Behavior Composition in the Presence of Failure

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Introduction

There are at least two kinds of games. One could be called finite, the other infinite.

A finite game is played for the purpose of winning ...

... an infinite game for the purpose of continuing the play.

Finite and Infinite Games
J. P. Carse

Behavior composition vs Planning

Planning

- Operators: atomic
- Goal: desired state of affair
- Finite game: compose operator sequentially so as to reach the goal
- Playing strategy: plan

Behavior composition

- “Operators”: available transition systems
- “Goal”: target transition system
- Infinite game: compose available transition systems concurrently so as to play the target transition systems
- Playing strategy: composition controller

Behavior composition

Given:

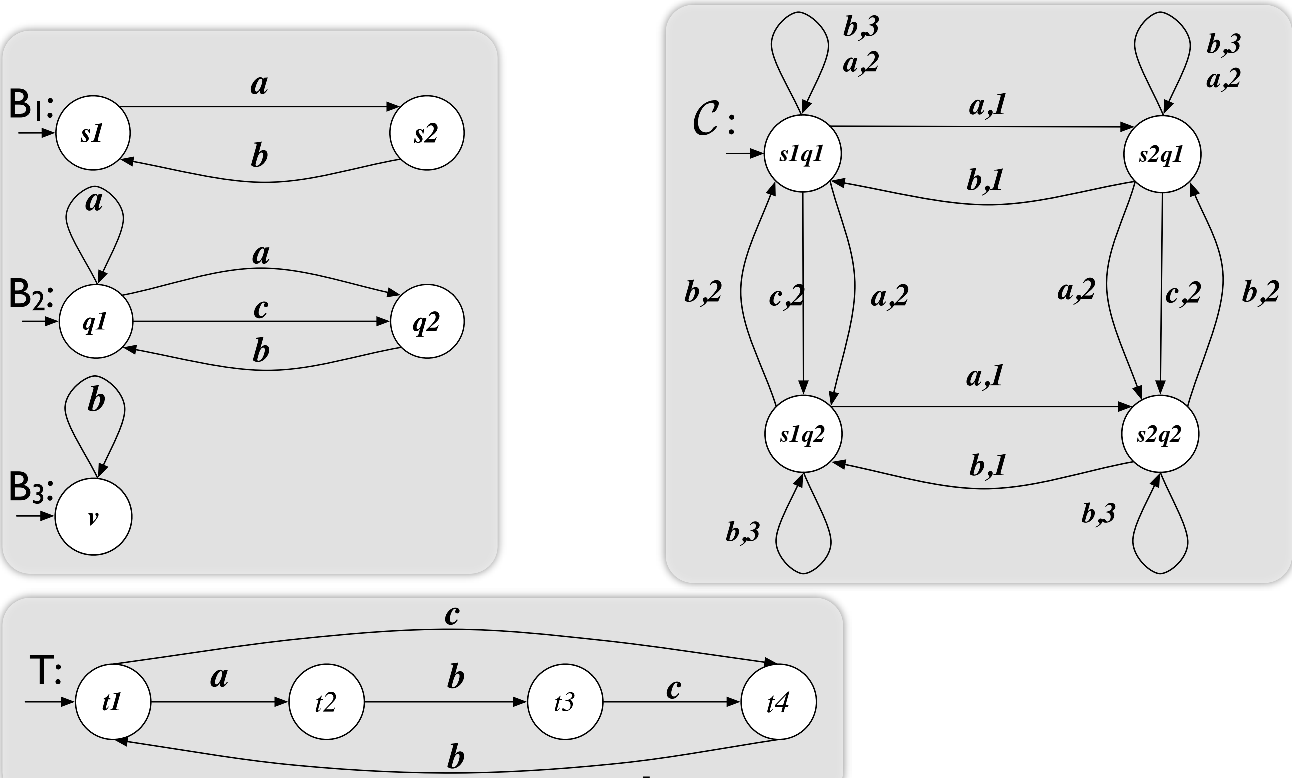
- a set of available behaviors $B_1,\ldots,B_n$
- a target behavior T

we want to realize T by delegating actions to $B_1,\ldots,B_n$

i.e.: *control* the concurrent execution of $B_1,\ldots,B_n$ so as to *mimic* T over time

Behavior composition: *synthesis of the controller*

Example



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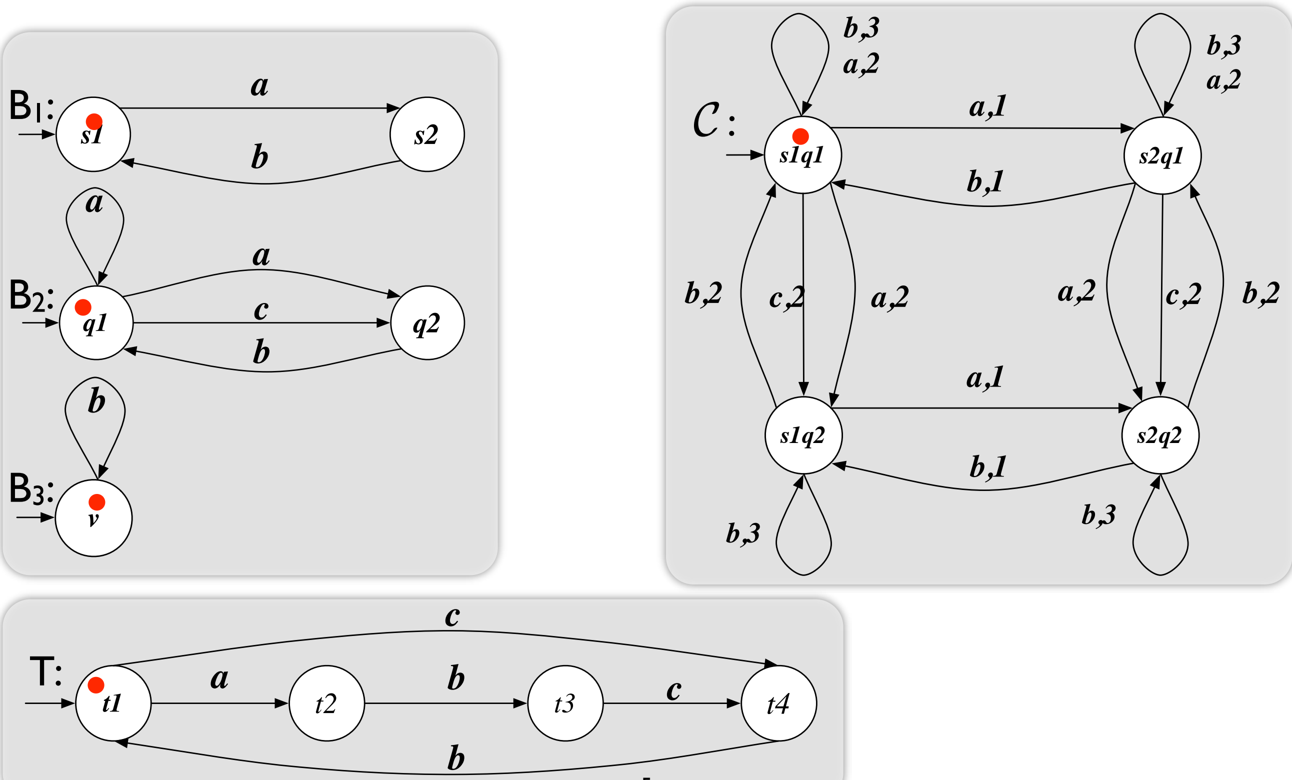

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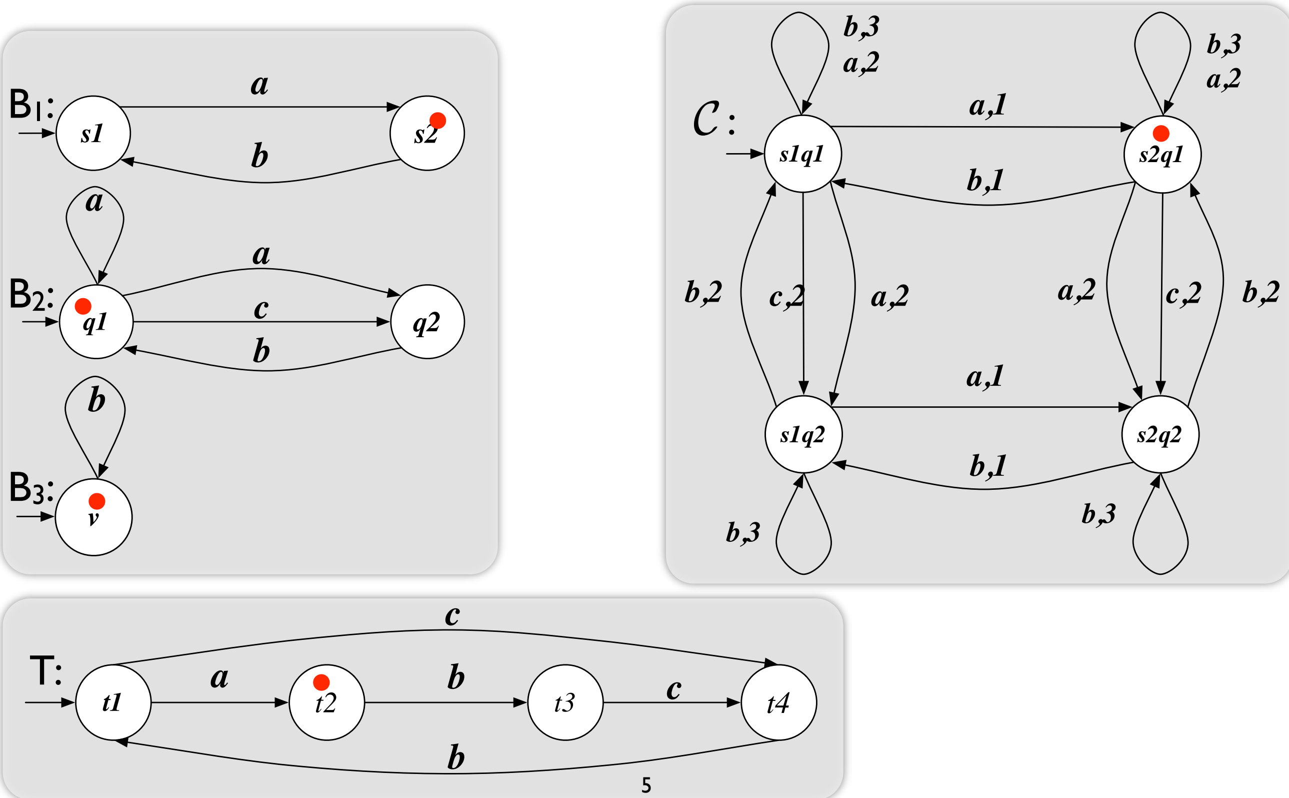

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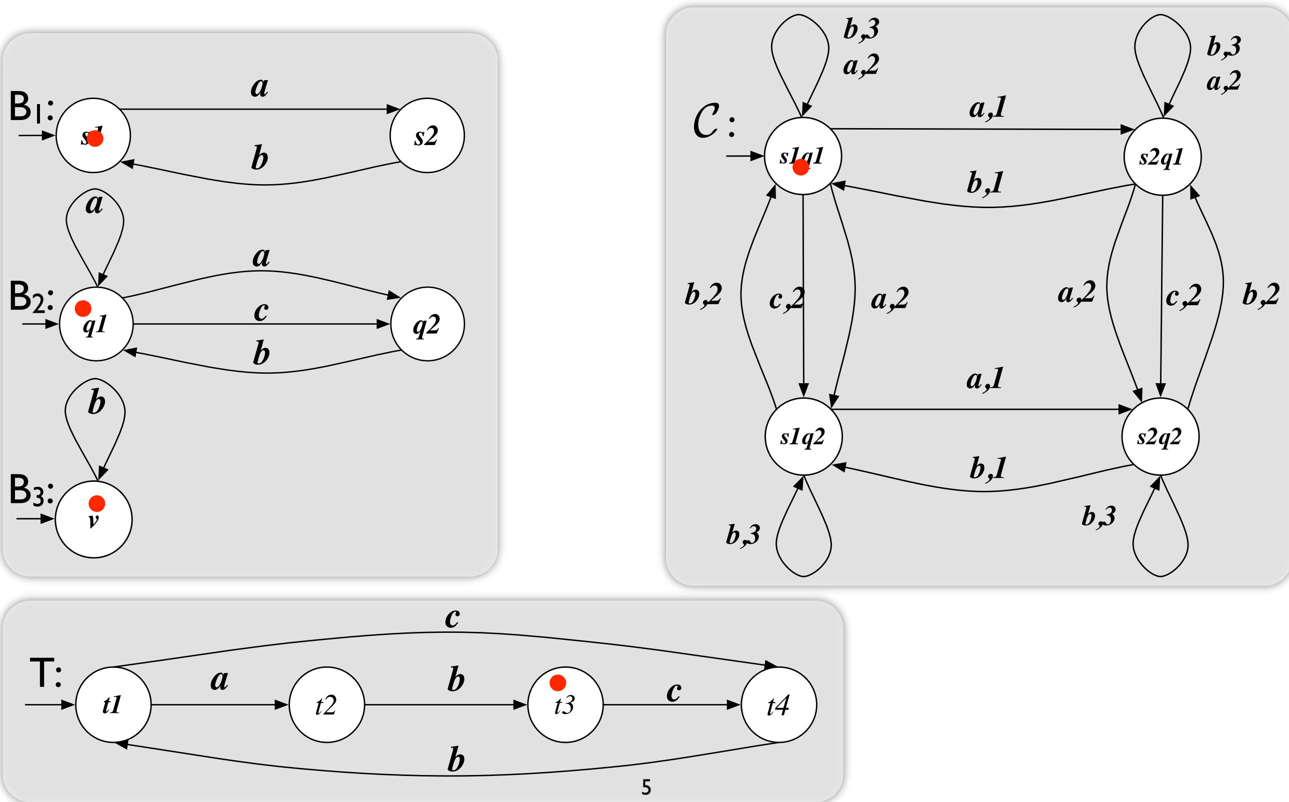

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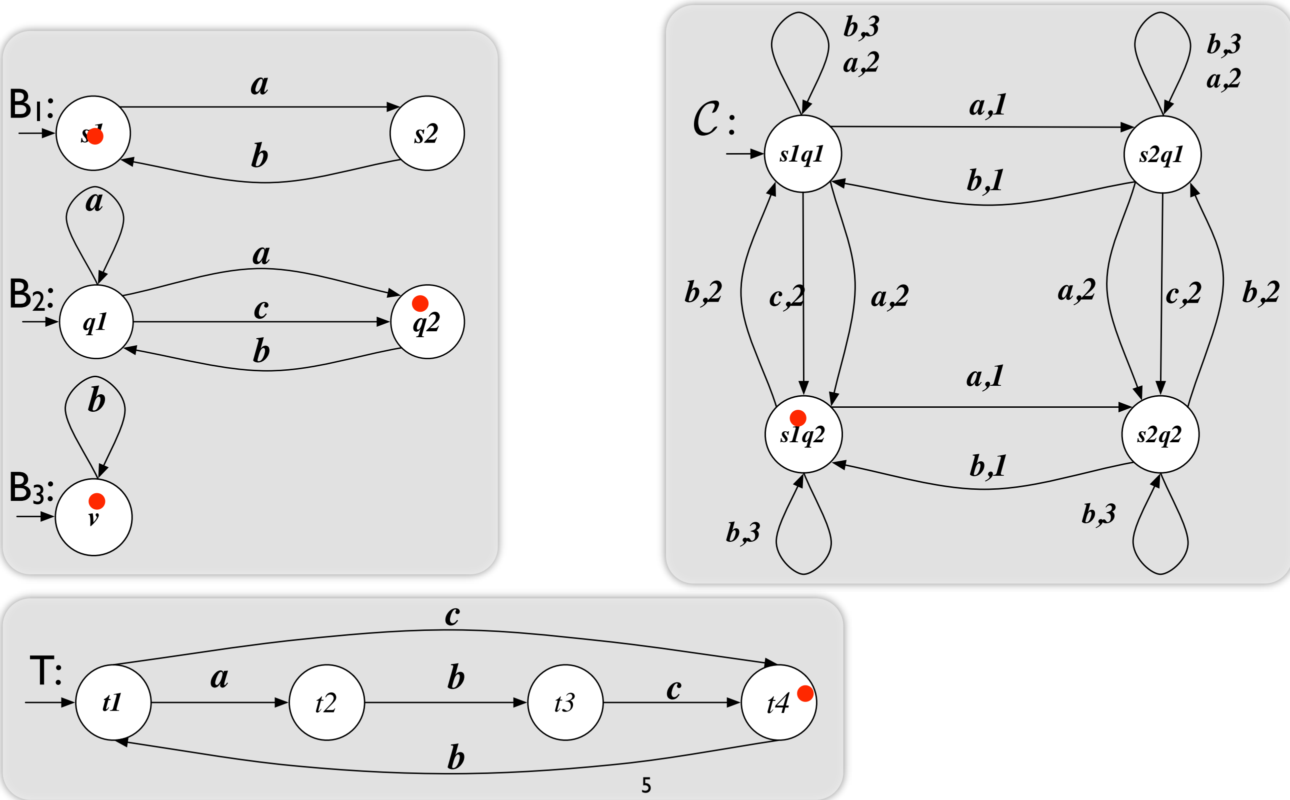

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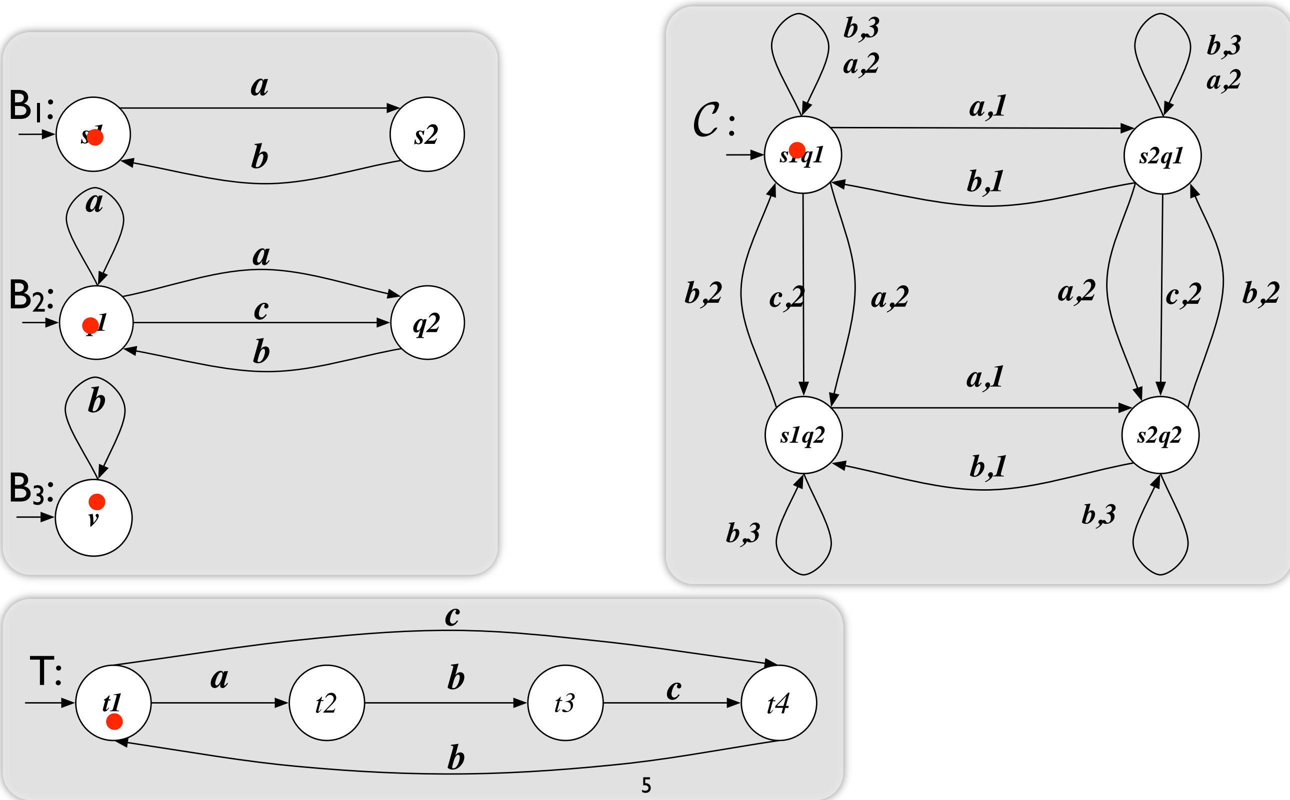

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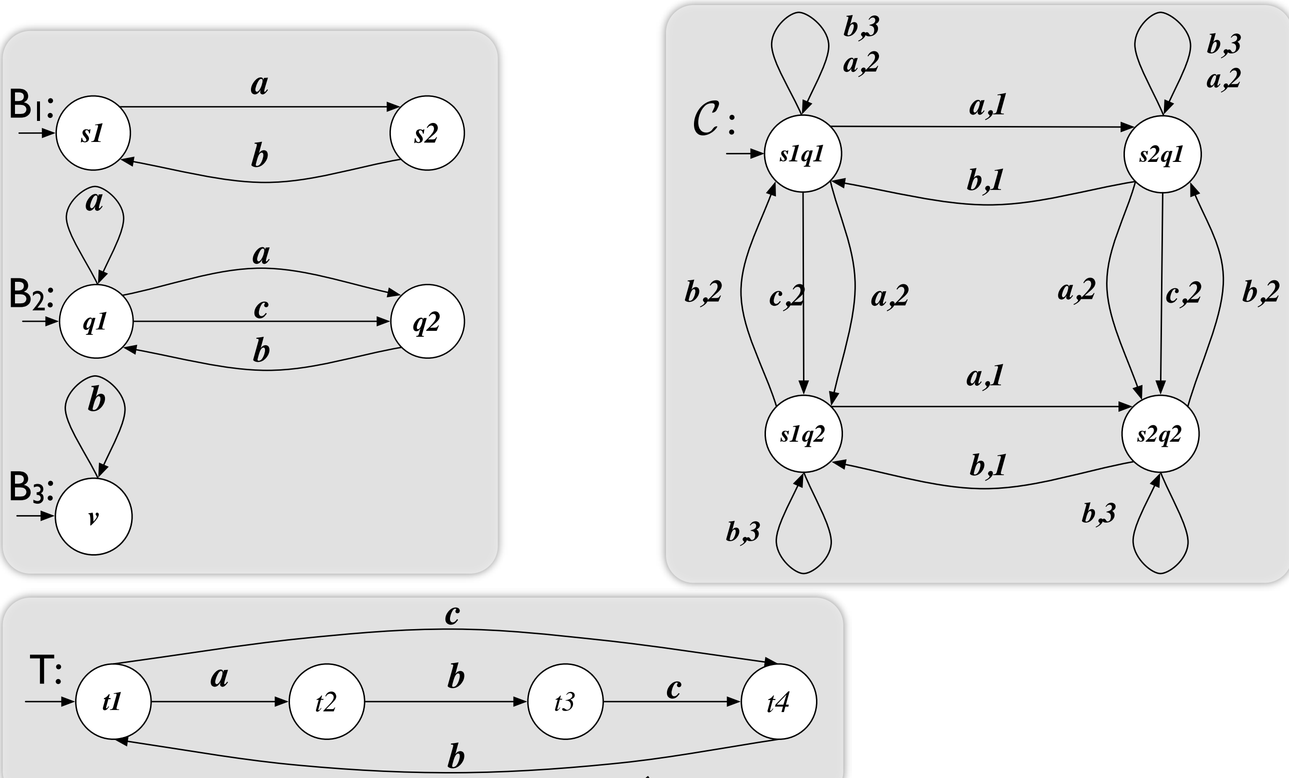

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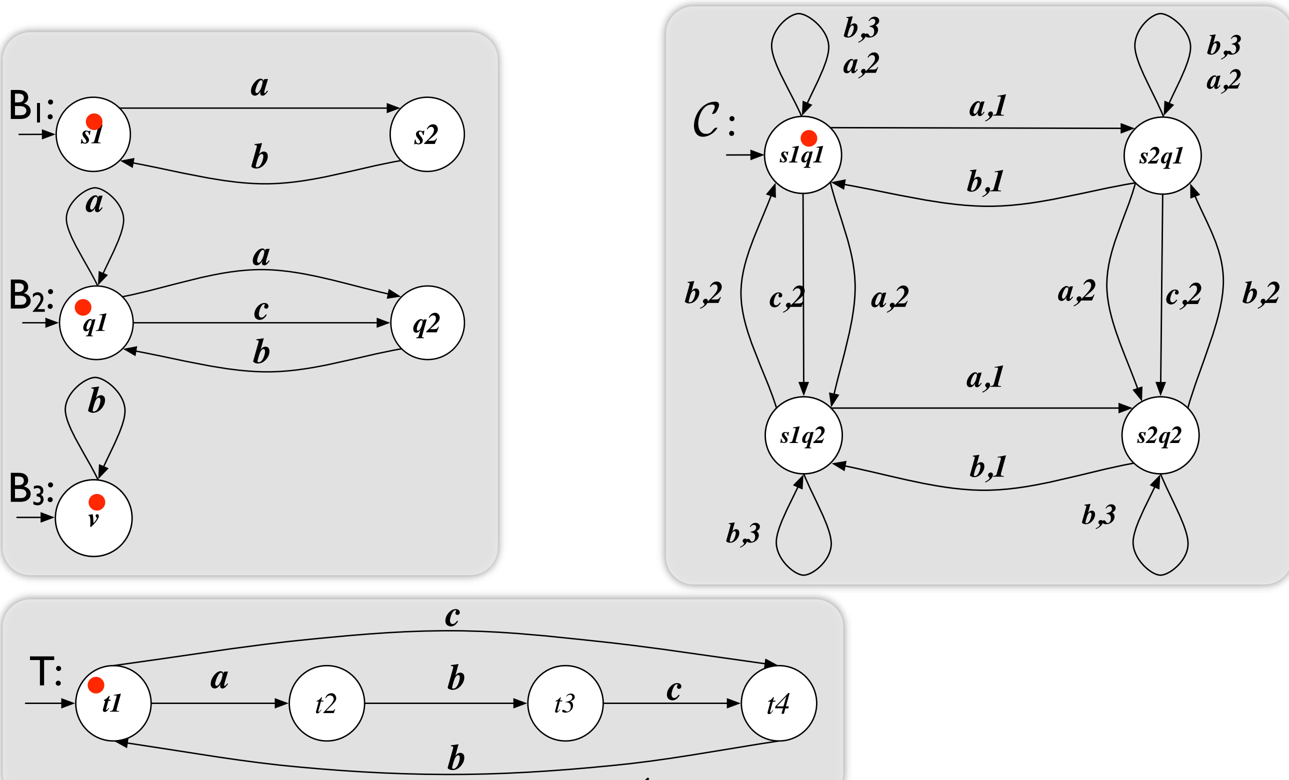

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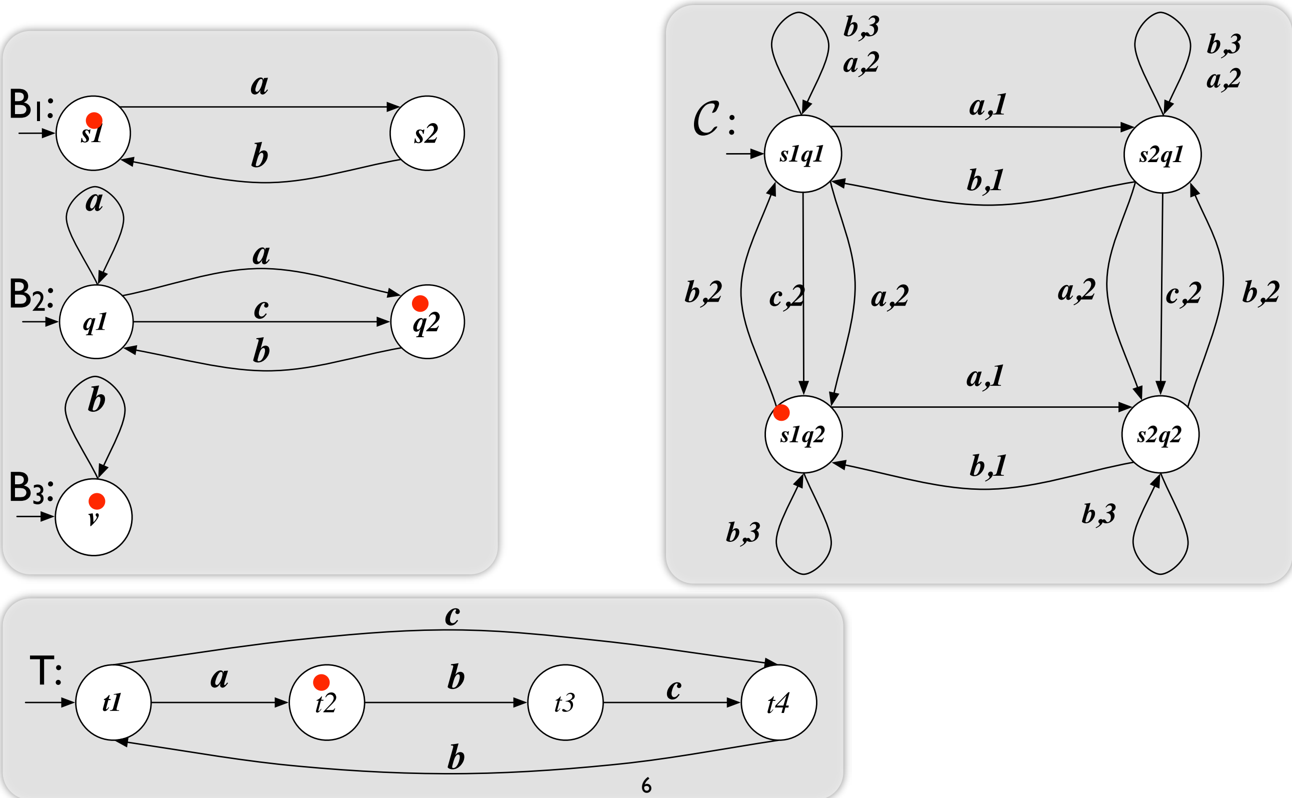

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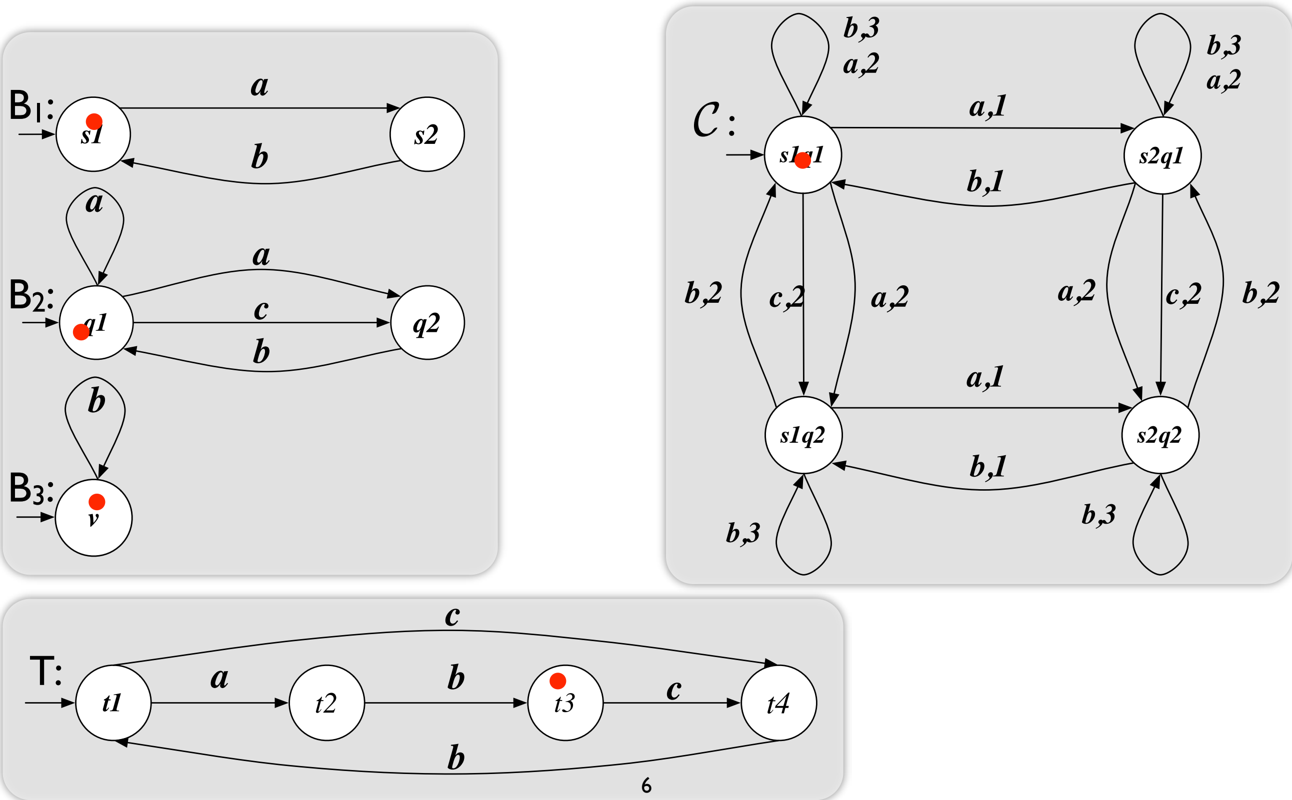

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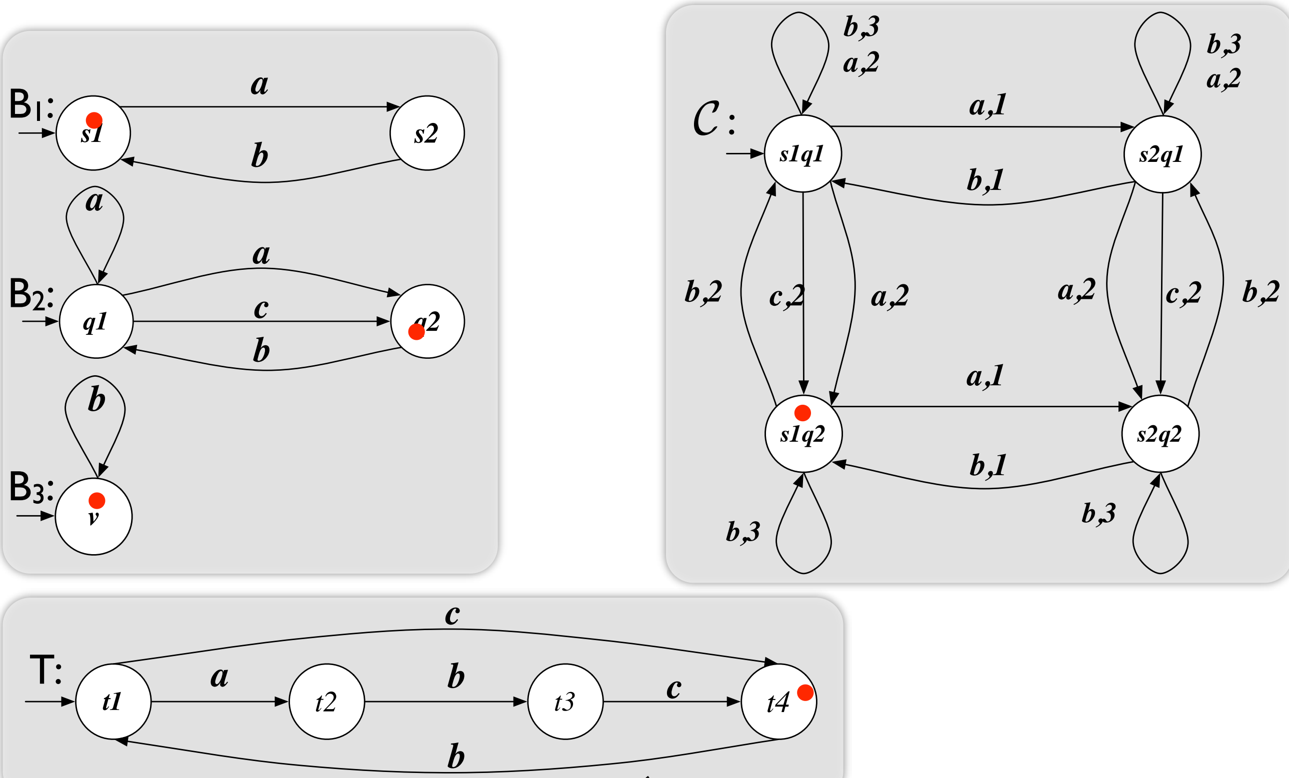

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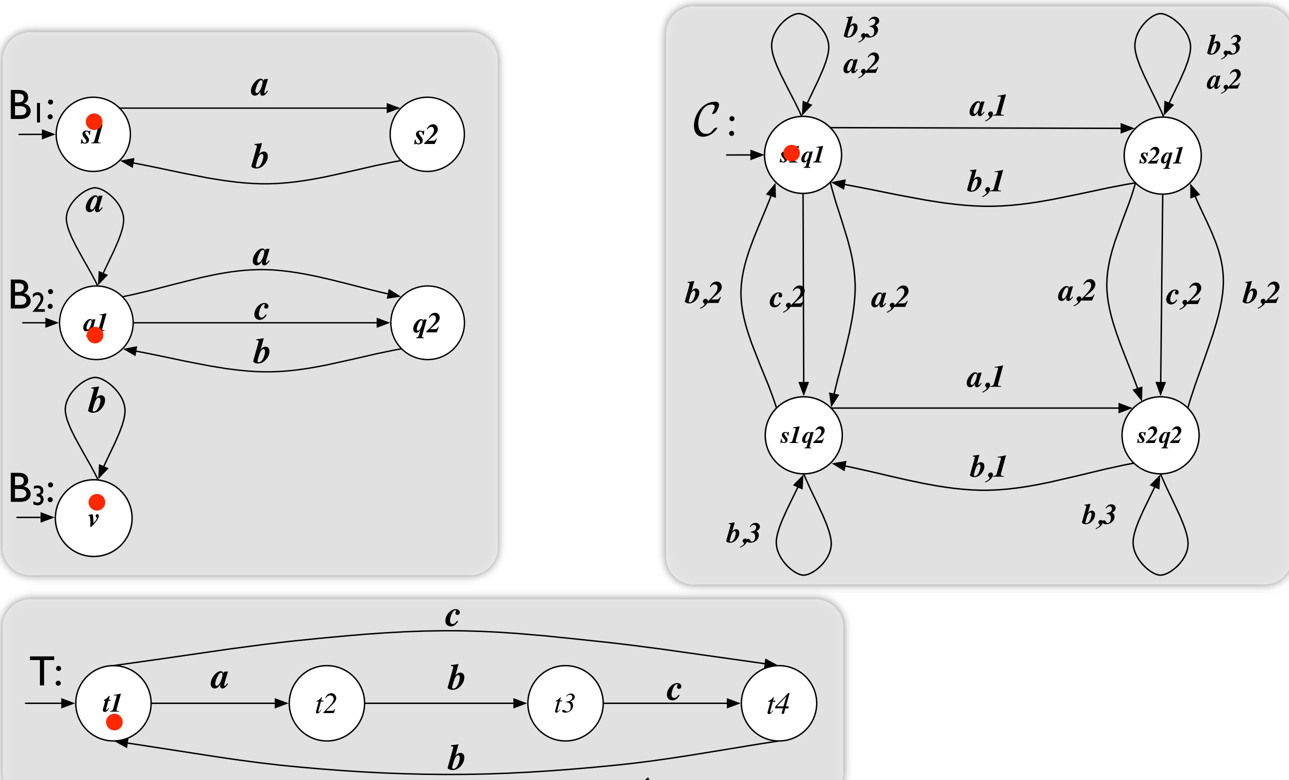

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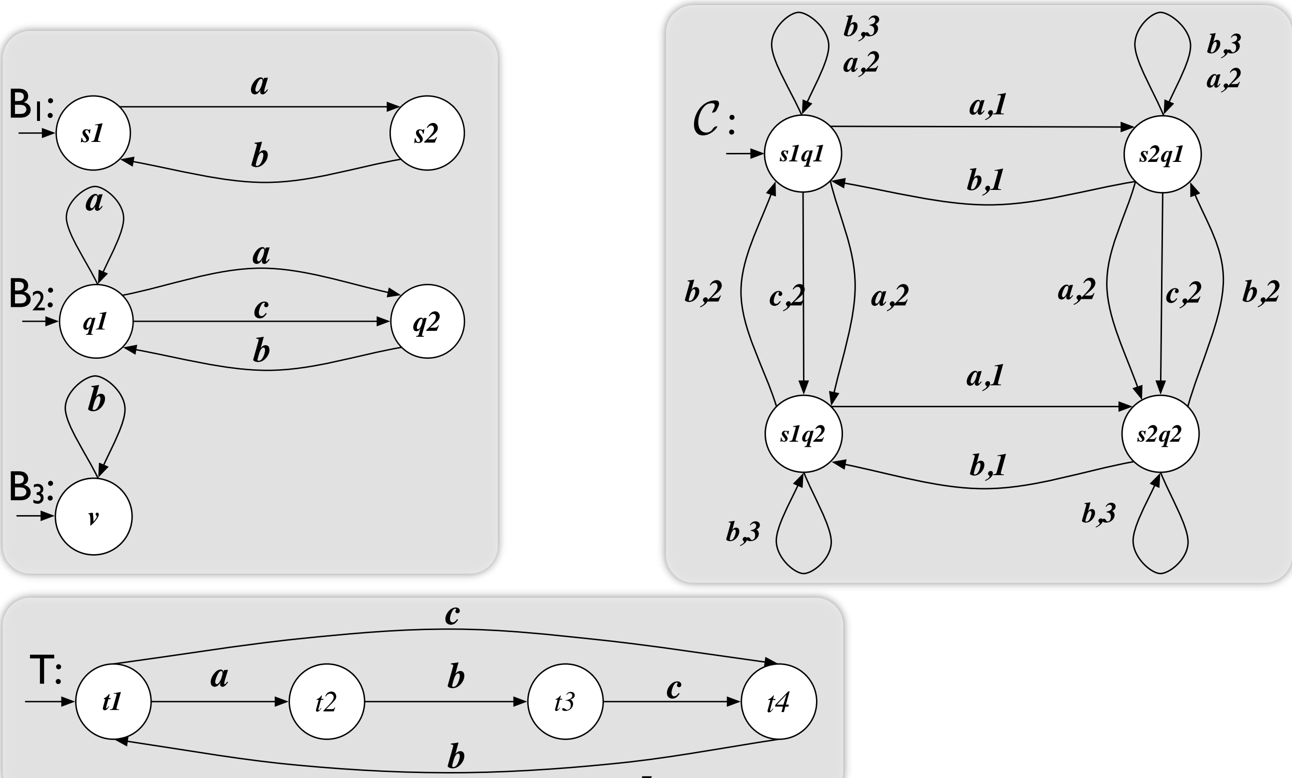

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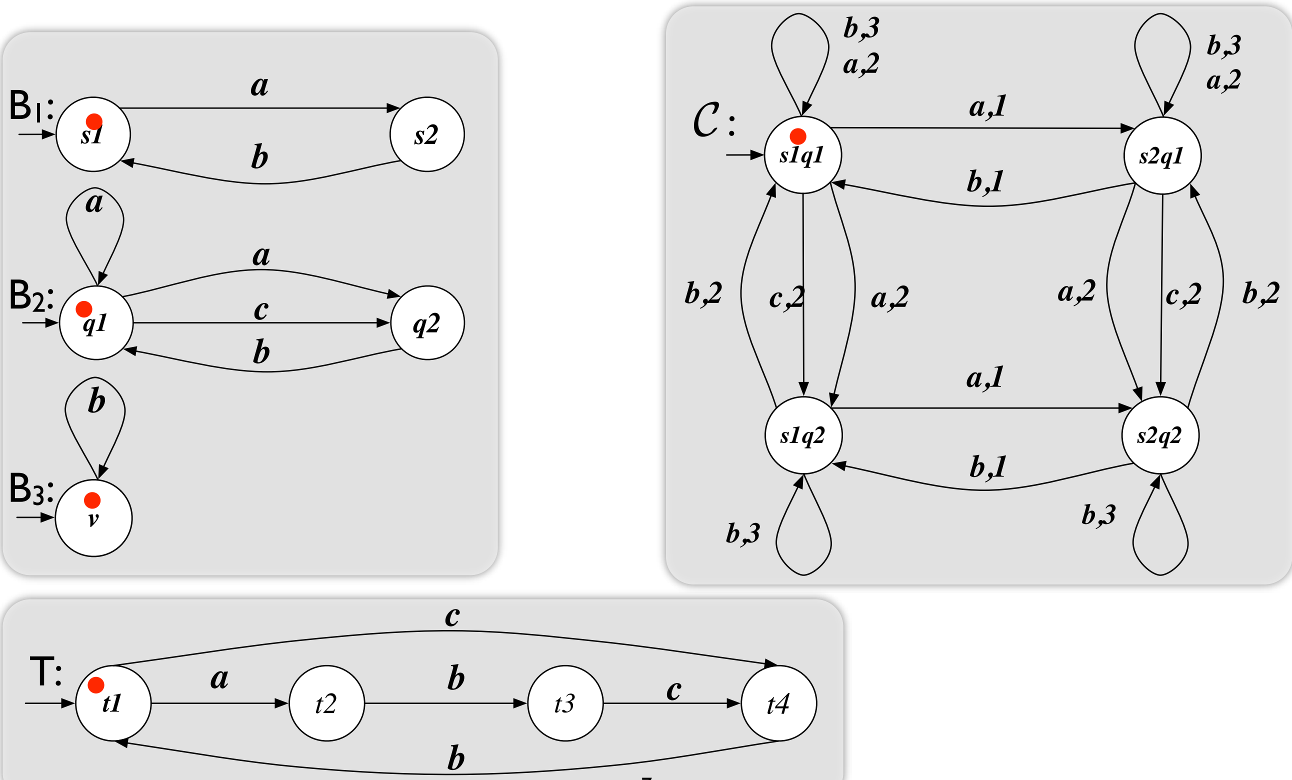

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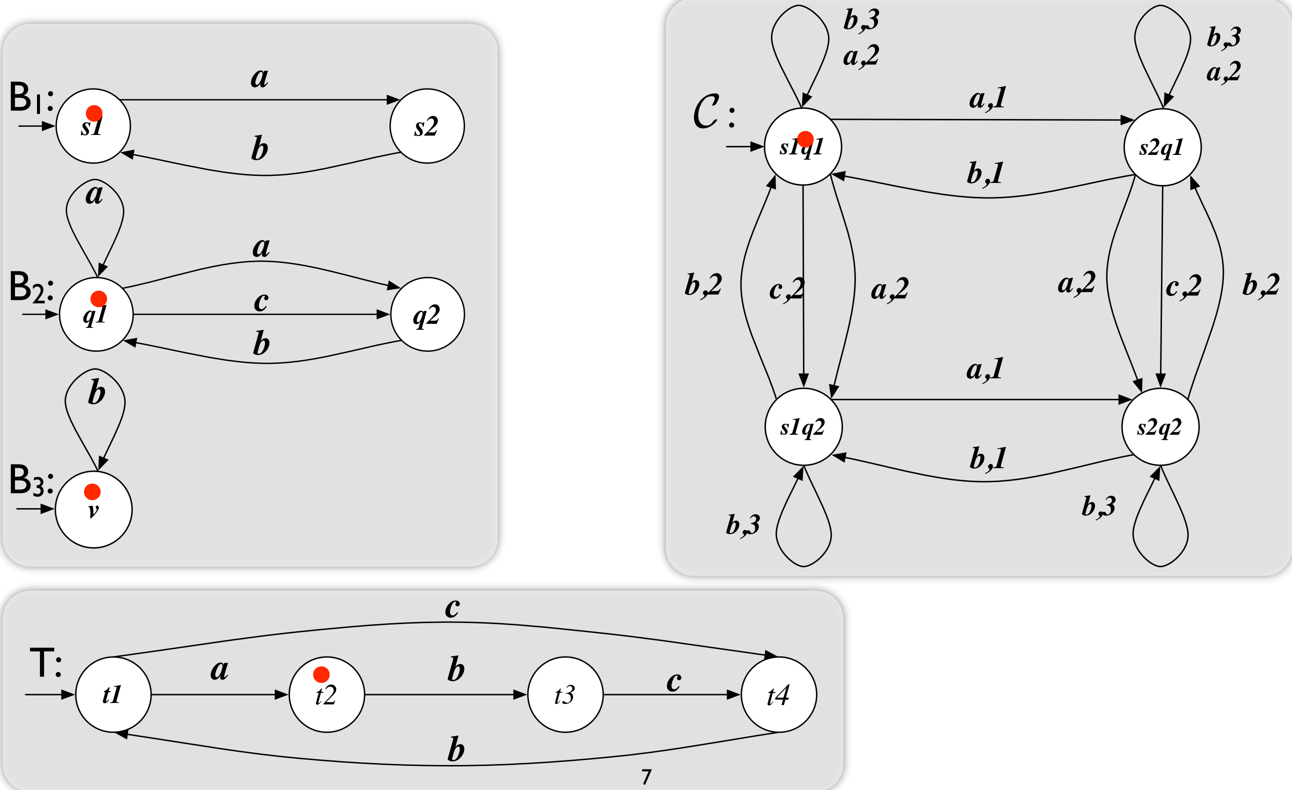

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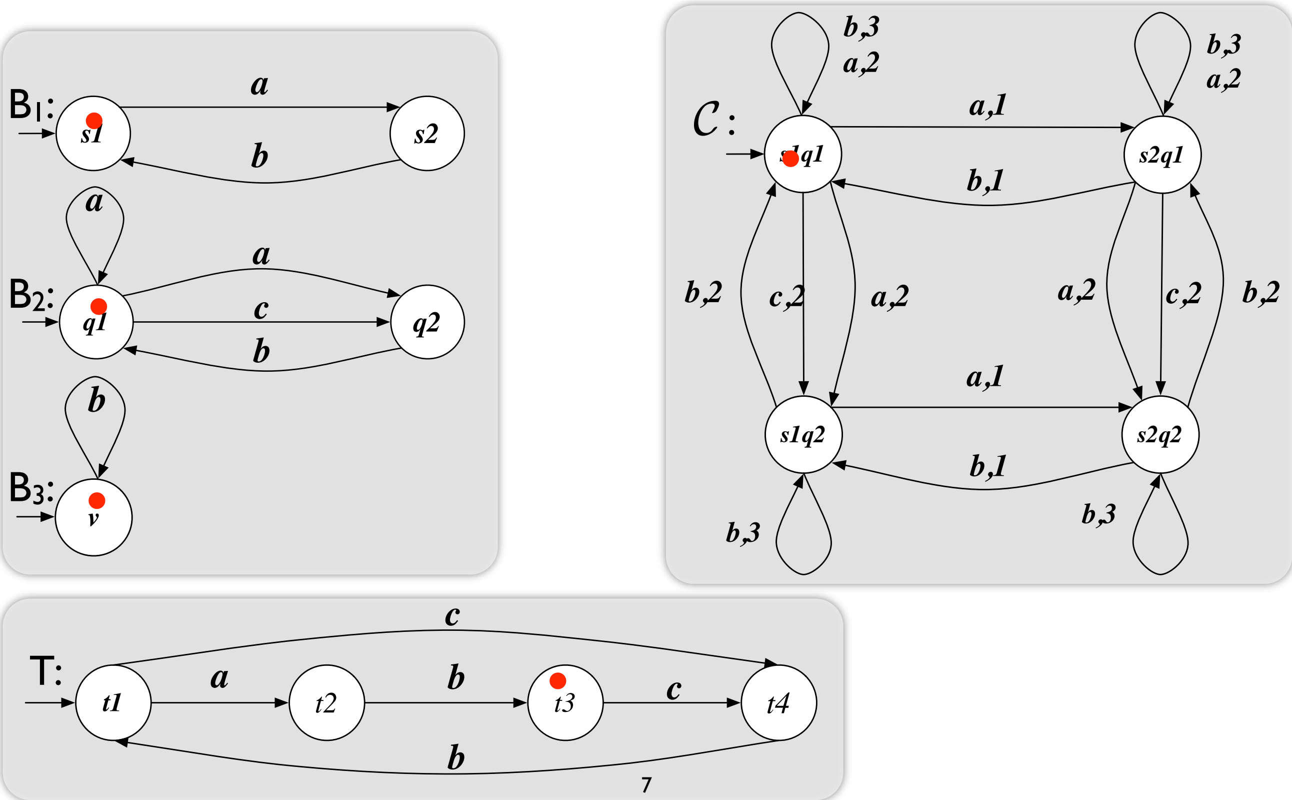

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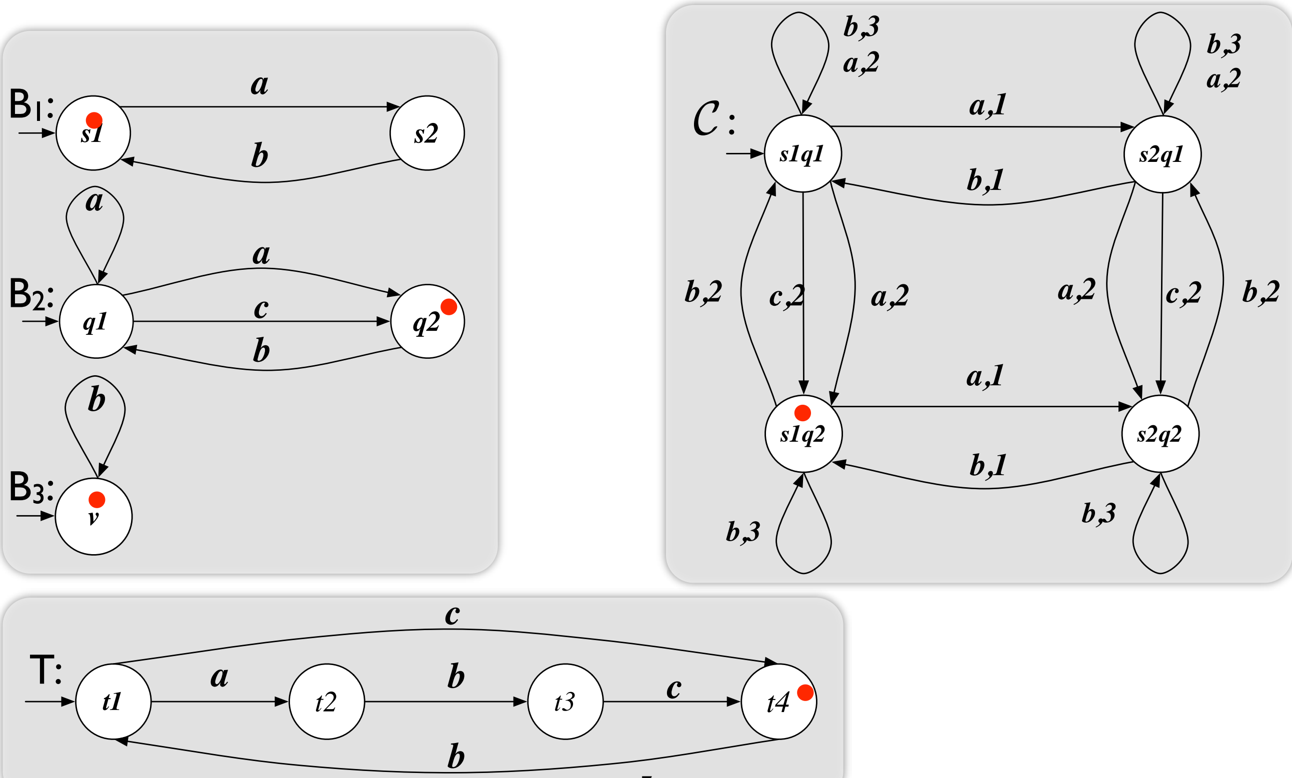

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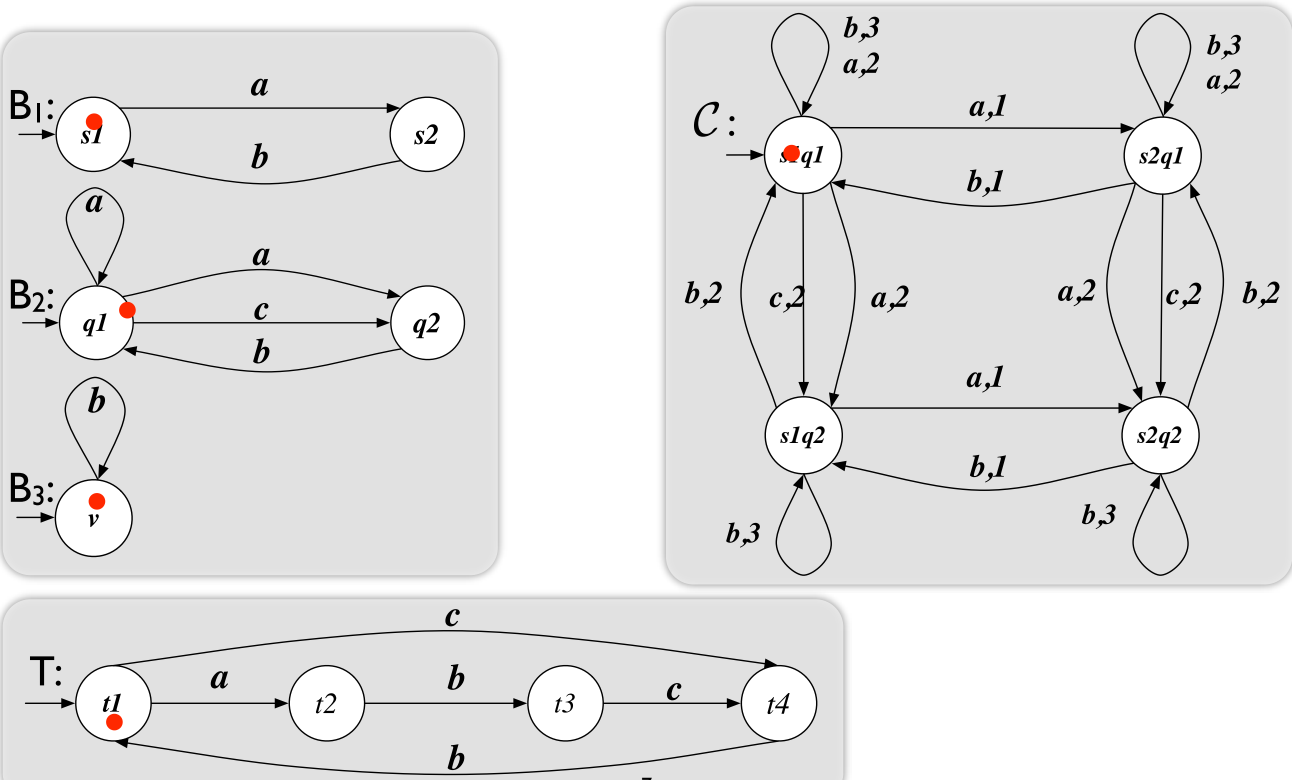

Synthesizing a composition

Techniques for computing compositions:

- Reduction to PDL SAT [IJCAI07, AAAI07, VLDB05, ICSOC03]
- Simulation-based
- LTL synthesis as model checking of game structure [ICAPS08]

All techniques are for finite state behaviors

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Simulation-based technique

Directly based on

"... *control* the concurrent execution of $B_1,\ldots,B_n$ so as to *mimic* T "

Note this is possible ...

.... if the concurrent execution of $B_1,\ldots,B_n$ *can mimic* T

Thm: *this is possible iff*

... the asynchronous (Cartesian) product $\mathcal{C}$ of $B_1,\ldots,B_n$ can (ND-)simulate T

Simulation relation

- Given two transition systems $T = < A, S_T, t^0, \delta_T >$ and $\mathcal{C} = < A, S_\mathcal{C}, s_\mathcal{C}^0, \delta_\mathcal{C} >$ a (**ND-**)**simulation** is a relation R between the states $t \in \mathcal{T}$ an $(s_1,..,s_n)$ of $\mathcal{C}$ such that:
  - $(t, s_1,..,s_n) \in R$ implies that
    - for all $t \to_a t'$ exists a $B_i \in \mathcal{C}$ s.t.
      - $\exists\, s_i \to_a s'_i$ in B_i
      - $\forall\, s_i \to_a s'_i$ in $B_i \Rightarrow (t', s_1,..,s'_i,..,s_n) \in R$
- If **exists a simulation** relation R such that $(t^0, s_\mathcal{C}^0) \in R$, then we say that **T is simulated by** $\mathcal{C}$.
- **Simulated-by** is (i) a simulation;
  (ii) the largest simulation.

Simulated-by is a coinductive definition

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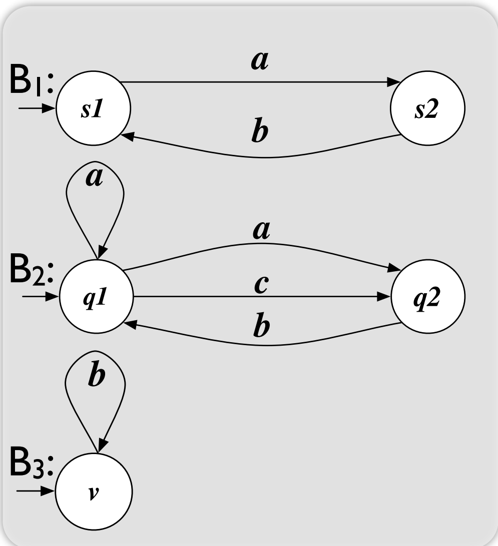

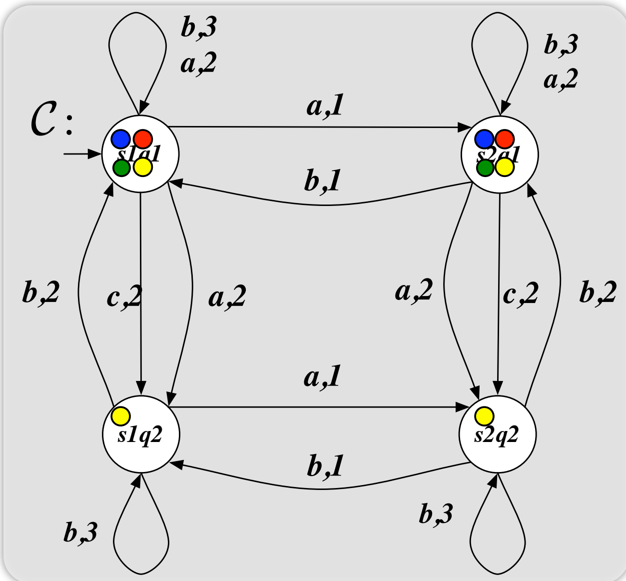

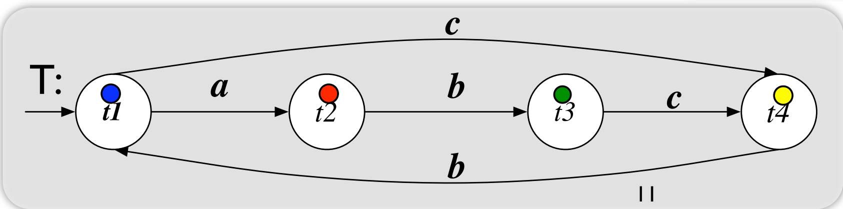

Reachability relation (Planning)

- A binary relation R is a **reachability-like relation** iff:
  - $(s,s) \in R$
  - if $\exists$ a. s′. $s \rightarrow_a s' \wedge (s',s'') \in R$ then $(s,s'') \in R$

- A state s_g of transition system S is **reachable-from** a state s_0 iff for **all** a **reachability-like relations** R we have $(s_0, s_g) \in R$.

- **reachable-from** is (i) a reachability-like relation itself;
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Reachable-from is a inductive definition!

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Simulation relation (cont.)

Algorithm Compute (ND-)simulation
Input: target behavior $T = \langle A, S_T, t^0, \delta_T, F_T \rangle$ and
(Cart. prod. of) available behaviors $\mathcal{C} = \langle A, S_{\mathcal{C}}, s_{\mathcal{C}}^0, \delta_{\mathcal{C}}, F_{\mathcal{C}} \rangle$
Output: the **simulated-by** relation (the largest simulation)

Body
$R = \emptyset$
$R' = S_T \times S_{\mathcal{C}}$
while $(R \neq R')$ {
$R := R'$
$R' := R' - \{(t, s_1,..,s_n) \mid \exists\, t \to_a t' \text{ in } T \wedge$
$\forall B_i \,.\, \neg\exists\, s \to_a s' \text{ in } B_i \vee \exists\, s_i \to_a s'_i \text{ in } B_i \wedge (t', s_1,..s'_i,..s_n) \notin R' \}$
}
return R'
End

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}
return R'
End

Computing composition via simulation

Let $S_1, \ldots, S_n$ be the TSs of the available behaviors.

The **Available behaviors TS** $\mathcal{C}$ = < A, $S_\mathcal{C}$, $s_\mathcal{C}^0$, $\delta_\mathcal{C}$, $F_\mathcal{C}$>

is the **asynchronous product** of $S_1, \ldots, S_n$ where:

- A is the set of actions
- $S_\mathcal{C} = S_1 \times \ldots \times S_n$
- $s_\mathcal{C}^0 = (s^0_1, \ldots, s^0_m)$
- $\delta_\mathcal{C} \subseteq S_\mathcal{C} \times A \times S_\mathcal{C}$ is defined as follows:

  $(s_1 \times \ldots \times s_n) \rightarrow_a (s'_1 \times \ldots \times s'_n)$ iff

  - $\exists$ i. $s_i \rightarrow_a s'_i \in \delta_i$
  - $\forall$ j≠i. $s'_j = s_j$

Using simulation for composition

Given the largest simulation R of T by $\mathcal{C}$, we can build every composition through the ***controller generator (CG)***.

CG = < A, [1,…,n], S_r, s_r^0, δ, ω> with

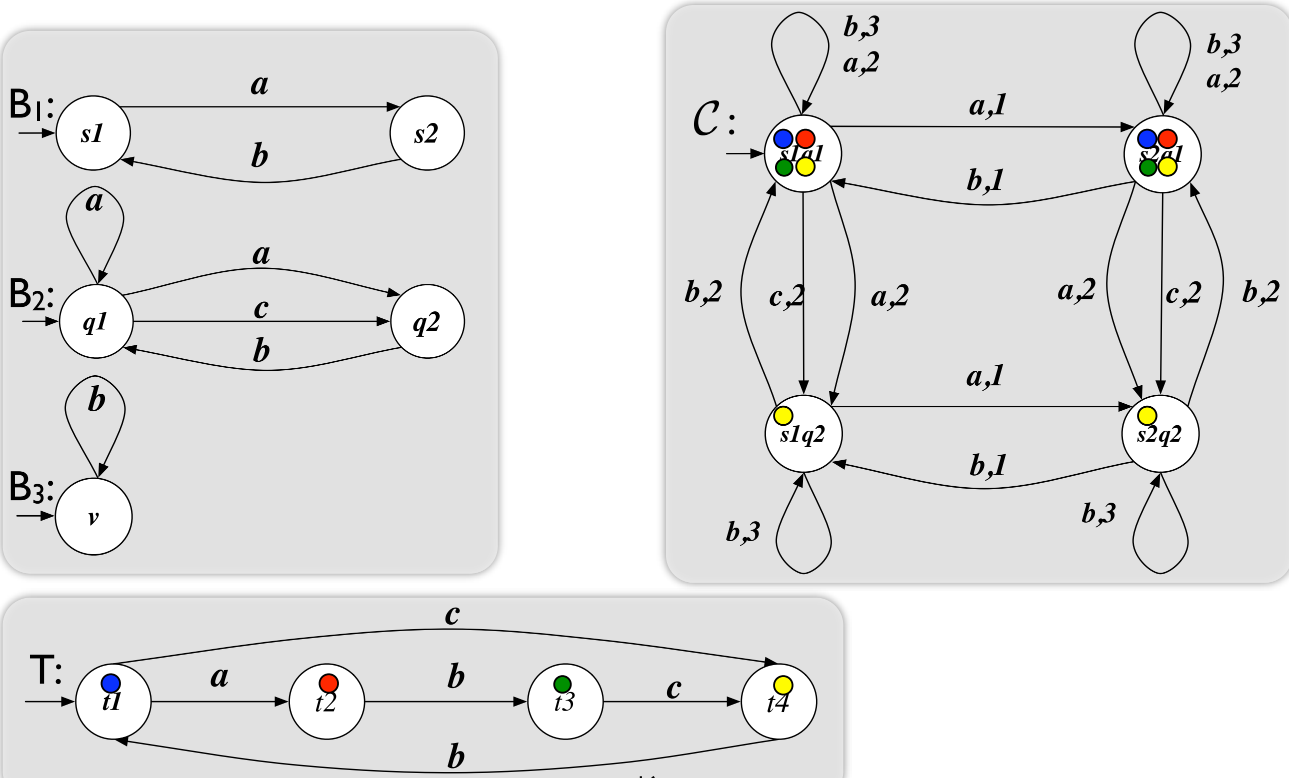
- A : the **actions** shared by the behaviors
- [1,…,n]: the **identifiers** of the available behaviors
- $S_r = S_T \times S_1 \times \ldots \times S_n$: the **states** of the controller generator
- $s_r^0 = (t^0, s^0_1, \ldots, s^0_n)$: the **initial state** of the controller generator
- $\omega: S_r \times A \rightarrow 2^{[1,\ldots,n]}$: the **output function**, defined as follows:

$\omega(t, s_1,..,s_n, a)$ = { i | B_i can do a and remain in R}

- $\delta \subseteq S_r \times A \times [1,\ldots,n] \rightarrow S_r$: the **state transition function**, defined as follows

  $(t, s_1,..,s_i,..,s_n) \rightarrow_{a,i} (t', s_1,..,s'_i,..,s_n)$ iff $i \in \omega(t, s_1,..,s_i,..,s_n, a)$

Example



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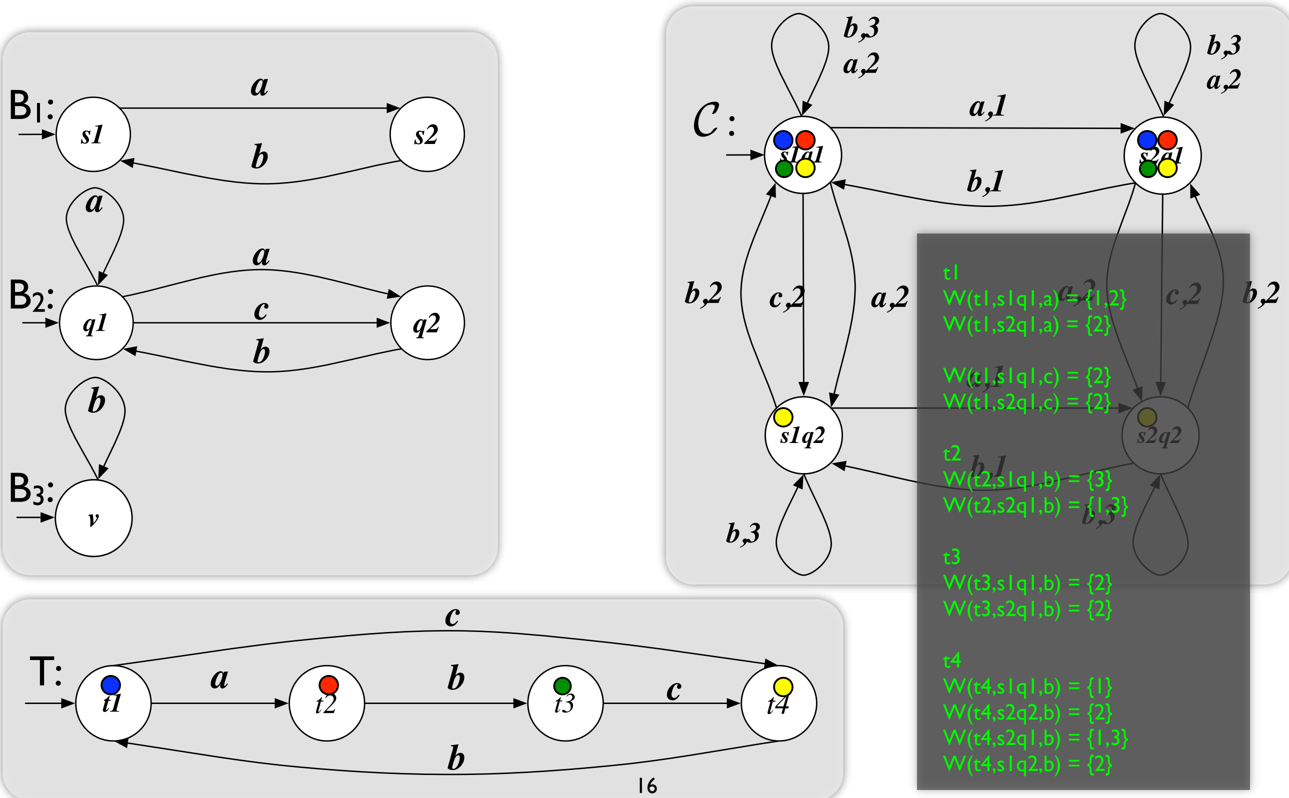

t1
W(t1,s1q1,a) = {1,2}
W(t1,s2q1,a) = {2}

W(t1,s1q1,c) = {2}
W(t1,s2q1,c) = {2}

t2
W(t2,s1q1,b) = {3}
W(t2,s2q1,b) = {1,3}

t3
W(t3,s1q1,b) = {2}
W(t3,s2q1,b) = {2}

t4
W(t4,s1q1,b) = {1}
W(t4,s2q2,b) = {2}
W(t4,s2q1,b) = {1,3}
W(t4,s1q2,b) = {2}

Results for simulation

Thm: *Choosing at each point any value in ω gives us a correct controller for the composition.*

Thm: *Every controller that is a composition can be obtained by choosing, at each point, a suitable value in ω.*

Thm: *Computing the controller generator is EXPTIME (composition is EXPTIME-complete [IJCAI07]) where the exponential depends only on the number (not the size) of the available behaviors.*

Behavior failures

Components may become unexpectedly unavailable for various reasons.

We consider four kinds of behavior failures:

- A behavior **temporarily freezes**; it will eventually resume in the same state it was in;
- A behavior (or the environment) unexpectedly and arbitrarily (i.e., without respecting its transition relation) **changes its current state**;
- A behavior **dies** - it becomes permanently unavailable.
- A dead behavior unexpectedly comes **alive again** (this is an opportunity more than a failure).

Just-in-time composition

Once we have the controller generator ...

... we can **avoid choosing any particular composition** apriori ...

... and **use directly *ω*** to choose the available behavior to which delegate the next action.

We can be ***lazy*** and make such choice ***just-in-time***, possibly adapting reactively to ***runtime*** feedback.

Reactive failure recovery with CG

CG already solves:

- **Temporary freezing** of an available behavior B_i
  - In principle: wait for B_i
  - But with CG: stop selecting B_i until it comes back!
- **Unexpected behavior (environment) state change**
  - In principle: recompute CG / simulated-by from new initial state ...
  - ... but CG / simulated-by independent from initial state!
  - Hence: simply use old CG / simulated-by from the new state!!

Parsimonious failure recovery

Algorithm Computing (ND-)simulation - parametrized version
Input: transition system $T = \langle A, T, t^0, \delta_T, F_T \rangle$ and
transition system $\mathcal{C} = \langle A, S, s_{\mathcal{C}}^0, \delta_{\mathcal{C}}, F_{\mathcal{C}} \rangle$
relation $\mathbf{R_{raw}}$ including the simulated-by relation
relation $\mathbf{R_{sure}}$ included the simulated-by relation
Output: the **simulated-by** relation (the largest simulation)
Body

$Q = \emptyset$

$Q' = \mathbf{R_{raw}} - \mathbf{R_{sure}}$ *//Note* $R' = (Q' \cup \mathbf{R_{sure}})$

while $(Q \neq Q')$ {

$Q := Q'$

$Q' := Q' - \{(t, s_1,..,s_n) \mid \exists\, t \to_a t' \text{ in } T \wedge$
$\forall B_i \,.\, \neg\exists\, s \to_a s' \text{ in } B_i \vee \exists\, s_i \to_a s'_i \text{ in } B_i \wedge (t', s_1,..s'_i,..s_n) \notin Q' \cup \mathbf{R_{sure}}\}$

}

return $Q' \cup \mathbf{R_{sure}}$

End

Parsimonious failure recovery (cont.)

Let $[1,.., n] = W \cup F$ be the available behaviors.

Let $\boldsymbol{R} = \boldsymbol{R}_{W \cup F}$ be the **simulated-by** relation of target by behaviors $W \cup F$.
Then the following hold:

- $\boldsymbol{R}_W \subseteq \pi_W(\boldsymbol{R}_{W \cup F})$
  - $\pi_W(\boldsymbol{R}_{W \cup F})$ is not a simulation in general
  - **Behaviors F die:** compute $\boldsymbol{R}_W$ with $\mathbf{R_{raw}} = \pi_W(\boldsymbol{R}_{W \cup F})$!
- $\boldsymbol{R}_W \times F \subseteq \boldsymbol{R}_{W \cup F}$
  - $\boldsymbol{R}_W \times F$ is a simulation of target by behaviors $W \cup F$
  - **Dead behaviors F** come back: compute $\boldsymbol{R}_{W \cup F}$ with $\mathbf{R_{sure}} = \boldsymbol{R}_W \times F$!

Tools for computing composition based on simulation

- Computing simulation is a well-studied problem (related to bisimulation, a key notion in process algebra).
Tools, like the Edinburgh Concurrency Workbench and its clones, can be adapted to compute composition via simulation.

- Also LTL-based syntesis tools, like TLV, can be used for (indirectly) computing composition via simulation [Patrizi PhD08]

We are currently focussing on the second approach.

Conclusion

- Behavior composition: *an infinite game*.
- Simulation based composition techniques allow for *failure tolerance*!
- It realies on *a controller generator:* kind of stateful universal plan generator for composition.
- *Full observability* of available behavior' states is crucial for CG to work properly. But ...
Partial observability addressable by manipulating knowledge states! [work in progress]
- All techniques are for finite states. What about dealing with infinite states? Very difficult, but also crucial when *mixing processes and data*!