mathcal{S}$ for $\mathcal{A}$ such that $\mathcal{N}_{\mathcal{S}} = \mathcal{N}_{\mathcal{A}}$ (the structure has all the nodes of the schema), and
- for each node, or actor n, a valuation $\mathcal{V}_n$ of the symbols in $\mathcal{P}_{\mathcal{A}}$.



Actor Networks, formally

Definition (Actor network). An actor network ν consists of:

- an ANt schema $\mathcal{A}$,
- a *domain* $\mathcal{D}$ together with a labeling function $\sigma\colon \mathcal{D} \to \mathbb{S}_{\mathcal{A}}$,
- a non-empty subset $\mathcal{D}_0 \subseteq \mathcal{D}$ of *initial worlds*,
- a set $\mathcal{I}$ of *interactions* for $\mathcal{A}$,
- a *transition relation* $(\longrightarrow) \subseteq \mathcal{D} \times \mathcal{I} \times \mathcal{D}$ such that, for each interaction $\iota \in \mathcal{I}$, $w \xrightarrow{\iota} w'$ implies $\iota \preceq \mathcal{S}_{\sigma(w)}$.



The formal specification and verification challenge

Find a logical formalism that is suitable for

- writing specifications (logical theories, which may be modular and, to some extent, loose) of actor networks,
- capturing ANt properties by means of logical sentences,

and is equipped with appropriate tools, and amenable to adequate techniques for checking whether a given specification guarantees (entails logically) certain properties of interest.

The hybridisation process

- start with a base logical system, for which we assume signatures (Σ), sentences (p), models (M), and a satisfaction relation ($\models$) between models and sentences
- define hybrid-logic signatures as tuples $\langle \mathrm{Nom}, \Lambda, \Sigma \rangle$
- hybrid sentences are given by the grammar

$$\rho ::= i \mid p \mid \neg\rho \mid \rho * \rho \mid \langle\lambda\rangle\,\rho \mid [\lambda]\,\rho \mid @_i\,\rho \mid \exists j\,\rho \mid \forall j\,\rho$$

- the models are Kripke structures

$$\langle W, (W_i)_{i \in \mathrm{Nom}}, (R_\lambda)_{\lambda \in \Lambda}, (M_w)_{w \in W} \rangle$$

- the satisfaction relation is parameterized by states

$$\langle W, R, M \rangle \models^w \rho$$

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- the models are Kripke structures (possibly constrained)

$$\langle W, (W_i)_{i \in \mathrm{Nom}}, (R_\lambda)_{\lambda \in \Lambda}, (M_w)_{w \in W} \rangle$$

- the satisfaction relation is parameterized by states

$$\langle W, R, M \rangle \models^w \rho$$

Two levels of hybridisation

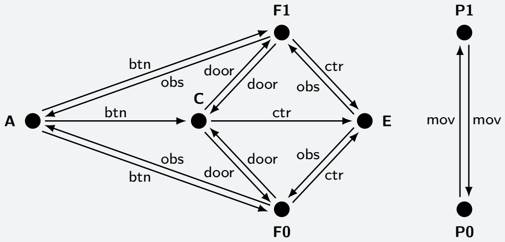
Level I: The state logic

- the base logic is the three-valued propositional Łukasiewicz logic
- the set Nom of nominals is countably infinite and includes a set $\mathcal{N}$ of actor names
- the modalities are either channel types from a set $\mathcal{T}$, or a distinguished *parent* modality π

Two levels of hybridisation

Level I: The state logic

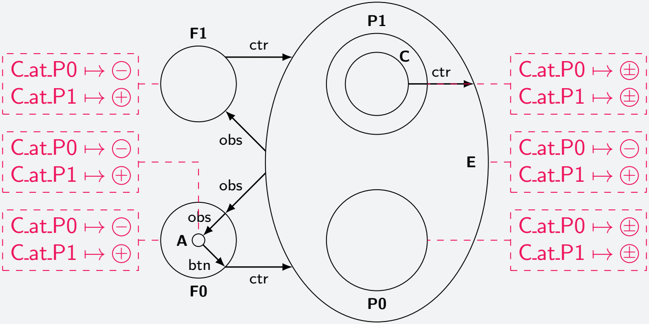
- constraints are given by an ANt schema $\mathcal{A}$ over $\mathcal{N}$ and $\mathcal{T}$
  - there is a one-to-one correspondence between actors and possible worlds
  - accessibility relations conform to the channels and the channel types of the schema
  - the interpretation of the parent modality π is functional and acyclic



Two levels of hybridisation

Level I: The state logic

- constrained models are states of the actor-network schema $\mathcal{A}$

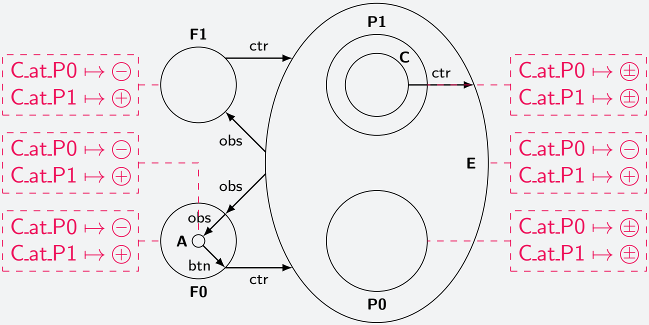


Two levels of hybridisation

Level I: The state logic

- The cabin is at platform i if and only if the elevator knows it.

$$@_C \langle \pi \rangle Pi \leftrightarrow @_E \mathbf{L}\, (\mathrm{C\_at\_P}i) \quad \text{for } i \in \{0, 1\}$$

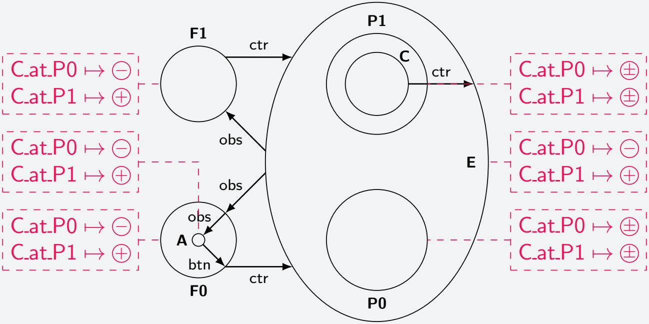


Two levels of hybridisation

Level I: The state logic

- Knowledge is propagated through observation channels.

$$p \to [\mathrm{obs}]\, p \quad \text{for every } p \in Ł(\mathcal{P})$$

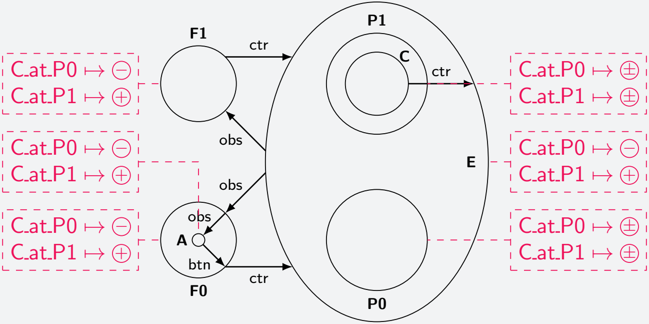


Two levels of hybridisation

Level I: The state logic

- The floors can only be observed by Alice, and that is all Alice can observe.

$$\big((\mathrm{F0} \vee \mathrm{F1}) \rightarrow [\mathrm{obs}]\, A\big) \wedge \big(\langle \mathrm{obs} \rangle\, A \rightarrow (\mathrm{F0} \vee \mathrm{F1})\big)$$



Two levels of hybridisation

Level II: The ANt logic

- the base logic is the state logic
- the set Nom of nominals is countably infinite and includes a set Init of names of initial states
- the modalities are interactions (from a finite set $\mathcal{I}$) of the actor-network schema $\mathcal{A}$

Two levels of hybridisation

Level II: The ANt logic

- constraints: all interactions $\iota \in \mathcal{I}$ are substructures of the states on which ι is defined

$$\text{if } (w, w') \in R_\iota \text{ then } \iota \preceq \mathcal{S}_{\sigma(w)}$$

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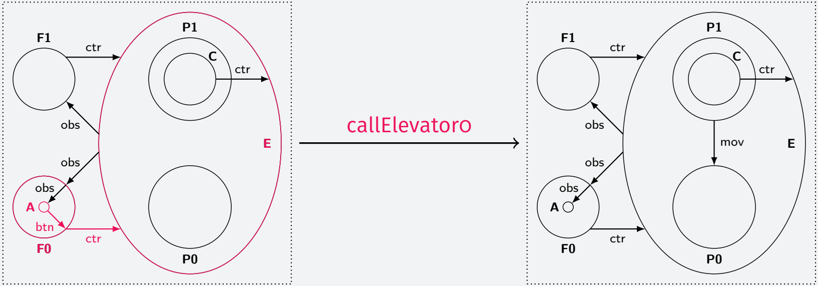

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$$\text{if } (w, w') \in R_\iota \text{ then } \iota \preceq \mathcal{S}_{\sigma(w)}$$

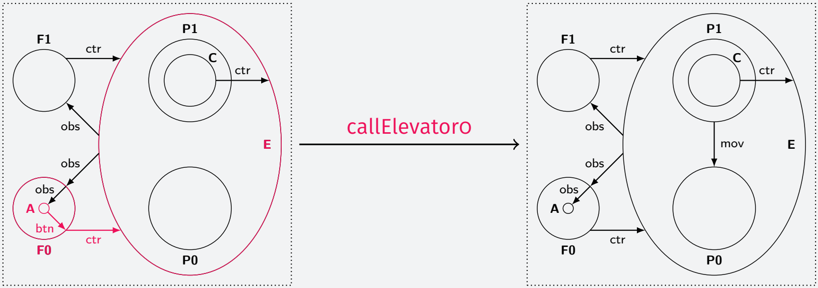
- therefore, the models of the ANt logic are actor networks

Two levels of hybridisation

Level II: The ANt logic

- When the elevator is called (at the ground floor) and the cabin is at the first platform, a request to move the cabin to the ground platform is issued.

$$@_{C}\,\langle\pi\rangle\,\mathrm{P1} \Rightarrow [\![\mathsf{callElevator0}]\!]\,@_{\mathrm{P1}}\,\langle\mathrm{mov}\rangle\,\mathrm{P0}$$

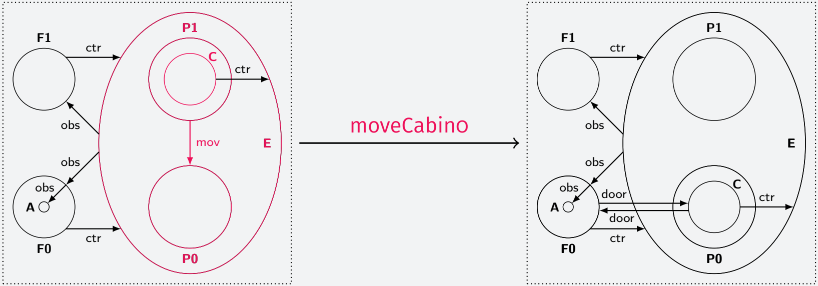


Two levels of hybridisation

Level II: The ANt logic

- The doors are opened whenever the cabin moves to the (ground) platform.

$$[\![\mathsf{moveCabin0}]\!]\ @_{\mathrm{F0}}\ \langle \mathrm{door} \rangle\ (\mathrm{C} \wedge \langle \mathrm{door} \rangle\ \mathrm{F0})$$

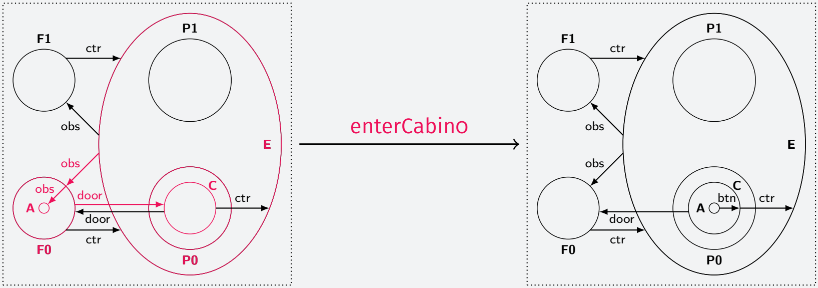


Two levels of hybridisation

Level II: The ANt logic

- If Alice is at F0 and the doors are open, then she can enter the cabin.

$$@_A \langle\pi\rangle (\mathrm{F0} \wedge \langle\mathrm{door}\rangle\, \mathrm{C}) \Rightarrow \langle\!|\mathrm{enterCabino}|\!\rangle\ \mathrm{true}$$



Towards formal verification

- consider a sound and complete proof system for hybrid logic

$$\mathrm{SP} \models^{\mathrm{HL}} \rho \qquad \text{if and only if} \qquad \mathrm{SP} \vdash^{\mathrm{HL}} \rho$$

- this provides for free sound (but not necessarily complete) proof systems for both the state logic and the ANt logic
- the constraints of the two levels of hybridisation can be axiomatised within hybrid logic, so completeness can be regained
- to that end, we define

$$\mathrm{SP} \vdash^{\mathrm{SL}} \rho \qquad \text{if and only if} \qquad \mathrm{SP} \cup \mathrm{AxSL} \vdash^{\mathrm{HL}} \rho$$

$$\mathrm{SP} \vdash^{\mathrm{ANtL}} \rho \qquad \text{if and only if} \qquad \mathrm{SP} \cup \mathrm{AxANtL} \vdash^{\mathrm{HL}} \rho$$

Theorem. The syntactic entailment relations $\vdash^{\mathrm{SL}}$ and $\vdash^{\mathrm{ANtL}}$ are sound and complete with respect to $\models^{\mathrm{SL}}$ and $\models^{\mathrm{ANtL}}$.

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$$\mathrm{SP} \models^{\mathrm{HL}} \rho \qquad \text{if and only if} \qquad \mathrm{SP} \vdash^{\mathrm{HL}} \rho$$

- this provides for free sound (but not necessarily complete) proof systems for both the state logic and the ANt logic
- the constraints of the two levels of hybridisation can be axiomatised within hybrid logic, so completeness can be regained
- to that end, we define

$$\mathrm{SP} \vdash^{\mathrm{SL}} \rho \qquad \text{if and only if} \qquad \mathrm{SP} \cup \mathrm{AxSL} \vdash^{\mathrm{HL}} \rho$$
$$\mathrm{SP} \vdash^{\mathrm{ANtL}} \rho \qquad \text{if and only if} \qquad \mathrm{SP} \cup \mathrm{AxANtL} \vdash^{\mathrm{HL}} \rho$$

Theorem. The syntactic entailment relations $\vdash^{\mathrm{SL}}$ and $\vdash^{\mathrm{ANtL}}$ are sound and complete with respect to $\models^{\mathrm{SL}}$ and $\models^{\mathrm{ANtL}}$.

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Conclusions

In this talk

- we have introduced a model theory for ANts, which provides a framework for reasoning about cyber-physical system protocols
- briefly revisited the hybridisation of logics
- shown how the specification and verification of ANts can be realised through a two-stage constrained-hybridisation process

Outlook

- dedicated proof systems; soundness and completeness
- model-theoretic counterpart of the graph-transformation approach to actor networks
- applications to security policies and models via noninterference

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Further Reading

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Thank you!

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submission deadline
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notifications
18 May 2018

early registration deadline
1 June 2018

invited speakers
Artur d'Avila Garcez, UK
Rolf Hennicker, Germany
Kai-Uwe Kühnberger, Germany
Fernando Orejas, Spain

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