

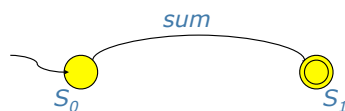
Transition Systems and Service Composition

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Seminari di Ingegneria del Software
A.A. 2007/08

Concentrating on behaviors: SUM two integers

- Consider a program for computing the sum of two integers.
- Such a program has essentially two states
 - the state S_0 of the memory before the computation: including the two number to sum
 - the state S_1 of the memory after the computation: including the result of the computation
- Only one action, i.e. "sum", can be performed



Transition Systems

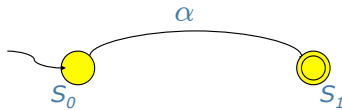
Concentrating on behaviors: CheckValidity

- Consider a program for computing the validity of a FOL formula:
- Also such a program has essentially two states
 - the state S_1 of the memory before the computation: including the formula to be checked
 - the state S_2 of the memory after the computation: including "yes", "no", "time-out"
- Only one action, i.e. "checkValidity", can be performed



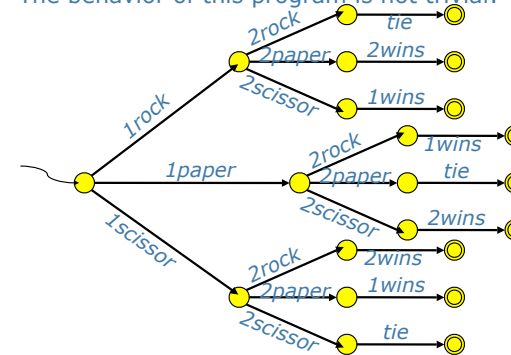
Concentrating on behaviors

- The programs SUM and CheckValidity are very different from a computational point of view.
 - SUM is trivial
 - CheckValidity is a theorem prover hence very complex
- However they are equally trivial from a behavioral point of view:
 - two states S_1 and S_2
 - a single action α causing the transition



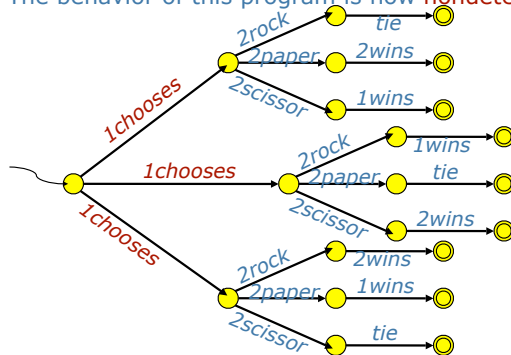
Concentrating on behaviors: RockPaperScissor

- Consider the program RockPaperScissor that allows to play two players the the well-known game.
- The behavior of this program is not trivial:



Concentrating on behaviors: RockPaperScissor (automatic)

- Consider a variant of the program RockPaperScissor that allows one players to play against the computer.
- The behavior of this program is now **nondeterministic**:



Concentrating on behaviors: WebPage

<http://www.informatik.uni-trier.de/~ley/db/>



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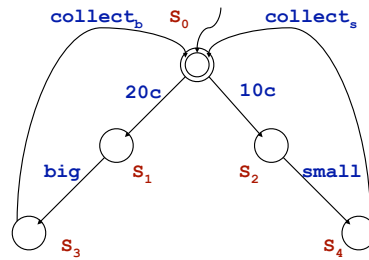
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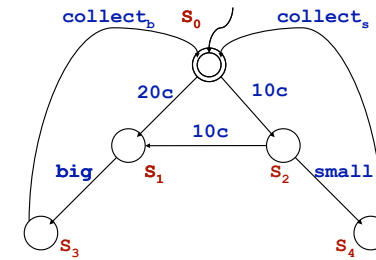
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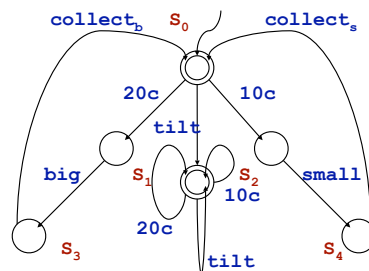
Concentrating on behaviors: Vending Machine



Concentrating on behaviors: Another Vending Machine



Concentrating on behaviors: Vending Machine with Tilt



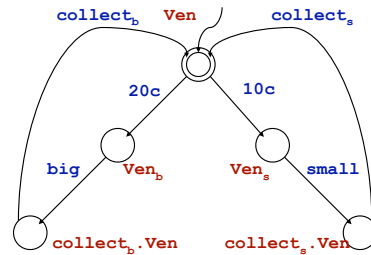
Transition Systems

- A transition system TS is a tuple $T = \langle A, S, S^0, \delta, F \rangle$ where:
 - A is the set of actions
 - S is the set of states
 - $S^0 \subseteq S$ is the set of initial states
 - $\delta \subseteq S \times A \times S$ is the transition relation
 - $F \subseteq S$ is the set of final states
- Variants:
 - No initial states
 - Single initial state
 - Deterministic actions
 - States labeled by propositions other than Final/ $\neg$ Final

(c.f. Kripke Structure)

Process Algebras are Formalisms for Describing TS

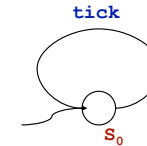
- Trans (a la CCS)
 - $Ven = 20c.Ven_b + 10c.Ven_s$
 - $Ven_b = big.collect_b.Ven$
 - $Ven_s = small.collect_s.Ven$
- Final
 - $\checkmark Ven$



- TS may have infinite states - e.g., this happens when generated by process algebras involving iterated concurrency
- However we have good formal tools to deal only with finite states TS

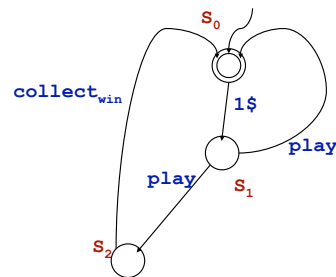
Example (Clock)

TS may describe (legal) nonterminating processes

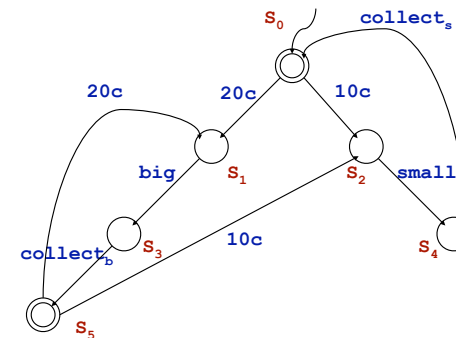


Example (Slot Machine)

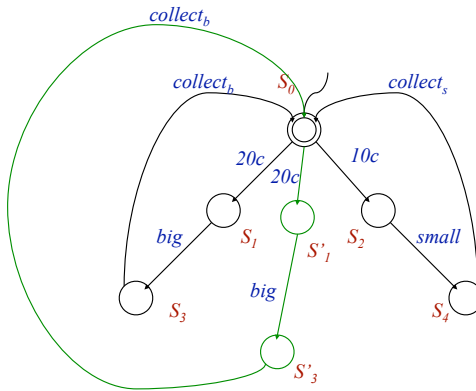
Nondereminisic transitions express choice that is not under the control of clients



Example (Vending Machine - Variant 1)



Example (Vending Machine - Variant 2)



Inductive vs Coinductive Definitions: Reachability, Bisimilarity, ...

Reachability

- A binary relation R is a **reachability-like relation** iff:
 - $(s, s) \in R$
 - if $\exists a. s' : s \xrightarrow{a} s' \wedge (s', s'') \in R$ then $(s, s'') \in R$
- A state s_0 of transition system S is **reachable-from** a state s_f iff for **all** a **reachability-like relations** R we have $(s_0, s_f) \in R$.
- Notably that
 - reachable-from** is a reachability-like relation itself
 - reachable-from** is the **smallest** reachability-like relation

Note it is a inductive definition!

Computing Reachability on Finite Transition Systems

Algorithm ComputingReachability

Input: transition system TS

Output: the **reachable-from** relation (the smallest reachability-like relation)

Body

```

R = {}
R' = {(s,s) | s ∈ S}
while (R ≠ R') {
    R := R'
    R' := R' ∪ {(s,s'') | ∃ s', a. s →a s' ∧ (s', s'') ∈ R}
}
return R'

```

YdoB

Bisimulation

- A binary relation R is a **bisimulation** iff:
 - $(s, t) \in R$ implies that
 - s is *final* iff t is *final*
 - for all actions a
 - if $s \rightarrow_a s'$ then $\exists t' . t \rightarrow_a t'$ and $(s', t') \in R$
 - if $t \rightarrow_a t'$ then $\exists s' . s \rightarrow_a s'$ and $(s', t') \in R$
- A state s_0 of transition system S is **bisimilar**, or simply **equivalent**, to a state t_0 of transition system T iff there **exists** a **bisimulation** between the initial states s_0 and t_0 .
- Notably
 - bisimilarity** is a bisimulation
 - bisimilarity** is the **largest** bisimulation

Computing Bisimilarity on Finite Transition Systems

Algorithm ComputingBisimulation

Input: transition system $TS_S = \langle A, S, S^0, \delta_S, F_S \rangle$ and

transition system $TS_T = \langle A, T, T^0, \delta_T, F_T \rangle$

Output: the **bisimilarity** relation (the largest bisimulation)

Body

$R = \emptyset$

$R' = S \times T - \{(s, t) \mid \neg(s \in F_S \equiv t \in F_T)\}$

while $(R \neq R')$ {

$R := R'$

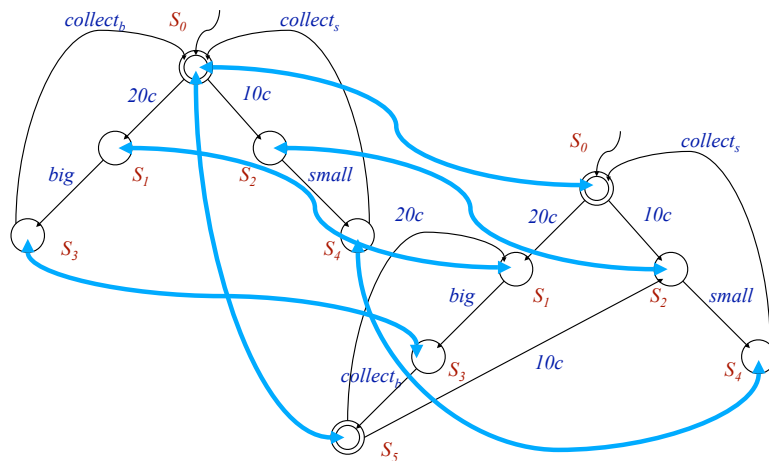
$R' := R' - \{(s, t) \mid \exists s', a. s \rightarrow_a s' \wedge \neg \exists t'. t \rightarrow_a t' \wedge (s', t') \in R\}$
 $\{(s, t) \mid \exists t', a. t \rightarrow_a t' \wedge \neg \exists s'. s \rightarrow_a s' \wedge (s', t') \in R\}$

}

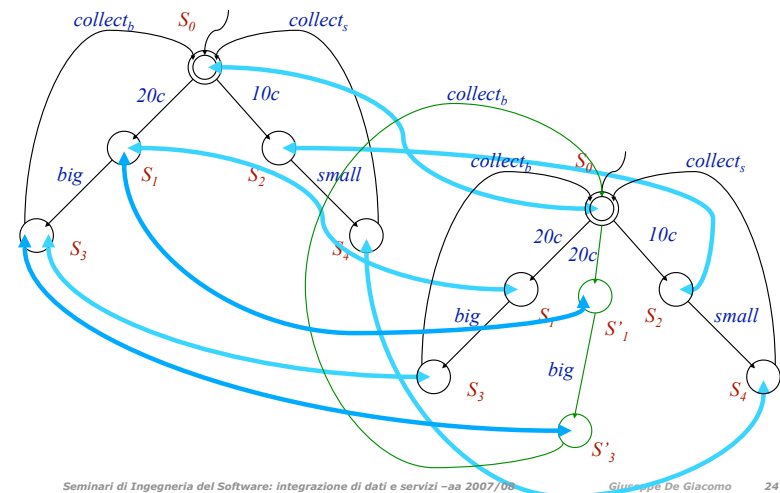
return R'

Ydob

Example of Bisimulation

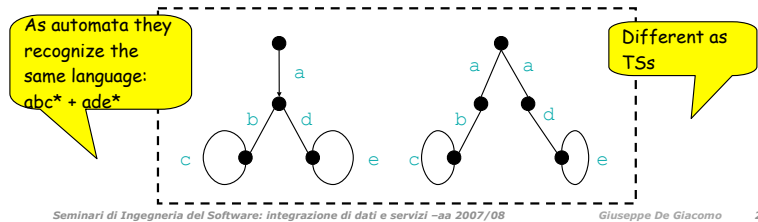


Example of Bisimulation



Automata vs. Transition Systems

- Automata
 - define sets of runs (or traces or strings): (finite) length sequences of actions
- TSs
 - ... but I can be interested also in the alternatives “encountered” during runs, as they represent client’s “choice points”



Logics of Programs

Logics of Programs

- Are modal logics that allow to describe properties of transition systems
- Examples:
 - HennesyMilner Logic
 - Propositional Dynamic Logics
 - Modal (Propositional) Mu-calculus
- Perfectly suited for describing transition systems: they can tell apart transition systems modulo bisimulation

HennesyMilner Logic

- $\Phi := P \mid$ *(atomic propositions)*
 - $\neg \Phi \mid \Phi_1 \wedge \Phi_2 \mid \Phi_1 \vee \Phi_2 \mid$ *(closed under boolean operators)*
 - $[a]\Phi \mid \langle a \rangle \Phi$ *(modal operators)*
- Propositions are used to denote final states
- $\langle a \rangle \Phi$ means there exists an a -transition that leads to a state where Φ holds; i.e., expresses the capability of executing action a bringing about Φ
- $[a]\Phi$ means that all a -transitions lead to states where Φ holds; i.e., express that executing action a brings about Φ

Logics of Programs: Examples



- Usefull abbreviation:
 - $\langle \text{any} \rangle \Phi$ stands for $\langle a_1 \rangle \Phi \vee \dots \vee \langle a_n \rangle \Phi$
 - $[\text{any}] \Phi$ stands for $[a_1] \Phi \wedge \dots \wedge [a_n] \Phi$
 - $\langle \text{any} - a_1 \rangle \Phi$ stands for $\langle a_2 \rangle \Phi \vee \dots \vee \langle a_n \rangle \Phi$
 - $[\text{any} - a_1] \Phi$ stands for $[a_2] \Phi \wedge \dots \wedge [a_n] \Phi$
- Examples:
 - $\langle a \rangle \text{true}$ *cabability of performing action a*
 - $[a] \text{false}$ *inability of performing action a*
 - $\neg \text{Final} \wedge \langle \text{any} \rangle \text{true} \wedge [\text{any}-a] \text{false}$ *necessity/inevitability of performing action a (i.e., action a is the only action possible)*
 - $\neg \text{Final} \wedge [\text{any}] \text{false}$ *deadlock!*

Propositional Dynamic Logic



- $\Phi := P \mid$ *(atomic propositions)*
 $\neg \Phi \mid \Phi_1 \wedge \Phi_2 \mid \Phi_1 \vee \Phi_2 \mid$ *(closed under boolean operators)*
 $[r] \Phi \mid \langle r \rangle \Phi$ *(modal operators)*
 $r := a \mid r_1 + r_2 \mid r_1 ; r_2 \mid r^* \mid P?$ *(complex actions as regular expressions)*
- Essentially add the capability of expressing partial correctness assertions via formulas of the form
 - $\Phi_1 \rightarrow [r] \Phi_2$ *under the conditions Φ_1 all possible executions of r that terminate reach a state of the TS where Φ_2 holds*
- Also add the ability of asserting that a property holds in all nodes of the transition system
 - $[(a_1 + \dots + a_n)^*] \Phi$ *in every reachable state of the TS Φ holds*
- Useful abbreviations:
 - any stands for $(a_1 + \dots + a_n)$ *Note that + can be expressed also in HM Logic*
 - u stands for any^* *This is the so called master/universal modality*

Modal Mu-Calculus



- $\Phi := P \mid$ *(atomic propositions)*
 $\neg \Phi \mid \Phi_1 \wedge \Phi_2 \mid \Phi_1 \vee \Phi_2 \mid$ *(closed under boolean operators)*
 $[r] \Phi \mid \langle r \rangle \Phi$ *(modal operators)*
 $\mu X. \Phi(X) \mid \nu X. \Phi(X)$ *(fixpoint operators)*
- It is the most expressive logic of the family of logics of programs.
- It subsumes
 - PDL (modalities involving complex actions are translated into fomulas involving fixpoints)
 - LTL (linear time temporal logic),
 - CTS, CTS* (branching time temporal logics)
- Examples:
 - $[\text{any}^*] \Phi$ can be expressed as $\nu X. \Phi \wedge [\text{any}] X$
 - $\mu X. \Phi \vee [\text{any}] X$ *along all runs eventually Φ*
 - $\mu X. \Phi \vee \langle \text{any} \rangle X$ *along some run eventually Φ*
 - $\nu X. [a](\mu Y. \langle \text{any} \rangle \text{true} \wedge [\text{any}-b] Y) \wedge X$ *every run that that contains a contains later b*

Model Checking



- Model checking is polynomial in the size of the TS for
 - HennesyMilner Logic
 - PDL
 - Mu-Calculus
- Also model checking is wrt the formula
 - Polynomial for HennesyMiner Logic
 - Polynomial for PDL
 - Polynomial for Mu-Calculus with bounded alternation of fixpoints and NPcoNP in general

Model Checking

- Given a TS T , one of its states s , and a formula Φ verify whether the formula holds in s . Formally:

$$T, s \models \Phi$$

- Examples (TS is our vending machine):
 - $S_0 \models \text{Final}$
 - $S_0 \models \langle 10c \rangle \text{true}$ *capability of performing action 10c*
 - $S_2 \models [\text{big}] \text{false}$ *inability of performing action big*
 - $S_0 \models [10c][\text{big}] \text{false}$ *after 10c cannot execute big*
 - $S_1 \models \mu X. \text{Final} \vee [\text{any}] X$ *eventually a final state is reached*
 - $S_0 \models \nu Z. (\mu X. \text{Final} \vee [\text{any}] X) \wedge [\text{any}] Z$ *or equivalently*
 $S_0 \models [\text{any}^*](\mu X. \text{Final} \vee [\text{any}] X)$ *from everywhere eventually final*

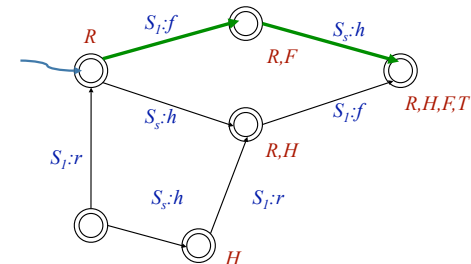
AI Planning as Model Checking

- Build the TS of the domain:**
 - Consider the set of states formed all possible truth value of the propositions (this works only for propositional setting).
 - Use Pre's and Post of actions for determining the transitions
 - Note: the TS is exponential in the size of the description.*
- Write the goal in a logic of program**
 - typically a single least fixpoint formula of Mu-Calculus (compute **reachable** states intersection states where goal true)
- Planning:**
 - model check the formula on the TS starting from the given initial state.
 - use the path (paths) used in the above model checking for returning the plan.
- This basic technique works only when we have complete information (or at least total observability on state):*
 - Sequential plans if initial state known and actions are deterministic
 - Conditional plans if many possible initial states and/or actions are nondeterministic

Example

- Operators (Services + Mappings)
 - $\text{Registered} \wedge \neg \text{FlightBooked} \rightarrow [S_1:\text{bookFlight}] \text{FlightBooked}$
 - $\neg \text{Registered} \rightarrow [S_1:\text{register}] \text{Registered}$
 - $\neg \text{HotelBooked} \rightarrow [S_2:\text{bookHotel}] \text{HotelBooked}$
- Additional constraints (Community Ontology):
 - $\text{TravelSettledUp} \equiv \text{FlightBooked} \wedge \text{HotelBooked} \wedge \text{EventBooked}$
- Goals (Client Service Requests):
 - Starting from **the** state
 $\text{Registered} \wedge \neg \text{FlightBooked} \wedge \neg \text{HotelBooked} \wedge \neg \text{EventBooked}$
 check $\langle \text{any}^* \rangle \text{TravelSettledUp}$
 - Starting from **all** states such that
 $\neg \text{FlightBooked} \wedge \neg \text{HotelBooked} \wedge \neg \text{EventBooked}$
 check $\langle \text{any}^* \rangle \text{TravelSettledUp}$

Example



Plan:
 $S_1:\text{bookFlight};$
 $S_2:\text{bookHotel}$

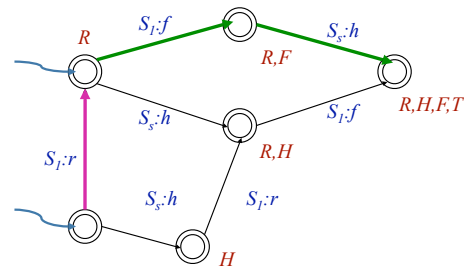
Starting from **the** state

$\text{Registered} \wedge \neg \text{FlightBooked} \wedge \neg \text{HotelBooked} \wedge \neg \text{EventBooked}$

check

$\langle \text{any}^* \rangle \text{TravelSettledUp}$

Example



Starting from **all** states where

$\neg \text{FlightBooked} \wedge \neg \text{HotelBooked} \wedge \neg \text{EventBooked}$

check

$\langle \text{any}^* \rangle \text{TravelSettledUp}$

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Plan:

```
if( $\neg$ Registered) {
  S1:register;
}
S1:bookFlight;
S2:bookHotel
```

Satisfiability

- Observe that a formula Φ may be used to select among all TS T those such that for a given state s we have that $T, s \models \Phi$

- SATISFIABILITY:** Given a formula Φ verify whether there exists a TS T and a state s such that. Formally:

check whether exists T, s such that $T, s \models \Phi$

- Satisfiability is:
 - PSPACE for HennesyMilner Logic
 - EXPTIME for PDL
 - EXPTIME for Mu-Calculus

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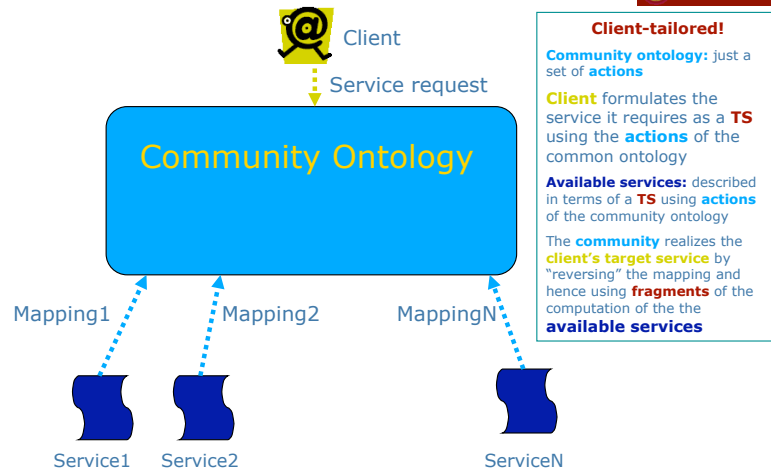
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Name by
Rick Hull

Composition: the "Roman" Approach

The Roman Approach

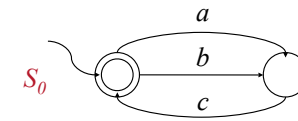


(Target & Available) Service TS

- We model services as finite TS $T = (\Sigma, S, s^0, \delta, F)$ with
 - single initial state (s^0)
 - deterministic transitions (i.e., δ is a partial function from $S \times \Sigma$ to S)

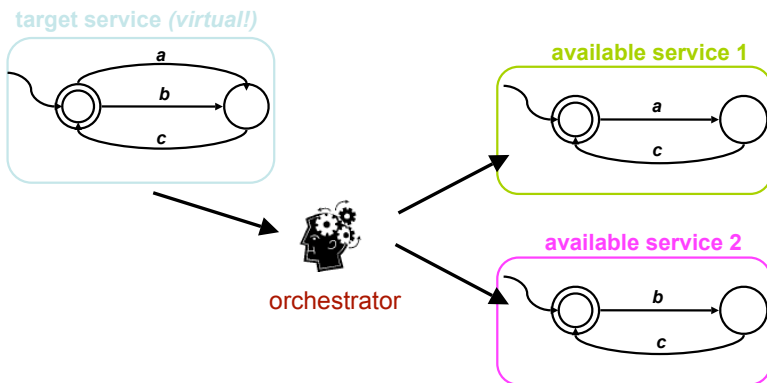
Note: In this way the client entirely controls/chooses the transition to execute

Example:



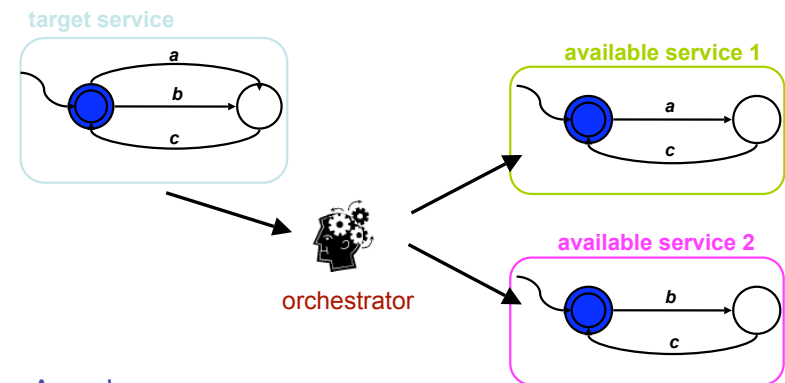
a : "search by author (and select)"
 b : "search by title (and select)"
 c : "listen (the selected song)"

Composition: an Example



Lets get some intuition of what a composition is through an example

Composition: an Example

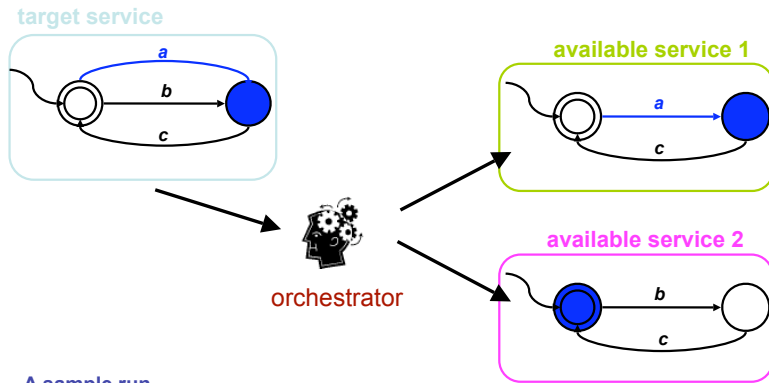


A sample run

action request:

orchestrator response:

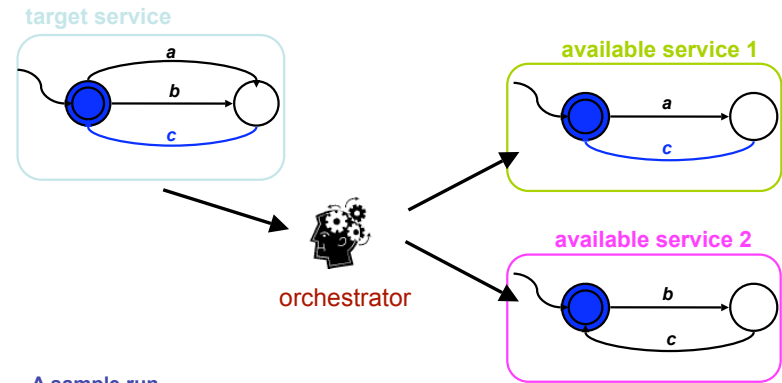
Composition: an Example



A sample run

action request: *a*
orchestrator response: *a,1*

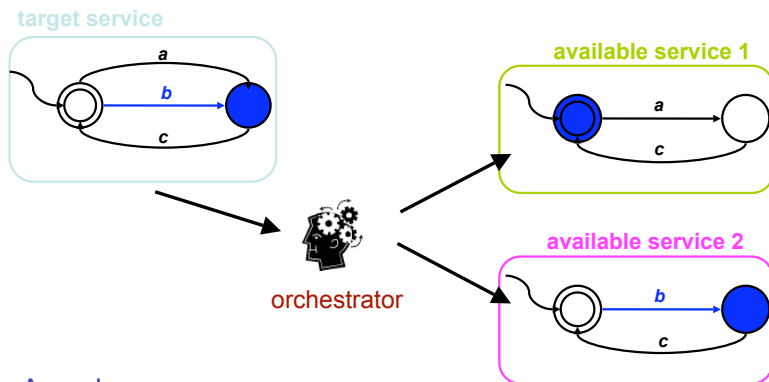
Composition: an Example



A sample run

action request: *a* *c*
orchestrator response: *a,1* *c,1*

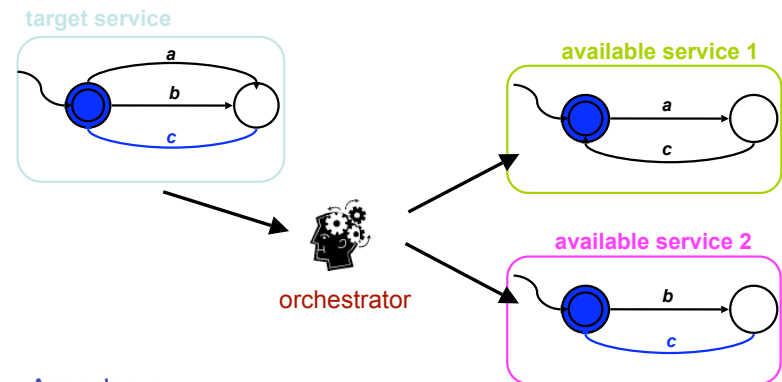
Composition: an Example



A sample run

action request: *a* *c* *b*
orchestrator response: *a,1* *c,1* *b,2*

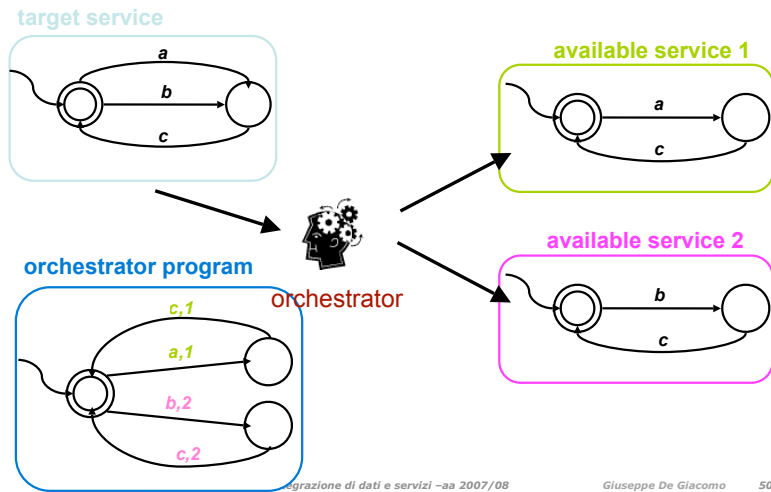
Composition: an Example



A sample run

action request: *a* *c* *b* *c* ...
orchestrator response: *a,1* *c,1* *b,2* *c,2*

A orchestrator program realizing the target behavior



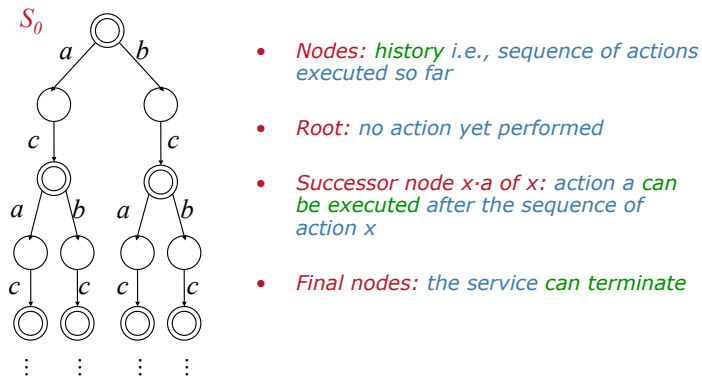
Orchestrator programs

- **Orchestrator program** is any function $P(h,a) = i$ that takes a **history** h and an **action** a to execute and **delegates** a to one of the available services i
- A **history** is the sequence of actions done so far:

$$h = a_1 a_2 \dots a_k$$
- Observe that to take a decision P has **full access to the past**, but no access to the future
 - Note given an history $h = a_1 a_2 \dots a_k$ on the function P we can reconstruct the state of the target service and of each available service
 - $a_1 a_2 \dots a_k$ determines the state of the target service
 - $(a_1, P([], a_k))(a_2, P([a_1], a_2)) \dots (a_k, P([a_1 a_2 \dots a_{k-1}], a_k))$ determines the state of each available service
- **Problem: synthesize a orchestrator program P that realizes the target service making use of the available services**

Service Execution Tree

By “unfolding” a (finite) TS one gets an (infinite) execution tree
 -- yet another (infinite) TS which bisimilar to the original one)



Alternative (but Equivalent) Definition of Service Composition

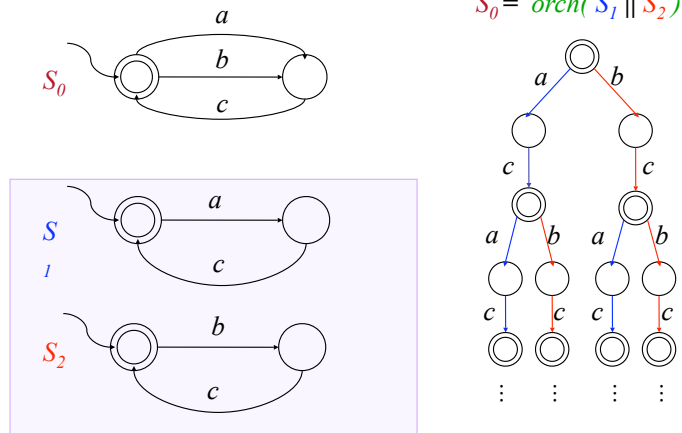
Composition:

- coordinating program ...
- ... that realizes the target service ...
- ... by suitably coordinating available services

⇒ Composition can be seen as:

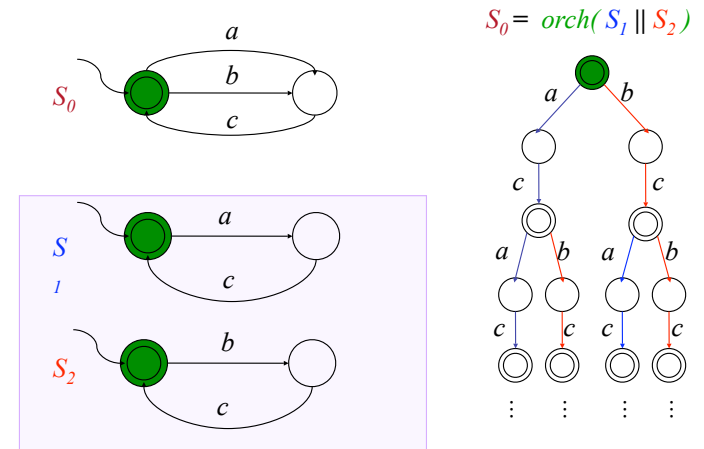
- a labeling of the execution tree of the **target service** such that ...
- ... each **action** in the execution tree is labeled by the available service that executes it ...
- ... and each possible sequence of actions on the target service execution tree corresponds to possible sequences of actions on the available service execution trees, **suitably interleaved**

Example of Composition



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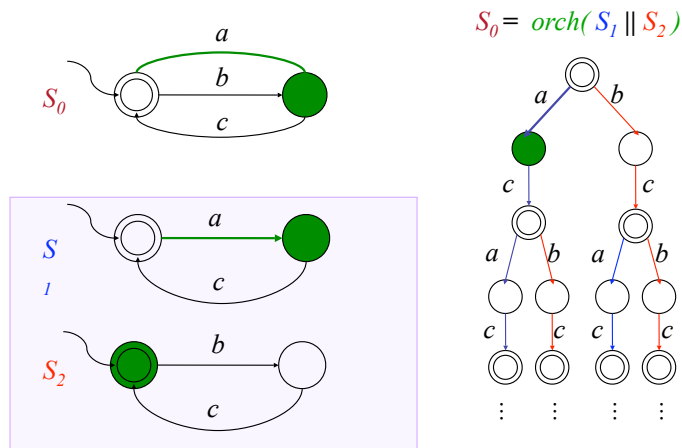
Example of Composition



All services start from their starting state

55

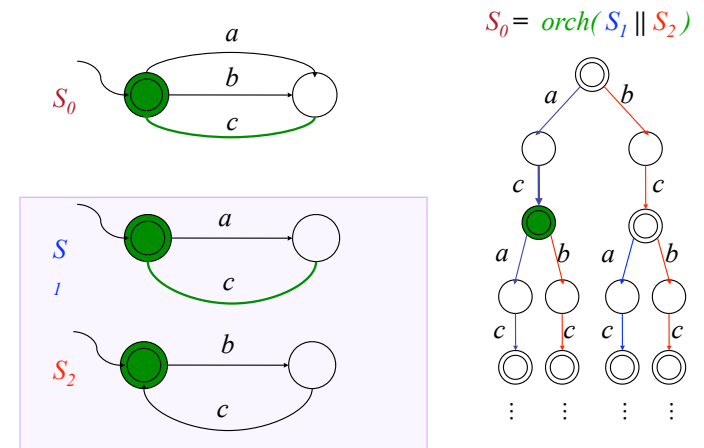
Example of Composition (5)



Each action of the target service is executed by at least one of the component services

56

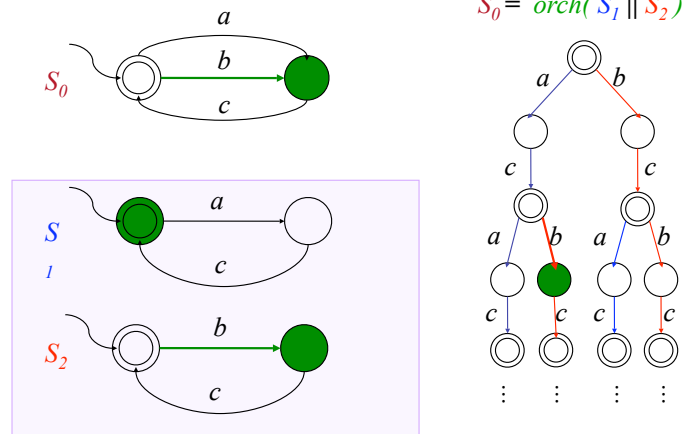
Example of composition (6)



When the target service can be left, then all component services must be in a final state

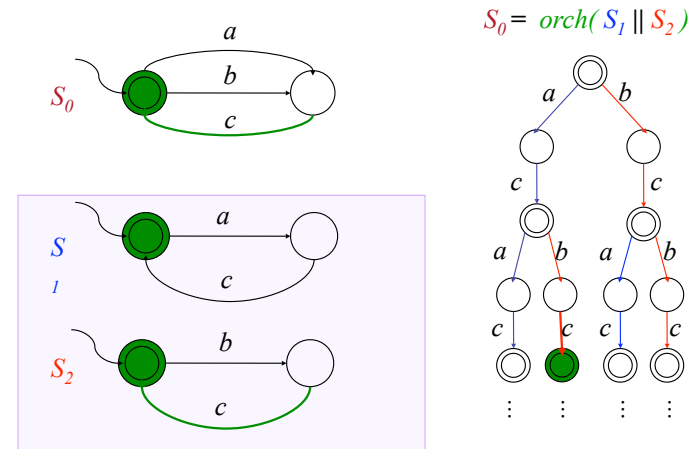
57

Example of composition (7)



Giuseppe De Giacomo 58

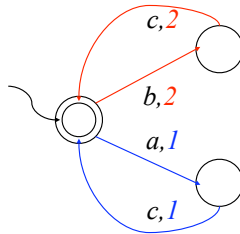
Example of composition (8)



Giuseppe De Giacomo 59

Observation

- This labeled execution tree has a finite representation as a finite TS ...
- ...with transitions labeled by an action and the service performing the action



Is this always the case when we deal with services expressible as finite TS? See later...

Questions

Assume services of community and target service are finite TSs

- Can we always check composition existence?
- If a composition exists there exists one which is a finite TS?
- If yes, how can a finite TS composition be computed?

To answer ICSOC'03 exploits PDL SAT

Answers

Reduce service composition synthesis to satisfiability in (deterministic) PDL

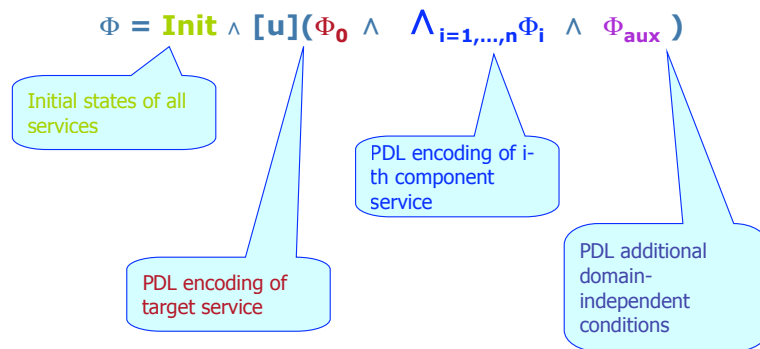
- Can we always check composition existence?
Yes, SAT in PDL is decidable in EXPTIME
- If a composition exists there exists one which is a finite TS?
Yes, by the small model property of PDL
- How can a finite TS composition be computed?
From a (small) model of the corresponding PDL formula

Encoding in PDL

Basic idea:

- A orchestrator program P realizes the target service T iff at each point:
 - $\forall$ transition labeled a of the target service T ...
 - ... $\exists$ an available service B_i (the one chosen by P) that can make an a -transition, realizing the a -transition of T
- Encoding in PDL:
 - $\forall$ transition labeled a ...
use **branching**
 - $\exists$ an available service B_i that can make an a -transition ...
use underspecified predicates **assigned through SAT**

Structure of the PDL Encoding



PDL encoding is polynomial in the size of the service TSs

PDL Encoding

- Target service $S_0 = (\Sigma, S_0, s_0^0, \delta_0, F_0)$ in PDL we define Φ_0 as the conjunction of:
 - $s \rightarrow \neg s'$ for all pairs of distinct states in S_0
service states are pair-wise disjoint
 - $s \rightarrow \langle a \rangle T \wedge [a]s'$ for each $s' = \delta_0(s, a)$
target service can do an a -transition going to state s'
 - $s \rightarrow [a] \perp$ for each $\delta_0(s, a)$ undef.
target service cannot do an a -transition
 - $F_0 = \bigvee_{s \in F_0} S$
denotes target service final states
- ...

PDL Encoding (cont.d)

- available services $S_i = (\Sigma, S_i, s_i^0, \delta_i, F_i)$ in PDL we define Φ_i as the conjunction of:
 - $s \rightarrow \neg s'$ for all pairs of distinct states in S_i
Service states are pair-wise disjoint
 - $s \rightarrow [a](\text{moved}_i \wedge s' \vee \neg \text{moved}_i \wedge s)$ for each $s' = \delta_i(s, a)$
if service moved then new state, otherwise old state
 - $s \rightarrow [a](\neg \text{moved}_i \wedge s)$ for each $\delta_i(s, a)$ undef.
if service cannot do a, and a is performed then it did not move
 - $F_i = \bigvee_{s \in F_i} S$
denotes available service final states
- ...

PDL Encoding (cont.d)

- Additional assertions Φ_{aux}
 - $\langle a \rangle T \rightarrow [a] \bigvee_{i=1, \dots, n} \text{moved}_i$ for each action a
at least one of the available services must move at each step
 - $F_0 \rightarrow \bigwedge_{i=1, \dots, n} F_i$
when target service is final all comm. services are final
 - $\text{Init} = s_0^0 \wedge \bigwedge_{i=1, \dots, n} s_i^0$
Initially all services are in their initial state

PDL encoding: $\Phi = \text{Init} \wedge [u](\Phi_0 \wedge \bigwedge_{i=1, \dots, n} \Phi_i \wedge \Phi_{aux})$

Results

Thm[ICSOC'03,IJCIS'05]:

Composition exists iff PDL formula Φ SAT

From composition labeling of the target service one can build a tree model of the PDL formula and viceversa

Information on the labeling is encoded in predicates moved_i

Corollary [ICSOC'03,IJCIS'05]:

Checking composition existence is decidable in **EXPTIME**

Thm[Muscholl&Walukiewicz FoSSaCS'07]:

Checking composition existence is **EXPTIME-hard**

Results on TS Composition

Thm[ICSOC'03,IJCIS'05]:

If composition exists then finite TS composition exists.

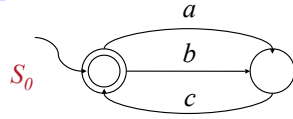
From a small model of the PDL formula Φ , one can build a finite TS machine

Information on the output function of the machine is encoded in predicates moved_i

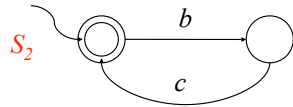
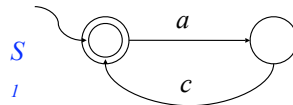
$\Rightarrow$ finite TS composition existence of services expressible as finite TS is EXPTIME-complete

Example (1)

Target service



Available services

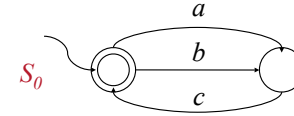


PDL

...
...
...
 $s_0^0 \wedge s_1^0 \wedge s_2^0$
 $\langle a \rangle T \rightarrow [a] (\text{moved}_1 \vee \text{moved}_2)$
 $\langle b \rangle T \rightarrow [b] (\text{moved}_1 \vee \text{moved}_2)$
 $\langle c \rangle T \rightarrow [c] (\text{moved}_1 \vee \text{moved}_2)$
 $F_0 \rightarrow F_1 \wedge F_2$

Example (2)

Target service

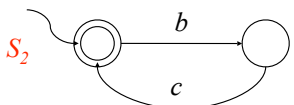
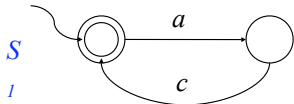


$s_0^0 \rightarrow \neg s_0^1$
 $s_0^0 \rightarrow \langle a \rangle T \wedge [a] s_0^1$
 $s_0^0 \rightarrow \langle b \rangle T \wedge [b] s_0^1$
 $s_0^1 \rightarrow \langle c \rangle T \wedge [c] s_0^0$
 $s_0^0 \rightarrow [c] \perp$
 $s_0^1 \rightarrow [a] \perp$
 $s_0^1 \rightarrow [b] \perp$
 $F_0 = s_0^0$

...
...
...

Example (3)

Available services



...
 $s_1^0 \rightarrow \neg s_1^1$
 $s_1^0 \rightarrow [a] (\text{moved}_1 \wedge s_1^1 \vee \neg \text{moved}_1 \wedge s_1^0)$
 $s_1^0 \rightarrow [c] \neg \text{moved}_1 \wedge s_1^0$
 $s_1^0 \rightarrow [b] \neg \text{moved}_1 \wedge s_1^0$
 $s_1^1 \rightarrow [a] \neg \text{moved}_1 \wedge s_1^1$
 $s_1^1 \rightarrow [b] \neg \text{moved}_1 \wedge s_1^1$
 $s_1^1 \rightarrow [c] (\text{moved}_1 \wedge s_1^0 \vee \neg \text{moved}_1 \wedge s_1^0)$
 $F_1 = s_1^0$

$s_2^0 \rightarrow \neg s_2^1$
 $s_2^0 \rightarrow [b] (\text{moved}_2 \wedge s_2^1 \vee \neg \text{moved}_2 \wedge s_2^0)$
 $s_2^0 \rightarrow [c] \neg \text{moved}_2 \wedge s_2^0$
 $s_2^0 \rightarrow [a] \neg \text{moved}_2 \wedge s_2^0$
 $s_2^1 \rightarrow [b] \neg \text{moved}_2 \wedge s_2^1$
 $s_2^1 \rightarrow [a] \neg \text{moved}_2 \wedge s_2^1$
 $s_2^1 \rightarrow [c] (\text{moved}_2 \wedge s_2^0 \vee \neg \text{moved}_2 \wedge s_2^0)$
 $F_2 = s_2^0$

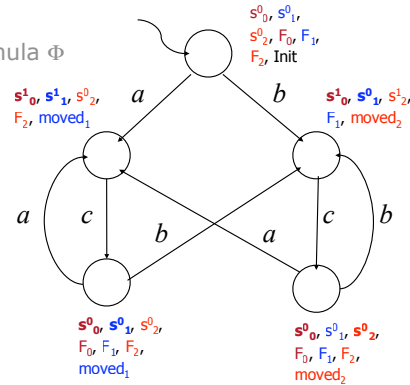
Example (4)

Check: run SAT on PDL formula Φ

Example

Check: run SAT on PDL formula Φ

Yes $\Rightarrow$ (small) model

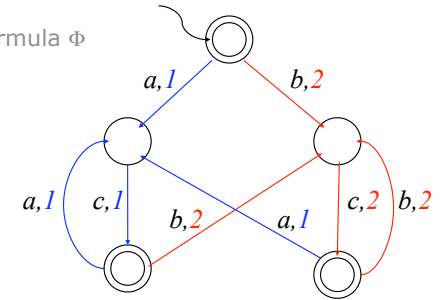


Example

Check: run SAT on PDL formula Φ

Yes $\Rightarrow$ (small) model

$\Rightarrow$ extract finite TS



Example

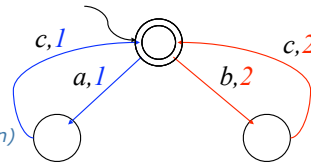
Check: run SAT on PDL formula Φ

Yes $\Rightarrow$ (small) model

$\Rightarrow$ extract finite TS

$\Rightarrow$ minimize finite TS

(similar to Mealy machine minimization)



Results on Synthesizing Composition

- Using PDL reasoning algorithms based on model construction (cf. tableaux), build a (small) model
Exponential in the size of the PDL encoding/services finite TS

Note: SitCalc, etc. can compactly represent finite TS, PDL encoding can preserve compactness of representation

- From this model extract a corresponding finite TS
Polynomial in the size of the model
- Minimize such a finite TS using standard techniques (opt.)
Polynomial in the size of the TS

Note: finite TS extracted from the model is not minimal because encodes output in properties of individuals/states

Tools for Synthesizing Composition



- In fact we use only a fragment of PDL in particular we use fixpoint (transitive closure) only to get the universal modality ...
- ... thanks to a tight correspondence between PDLs and Description Logics (DLs), we can use current highly optimized DL reasoning systems to do synthesis ...
- ... when the ability or returning models will be added ...
Pellet already has this ability, and we are exploring its use
- ... meanwhile we developed a prototype tool on this idea (see possibly Mecella's lectures)

Composition via Simulation

Bisimulation



- A binary relation R is a **bisimulation** iff:
 - $(s, t) \in R$ implies that
 - s is *final* iff t is *final*
 - for all actions a
 - if $s \rightarrow_a s'$ then $\exists t' . t \rightarrow_a t'$ and $(s', t') \in R$
 - if $t \rightarrow_a t'$ then $\exists s' . s \rightarrow_a s'$ and $(s', t') \in R$
- A state s_0 of transition system S is **bisimilar**, or simply **equivalent**, to a state t_0 of transition system T iff there **exists** a **bisimulation** between the initial states s_0 and t_0 .
- Notably
 - **bisimilarity** is a bisimulation
 - **bisimilarity** is the **largest** bisimulation

Note it is a co-inductive definition!

Computing Bisimilarity on Finite Transition Systems



Algorithm ComputingBisimulation

Input: transition system $TS_S = \langle A, S, S^0, \delta_S, F_S \rangle$ and transition system $TS_T = \langle A, T, T^0, \delta_T, F_T \rangle$

Output: the **bisimilarity** relation (the largest bisimulation)

Body

```

R = {}
R' = S × T - {(s, t) | ¬(s ∈ F_S ∧ t ∈ F_T)}
while (R ≠ R') {
  R := R'
  R' := R' - {(s, t) | ∃ s', a. s →_a s' ∧ ¬∃ t'. t →_a t' ∧ (s', t') ∈ R'}
  R' := R' ∪ {(s, t) | ∃ t', a. t →_a t' ∧ ¬∃ s'. s →_a s' ∧ (s', t') ∈ R'}
}
return R'

```

Ydub

Simulation



- A binary relation R is a **simulation** iff:
 - $(s, t) \in R$ implies that
 - s is *final* implies that t is *final*
 - for all actions a
 - if $s \rightarrow_a s'$ then $\exists t' . t \rightarrow_a t'$ and $(s', t') \in R$
- A state s_0 of transition system S is **simulated by** a state t_0 of transition system T iff there **exists a simulation** between the initial states s_0 and t_0 .
- Notably
 - simulated-by** is a simulation
 - simulated-by** is the **largest** simulation

Note it is a co-inductive definition!

- NB: A simulation is just one of the two directions of a bisimulation

Computing Simulation on Finite Transition Systems



Algorithm ComputingSimulation

Input: transition system $TS_S = \langle A, S, S^0, \delta_S, F_S \rangle$ and

transition system $TS_T = \langle A, T, T^0, \delta_T, F_T \rangle$

Output: the **simulated-by** relation (the largest simulation)

Body

$R = \emptyset$

$R' = S \times T - \{(s, t) \mid s \in F_S \wedge \neg(t \in F_T)\}$

while $(R \neq R')$ {

$R := R'$

$R' := R' - \{(s, t) \mid \exists s', a. s \rightarrow_a s' \wedge \neg \exists t' . t \rightarrow_a t' \wedge (s', t') \in R'\}$

}

return R'

Ydob

Potential Behavior of the Whole Community



- Let $TS_1, \dots, TS_n$ be the TSs of the component services.
- The **Community TS** is defined as the **asynchronous product** of $TS_1, \dots, TS_n$, namely:

$$TS_c = \langle A, S_c, S_c^0, \delta_c, F_c \rangle$$
 where:
 - A is the set of actions
 - $S_c = S_1 \times \dots \times S_n$
 - $S_c^0 = \{(s_1^0, \dots, s_n^0)\}$
 - $F \subseteq F_1 \times \dots \times F_n$
 - $\delta_c \subseteq S_c \times A \times S_c$ is defined as follows:

$$(s_1 \times \dots \times s_n) \rightarrow_a (s'_1 \times \dots \times s'_n) \text{ iff}$$
 - $\exists i. s_i \rightarrow_a s'_i \in \delta_i$
 - $\forall j \neq i. s'_j = s_j$

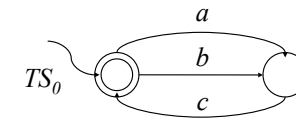
Example of Composition



- Available Services

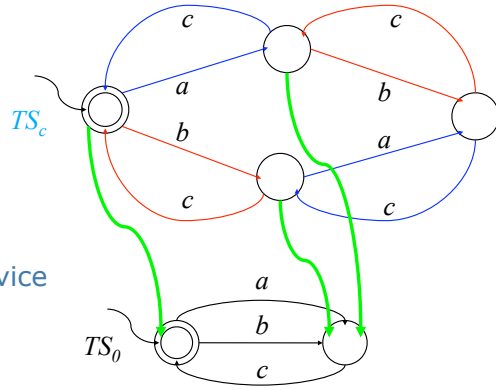


- Target Service



Example of Composition

Community TS



Target Service

Composition exists!

Composition via Simulation

- **Thm[IJFCS08]**

A composition realizing a target service TS TS_t exists if there **exists** a simulation relation between the initial state s_t^0 of TS_t and the initial state $(s_1^0, \dots, s_n^0)$ of the community TS TS_c .

- Notice if we take the union of all simulation relations then we get the largest simulation relation **S**, still satisfying the above condition.

- **Corollary[IJFCS08]**

A composition realizing a target service TS TS_t exists iff $(s_t^0, (s_1^0, \dots, s_n^0)) \in \mathbf{S}$.

- **Thm[IJFCS08]**

Computing the largest simulation **S** is polynomial in the size of the target service TS and the size of the community TS...

- ... hence it is **EXPTIME** in the size of the available services.

Composition via Simulation

- Given the largest simulation **S** from TS_t to TS_c (which include the initial states), we can build the **orchestrator generator**.

- This is an orchestrator program that can change its behavior reacting to the information acquired at run-time.

- Def: $OG = \langle A, [1, \dots, n], S_{tr}, s_t^0, \omega_r, \delta_r, F_r \rangle$ with
 - A : the **actions** shared by the community
 - $[1, \dots, n]$: the **identifiers** of the available services in the community
 - $S_t = S_1 \times S_2 \times \dots \times S_n$: the **states** of the orchestrator program
 - $s_t^0 = (s_{t1}^0, s_{t2}^0, \dots, s_{tn}^0)$: the **initial state** of the orchestrator program
 - $F_r \subseteq \{ (s_t, s_1, \dots, s_n) \mid s_t \in F_t : \text{the final states of the orchestrator program} \}$
 - $\omega_r : S_t \times A_r \rightarrow [1, \dots, n]$: the **service selection function**, defined as follows:
 - If $s_t \rightarrow_a s'_t$ then
 chose k s.t. $\exists s'_k : s_k \rightarrow_a s'_k \wedge (s'_t, (s_1, \dots, s'_k, \dots, s_n)) \in \mathbf{S}$
 - $\delta_r \subseteq S_t \times A_r \times [1, \dots, n] \rightarrow S_r$: the **state transition function**, defined as follows:
 - Let $\omega_r(s_t, s_1, \dots, s_k, \dots, s_n, a) = k$ then
 $(s_t, s_1, \dots, s_k, \dots, s_n) \rightarrow_{a,k} (s'_t, s_1, \dots, s'_k, \dots, s_n)$ where $s_k \rightarrow_a s'_k$

Composition via Simulation

- For **generating OG** we need only to compute **S** and then apply the template above

- For **running an orchestrator from the OG** we need to store and access **S** (polynomial time, exponential space) ...
- ... and compute ω_r and δ_r at each step (polynomial time and space)

Extension to the Roman Model

Extensions

- **Nondeterministic** (angelic) **target** specification
 - Loose specification in client request
 - **Angelic** (**don't care**) vs devilish (don't know) nondeterminism
 - See [ICSOC'04]
- **Nondeterministic** (devilish) available **services**
 - Incomplete specification in available services
 - **Devilish** (**don't know**) vs angelic (don't care) nondeterminism
 - See below & [IJCAI'07]
- **Distributing** the orchestration
 - Often a centralized orchestration is unrealistic: eg. services deployed on mobile devices
 - too tight coordination
 - too much communication
 - orchestrator cannot be embodied anywhere
 - Drop centralized orchestrator in favor of **independent controllers** on single available services (exchanging messages)
 - Under suitable conditions: a distributed orchestrator exists iff a centralized one does
 - Still decidable (EXPTIME-complete)
 - See [AAAI'07]
- Dealing with **data**
 - This is the single most difficult issue to tackle
 - First results: actions as DB updates, see [VLDB'05]
 - Literature on Abstraction in Verification
 - From finite to **infinite transition** systems!
- **Security and trust** aware composition [SWS'06]
- Automatic **Workflows** Composition of Mobile Services [ICWS'07]

See later

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Nondeterministic Available Services

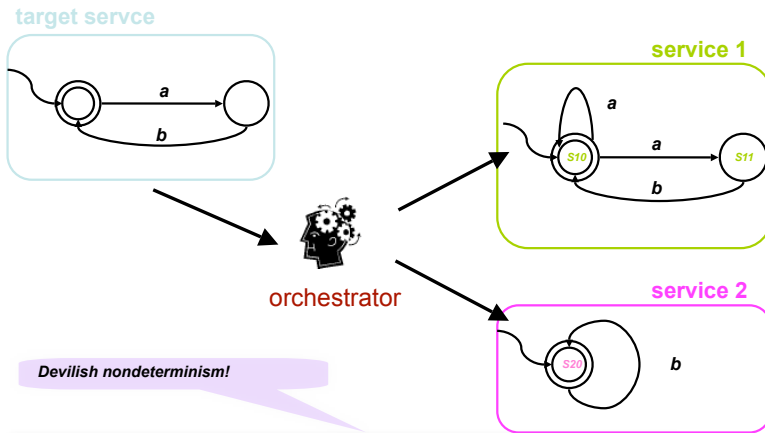
Nondeterminism in Available Services

Devilish (don't know)!

- Nondeterministic available services
 - **Incomplete information** on the actual **behavior**
 - **Mismatch between behavior description** (which is in terms of the environment actions) and **actual behavior** of the agents/devices
- Deterministic target service
 - it's a spec of a desired service: (devilish) nondeterminism is banned

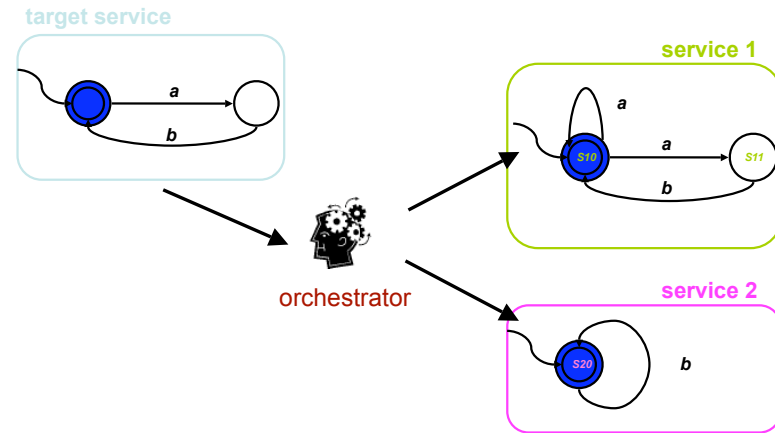
In general, devilish nondeterminism difficult to cope with
eg. nondeterminism moves AI Planning from PSPACE (classical planning) to EXPTIME
(contingent planning with full observability [Rintanen04])

Example: Nondeterministic Available Services

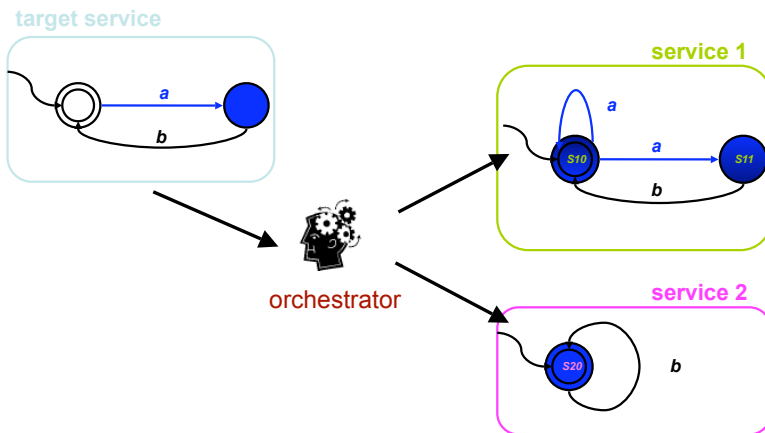


Available services represented as nondeterministic transition systems

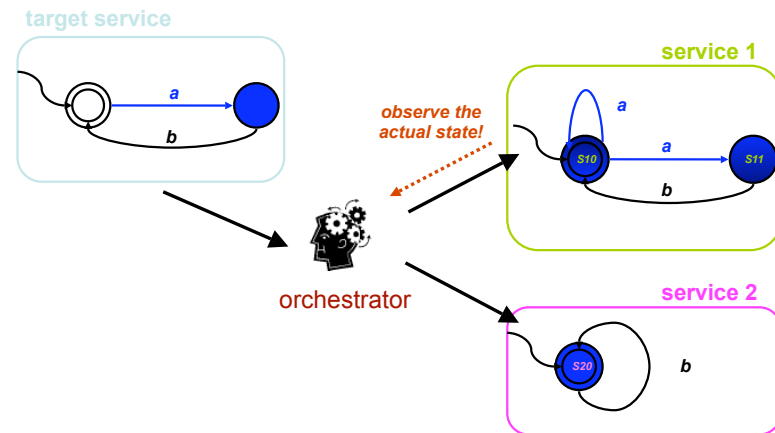
Example: Nondeterministic Available Services



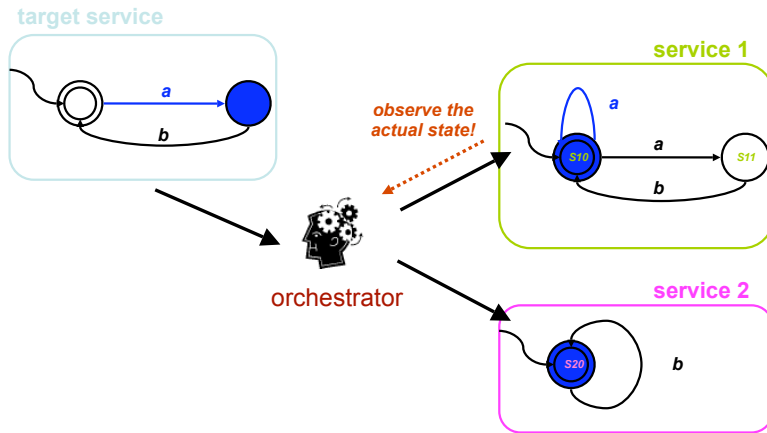
Example: Nondeterministic Available Services



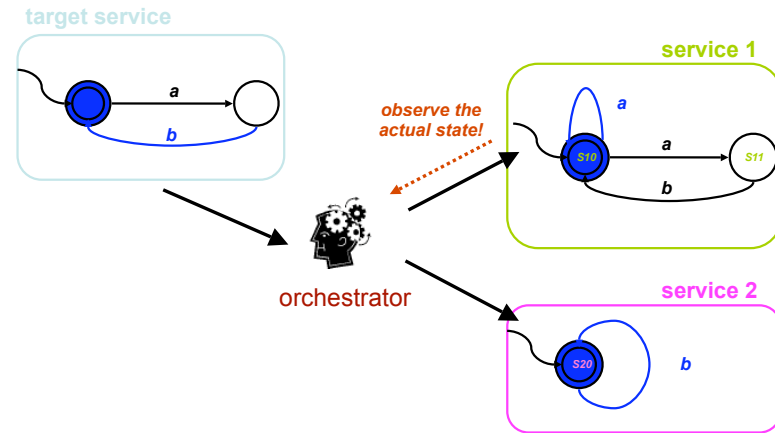
Example: Nondeterministic Available Services



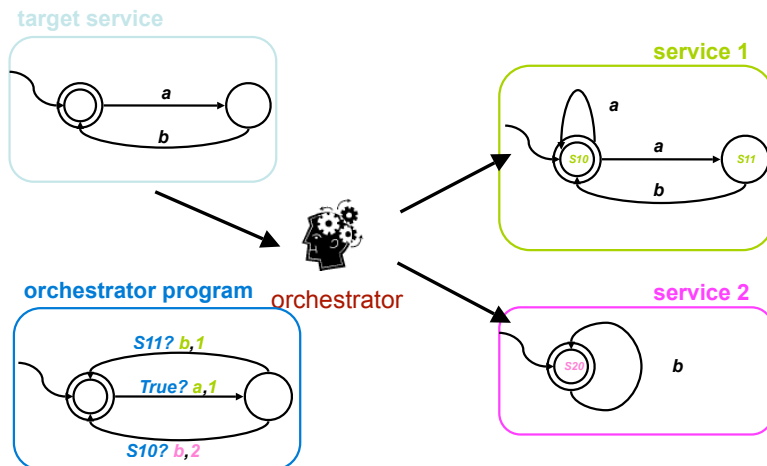
Example: Nondeterministic Available Services



Example: Nondeterministic Available Services



An Orchestrator Program Realizing the Target Service



Orchestrator Programs

contains all the observable information up the current situation

- **Orchestrator program** is any function $P(h,a) = i$ that takes a **history** h and an **action** a to execute and **delegates** a to one of the available services i
- A **history** is a sequence of the form:
 $(s_1^0, s_2^0, \dots, s_n^0, e^0) a_1 (s_1^1, s_2^1, \dots, s_n^1, e^1) \dots a_k (s_1^k, s_2^k, \dots, s_n^k, e^k)$
- Observe that to take a decision P has **full access to the past**, but no access to the future
- *Problem: synthesize a orchestrator program P that realizes the target service making use of the available services*

Technique: Reduction to PDL

Basic idea:

- A orchestrator program P realizes the target service T iff at each point:
 - $\forall$ transition labeled a of the target service T ...
 - ... $\exists$ an available service B_i (the one chosen by P) which can make an a -transition ...
 - ... and $\forall$ a -transition of B_i realize the a -transition of T
- Encoding in PDL:
 - $\forall$ transition labeled a ...
 - use **branching**
 - $\exists$ an available service B_i ...
 - use underspecified predicates **assigned through SAT**
 - $\forall$ a -transition of B_i ... :
 - use **branching** again

Technical Results: Theoretical

Thm[IJCAI'07] Checking the existence of orchestrator program realizing the target service is **EXPTIME-complete**.

EXPTIME-hardness due to Muscholl&Walukiewicz07 for deterministic services

Thm [IJCAI'07] If a **orchestrator program exists** there exists one that is **finite state**.

Exploits the finite model property of PDL

Note: same results as for deterministic services!

Technical Results: Practical

Reduction to PDL provides also a practical sound and complete technique to compute the orchestrator program also in this case

eg, PELLET @ Univ. Maryland

- Use state-of-the-art tableaux systems for OWL-DL for checking SAT of PDL formula Φ coding the composition existence
- If SAT, the tableau returns a finite model of Φ
 - exponential in the size of the behaviors*
- Project away irrelevant predicates from such model, and possibly minimize
- The resulting structure is a finite orchestrator program that realizes the target behavior
 - polynomial in the size of the model*

Nondeterministic Available Services: Composition à la Simulation

Composition à la Simulation

- We consider binary relations R satisfying the following co-inductive condition:

$(s_i(q_1, \dots, q_n)) \in R$ implies that

- if s is *final* then q_i , with $i=1, \dots, n$, is *final*
- for **all** actions a
 - if $s \rightarrow_a s'$ then $\exists k \in 1..n$.
 - $\exists q_k' : q_k \rightarrow_a q_k'$
 - $\forall q_k' : q_k \rightarrow_a q_k' \supset (s'_i(q_1, \dots, q_k', \dots, q_n)) \in R$

Note similar in the spirit to simulation relation!
But more involved, since it deals with

- the existential choice (as the simulation) of the service, and
 - the universal condition on the nondeterministic branches!
- A composition realizing a target service TS TS_t exists if there **exists** a relation R satisfying the above condition between the initial state s_i^0 of TS_t and the initial state $(s_1^0, \dots, s_n^0)$ of the community big TS TS_c .
 - Notice if we take the union of all such relation R then we get the largest relation RR satisfying the above condition.
 - A composition realizing a target service TS T exists iff $(s_i^0, (s_1^0, \dots, s_n^0)) \in RR$.

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Composition à la Simulation

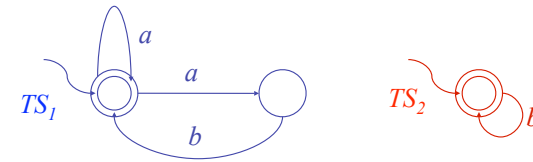
- Computing RR is polynomial in the size of the target service TS and the size of the community TS ...
- ... composition can be done in **EXPTIME** in the size of the available services
- For **generating** OG we need only to compute RR and then apply the template above
- For **running** the OG we need to store and access RR (polynomial time, exponential space) ...
- ... and compute ω_r and δ_r at each step (polynomial time and space)

Composition à la Simulation

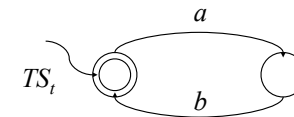
- Given RR from TS_t to TS_c (which include the initial states), we can build the **orchestrator generator**.
- This is an orchestrator program that can change its behavior reacting to the information acquired at run-time.
- Def: $OG = \langle A, [1, \dots, n], S_r, s_r^0, \omega_r, \delta_r, F_r \rangle$ with
 - A : the **actions** shared by the community
 - $[1, \dots, n]$: the **identifiers** of the available services in the community
 - $S_r = S_1 \times S_2 \times \dots \times S_n$: the **states** of the orchestrator program
 - $s_r^0 = (s_1^0, s_2^0, \dots, s_n^0)$: the **initial state** of the orchestrator program
 - $F_r \subseteq \{ (s_1, s_2, \dots, s_n) \mid s_i \in F_i : \text{the final states of the orchestrator program} \}$
 - $\omega_r : S_r \times A_r \rightarrow [1, \dots, n]$: the **service selection function**, defined as follows:
 - If $s_t \rightarrow_a s'_t$ then
chose k s.t. $\exists s_k' : s_k \rightarrow_a s_k' \wedge \forall s_k' : s_k \rightarrow_a s_k' \supset (s_t', (s_1, \dots, s_k', \dots, s_n)) \in RR$
 - $\delta_r \subseteq S_r \times A_r \times [1, \dots, n] \times S_r$: the **state transition relation**, defined as follows:
 - Let $\omega_r(s_t, s_1, \dots, s_k, \dots, s_n, a) = k$ then
 $(s_t, s_1, \dots, s_k, \dots, s_n) \rightarrow_{a,k} (s_t', s_1, \dots, s_k', \dots, s_n)$ for each $s_k \rightarrow_a s_k'$

Example of Composition

Available Services



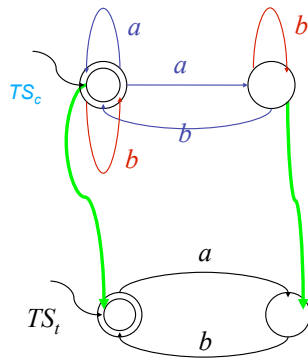
Target Service



Example of Composition

Community TS

Target Service



Composition exists!

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