Strategy Synthesis for Multi-dimensional Quantitative Objectives

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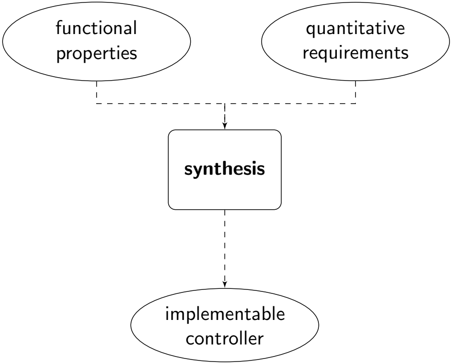
Workshop on Quantitative and Game Models for the Synthesis of Reactive Systems

Aim of this work



$\rightsquigarrow$ restriction to finite-memory strategies.

Aim of this work

- Study games with
  - ▷ multi-dimensional quantitative objectives (energy and mean-payoff)
  - ▷ *and* a parity objective.

$\rightsquigarrow$ First study of such a conjunction.

- Address questions that revolve around *strategies*:
  - ▷ bounds on memory,
  - ▷ synthesis algorithm (cf. Acacia+),
  - ▷ randomness $\overset{?}{\sim}$ memory.

Results Overview

- Memory bounds

MEPGs	MMPPGs	
optimal	finite-memory optimal	optimal
exp.	**exp.**	infinite [CDHR10]

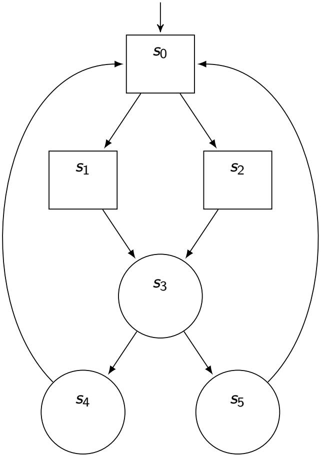
- Strategy synthesis (finite memory)

MEPGs	MMPPGs
EXPTIME	**EXPTIME**

- Randomness as a substitute for finite memory

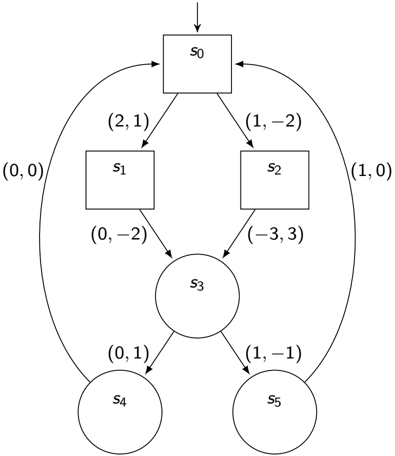
	MEGs	EPGs	MMP(P)Gs	MPPGs
one-player	$\times$	$\times$	$\surd$	$\surd$
two-player	$\times$	$\times$	$\times$	$\surd$

Turn-based games



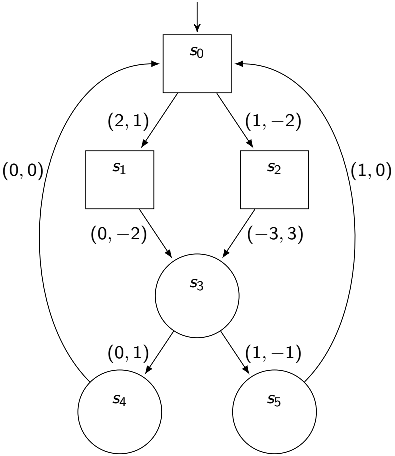
- $G = (S_1, S_2, s_{init}, E)$
- $S = S_1 \cup S_2, S_1 \cap S_2 = \emptyset, E \subseteq S \times S$
- $\mathcal{P}_1$ states = ◯
- $\mathcal{P}_2$ states = □
- Plays, prefixes, **pure** strategies.

Integer k-dim. payoff function



- $G = (S_1, S_2, s_{init}, E, \underline{w})$
- $w : E \to \mathbb{Z}^k$
- *Energy level*
  $\mathrm{EL}(\rho) = \sum_{i=0}^{i=n-1} w(s_i, s_{i+1})$
- *Mean-payoff*
  $\mathrm{MP}(\pi) = \liminf_{n\to\infty} \frac{1}{n}\mathrm{EL}(\pi(n))$

Energy and mean-payoff problems

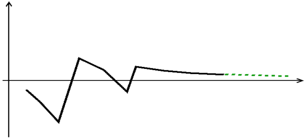


- **Unknown initial credit**

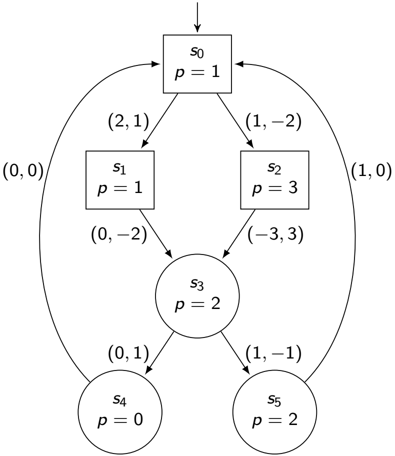
  $\exists?\, v_0 \in \mathbb{N}^k, \lambda_1 \in \Lambda_1$ s.t.

- **Mean-payoff threshold**

  Given $v \in \mathbb{Q}^k$, $\exists?\, \lambda_1 \in \Lambda_1$ s.t.



Parity problem



- $G_p = \left(S_1, S_2, s_{init}, E, w, \underline{p}\right)$
- $p : S \to \mathbb{N}$
- $\mathrm{Par}(\pi) = \min \{p(s) \mid s \in \mathrm{Inf}(\pi)\}$
- **Even parity**

  $\exists?\, \lambda_1 \in \Lambda_1$ s.t. the parity is even

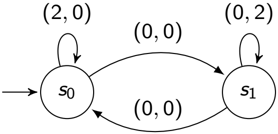
▷ canonical way to express ω-regular objectives

Known results

		Memory ($\mathcal{P}_1$)	Decision problem
Energy	1-dim [CdAHS03, BFL+08]	memoryless	NP ∩ coNP
	k-dim [CDHR10]	finite	coNP-c
	1-dim + parity [CD10]	exponential	NP ∩ coNP
Mean-payoff	1-dim [EM79, LL69]	memoryless	NP ∩ coNP
	k-dim [CDHR10]	infinite	coNP-c (fin.)
	1-dim + parity [CHJ05, BMOU11]	infinite	NP ∩ coNP

Infinite memory?

Example for MMPGs, even with only one player! [CDHR10]



- ▷ To obtain $\mathrm{MP}(\pi) = (1, 1)$, $\mathcal{P}_1$ has to visit s_0 and s_1 for longer and longer intervals before jumping from one to the other.
- ▷ Any finite-memory strategy involving these edges induces an ultimately periodic play s.t. $\mathrm{MP}(\pi) = (x, y)$, $x + y < 2$.

Restriction to finite memory

- Infinite memory:
  - ▷ needed for MMPGs & MPPGs,
  - ▷ practical implementation is unrealistic.

Restriction to finite memory

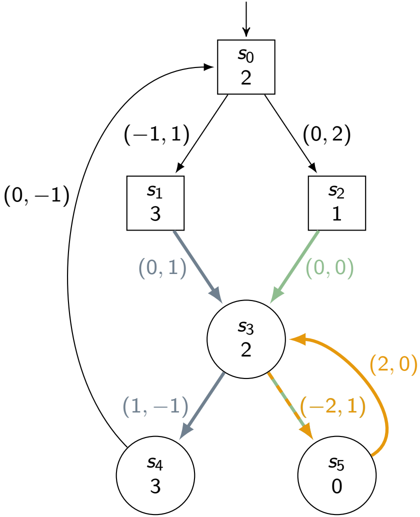
- Infinite memory:
  - ▷ needed for MMPGs & MPPGs,
  - ▷ practical implementation is unrealistic.
- Finite memory:
  - ▷ preserves game determinacy,
  - ▷ provides equivalence between energy and mean-payoff settings,
  - ▷ the way to go for strategy synthesis.

Obtained results

MEPGs	MMPPGs	
optimal	finite-memory optimal	optimal
exp.	**exp.**	infinite [CDHR10]

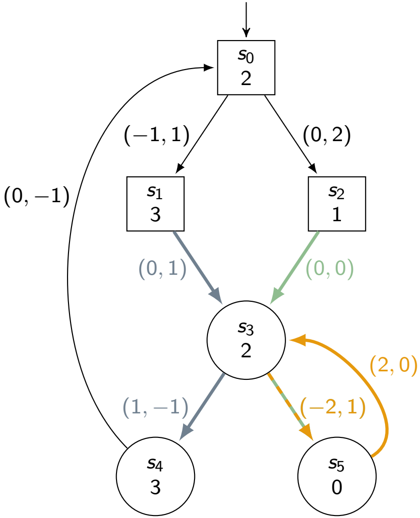
By [CDHR10], we only have to consider MEPGs. Recall that the unknown initial credit decision problem for MEGs (without parity) is coNP-complete.

Upper memory bound: even-parity SCTs



- A winning strategy λ_1 for initial credit $v_0 = (2, 0)$ is
  - $\lambda_1(*s_1 s_3) = s_4$,
  - $\lambda_1(*s_2 s_3) = s_5$,
  - $\lambda_1(*s_5 s_3) = s_5$.

Upper memory bound: even-parity SCTs



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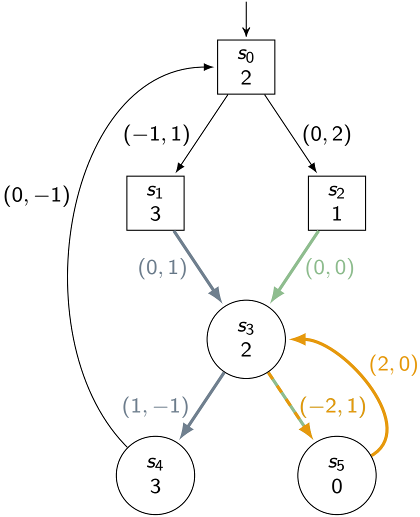
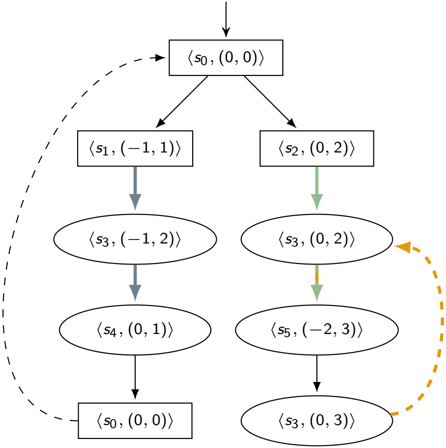
  - $\lambda_1(*s_2 s_3) = s_5$,
  - $\lambda_1(*s_5 s_3) = s_5$.
- Lemma: To win, $\mathcal{P}_1$ must be able to enforce positive cycles of even parity.
  - Self-covering paths on VASS [Rac78, RY86].
  - *Self-covering trees (SCTs)* on reachability games over VASS [BJK10].

Upper memory bound: even-parity SCTs



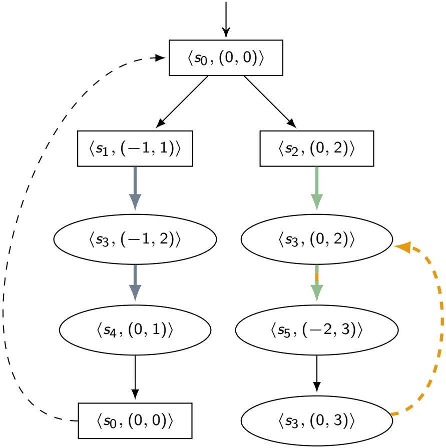


Pebble moves $\Rightarrow$ strategy.

Upper memory bound: even-parity SCTs

$T = (Q, R)$ is an epSCT for s_0, $\Theta : Q \mapsto S \times \mathbb{Z}^k$ is a labeling function.

- Root labeled $\langle s_0, (0, \ldots, 0) \rangle$.
- Non-leaf nodes have
  - ▷ unique child if $\mathcal{P}_1$,
  - ▷ all possible children if $\mathcal{P}_2$.
- Leafs have *even-descendance energy ancestors*: ancestors with lower label and minimal priority even on the downward path.



Pebble moves $\Rightarrow$ strategy.

Upper memory bound: SCTs for VASS games

$\mathcal{P}_1$ wins $\Rightarrow \exists$ SCT of depth at most exponential [BJK10].

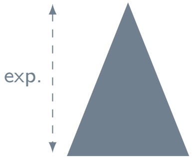
$\rightsquigarrow$ If there exists a winning strategy, there exists a "compact" one.

$\rightsquigarrow$ Idea is to eliminate unnecessary cycles.

Limits:

- ▷ weights in $\{-1, 0, 1\}$,
- ▷ no parity,
- ▷ depth only.

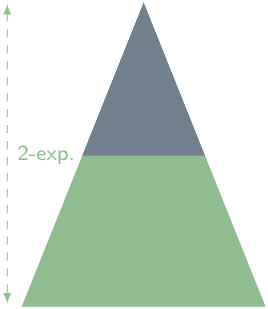
Upper memory bound: SCTs for MEGs (no parity)



$$w : E \to \{-1, 0, 1\}^k$$
$$l = 2^{(d-1)\cdot|S|} \cdot (|S| + 1)^{c\cdot k^2}$$

Depth bound from [BJK10].

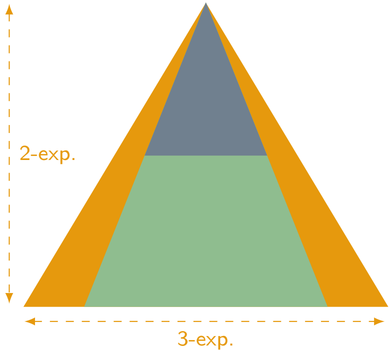
Upper memory bound: SCTs for MEGs (no parity)



$$w : E \to \{-1, 0, 1\}^k$$
$$l = 2^{(d-1)\cdot|S|} \cdot (|S| + 1)^{c\cdot k^2}$$
$$\Downarrow$$
$w : E \to \mathbb{Z}^k$, W max absolute weight,
V bits to encode W
$$l = 2^{(d-1)\cdot W \cdot|S|} \cdot (W \cdot |S| + 1)^{c\cdot k^2}$$
$$= 2^{(d-1)\cdot 2^V \cdot|S|} \cdot (W \cdot |S| + 1)^{c\cdot k^2}$$

Naive approach: blow-up by W in the size of the state space.

Upper memory bound: SCTs for MEGs (no parity)



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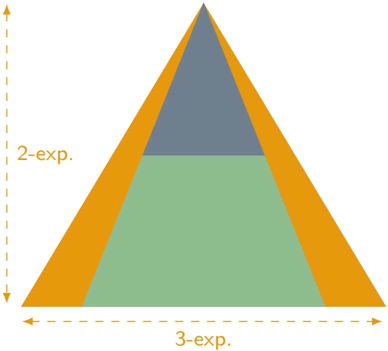
$$\Downarrow$$
Width bounded by $L = d^l$

Naive approach: width increases exponentially with depth.

Upper memory bound: SCTs for MEGs (no parity)



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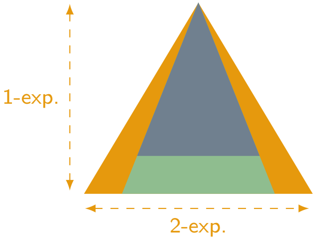
$$= 2^{(d-1)\cdot 2^V\cdot|S|} \cdot (W \cdot |S| + 1)^{c\cdot k^2}$$
$$\Downarrow$$
Width bounded by $L = d^l$

Naive approach: overall, 3-exp. memory $\leq L \cdot l$, without parity.

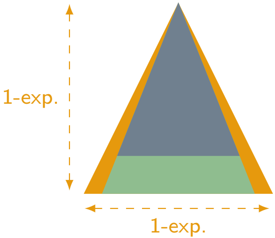
Upper memory bound: epSCTs for MEPGs



$$w : E \to \{-1, 0, 1\}^k$$
$$l = 2^{(d-1)\cdot|S|} \cdot (|S| + 1)^{c\cdot k^2}$$
$$\Downarrow$$
$w : E \to \mathbb{Z}^k$, W max absolute weight,
$$l = 2^{(d-1)\cdot|S|} \cdot (W \cdot |S| + 1)^{c\cdot k^2}$$
$$\Downarrow$$
Width bounded by $L = d^l$

Refined approach: no blow-up in exponent as branching is preserved, extension to parity.

Upper memory bound: epSCTs for MEPGs



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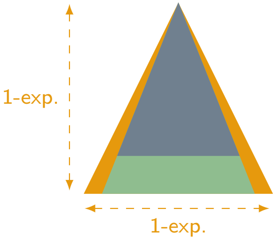
$$\Downarrow$$
Width bounded by $L = |S| \cdot (2 \cdot l \cdot W + 1)^k$

Refined approach: merge equivalent nodes, width is bounded by number of incomparable labels (see next slide).

Upper memory bound: epSCTs for MEPGs



$$w : E \to \{-1, 0, 1\}^k$$
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$w : E \to \mathbb{Z}^k$, W max absolute weight,
$$l = 2^{(d-1)\cdot|S|} \cdot (W \cdot |S| + 1)^{c\cdot k^2}$$

$$\Downarrow$$
Width bounded by $L = |S| \cdot (2 \cdot l \cdot W + 1)^k$

Refined approach: overall, **single exp. memory** $\leq L \cdot l$, for multi energy *along with* parity. Initial credit bounded by $l \cdot W$.

Upper memory bound: from MEPGs to MEGs

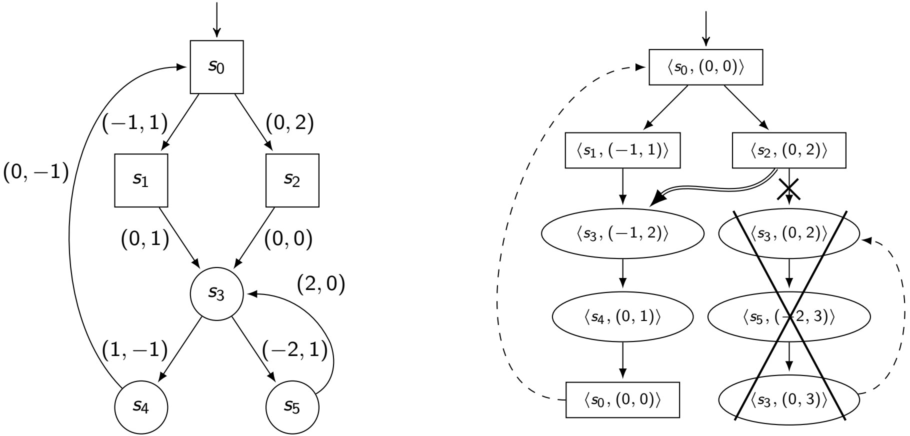
- Bound on depth.

  $\Rightarrow$ Bound on steps before seeing an even minimal priority.

  $\Rightarrow$ Encoding of parity as additional energy dimensions.

Upper memory bound: merging nodes in SCTs

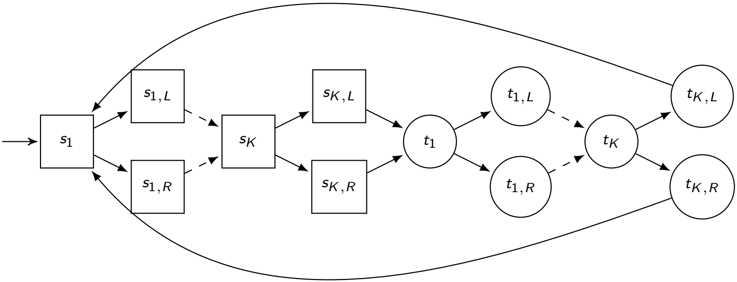
- Key idea to reduce width to single exp.
  - $\mathcal{P}_1$ only cares about the energy level.
  - If he can win with energy v, he can win with energy $\geq v$.



Lower memory bound

Lemma: *There exists a family of multi energy games* $(G(K))_{K \geq 1,} = (S_1, S_2, s_{init}, E, k = 2 \cdot K, w : E \rightarrow \{-1, 0, 1\})$ *s.t. for any initial credit,* $\mathcal{P}_1$ *needs exponential memory to win.*

Lower memory bound

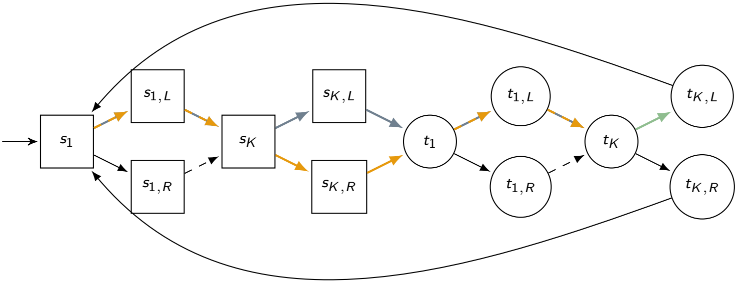


$$\forall\, 1 \leq i \leq K, w((\circ, s_i)) = w((\circ, t_i)) = (0, \ldots, 0),$$

$$w((s_i, s_{i,L})) = -w((s_i, s_{i,R})) = w((t_i, t_{i,L})) = -w((t_i, t_{i,R})),$$

$$\forall\, 1 \leq j \leq k,\ w((s_i, s_{i,L}))(j) = \begin{cases} = 1 \text{ if } j = 2 \cdot i - 1 \\ = -1 \text{ if } j = 2 \cdot i \\ = 0 \text{ otherwise} \end{cases}.$$

Lower memory bound



If $\mathcal{P}_1$ plays according to a Moore machine with less than 2^K states, he takes the same decision in some state t_x for the two highlighted prefixes (let $x = K$ w.l.o.g.).

$\Rightarrow \mathcal{P}_2$ can force a decrease by 1 on some dimension every visit.

$\Rightarrow \mathcal{P}_1$ loses for any $v_0 \in \mathbb{N}^k$.

Symbolic synthesis algorithm

Algorithm CpreFP for MEPGs and MMPPGs:

- symbolic (antichains) and incremental,
- winning strategy of at most exponential size,
- worst-case exponential time.

Symbolic synthesis algorithm

Algorithm CpreFP for MEPGs and MMPPGs:

- ▷ symbolic (antichains) and incremental,
- ▷ winning strategy of at most exponential size,
- ▷ worst-case exponential time.

Idea: greatest fixed point of a $\mathsf{Cpre}_{\mathbb{C}}$ operator.

- ▷ $\mathbb{C}$: incremental, ensures convergence.
- ▷ Exponential bound on the size of manipulated sets ($\sim$ width).
- ▷ Exponential bound on the number of iterations if a winning strategy exists ($\sim$ depth).

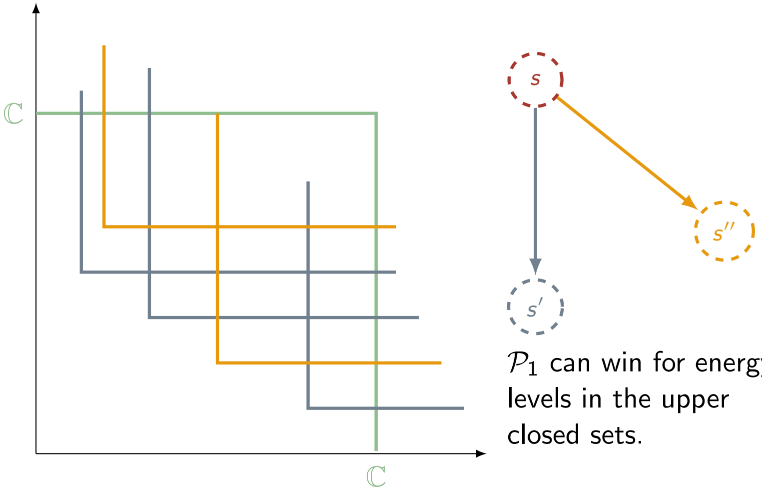
Symbolic synthesis algorithm: Cpre

- $\mathbb{C} = 2 \cdot l \cdot W \in \mathbb{N}$, $U(\mathbb{C}) = (S_1 \cup S_2) \times \{0, 1, \ldots, \mathbb{C}\}^k$,
- $\mathcal{U}(\mathbb{C}) = 2^{U(\mathbb{C})}$, the powerset of $U(\mathbb{C})$,
- $\mathsf{Cpre}_{\mathbb{C}} : \mathcal{U}(\mathbb{C}) \rightarrow \mathcal{U}(\mathbb{C})$, $\mathsf{Cpre}_{\mathbb{C}}(V) =$

$$\{(s_1, e_1) \in U(\mathbb{C}) \mid s_1 \in S_1 \wedge \exists (s_1, s) \in E, \exists (s, e_2) \in V : e_2 \leq e_1 + w(s_1, s)\}$$
$$\cup$$
$$\{(s_2, e_2) \in U(\mathbb{C}) \mid s_2 \in S_2 \wedge \forall (s_2, s) \in E, \exists (s, e_1) \in V : e_1 \leq e_2 + w(s_2, s)\}$$

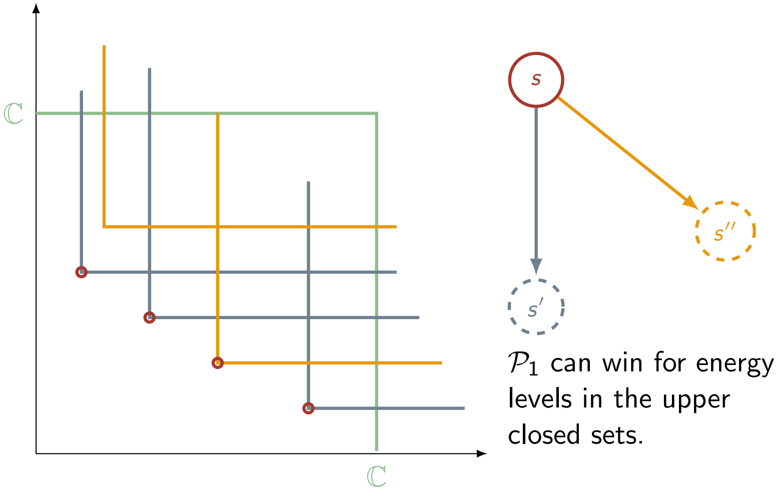
▷ Intuitively, compute for each state the set of winning initial credits, represented by the minimal elements of these upper closed sets.

Symbolic synthesis algorithm: Cpre



$\mathcal{P}_1$ can win for energy levels in the upper closed sets.

Symbolic synthesis algorithm: Cpre



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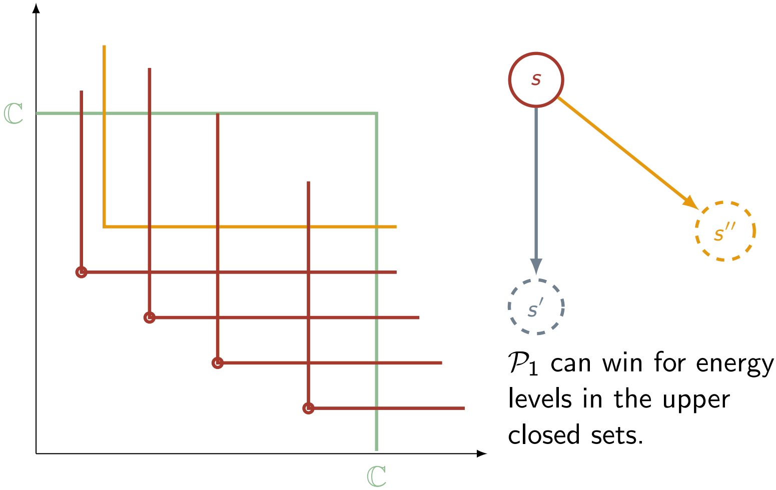

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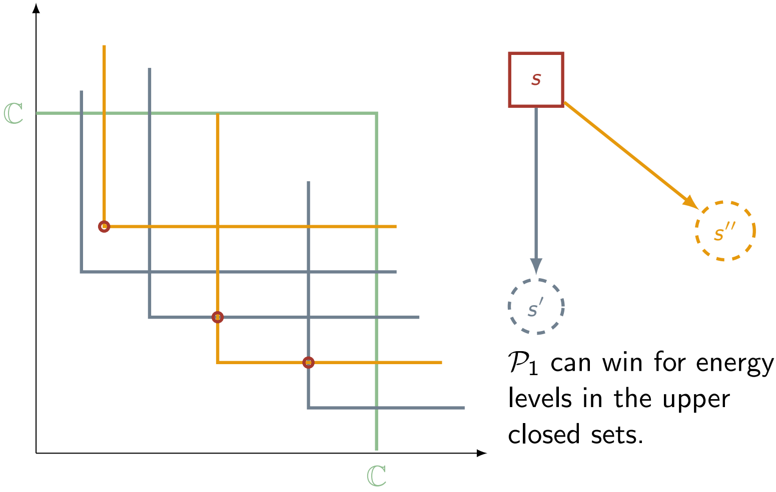

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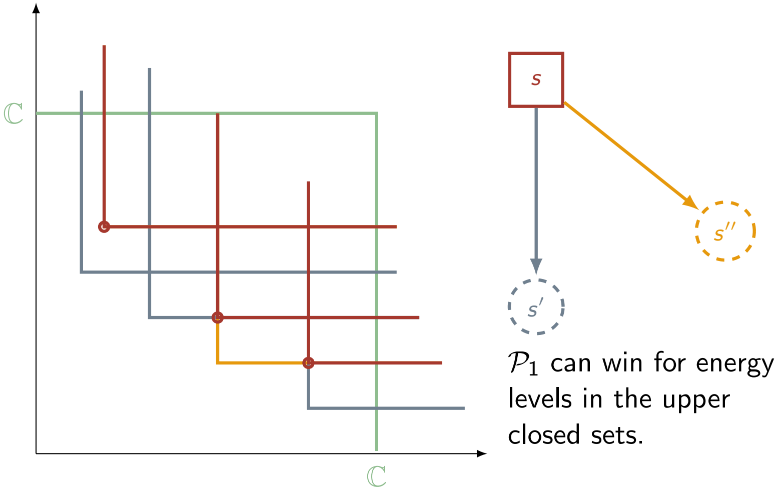
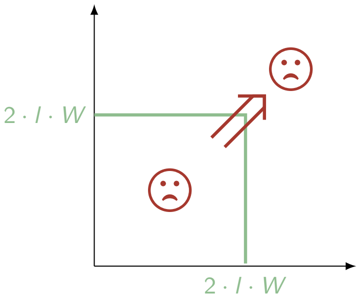


$\mathcal{P}_1$ can win for energy levels in the upper closed sets.

Symbolic synthesis algorithm: CpreFP

- **Correctness**
  - ▷ $(s_{init}, (c_1, \ldots, c_k)) \in \mathrm{Cpre}^*_{\mathbb{C}} \rightsquigarrow$ winning strategy for initial credit $(c_1, \ldots, c_k)$.

- **Completeness**
  - ▷ Winning strategy and SCT of depth $l \rightsquigarrow (s_{init}, (\mathbb{C}, \ldots, \mathbb{C})) \in \mathrm{Cpre}^*_{\mathbb{C}}$ for $\mathbb{C} = 2 \cdot l \cdot W$ (cf. max init. credit).



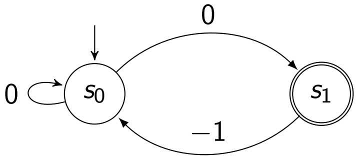
Question

When and how can $\mathcal{P}_1$ trade his pure finite-memory strategy for an equally powerful randomized memoryless one ?

- Sure semantics $\rightsquigarrow$ almost-sure semantics (i.e., probability 1).
- Illustration on **single mean-payoff Büchi games**.

Mean-payoff Büchi games

Remark. MPBGs require infinite memory for optimality.



▷ $\mathcal{P}_1$ has to delay his visits of s_1 for longer and longer intervals.

Mean-payoff Büchi games

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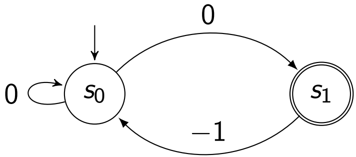
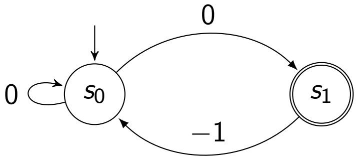


▷ $\mathcal{P}_1$ has to delay his visits of s_1 for longer and longer intervals.

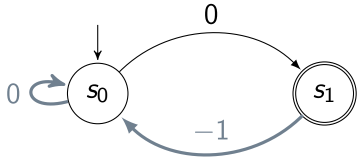
Lemma: *In MPBGs, ε-optimality can be achieved surely by pure finite-memory strategies and almost-surely by randomized memoryless strategies.*

MPBGs: key idea



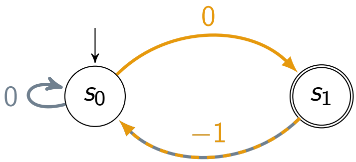
1. Uniform memoryless strategies:

MPBGs: key idea



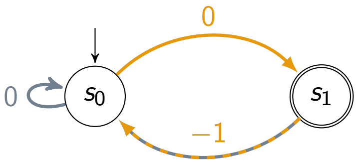
1. Uniform memoryless strategies:
   - λ_1^{gfe} ensures any cycle c has $\mathsf{EL}(c) \geq 0$ [CD10],

MPBGs: key idea



1. Uniform memoryless strategies:
   - λ_1^{gfe} ensures any cycle c has $\mathsf{EL}(c) \geq 0$ [CD10],
   - $\lambda_1^{\Diamond F}$ ensures reaching F in at most n steps (attractor).

MPBGs: key idea



1. Uniform memoryless strategies:
   - λ_1^{gfe} ensures any cycle c has $\mathsf{EL}(c) \geq 0$ [CD10],
   - $\lambda_1^{\Diamond F}$ ensures reaching F in at most n steps (attractor).
2. Alternate using *pure memory* or *probability distributions*.
   - ▷ Frequency of $\lambda_1^{gfe} \to 1 \Rightarrow \mathsf{MP} \to \mathsf{MP}^*$.

Obtained results

	MEGs	EPGs	MMP(P)Gs	MPPGs
one-player	$\times$	$\times$	$\surd$	$\surd$
two-player	$\times$	$\times$	$\times$	$\surd$

Conclusion

- Quantitative objectives
- Parity
- Restriction to finite memory (practical interest)
- Exponential memory bounds
- EXPTIME symbolic and incremental synthesis
- Randomness instead of memory

Results Overview

- Memory bounds

MEPGs	MMPPGs	
optimal	finite-memory optimal	optimal
exp.	**exp.**	infinite [CDHR10]

- Strategy synthesis (finite memory)

MEPGs	MMPPGs
EXPTIME	**EXPTIME**

- Randomness as a substitute for finite memory

	MEGs	EPGs	MMP(P)Gs	MPPGs
one-player	$\times$	$\times$	$\surd$	$\surd$
two-player	$\times$	$\times$	$\times$	$\surd$

Thanks. Questions ?

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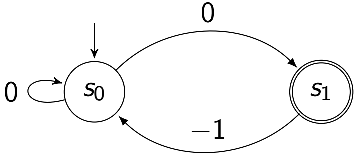
Upper memory bound: from MEPGs to MEGs

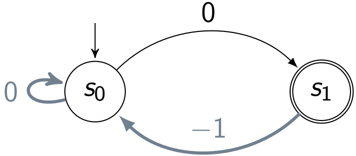
- Thanks to the bound on depth for MEPGs, encode parity ($2 \cdot m$ priorities) as m additional energy dimensions.
  - ▷ For each odd priority, add one dimension.
  - ▷ Decrease by 1 when this odd priority is visited.
  - ▷ Increase by l each time a smaller even priority is visited.
- $\mathcal{P}_1$ maintains the energy positive on all additional dimensions iff he wins the original parity objective.

MPBGs: sketch of proof



1. Let $G = (S_1, S_2, s_{init}, E, w, F)$, with F the set of Büchi states. Let $n = |S|$. Let Win be the set of winning states for the MPB objective with threshold 0 (w.l.o.g.). For all $s \in$ Win, $\mathcal{P}_1$ has two uniform memoryless strategies λ_1^{gfe} and $\lambda_1^{\Diamond F}$ s.t.

MPBGs: sketch of proof



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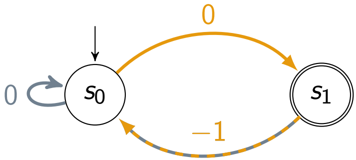
MPBGs: sketch of proof



1. Let $G = (S_1, S_2, s_{init}, E, w, F)$, with F the set of Büchi states. Let $n = |S|$. Let Win be the set of winning states for the MPB objective with threshold 0 (w.l.o.g.). For all $s \in \text{Win}$, $\mathcal{P}_1$ has two uniform memoryless strategies λ_1^{gfe} and $\lambda_1^{\Diamond F}$ s.t.
   - λ_1^{gfe} ensures that any cycle c of its outcome has $\text{EL}(c) \geq 0$ [CD10],
   - $\lambda_1^{\Diamond F}$ ensures reaching F in at most n steps, while staying in Win.

MPBGs: sketch of proof

2. For $\varepsilon > 0$, we build a pure finite-memory λ_1^{pf} s.t.
   (a) it plays λ_1^{gfe} for $\frac{2 \cdot W \cdot n}{\varepsilon} - n$ steps, then
   (b) it plays $\lambda_1^{\Diamond F}$ for n steps, then again (a).

MPBGs: sketch of proof

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   This ensures that

   - F is visited infinitely often,
   - the total cost of phases (a) + (b) is bounded by $-2 \cdot W \cdot n$, and thus the mean-payoff is at least $-\varepsilon$.

MPBGs: sketch of proof

3. Based on λ_1^{gfe} and $\lambda_1^{\Diamond F}$, we obtain almost-surely ε-optimal *randomized memoryless* strategies, i.e.,

$$\forall\, \varepsilon > 0,\ \exists\, \lambda_1^{rm} \in \Lambda_1^{RM},\ \forall\, \lambda_2 \in \Lambda_2,$$
$$\mathbb{P}_{s_{init}}^{\lambda_1^{rm},\lambda_2}(\mathsf{Par}(\pi) \bmod 2 = 0) = 1 \ \wedge\ \mathbb{P}_{s_{init}}^{\lambda_1^{rm},\lambda_2}(\mathsf{MP}(\pi) \geq -\varepsilon) = 1.$$

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Strategy:

$$\forall s \in S,\ \lambda_1^{rm}(s) = \begin{cases} \lambda_1^{gfe}(s) \text{ with probability } 1-\gamma, \\ \lambda_1^{\Diamond F}(s) \text{ with probability } \gamma, \end{cases}$$

for some *well-chosen* $\gamma \in]0,1[$.

MPBGs: sketch of proof

Büchi

- Probability of playing as $\lambda_1^{\Diamond F}$ for n steps in a row and ensuring visit of F strictly positive at all times.
- Thus λ_1^{rm} almost-sure winning for the Büchi objective.

MPBGs: sketch of proof

Mean-payoff

- Consider
  - all end components
  - in all MCs induced by pure memoryless strategies of $\mathcal{P}_2$.
- Choose γ so that all ECs have expectation $> -\varepsilon$.
- Put more probability on lengthy sequences of *gfe* edges.