Parity-energy ATL for Qualitative and Quantitative Reasoning in MAS

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FMLAMAS 2018
Stockholm, July 10, 2018

Outline

1. Introduction and motivations
2. The logic pe-ATL
   - pe-ATL at work
3. Model checking pe-ATL
   - Warming up: Parity and energy conditions in isolation
   - Unbounded $[-\infty, +\infty]$ and bounded $[a, b]$ energy range
   - Left-bounded $[a, +\infty]$ and right-bounded $[-\infty, b]$ energy range
4. Conclusions

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- Intelligent (take decisions, moves)
- Independent
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Logical Formalisms

Coalition Logic (CL) and Alternating-time Temporal Logic (ATL)

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Logical Formalisms

Coalition Logic (CL) and Alternating-time Temporal Logic (ATL)

Theorem (Goranko, TARK 2001)

CL can be embedded into ATL

ATL: syntax and models

- **Syntax.** Formulae of ATL are given by the grammar:

$$\varphi ::= p \mid \neg\varphi \mid \varphi \wedge \varphi \mid \langle\langle A \rangle\rangle \bigcirc \varphi \mid \langle\langle A \rangle\rangle \Box \varphi \mid \langle\langle A \rangle\rangle \varphi \mathcal{U} \varphi$$

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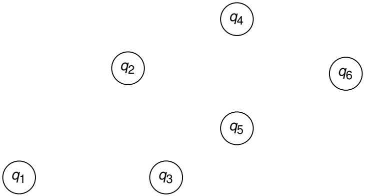

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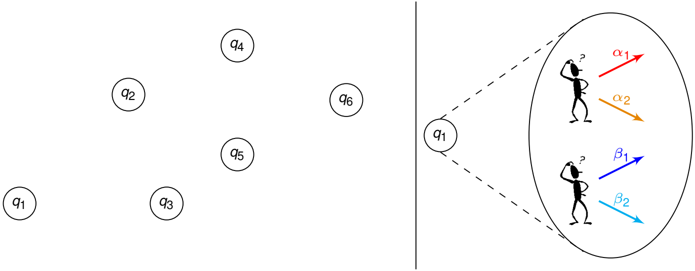

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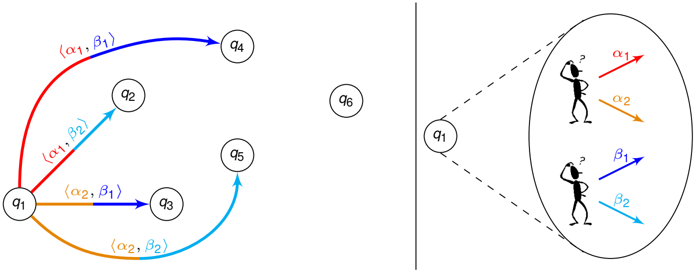

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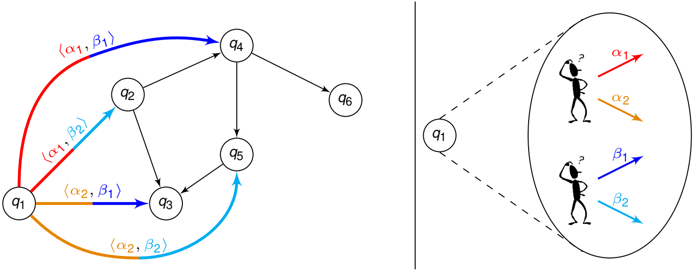

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ATL: (intuitive) semantics

Collective strategy for the proponent team to guarantee φ holds

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Motivations

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Sample scenario:

- printing system: n printers + shared bounded printing queue
- $n + m$ agents (n printers + m users/environment)
- printer actions: { **n** (*do-nothing*), **p** (*print*) }
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pe-ATL abilities

- avoid errors (i printers do *print* and queue only contains $j < i$ jobs)
  (safety $\mapsto$ coalition+temporal)
- queue is emptied infinitely often (Büchi $\mapsto$ parity)
- users send infinitely many jobs $\Rightarrow$ queue is filled up infinitely often
  (fairness $\mapsto$ parity)
- devices' turnover (alternation $\mapsto$ energy)

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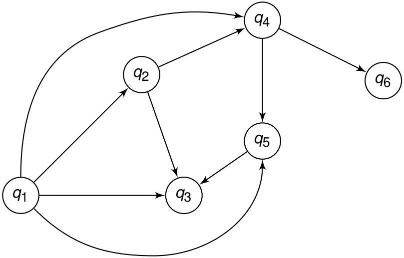
- **Models.** pe-CGS = CGS + parity + energy conditions



G

- **vertices** labeled by **atomic propositions**
- in vertices agents choose **actions**
- possible combinations $\rightarrow$ **transitions** (edges of the graph)
- parity condition
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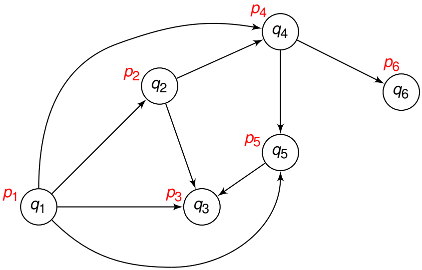

$\langle G, p \quad \rangle$

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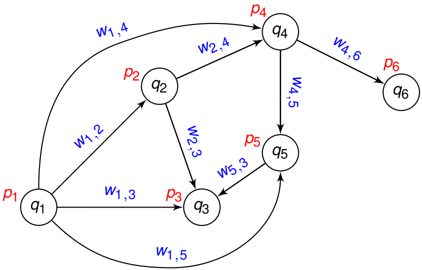

$\langle G, p, e \rangle$

- initial energy level $\mathcal{E}_0$
- energy range $[a, b]$

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Collective (p, e)-strategy for the proponent team to guarantee φ holds

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strategies must be (p, e)-strategies, i.e.,
they only produce plays satisfying parity and energy conditions

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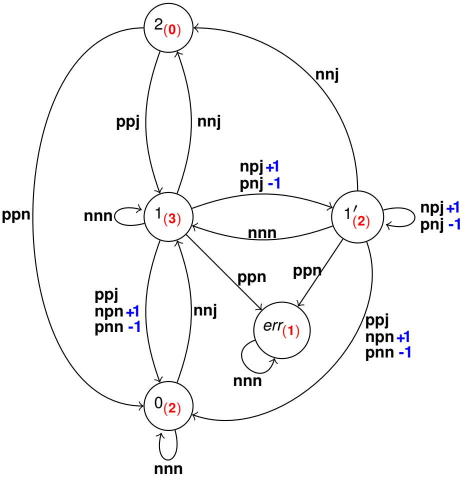
The printing system scenario



agents $= \{p_1, p_2, u\}$

actions

	p_1	p_2	u	*joint actions*
0	**n**	**n**	**nj**	$\{$**nnn**, **nnj**$\}$
1	**np**	**np**	**nj**	$\{$**nnn**, **nnj**, **npn**, **npj**, **pnn**, **pnj**, **ppn**, **ppj**$\}$
$1'$	**np**	**np**	**nj**	$\{$**nnn**, **nnj**, **npn**, **npj**, **pnn**, **pnj**, **ppn**, **ppj**$\}$
2	**p**	**p**	**nj**	$\{$**ppn**, **ppj**$\}$
err	**n**	**n**	**n**	$\{$**nnn**$\}$

energy weights

$$w(\mathbf{nn}x) = w(\mathbf{pp}x) = 0$$
$$w(\mathbf{np}x) = +1$$
$$w(\mathbf{pn}x) = -1$$

energy range = [0,1]

initial energy level $\mathcal{E}_0 = 0$

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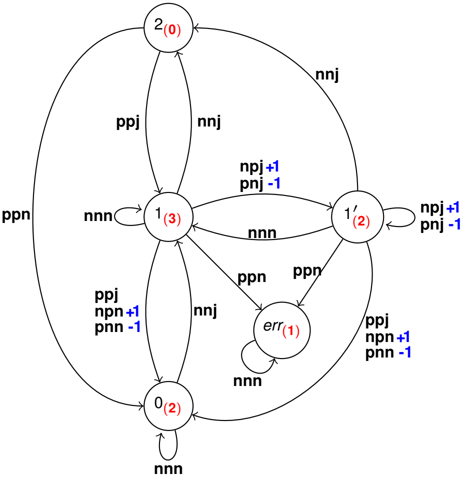

$$\mathcal{G}, 0 \models \langle\langle\{p_1, p_2\}\rangle\rangle \Box \neg err$$

$\exists$ joint strategy for p_1 and p_2 s.t.:

- error state is avoided (temporal)
- all jobs are processed (parity)
- printers alternate (energy)

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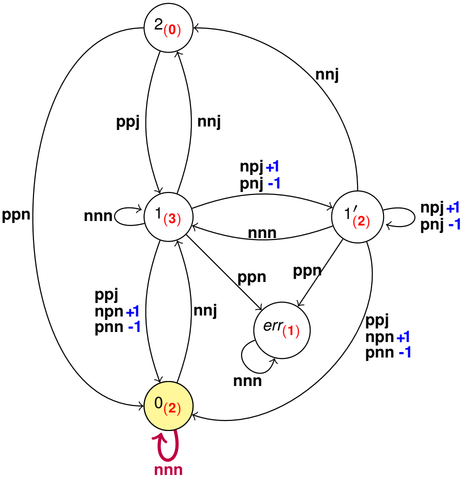

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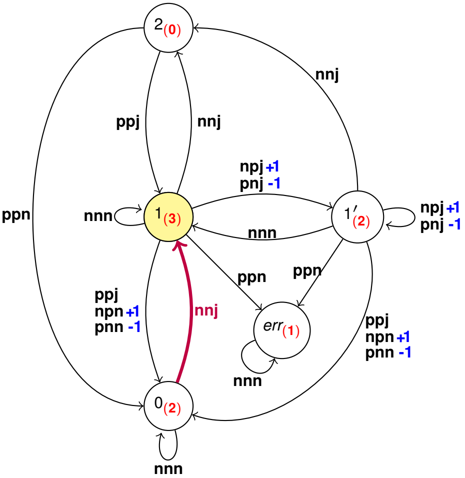

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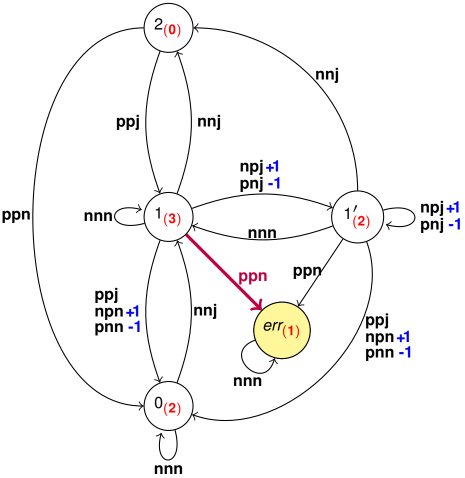

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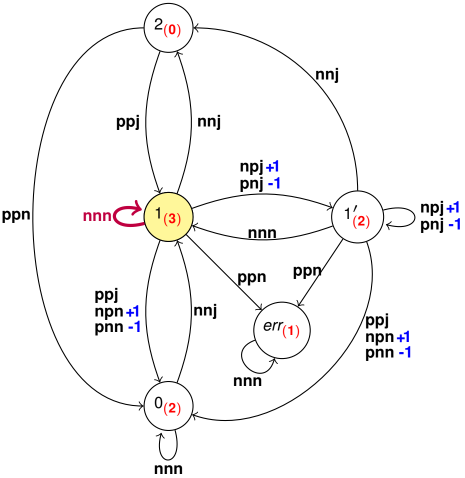

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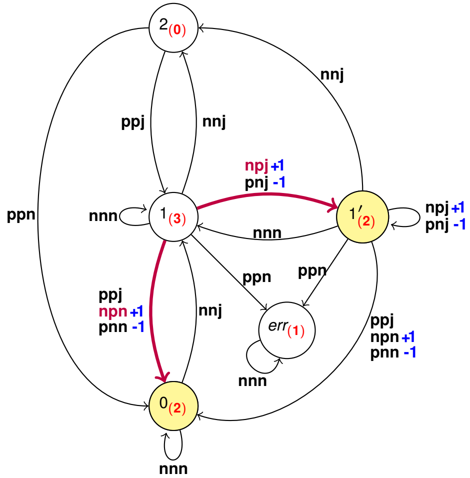

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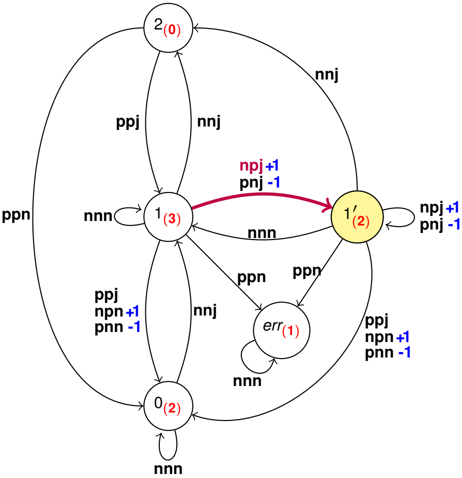

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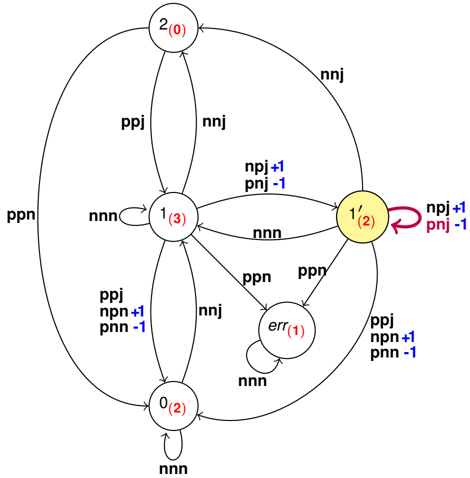

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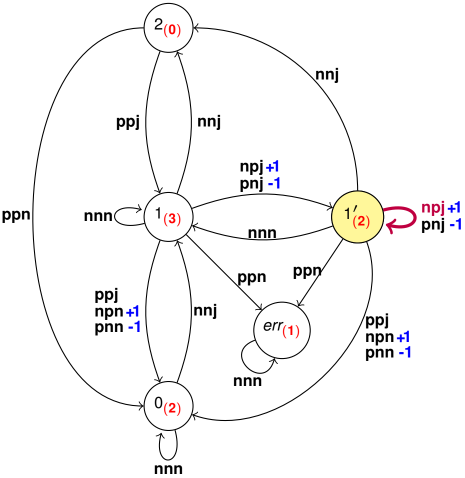

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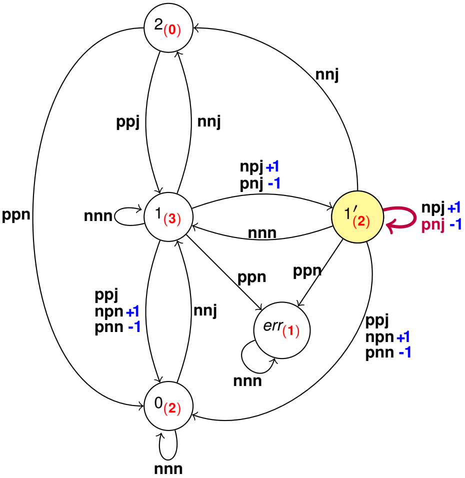

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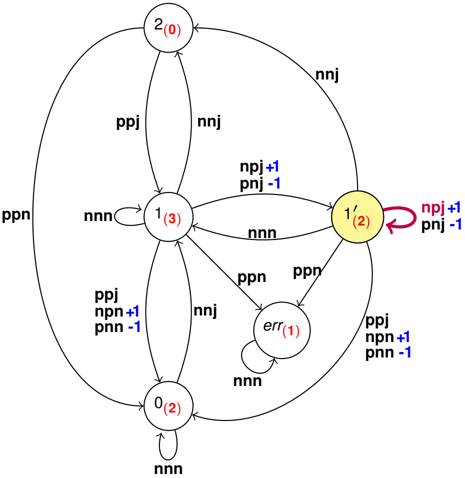

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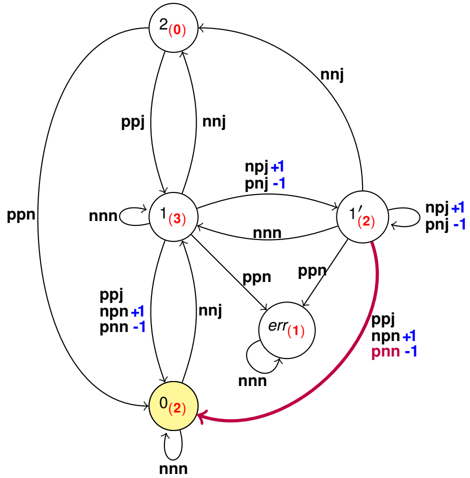

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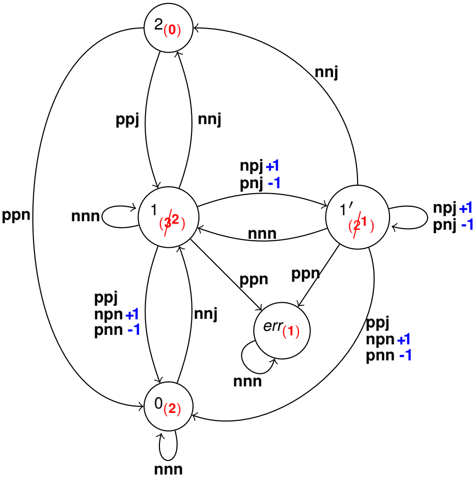

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The model checking problem

Definition ($\mathrm{pe\text{-}ATL}$ model checking problem)

Given a pe-CGS $\mathcal{G} = \langle G, p, e \rangle$ and a $\mathrm{pe\text{-}ATL}$ formula φ, establish whether $\mathcal{G} \models \varphi$

Definition ($\mathrm{p\text{-}ATL}/\mathrm{e\text{-}ATL}$)

- $\mathrm{p\text{-}ATL}$: relax the energy condition
  strategies fulfill parity condition only
- $\mathrm{e\text{-}ATL}$ relaxing the parity condition
  strategies fulfill energy condition only

Parity and energy conditions in isolation

Lemma

p-ATL/e-ATL model checking problem easily reduce to pe-ATL one

- spurious parity condition:
  - $p(q) = 0$ for all $q \in Q$

all parity are even and so is the smallest occurring infinitely often

- spurious energy condition:
  - weight is 0 for every transition
  - initial energy level is any value in the energy range, e.g., a

initial energy level is in range and never changes

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Unbounded energy range $[-\infty, +\infty]$

- Just ignore the energy condition (p-ATL instead of pe-ATL)
- Also, the problem easily reduces to the bounded case:
  - $w(t) = 0$ for all transitions
  - $[a, b] = [0, 0]$
  - $\mathcal{E}^{init} = 0$

Bounded energy range $[a, b]$

- $a \neq -\infty$, $b \neq +\infty$

Lemma (normalization)

It is possible to focus on instances where no rationals are involved

- integer energy range ($a, b \in \mathbb{Z}$)
- integer initial energy level ($\mathcal{E}^{init} \in \mathbb{Z}$)
- weights over transitions are integers as well

Lemma (positional strategies)

- a (p, e)-strategy exists iff a uniform one exists (bounded instance)
- a (p, e)strategy exists iff a memoryless one exists (unbounded instance)

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(Un)Bounded energy range $[a, b]$: Complexity

- uniform strategies: positional in $Q \times [a, b]$ (exponentially many positions $(q, \mathit{energy\text{-}level})$ when a and b are in binary—thanks to normalization)
- memoryless strategies: positional in Q (polynomially many positions q)

A non-deterministic algorithm:

- guess the strategy
- return *false* when a loop with odd parity or an out-of-range is detected
- no position is visited twice
- bounded case: exponential time
- unbounded case: polynomial time

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Left-bounded energy range $[a, +\infty]$

(right-bounded energy range $[-\infty, b]$ is symmetric)

- Model-theoretic argument (technically quite involved)
- Difficulty: the space of positions (q, *energy-level*) is infinite
- We define suitable structures (witnesses
  - compact representations for strategies
  - bounded size
  - we prove it to be complete for strategies
- A non-deterministic algorithm guesses one such structure and check that it is indeed a witness for the desired strategy

Key ideas

- A witness (for a $\langle\langle A\rangle\rangle\Box\psi$ formula) is a pair of graphs

$$(S_1, S_2)$$

- Elements of such graphs are positions $(q, \mathit{energy\text{-}level})$

$(q, \mathit{energy\text{-}level}) \in S$ iff there is a *winning* strategy for A, i.e., a (p, e)-strategy that guarantees the invariant ψ

- Left-bounded range ensures monotonicity

a strategy exists from $(q, \mathit{energy\text{-}level})$ iff a strategy exists from (q, E) for all $E \geq \mathit{energy\text{-}level}$

- Thus, only the smallest energy level appears in S_1 and S_2 for each q

$$|S_1| \leq |Q|, \qquad |S_2| \leq |Q|$$

- S_1 represents the strategy for parity and temporal goals
  S_2 contains increasing loops to increase the energy levels

Key ideas

- A witness (for a $\langle\langle A\rangle\rangle\Box\psi$ formula) is a pair of graphs

$$(S_1, S_2)$$

- Elements of such graphs are positions $(q, \mathit{energy\text{-}level})$

$(q, \mathit{energy\text{-}level}) \in S$ iff there is a *winning* strategy for A, i.e., a (p, e)-strategy that guarantees the invariant ψ

- Left-bounded range ensures monotonicity

a strategy exists from $(q, \mathit{energy\text{-}level})$ iff a strategy exists from (q, E) for all $E \geq \mathit{energy\text{-}level}$

- Thus, only the smallest energy level appears in S_1 and S_2 for each q

$$|S_1| \leq |Q|, \qquad |S_2| \leq |Q|$$

- S_1 represents the strategy for parity and temporal goals
  S_2 contains increasing loops to increase the energy levels

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Alechina, Logan, Nguyen, Raimondi, JCSS (2017)

Model-checking for Resource-Bounded ATL with production and consumption of resources, p. 126–144

From witnesses to strategies

- *internal constraints*
  - e.g., elements of S_1 and S_2 satisfy the invariant ψ in a formula $\langle\langle A\rangle\rangle\Box\psi$
- *diagonal constraints*
  - e.g., elements of S_1 with low energy level also occur as (and can be merged with) elements of S_2
- the unfolding/merging of S_1 and S_2 corresponds to the outcome of a winning strategy for A

From strategies to witnesses

Witness construction
(from the tree $\mathcal{T}$ of outcomes of a winning strategy for A)

- q appears in the witness iff it appears in the tree $\mathcal{T}$
- suitably cut tree $\mathcal{T}$ into a finite (not bounded) prefix
- for every q, a representative node in the cut of $\mathcal{T}$ is chosen
  - based on their topological order and their energy level in the tree
- energy level and outgoing transition for q in the witness are determined by its representative in the cut of $\mathcal{T}$

Outline

1. Introduction and motivations
2. The logic pe-ATL
   - pe-ATL at work
3. Model checking pe-ATL
   - Warming up: Parity and energy conditions in isolation
   - Unbounded $[-\infty, +\infty]$ and bounded $[a, b]$ energy range
   - Left-bounded $[a, +\infty]$ and right-bounded $[-\infty, b]$ energy range
4. Conclusions

Conclusions

- pe-ATL: coalitional abilities to pursue temporal goals while satisfying qualitative (parity) and quantitative (energy) conditions
- pe-ATL model checking problem

Theorem

The model checking problem for pe-ATL is:

- in NEXPTIME if the energy range is bounded ($[a, b]$)
- in NPTIME if the energy range is unbounded ($[-\infty, +\infty]$)
- in NPTIME if the energy range is left- or right-unbounded ($[a, +\infty]$ or $[-\infty, b]$)

Future work

- establishing thigh complexity bounds (parity game complexity)
- to extend the proposed framework to ATL^*
  - comparison of the expressive power with ATL^* and other logics for strategic reasoning, e.g., SR
- different modeling choices
  - energy level evolves along the entire game
  - opponent must also act according to parity and energy conditions

Bulling & Farwer, ECAI 2010

On the (Un-)Decidability of Model Checking Resource-Bounded Agents, p. 567–572

Thank you!