Modular Synthesis of Enforcement Mechanisms for the Workflow Satisfiability Problem: Scalability and Reusability

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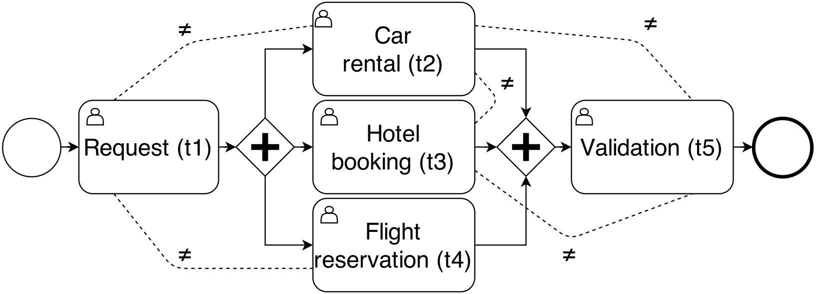
Outline

Context

- A workflow specifies a collection of tasks and the causal relationships between them
- Authorization policy specifies which users can execute which tasks
- Additional constraints, such as Separation/Binding of Duty, further restrict the execution of tasks by users
  - Important to avoid errors and fraud, limiting opportunities for abuse
- We call those workflows security-sensitive



task	roles
t1	r3
t2	r2
t3	r2
t4	r1
t5	r2

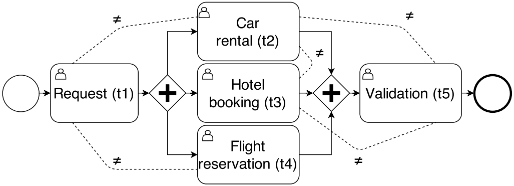
roles	users
r1	a
r2	a, b, c
r3	a, b

Workflow Satisfiability Problem

WSP

Is there an assignment of users to tasks such that a workflow terminates while satisfying all authorization constraints?

Problem



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roles	users
r1	a
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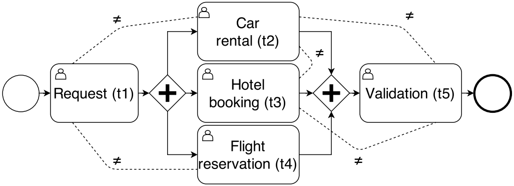
r3	a, b

Execution = t1(a), t2(b), t3(c), X

WSP solution



task	roles
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t4	r1
t5	r2

roles	users
r1	a
r2	a, b, c
r3	a, b

Execution = t1(b), t2(a), t3(c), t4(a), t5(b)

Run-time WSP

Run-time WSP

Answering sequences of user requests at execution time ensuring termination with the satisfaction of authorization constraints

WSP is computationally hard, but run-time version allows us to divide the problem in two steps

Solving the WSP - previous work[1]

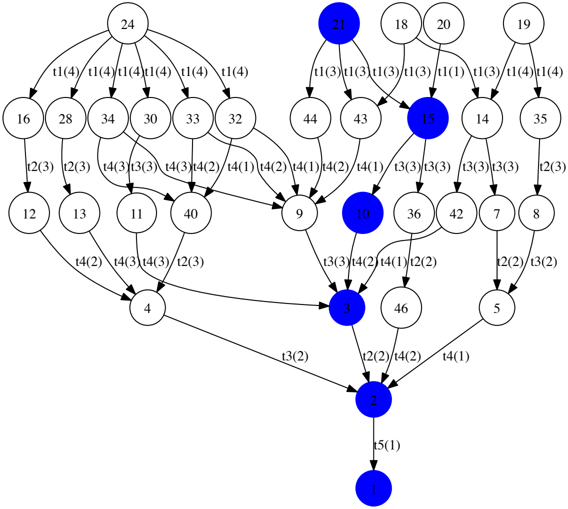
- Technique for the synthesis of run-time monitors for the WSP in two steps:
  - Off-line: takes as input the specification of control-flow and constraints
  - On-line: takes as input the authorization policy
- Off-line result is based on a set of symbolic users and an unconstrained policy
  - Supports different authorization policies at run-time
- On-line result is a set of queries $can\_do(u, t)$ that encode the conditions under which a user can perform a task while ensuring satisfiability

[1] - C. Bertolissi, D.R. dos Santos, S. Ranise, "Automated Synthesis of Run-time Monitors to Enforce Authorization Policies in Business Processes", ASIACCS 2015

Off-line

- A symbolic transition system $S = (V, Tr)$ is derived from a workflow specification
  - V contains variables related to execution and authorization constraints
  - Tr contains transitions $t(u) : en \rightarrow act$
- S is used to compute a symbolic reachability graph RG
  - Nodes labeled by a symbolic representation of the set of states from which it is possible to reach a state in which the workflow successfully terminates
  - Edges labeled by task-user pairs (symbolic users)
- Any path from a leaf node to the root corresponds to a symbolic execution

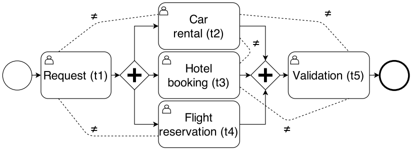
Off-line - Symbolic Reachability Graph



On-line

- A Datalog program is derived from *RG* by building clauses from the formulae labeling the nodes
- Each clause invokes predicates *auth* (interface to the authorization policy) and *h* (keeps track of which user has executed which task)
- If the monitor grants a request (clause is satisfied), then the user can execute the task and the workflow can terminate while satisfying the authorization policy and the authorization constraints

Run-time WSP solution



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t2	r2
t3	r2
t4	r1
t5	r2

roles	users
r1	a
r2	a, b, c
r3	a, b

#	History	Query	Answer
0	$\emptyset$	$can\_do(a, t1)$	deny
1	-	$can\_do(b, t1)$	grant
2	$h(t1, b)$	$can\_do(c, t3)$	grant
3	$h(t3, c)$	$can\_do(a, t4)$	grant
4	$h(t4, a)$	$can\_do(b, t2)$	deny
5	-	$can\_do(a, t2)$	grant
6	$h(t2, a)$	$can\_do(b, t5)$	grant
7	$h(t5, b)$	-	-

Problems with the previous solution

- How to scale monitor synthesis and handle large workflows?
- How to reuse already specified modules across processes?
- How to specify and enforce authorization constraints that span multiple modules?

Contributions of this paper

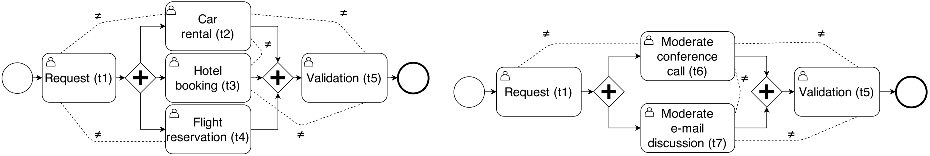
- Define security-sensitive workflow components equipped with interfaces that allow to glue components together
- Define gluing assertions to specify the constraints between components (control-flow and authorization)
- Automatically synthesize run-time monitors from workflow components, ensuring that all tasks can be executed without violating the policy or the constraints

Outline

Modularity

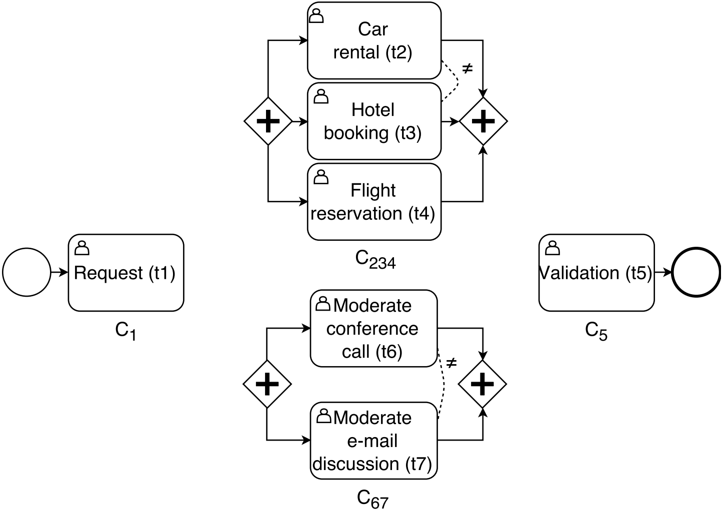
- Modularity is important for better and more reusable models
- Business process libraries and repositories
  - Allow designers to store, retrieve and combine reusable workflow models
- End-to-end processes spanning multiple workflows
  - Composition of smaller models, e.g., Purchase Order and Warehouse Management
  - Inter-module constraints

Example

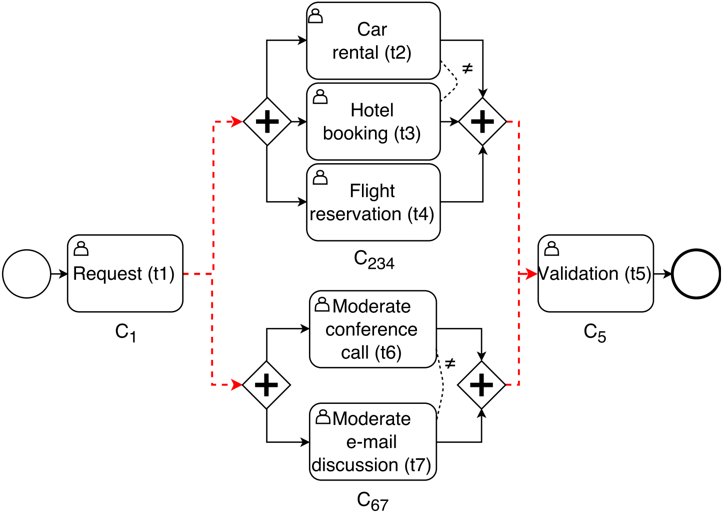


- Designer would like to reuse $t1$ and $t5$ for both workflows, while modeling from scratch only $t2, t3, t4$ and $t6, t7$
- Define them as components and specify complete workflows by combining the reused components with the new ones
  - $C_1 \oplus_G C_{234} \oplus_G C_5$ and $C_1 \oplus_G C_{67} \oplus_G C_5$
- Obtain a monitor for the composed workflows

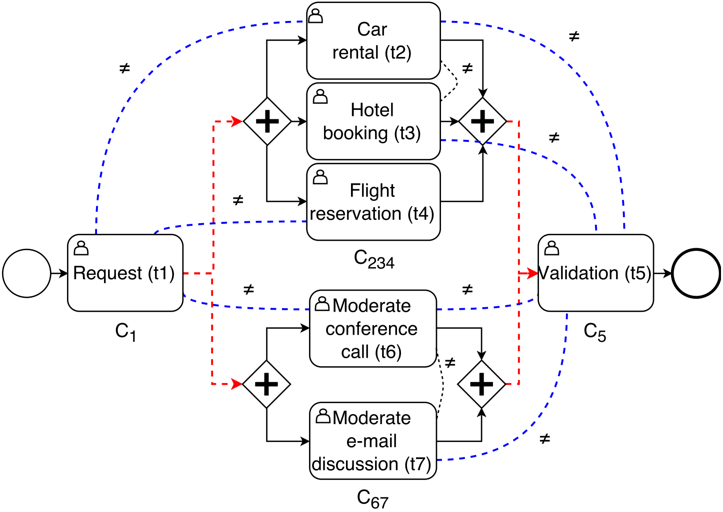
Example - components



Example - control-flow



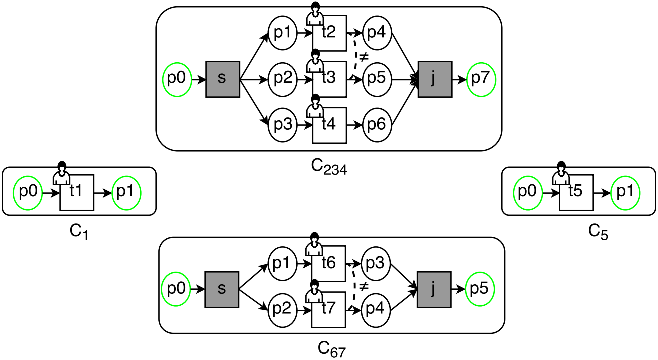
Example - constraints



Enforcement - monitor synthesis

- What to do:
  - Translate component specifications to transition systems
  - Synthesize and store monitors for new components
  - Retrieve and combine monitors for reused components
- How to do it:
  - Refine the transition systems from previous work
  - Define Components, Interfaces, and Gluing assertions
  - Use the same monitor synthesis procedure

Components

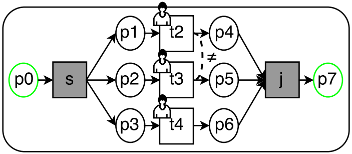


Component $C = (S', Int)$ contains a refined transition system S' and an interface Int

Transition system refinement

- $S = (V, Tr)$ refined to $S' = ((P, D, A, H, C), Tr', B)$
  - $V = P \cup D \cup A \cup H \cup C$
  - B specifies internal authorization constraints
  - Transitions in Tr' contain variables from V and B
- S' is a refinement for composition, and S can be obtained back from S'

Example - Transition system refinement



C_{234}

Transitions

$t2(u) : p1 \wedge \neg d_{t2} \wedge a_{t2}(u) \wedge c_{t2}(u) \wedge c^{i}_{t2}(u) \rightarrow$
$p1, p4, d_{t2}, h_{t2}(u) := F, T, T, T$

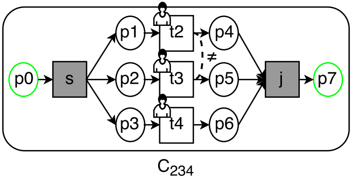
Constraints

$B = \{\forall u.c_{t2}(u) \Leftrightarrow \neg h_{t3}(u)\}$

Interface

- $Int = (A, P^i, P^o, H^o, C^i)$ defines the variables of S' that can be set by another component (*i*nput) and those that are set by the component itself (*o*utput)
    - A is defined by the authorization policy
    - P^i, P^o are the places that connect components (control-flow)
    - H^o transfers the execution history between components
    - C^i are the inter-component authorization constraints

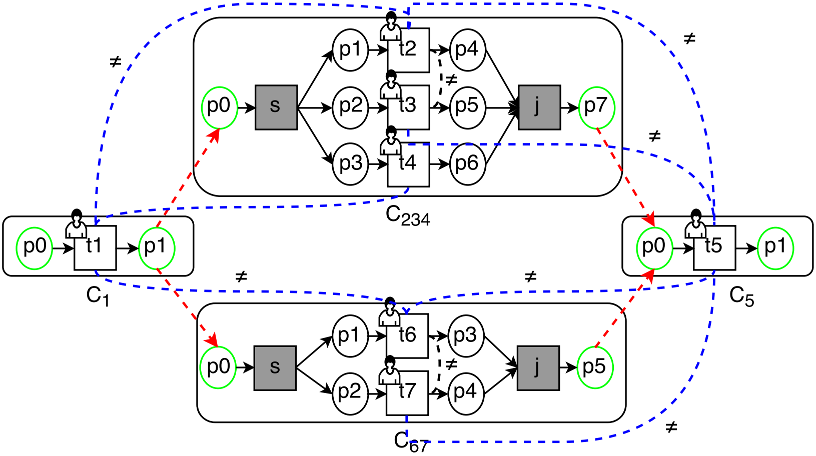
Example - Interface



Interface

$P^i = \{p0\}, P^o = \{p7\},$
$H^o = \{h_{t2}, h_{t4}\}, C^i = \{c^i_{t2}, c^i_{t4}\}$

Gluing

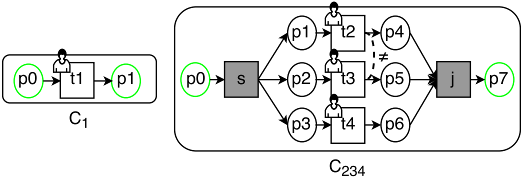


p0
s
p1
p2
p3
t2
t3
t4
p4
p5
p6
j
p7
≠
C234
p0
t1
p1
C1
p0
t5
p1
C5
p0
s
p1
p2
t6
t7
p3
p4
j
p5
C67

Gluing

- $G = G_{EC} \cup G_{Auth}$ is a set of gluing assertions over Int_1 and Int_2
  - inter-module execution constraints: $p_1^i \Leftrightarrow p_2^o$
  - inter-module authorization constraints: $C_1^i \cup H_2^o$
- $S = S_1 \oplus_G S_2$
  - $\oplus_G$ combines the variables and transitions in S_1 and S_2 to form a new component S
  - commutative and associative: result is independent of the order

Example - Gluing



Assertions

$$G_{EC} = \{p1_1 \Leftrightarrow p0_{234}\}$$
$$G_{Auth} = \{\forall u.c^i_{t2}(u) \Leftrightarrow \neg h_{t1}(u), \forall u.c^i_{t4}(u) \Leftrightarrow \neg h_{t1}(u)\}$$

Monitor Synthesis

- Workflow systems (original) and workflow components (refined) are equivalent
  - Define a procedure $\mathcal{M}$ that takes as input a component $S' = ((P, D, A, H, C), Tr', B)$ and returns a transition system $S = (V, Tr)$
- Let $\mathcal{RM}$ be the procedure (from previous work) that takes as input a transition system and returns a Datalog program $\mathcal{RM}(S)$
  - Then $\mathcal{RM}_{\mathcal{C}}(S_C) = \mathcal{RM}(\mathcal{M}(S_C))$

Monitor synthesis

- A monitor for components C_1 and C_2 is obtained by concatenating the Datalog monitors for the constituent components and adding clauses derived from the gluing assertions
- Monitors for components are computed by considering all possible values for the variables in the interfaces
- Gluing assertions consider a sub-set of these values:
  - how execution flows between components
  - how authorization further constraints possible executions

Outline

Applications

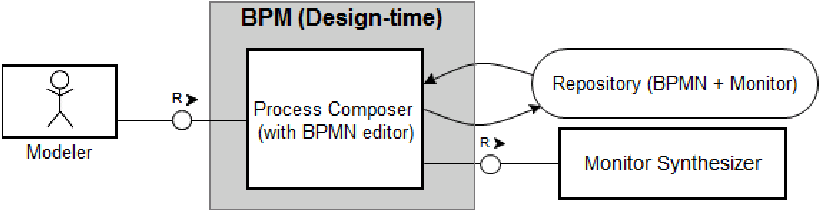
- The two main applications are: scalability and reuse
- Scalability allows the synthesis of monitors for large workflows
  - Modularly specified
  - Automatically decomposed
- Reuse allows designers to store/retrieve and combine workflow models alongside monitors in a repository

Scalability

- Experimented with a random workflow generator
  - Generate n workflows of 5 tasks and compose them sequentially
  - Varying number of constraints (intra- and inter-modules)
- Workflows of up to 500 tasks (100 components), with 5%, 10%, and 20% of the tasks in a constraint
  - Results show a linear growth in time to synthesize monitors, as opposed to the exponential explosion when using a monolithic technique
- Decomposition is left as future work

Reuse

- General architecture for WFMS integration
  - Back-end in Python using the MCMT model checker
  - Front-end adapted for different WFMS systems (e.g., SAP HANA Operational Intelligence)



Outline

Conclusion

- Modular approach to the specification of security-sensitive workflows and synthesis of run-time monitors for the WSP
  - It provides scalability and reuse
- Step towards practical enforcement mechanisms for security-sensitive workflows

Thank you!

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