Multi-Agent Workflows

joint work with Bernd Finkbeiner, Helmut Seidl, Eugen Zălinescu

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Overview

Section 1

Setting

Motivation

Conference Management (Easychair, HotCRP, . . .)
Used by authors, reviewers, PC chair, . . .

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HotCRP.com

2.60 19.Jul.2013
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This required extensive rearchitecting of system internals to (hopefully) avoid information leaks.

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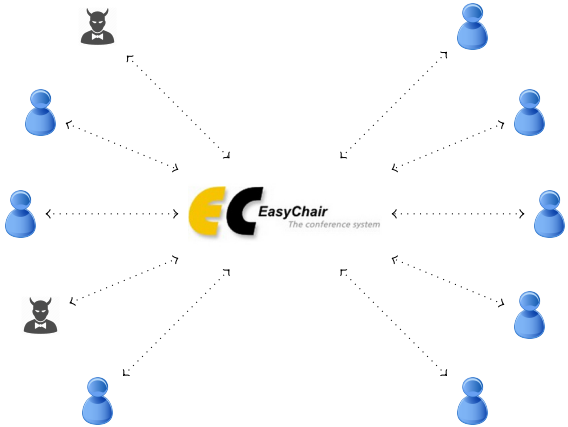
Systems need to protect sensitive information!

Challenges



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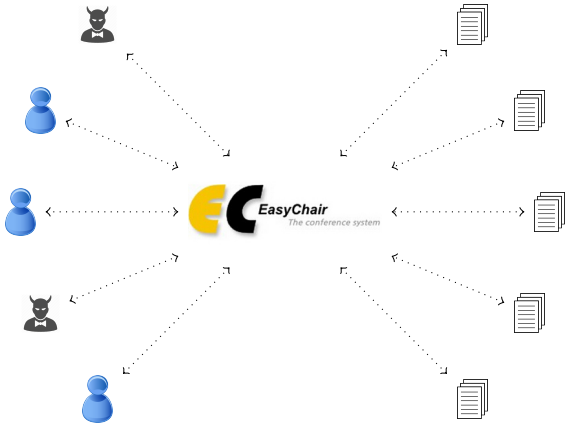

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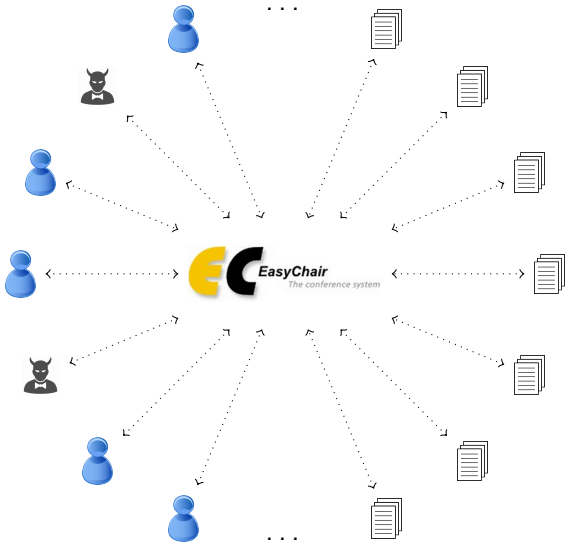

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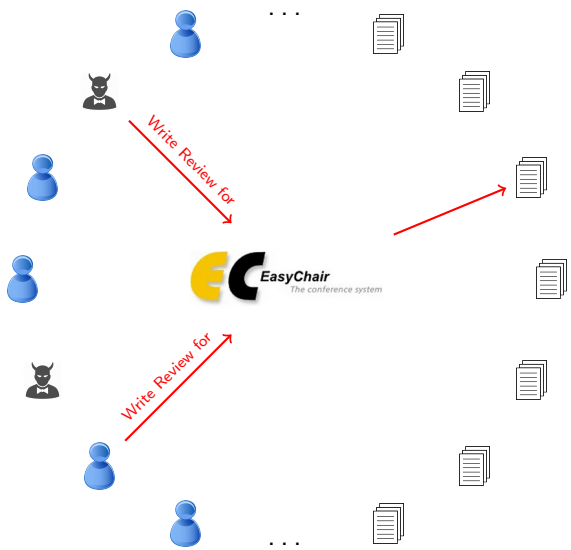
Write Review for
EasyChair
The conference system
Write Review for

Conference Management System

1. Declare Conflicts of Interest
2. Assign Papers to Reviewers
3. Write initial Reviews
4. Loop:
    1. Discuss Reviews
    2. Update Reviews

Conflict Declaration

Reviewers may declare conflicts of interest with papers.

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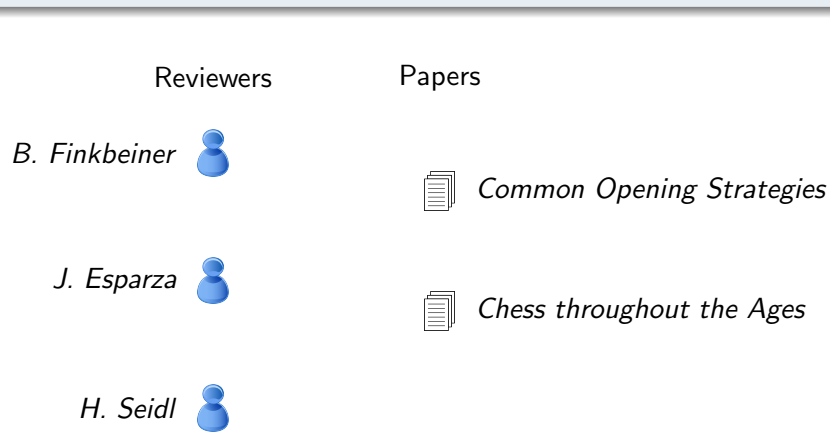

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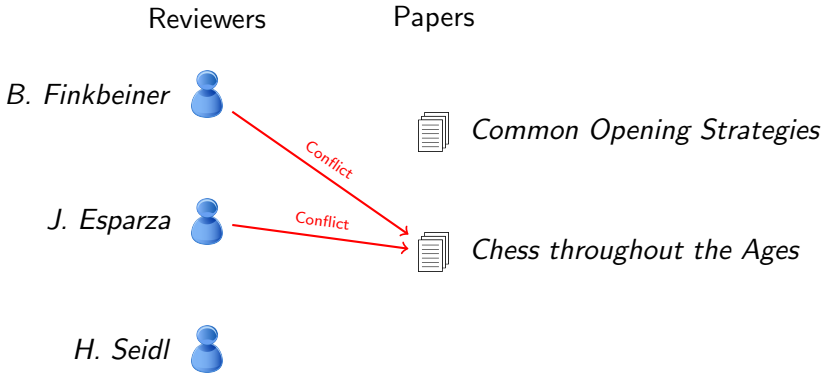

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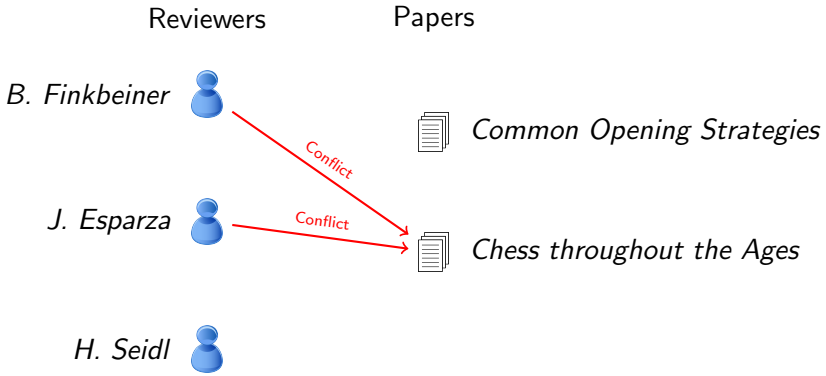

forall x: PC, p: $Paper$. **may** $true \rightarrow Conflict \mathrel{+}= (x, p)$

Complete Example Workflow

% 1. PC members may declare conflicts

% 2. PC members are assigned to papers

% 3. PC members write reviews for papers

% 4. PC members read all reviews

% 5. PC members can update their reviews

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loop $\{$

% 4. PC members read all reviews
forall x: *PCMember*, y: *PCMember*, p: *Paper*, r: *Review*. **may**
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Semantics

forall x: PC, p: $Paper$, r: $Review$. **may**

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$$\textbf{forall } x\colon PC, p\colon Paper, r\colon Review.\ \textbf{may}$$
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is expressed by

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Semantics of the Workflow in *Sorted First Order Temporal Logic (FOLTL)*

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Semantics of the Workflow in *Sorted First Order Temporal Logic (FOLTL)*

If all variables reappear, we call the workflow *non-omitting*

Properties

Reachability

Can we reach a state where agent a is assigned paper p?

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Security

Can any agent gain information on reviews of conflicting papers?

Section 2

Verification

Verification

Control Flow

Semantics

Specification

Verification

Control Flow

Semantics

Specification

Complete formal specification

Verification

Control Flow

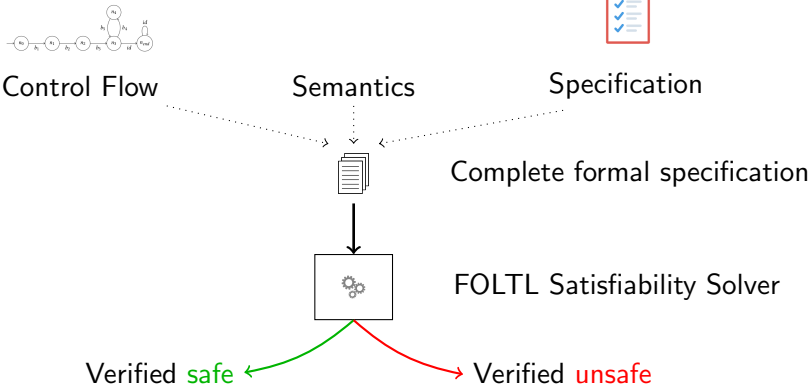
Specification

Semantics

Complete formal specification

FOLTL Satisfiability Solver

Verification



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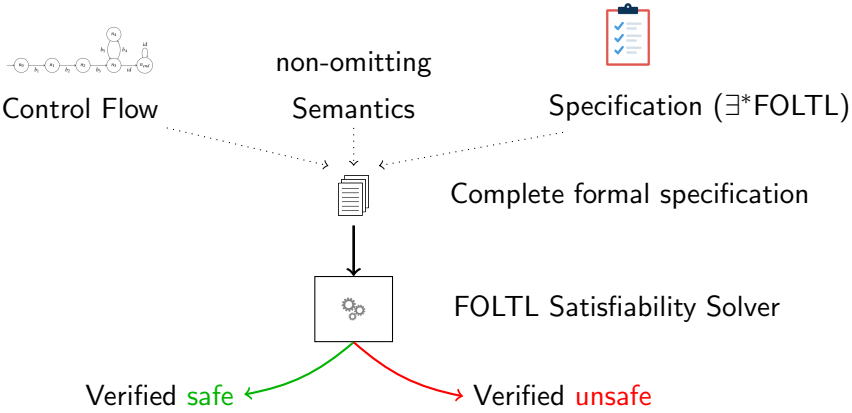

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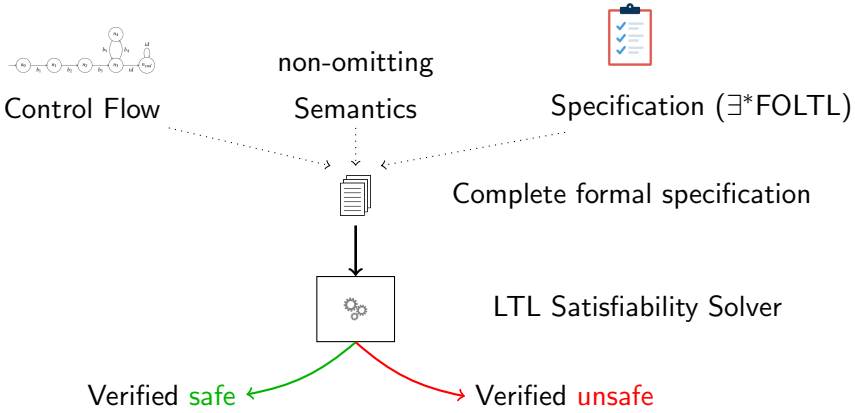

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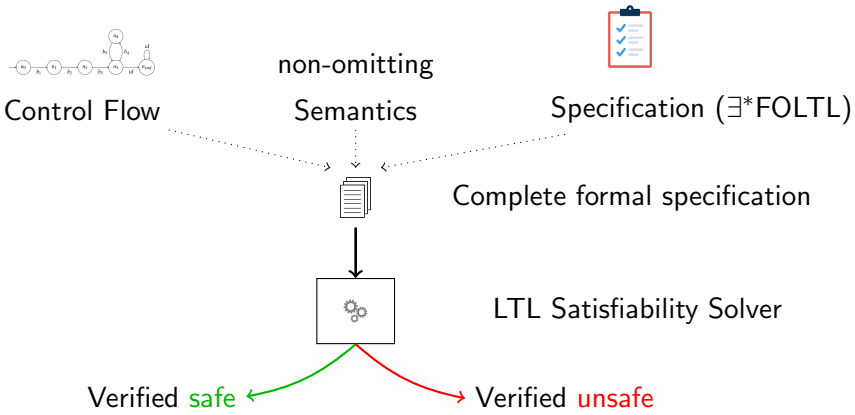

Theorem: Workflow Verification [CCS '17]

$w \models \neg\varphi$ is decidable for non-omitting workflows.

What's the problem?

$$\textbf{forall } x\colon PC, y\colon PC, p\colon Paper, r\colon Review.$$
$$Assign(x, p) \wedge Review(y, p, r) \rightarrow Read \mathrel{+}= (x, y, p, r)$$

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Theorem: Verification for Omitting Workflows [CCS '17]

$w \models \neg\varphi$ is undecidable for omitting workflows even if $\neg\varphi$ is decidable.

Section 3

Information Flow Security

Noninterference

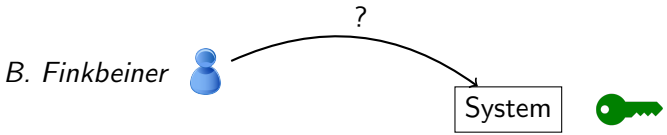
Can any agent learn secret information?

B. Finkbeiner 

System 

Noninterference

Can any agent learn secret information?



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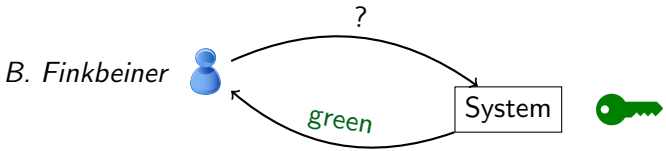

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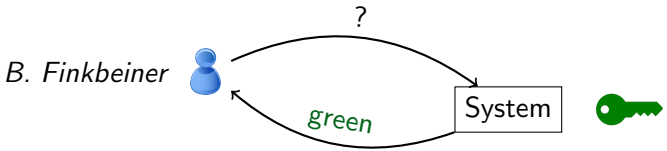
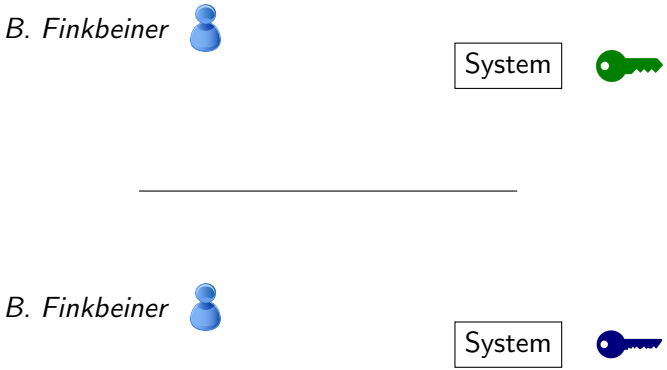


Does *B. Finkbeiner* learn something?

Noninterference — Hyperproperty



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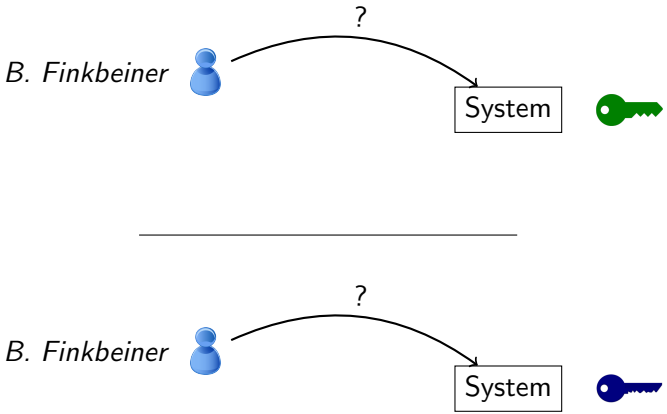

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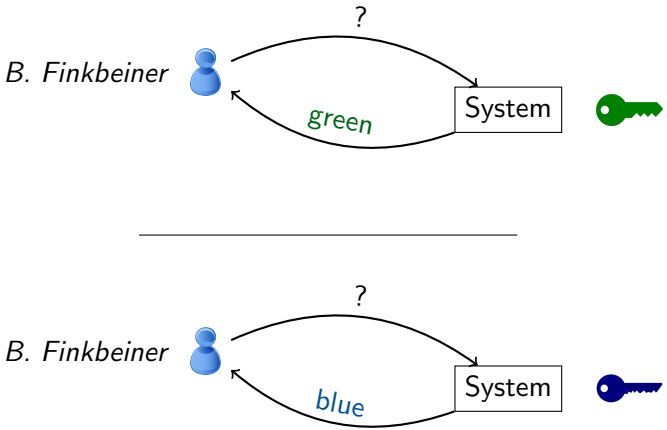

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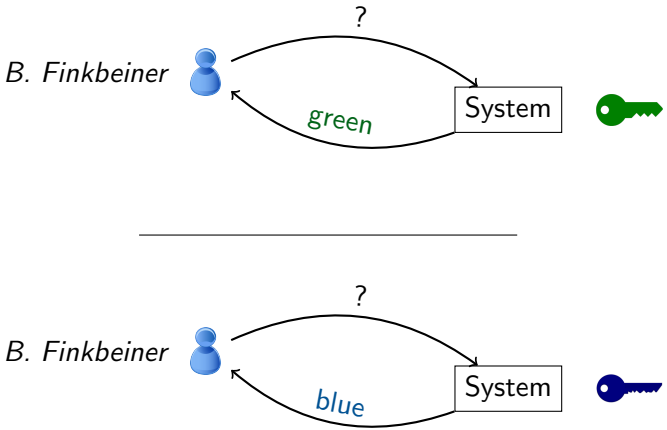
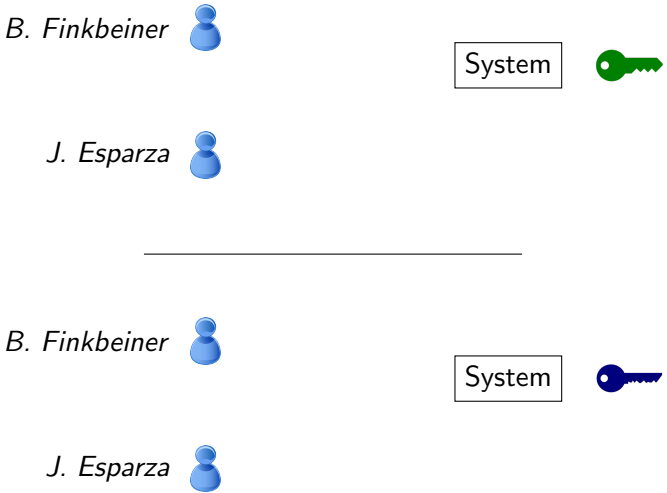


Is this enough?

Noninterference



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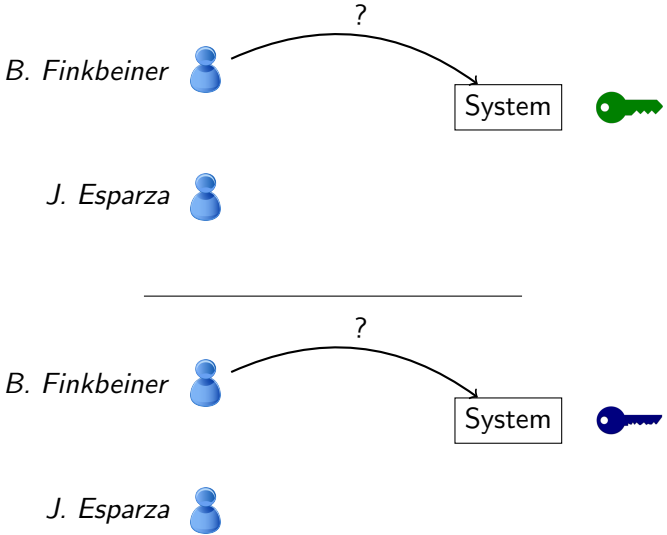

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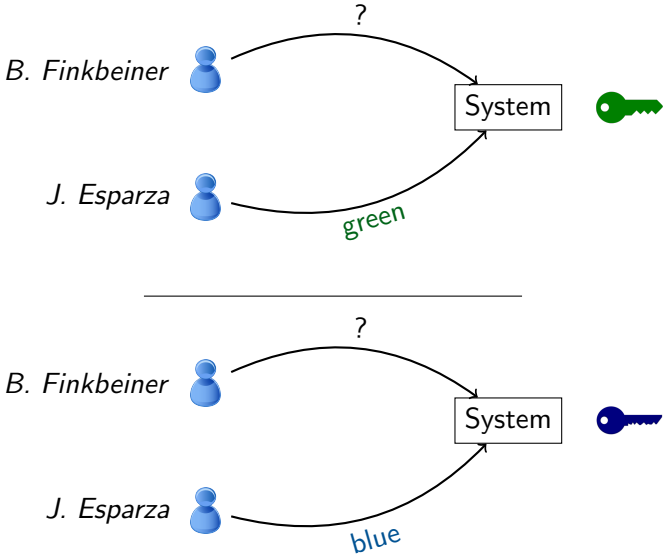

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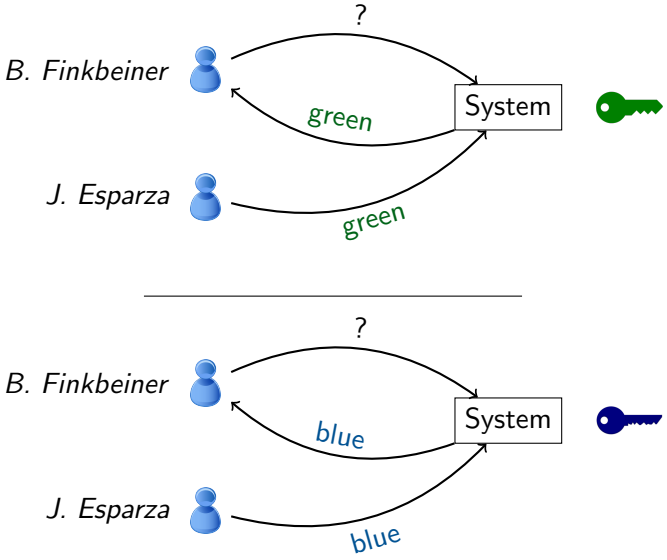

Agent Models

Stubborn Agents

Agent behavior does not depend on secret information.
$\Rightarrow$ Observing other agents does not leak information.

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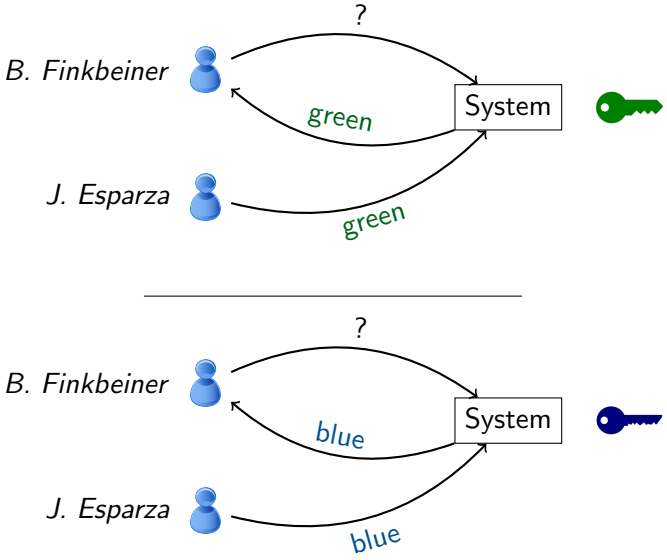
Causal Agents

Agents will actively change their behavior to leak as much information as possible.
$\Rightarrow$ Causal agents conspire against the system.

Noninterference



Verification for Hyperproperties

For any *non-omitting* workflow w and specification in $\exists^*_\pi \forall^*_\pi \exists^*$FOLTL

Theorem: Workflow Verification for Hyperproperties

1. $w \models \neg\varphi$ is decidable for a fixed upper bound of causal agents.
2. $w \models \neg\varphi$ is undecidable for an unlimited amount of causal agents.

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Corollary: Noninterference

Noninterference for a fixed upper bound of causal agents is decidable.

Section 4

Implementation

Nice theory — but does it work?

Meet *NIWO*, an automatic analyzer for **N**on**i**nterference in **Wo**rkflows

Input

- Non-omitting Workflow specification
- Declassification condition
- Amount and sort of causal agents

Builds the correct first-order formulas, translates to LTL
$\Rightarrow$ Solve using any LTL satisfiability solver.

NIWO — Scalability

Resulting LTL formula

- Scales linearly to larger workflows
- Scales exponentially in the number of causal agents.

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Resulting LTL formula

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Solving the resulting LTL satisfiability problem

- Only stubborn agents
  $\Rightarrow$ Verifies example workflows in seconds
- Small number of causal agents
  $\Rightarrow$ Verifies example workflows in minutes

Example Revisited

% 1. PC members may declare conflicts

% 2. PC members are assigned to papers

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Relation	π	π'
Conflict	$(Alice, p)$	

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Relation	π	π'
Conflict	$(Alice, p)$	
Assign	$(Alice, q), (Bob, q), (Bob, p)$	
Review	(Bob, p, r_p) (Bob, q, r_q)	(Bob, q, r_q)
Read	$(Alice, Bob, q, r_q)$	
Review	(Bob, q, r_p)	
Read	$(Alice, Bob, q, r_p)$	

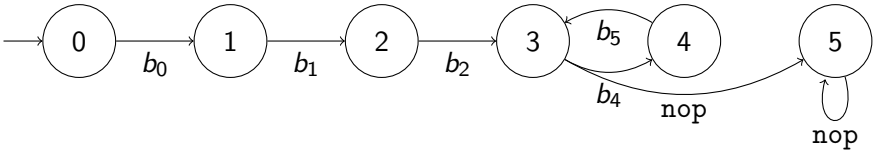
Summary — Non-omitting workflows

1. Developed theory for Workflow Verification
2. Proved (un-)decidability of Workflow Verification for a meaningful fragment of Hyper-Properties (e.g. Noninterference)
3. Built NIWO, an automatic analyzer for Noninterference in non-omitting Workflows

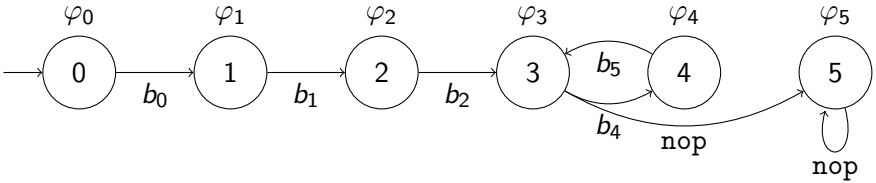
Section 5

Omitting Workflows — Inductive Invariants to the Rescue

Invariants



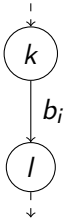
Invariants



Invariant

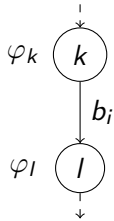
An *invariant* φ is an assignment of locations to first-order formulas φ_i.

Inductive Invariants



b_i : **forall** x: PC, p: $Paper$ **may**. $\neg Conflict(x, p) \rightarrow Assign \mathrel{+}= (x, p)$

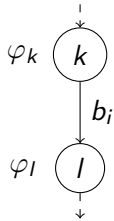
Inductive Invariants



Inductiveness

Whenever the workflow goes from state k to state l and φ_k held before, then φ_l will hold afterwards

Inductive Invariants



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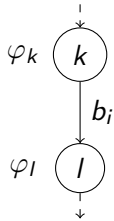
Inductive Invariants



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Theorem: Validity

For an invariant φ where all φ_i are *universal*, it is decidable wether φ holds for a given workflow.

Simplifying the desired properties

Noninterference property consists of

- 2 copies of all relations
- Agent model
- Declassification
- No observable differences

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- No observable differences — Universal **G** property

Corollary: Noninterference

Given a suitable universal invariant φ, it is decidable if φ proves that Noninterference holds (again for a fixed upper bound of causal agents)

Summary — Omitting Workflows

Summary

1. It is undecidable if a given FOLTL property holds.
2. Solution: Use inductive universal invariants to show that properties hold.
3. If properties are too complicated, transform the workflow.

What I haven't shown

For a large subclass of omitting workflows:
If there exists a universal invariant that can be used to prove Noninterference,
we can compute it.