Two-player Game Structures for Service Composition, Synthesis and Generalized Planning

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Solving Composition Problems

- Service Composition problems can be solved using a variety of approaches, e.g.,:
  - PDL-based

    [Berardi,Calvanese,De Giacomo,Lenzerini,Mecella@ICSOC03]
  - Direct simulation computation

    [Ströder,Pagnucco@IJCAI09]
  - LTL synthesis

    [Sardina,DeGiacomo@ICAPS08; P@Phd09]
- 2-GS: powerful framework to capture and solve all above

Two-player Game Structures (2-GS)

- Inspired by game structures for LTL synthesis
  [Piterman,Pnueli,Sa'ar@VMCAI06; Alur,Hentzinger,Kupferman@JACM-02]
- Model the rules of a game (e.g., Chess) between players:
  - Controller (the *good*)
  - Environment (the *bad*)
- With the game at hand, we can:
  - define a problem (e.g., can we checkmate from a starting situation?)
  - (Try to) solve the problem

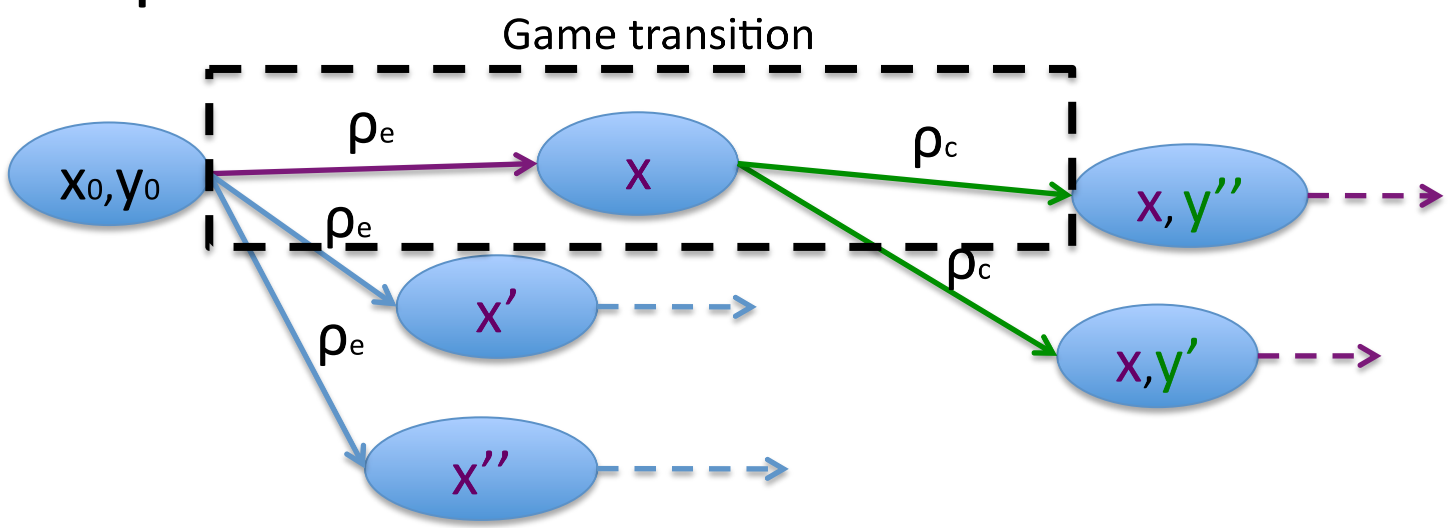
2-GS: Definition

$G = \langle \mathcal{X}, \mathcal{Y}, start, \rho_e, \rho_c \rangle$, where:

- $\mathcal{X}$: set of environment (uncontrolled) variables $x_1, \ldots, x_n$, ranging over $X = X_1 \times \ldots \times X_n$
- $\mathcal{Y}$: set of controller (controlled) variables $y_1, \ldots, y_m$, ranging over $Y = Y_1 \times \ldots \times Y_m$
- $start = \langle x_0, y_0 \rangle \in X \times Y$ is the initial game state
- $\rho_e \subseteq X \times Y \times X$ is the environment transition relation
- $\rho_c \subseteq X \times Y \times X \times Y$ is the controller transition relation

2-GS: Rounds

- Each round consists of an environment move and a controller reply
- Moves and replies must be compliant with ρ_e and ρ_c



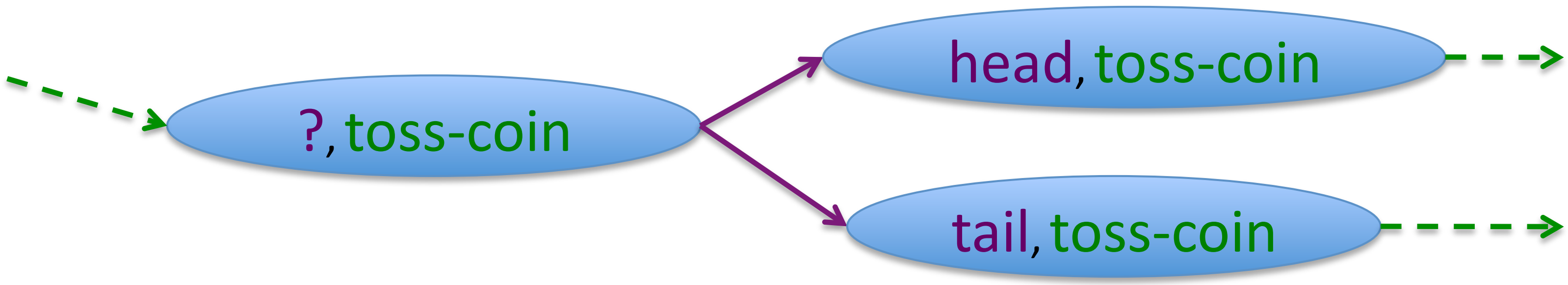
2-GS MC Example: TIC-TAC-TOE

	A	B	C
1			
2			
3			

- $\mathscr{X} = \{x_{A1},\ldots,x_{A3},\ldots,x_{C1}, x_{C3}\}$: propositional
- $\mathscr{Y} = \{y_{A1},\ldots,y_{A3},\ldots,y_{C1}, y_{C3}\}$: propositional
- Start: all variables are initially false
- ρ_e: assign true exactly one $\mathscr{X}$ variable x_{ij} s.t. y_{ij} is false
- ρ_c: assign true exactly one $\mathscr{Y}$ variable y_{ij} s.t. x_{ij} is false

Example(2)

- 2-GSs capture (ND) planning domains:
  - The controller executes an action
  - The environment chooses the outcome



- ρ_c accounts for preconditions
- ρ_e accounts for (ND) effects

Goals for 2GS

- When does a player win G?
- It depends on the goal
- In planning, we have reachability goals, e.g.:
  - checkmate the opponent's king
- In general, we can define complex goals, e.g.:
  - The controller can always reach a state where the coin can be tossed

μ-calculus over 2-GS

- To define goals, we use a variant of the μ-calculus[Emerson96], whose formulae are:
  - *atoms* of the form $x_i = x$ or $y_i = y$
  - $\odot\Psi$ (*next*), if Ψ is a formula
  - μZ.Ψ (*least fixpoint*), if Ψ is a formula
  - νZ.Ψ (*greatest fixpoint*), if Ψ is a formula
  - Boolean combinations of above formulae

μ-calculus over 2-GS (2)

For complete semantics, see [Emerson96]

- Key operator *next*

$\langle x,y\rangle \vDash \odot\Psi$ iff

$\exists x'.\ \rho_e(x,y,x') \wedge$

$\forall x'.\ \rho_e(x,y,x') \longrightarrow \exists y'.\ \rho_c(x,y,x',y')$ s.t. $\langle x',y'\rangle \vDash \Psi$

(Player controller is able to force the game to reach, in one step, a state where Ψ holds, no matter how the environment moves)

Defining Goals

- Given a (μ-calculus) goal formula ϕ, player *controller wins iff* $\langle x_0, y_0 \rangle \models \phi$
- We use particular goal patterns

  $\diamond\phi \doteq \mu Z.\phi \vee \odot Z$ (C. can force the game to eventually reach ϕ)

  $\boxdot\phi \doteq \nu Z.\phi \wedge \odot Z$ (C. can force the game to always satisfy ϕ)

  $\boxdot\diamond\phi$ (C. can force the game to always satisfy $\diamond\phi$)

2-GS Model Checking

- DEF: Given a 2-GS G and a goal formula ϕ,
  $G \models \phi$ iff $\langle x_0, y_0 \rangle \models \phi$
- The MC problem requires to check if, given G and ϕ, $G \models \phi$
- If so, the controller has a *strategy* to enforce ϕ, (no matter how the environment plays)
- Strategy: function of histories
- We are not only interested in the checking problem, but in computing the strategy

2-GS Model Checking (2)

- The computational cost of 2-GS MC is $O((|G| \cdot |\phi|)^k)$, where:
  - $|G|=|S_G|+|\rho_e|+|\rho_c|$
  - k is the number of fixpoint nestings in ϕ

Conditional Planning with 2-GS (2)

Domain: Tossing a coin
Predicates: inHand, head
Actions:

    toss(pre: inHand,
            eff: oneof(head,¬head) and ¬inHand
)
    turn(
            pre: ¬inHand
            eff: (when (head)(¬head) and when (¬head)(head))
)
    nop()

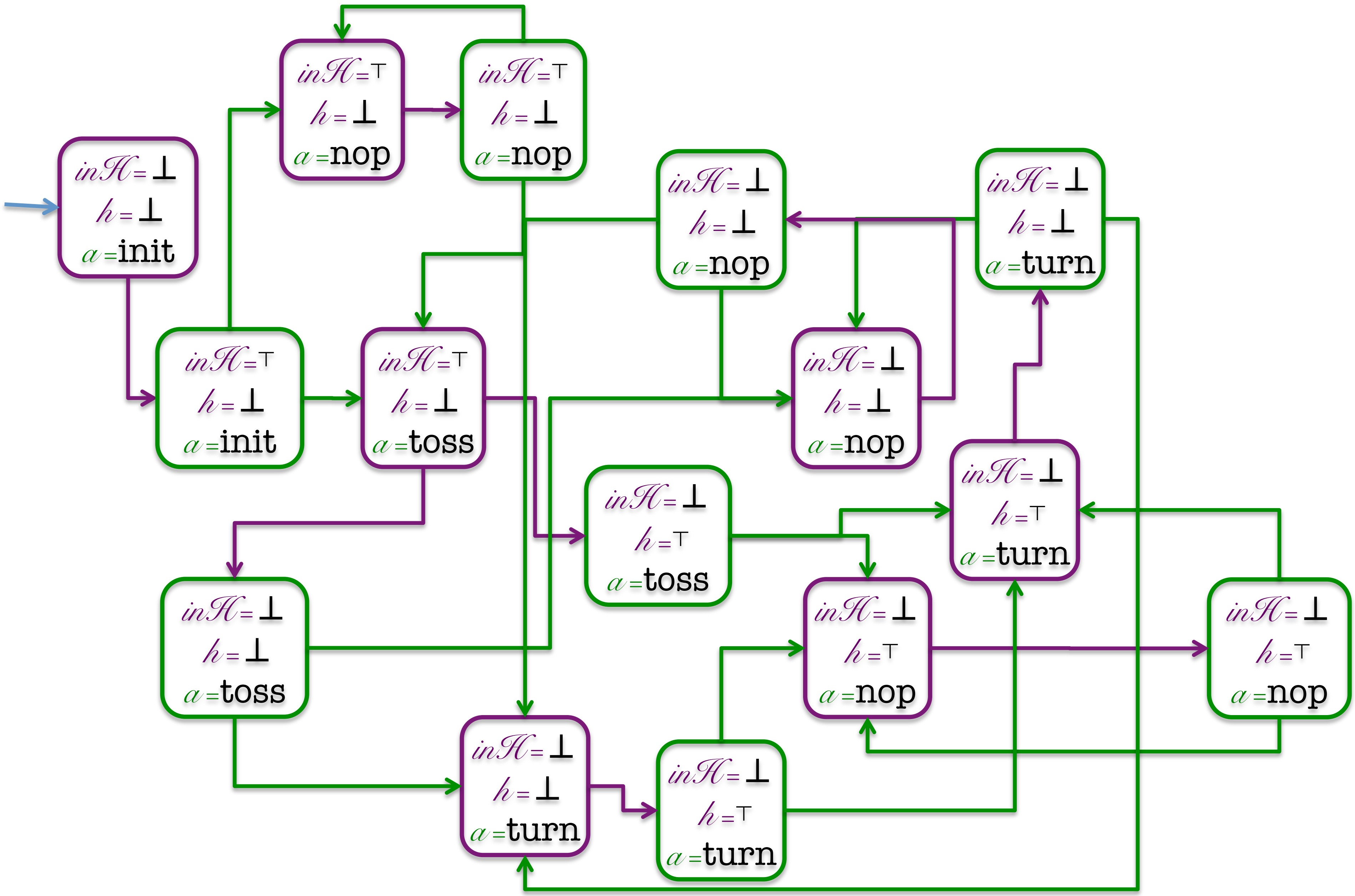
Init: inHand
Goal: head

Coin Tossing as a 2-GS

GS:

- $\mathcal{X} = \{inHand, head\}$: propositional
- $\mathcal{Y} = \{act\}$, over: {toss, turn, nop, init}
- start: $inHand = head = \bot$; $act = \mathrm{init}$
- ρ_e: selects action effects (according to current act)
- ρ_c: chooses next action, among those executable in current state
- Special action init for initialization only

Goal formula: $\Psi = \diamond(head = \top)$



$in\mathcal{H}=\bot$ $h=\bot$ $a=$init
$in\mathcal{H}=\top$ $h=\bot$ $a=$nop
$in\mathcal{H}=\top$ $h=\bot$ $a=$nop
$in\mathcal{H}=\bot$ $h=\bot$ $a=$nop
$in\mathcal{H}=\bot$ $h=\bot$ $a=$turn
$in\mathcal{H}=\top$ $h=\bot$ $a=$init
$in\mathcal{H}=\top$ $h=\bot$ $a=$toss
$in\mathcal{H}=\bot$ $h=\bot$ $a=$nop
$in\mathcal{H}=\bot$ $h=\top$ $a=$toss
$in\mathcal{H}=\bot$ $h=\top$ $a=$turn
$in\mathcal{H}=\bot$ $h=\bot$ $a=$toss
$in\mathcal{H}=\bot$ $h=\top$ $a=$nop
$in\mathcal{H}=\bot$ $h=\top$ $a=$nop
$in\mathcal{H}=\bot$ $h=\bot$ $a=$turn
$in\mathcal{H}=\bot$ $h=\top$ $a=$turn

Solution Approach

- We applied a MC algorithm for μ-calc
- Time cost: $O(|2^P||A|+|\rho|)$
- During the check, we saved additional information to extract a witness, i.e., a strategy for the controller
- A strategy for $\Diamond\!\!\!\cdot\,(head = \top)$ corresponds, in fact, to a conditional plan
- Explicit state manipulation not required: symbolic approaches (e.g., BDD-based) can be used

Solving Multi-Target Composition using 2-GS

- Encoding similar to Planning Programs

- Player Environment features:
  - the execution of target programs
  - (A target program is advanced only after the controller declares its request fulfilled)

- Player Controller:
  - delegates, at each step, an action requested by some target, to some available service able to execute it
  - At some point, based on action outcomes, declares some targets fulfilled
  - (When no more target requests are pending, at least one target must be declared satisfied, so as to get a new request)

Solving Multi-Target Composition using 2-GS (2)

- $\mathcal{X} = \{s_1, \ldots, s_n, t_1, \ldots, t_m\}$
  - s_i: state of available service
  - t_i: requested transition
- $\mathcal{Y} = \{act, ser, full_1, \ldots, full_m\}$
  - act : action to execute
  - ser : delegated service
  - $full_i$: fulfilled?
- start: $act = ser = \text{init}; full_i = \bot$ (all state initial)
- ρ_e: selects action effects, according to current act and ser, and advances the target, according to $full_i$
- ρ_c: chooses next action act , according to t_i, delegates to ser , and, when needed, declares targets' fulfillment, assigning $full_i$
- (Special action init for initialization only)

Goal formula: $\Psi = \Box\Diamond(full_1 = \top) \land \ldots \land \Box\Diamond(full_m = \top)$

Solution

- Still an exponential bound
- Optimal as the problem is EXPTIME-complete

Solving Agent Planning Programs using 2-GS

Domain: TVworld

Predicates: on, broken, mute

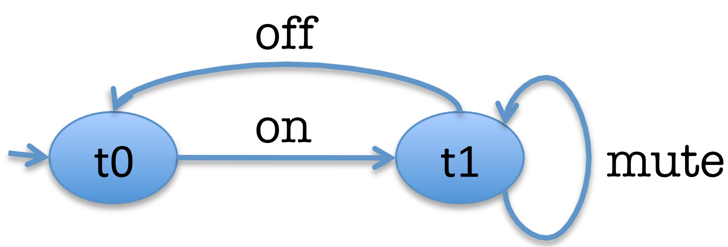
Actions:

muteTV (pre: on
eff: when(mute)(¬mute) ∧ when(¬mute)(mute))

switchOn (pre: off ∧ ¬broken
eff: on)

switchOff (pre: on
eff: off)

throwTV (eff: off ∧ broken)



Init: off ∧ ¬broken ∧ ¬mute

Solving Agent Planning Programs using 2-GS (2)

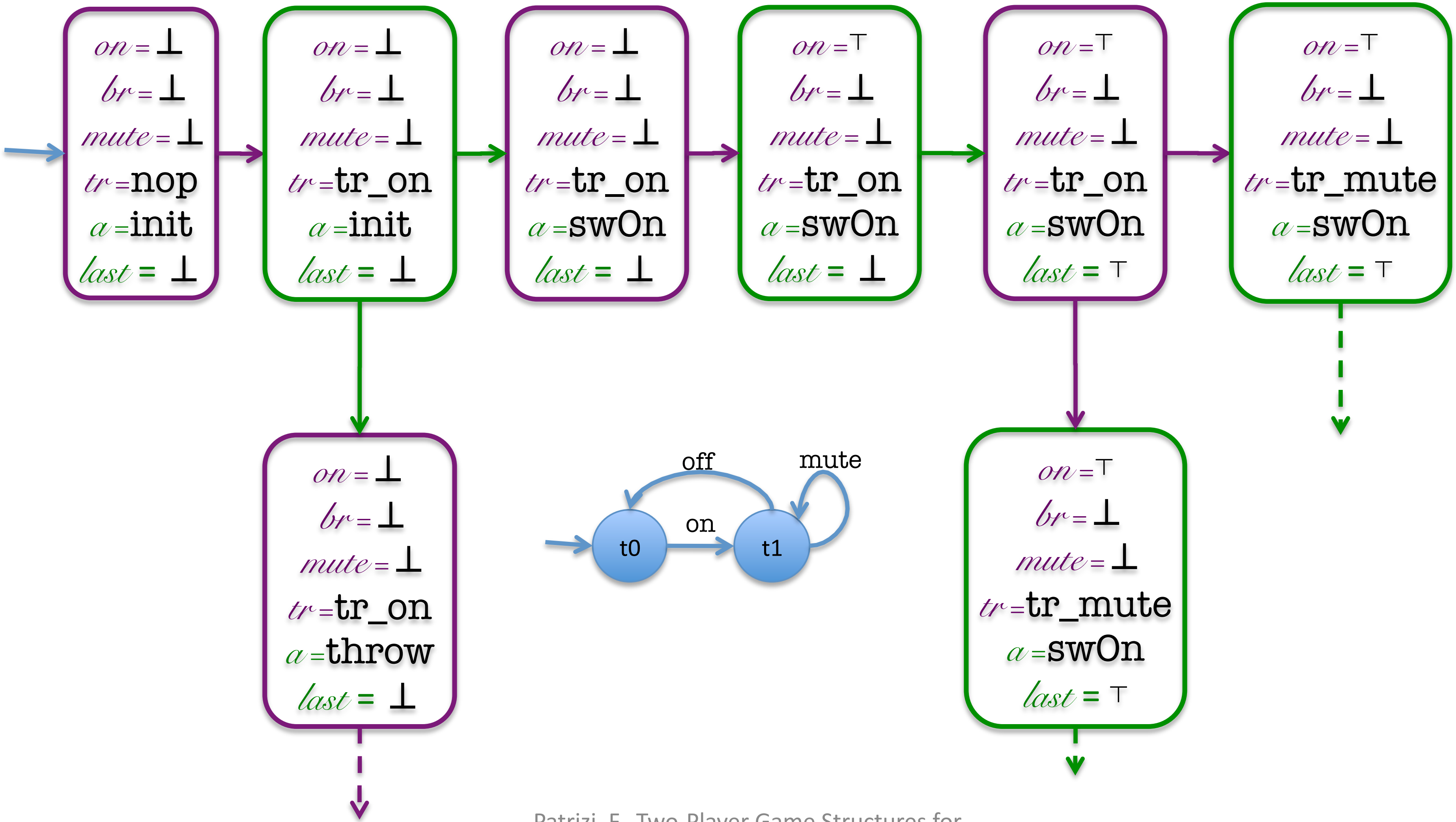
- Player Environment features:
  - the planning domain
  - the target service evolution, i.e., its requests
  - (The target service advances only when its current request is fulfilled)
- Player Controller:
  - selects, at each step, the actions needed to fulfill current request
  - announces current request fulfillment to the environment (which advances the target)

Solving Agent Planning Programs using 2-GS (3)

TV Domain:

- $\mathcal{X}$ = {*on,broken,mute,tr*}
- $\mathcal{Y}$ = {*act,last*}
- In the start state, *last* = $\perp$ (special action init also used)
- ρ_e:
  - according to current *act* changes *on,broken,mute*
  - If *last* = $\top$, changes *tr* according to the target service
- ρ_c:
  - chooses next action, among those executable in current state
  - sets *last* = $\top$ only if current *tr* is actually realized
- Goal formula: $\Psi = \Box\Diamond(last = \top)$

Example



on = ⊥
br = ⊥
mute = ⊥
tr = nop
a = init
last = ⊥
on = ⊥
br = ⊥
mute = ⊥
tr = tr_on
a = init
last = ⊥
on = ⊥
br = ⊥
mute = ⊥
tr = tr_on
a = swOn
last = ⊥
on = ⊤
br = ⊥
mute = ⊥
tr = tr_on
a = swOn
last = ⊥
on = ⊤
br = ⊥
mute = ⊥
tr = tr_on
a = swOn
last = ⊤
on = ⊤
br = ⊥
mute = ⊥
tr = tr_mute
a = swOn
last = ⊤
on = ⊥
br = ⊥
mute = ⊥
tr = tr_on
a = throw
last = ⊥
off
mute
on
t0
t1
on = ⊤
br = ⊥
mute = ⊥
tr = tr_mute
a = swOn
last = ⊤

Observation

- Each target transition is realized by a (conditional) plan
- However, plans *cannot* be computed as usually done in planning
- Realizability of possible future transitions must be guaranteed
- TV cannot be switched off by throwing it because this prevents future requests for `on`

Solution

- Again, we use a MC algorithm (in fact, the same as before) for μ-calc
- (This time, two ***non-nested*** fixpoint computations are needed, for $\diamond$ and $\boxdot$)

- Time cost: $O(|2^P|\cdot(|\rho|+|\delta|))$

- Optimal, as the problem is EXPTIME-complete

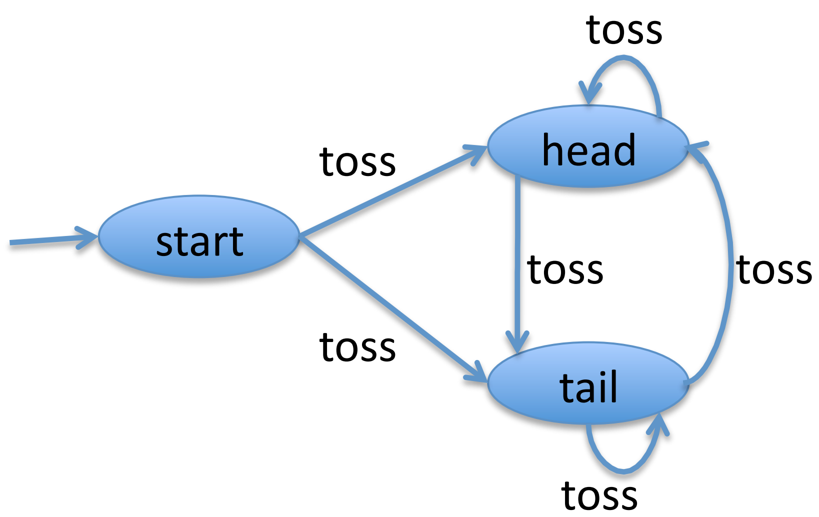
Agent Planning Programs and Services

- How planning programs are related to services?

- Given a set of available services, we *compose* a high-level procedure, instead of a new service

Generalized Planning w/ loops under strong fairness constraints

- 2-GS and the μ-calc are also useful to tackle generalized forms of planning
- Sample ND Domain:



Generalized Planning w/ loops under strong fairness constraints (2)

- Conditional Plan:

  Acyclic plan that reaches a goal , e.g., “head”, no matter how nondeterminism is resolved at runtime

- Strong Cyclic Plan[Cimatti,Pistore,Roveri,Traverso-AI 03]:

  Cyclic plan that reaches a goal, under the assumption that loops iterate only a finite (though unbounded) number of times

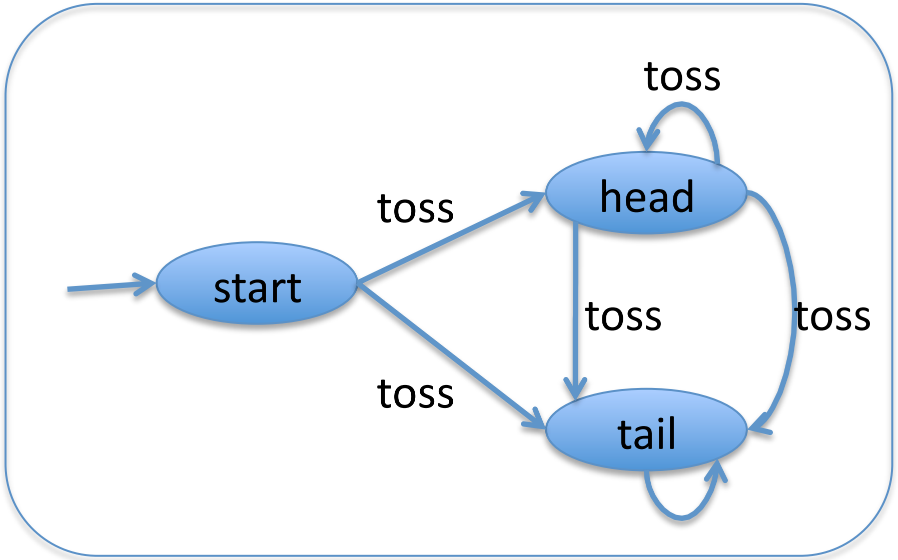
Fairness Constraints

Strong cyclic plans work under a specific *fairness* assumption, required to hold for all loops

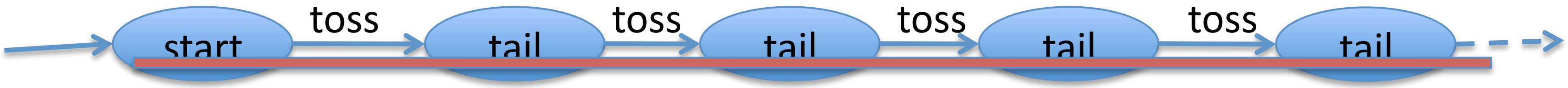
We want to be able to

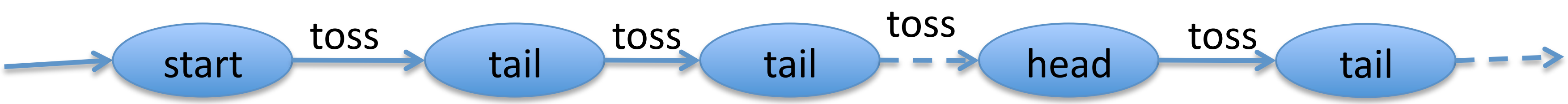
1. Asserting explicitly general fairness constraints on domain evolutions
2. Finding plans that work under such constraints

Fairness Constraints (2)



$\Box\Diamond(act=toss)\longrightarrow\Box\Diamond(head)$





Generalized Planning w/ loops under strong fairness constraints (3)

- Can be reduced to MC a 2GS (not done, yet)
- (Currently: reduction to LTL synthesis problem [DeGiacomo,P,Sardina@KR10])
- The problem is EXPTIME-complete

Conclusion

- “Local’’ MC techniques can be useful for optimization?