Coalitions and Communication

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General area of the talk

- This talk is on specification and verification of multi-agent systems (MAS)
- a MAS is specified in terms of states and joint actions by the agents
- actions can change both the physical properties of the state and the knowledge of agents (e.g. observation and communication actions)
- actions consume and produce resources
- verification is done by model checking (checking whether the system satisfies some properties)
  - an example property would be: do agents 1 and 2 have a strategy to come to know whether p is true, given their resource allocation?

Coalitions, (uniform) strategies

- a strategy is a choice of actions (determined by the current state of the agent or by a finite history = sequence of states)
- a coalition is a group of agents, intuitively with a common goal (such as, discover whether p is true)
- a coalitions's strategy is *uniform* if every agent in the coalition selects actions based on its knowledge (the same action is selected in all indistinguishable states/histories)

Specific focus of the talk

- in [Alechina,Dastani,Logan 2016] (IJCAI 2016 paper), we proposed a logic RB$\pm$ATSEL: an extension of Alternating Time Temporal Logic (ATL) with costs of actions (including epistemic actions) and knowledge
- since model checking for ATL with uniform strategies and perfect recall is undecidable, same holds for RB$\pm$ATSEL
- however we gave a model checking procedure for *coalition uniform* strategies where uniformity holds with respect to the knowledge of the whole coalition
- intuitively, coalition uniformity means that agents in the coalition somehow combine their knowledge to select joint actions

The problem with coalition uniformity

- in turn, agents' ability to combine knowledge intuitively means that agents have free unbounded communication . . .
- . . . which is not very intuitive in the context of resource-bounded multiagent systems

Proposal in this talk

- this talk is based on our LAMAS 2017 paper
- we explicitly add a communication step before the joint action selection (and assign it an explicit cost)
- *communication models* are models where there is a communication step inserted before every action step
- we show that for this special class of models, RB$\pm$ATSEL the model checking problem is decidable for perfect recall uniform strategies

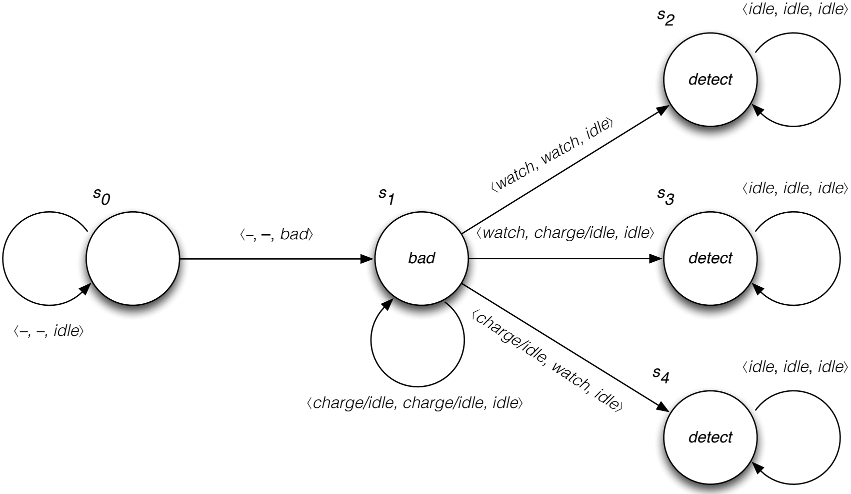
Background: RB±ATSEL

- Resource-Bounded Alternating Time Syntactic Epistemic Logic (RB±ATSEL) is designed to reason about resource-bounded agents executing both ontic and epistemic actions
- knowledge is modelled syntactically (as a finite set of formulas: the agent's knowledge base):
  - to avoid the problem of logical omniscience
  - to make modelling epistemic actions manageable

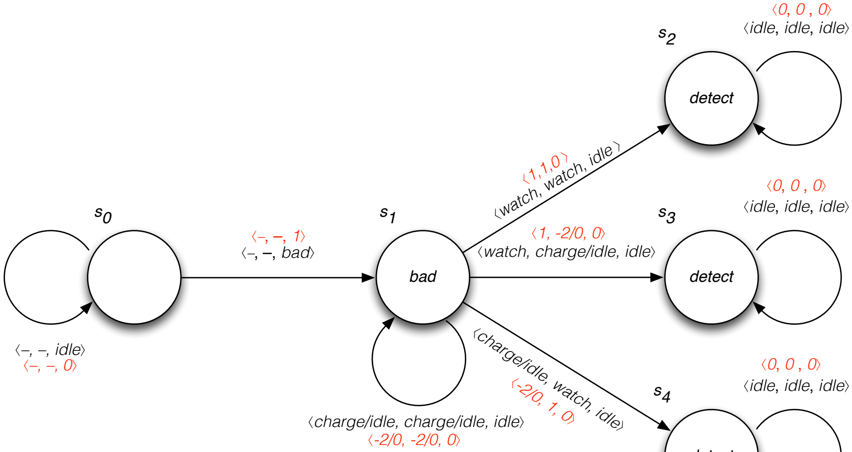
What kind of things can RB±ATSEL express

- ‘two robot museum guard robots have a strategy to observe and prevent any attempt approach the artworks in the museum, provided that at least one of them starts fully charged’
- epistemic actions: observing, communicating (anything that changes the agent’s knowledge base without changing the world)
- ontic actions: stopping someone from touching an artwork, charging the battery (changing the world)
- resource allocation: the amount of energy each agent has; there can be multiple resource types: energy, memory, etc.

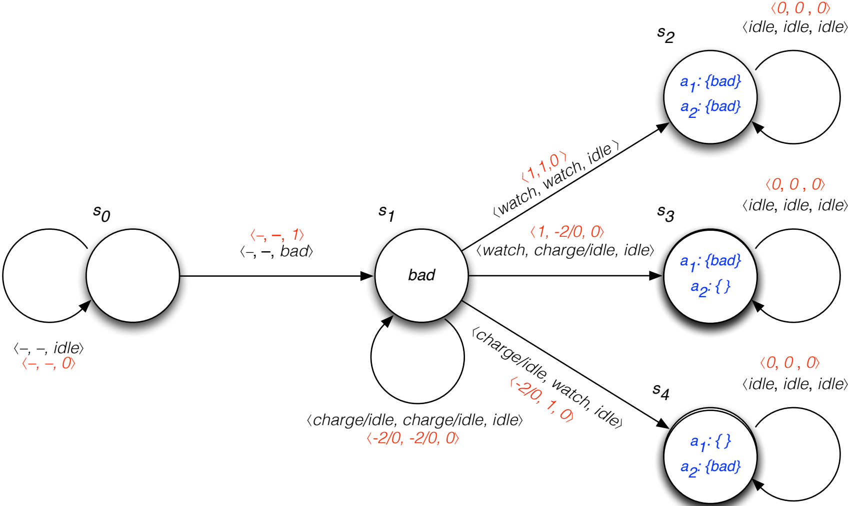
Concurrent game structure



Adding resources (one resource type: energy)



Adding knowledge bases



Strategies

- a strategy for coalition A is a mapping from finite sequences of states (histories) to joint actions by agents in A
- if A is the grand coalition (all agents), any strategy of A generates a single run of the system
- otherwise, a strategy corresponds to a tree (each branch of the tree is a run corresponding to a particular choice of actions by A's opponents)
- strategies possible given a particular resource allocation b: a strategy is a b-strategy if for every run generated by this strategy, for each action by A in the strategy, the agents in A will have enough resources to execute it

Language of RB±ATSEL

- In what follows, we assume a set $Agt = \{a_1, \ldots, a_n\}$ of n agents, $Res = \{res_1, \ldots, res_r\}$ a set of r resource types, and a set of propositions Π
- The set of possible resource bounds or resource allocations is $B = Agt \times Res \rightarrow \mathbb{N}_\infty$, where $\mathbb{N}_\infty = \mathbb{N} \cup \{\infty\}$.
- Formulas of the language $\mathcal{L}$ of RB±ATSEL are defined by the following syntax

$$\varphi ::= p \mid \neg\varphi \mid \varphi \vee \psi \mid \langle\langle A^b \rangle\rangle \bigcirc \varphi \mid \langle\langle A^b \rangle\rangle \varphi \, \mathcal{U} \, \psi \mid \langle\langle A^b \rangle\rangle \Box \varphi \mid K_a \varphi$$

  where $p \in \Pi$ is a proposition, $A \subseteq Agt$, $b \in B$ is a resource bound and $a \in Agt$.

Meaning of formulas

- $\langle\langle A^b \rangle\rangle \bigcirc \psi$ means that a coalition A has a strategy executable within resource bound b to ensure that the next state satisfies ψ
- $\langle\langle A^b \rangle\rangle \psi_1 \mathcal{U} \psi_2$ means that A has a strategy executable within resource bound b to ensure ψ_2 while maintaining the truth of ψ_1
- $\langle\langle A^b \rangle\rangle \Box \psi$ means that A has a strategy executable within resource bound b to ensure that ψ is always true
- $K_a \phi$ means that formula ϕ is in agent a's knowledge base. Note that this is a syntactic knolwedge definition.

What kind of things can RB±ATSEL express

- if something bad happens (approaching the artwork), one of the guards will know in the next state,provided one of them has one unit of energy:

$$\langle\langle \{a_1, a_2\}^{1,0} \rangle\rangle \Box (bad \rightarrow \langle\langle \{a_1, a_2\}^{0,0} \rangle\rangle \bigcirc (K_{a_1} bad \vee K_{a_2} bad))$$

Models of RB±ATSEL

A model of RB±ATSEL is a structure $M = (\Phi, Agt, Res, S, \Pi, Act, d, c, \delta)$ where:

- Φ is a finite set of formulas of $\mathcal{L}$ (possible contents of the local states of the agents).
- S is a set of tuples $(s_1, \ldots, s_n, s_e)$ where $s_e \subseteq \Pi$ and for each $a \in Agt$, $s_a \subseteq \Phi$.
- Agt, Res, Π are as before
- Act is a non-empty set of actions which includes *idle*, and $d : S \times Agt \to \wp(Act) \setminus \{\emptyset\}$ is a function which assigns to each $s \in S$ a non-empty set of actions available to each agent $a \in Agt$. We assume that for every $s \in S$ and $a \in Agt$, $idle \in d(s, a)$. We denote joint actions by all agents in Agt available at s by $D(s) = d(s, a_1) \times \cdots \times d(s, a_n)$.

Models continued

- for every $s, s' \in S, a \in Agt$, $d(s, a) = d(s', a)$ if $s_a = s'_a$.
- $c : Act \times Res \to \mathbb{Z}$ is the function which models consumption and production of resources by actions (a positive integer means consumption, a negative one production). Let $cons_{res}(\alpha) = max(0, c(\alpha, res))$ and $prod_{res}(\alpha) = -min(0, c(\alpha, res))$. We stipulate that $c(idle, res) = 0$ for all $res \in Res$.
- $\delta : S \times Act^n \to S$ is a partial function which for every $s \in S$ and joint action $\sigma \in D(s)$ returns the state resulting from executing σ in s.

Strategies and costs of strategies

- A *strategy for a coalition* $A \subseteq Agt$ is a mapping $F_A : S^+ \to Act^{|A|}$ (from finite non-empty sequences of states to joint actions by A) such that, for every $\lambda s \in S^+$, $F_A(\lambda s) \in D_A(s)$

- $\lambda \in S^\omega$ is consistent with a strategy F_A iff, for all $i \geq 0$, $\lambda[i+1] \in out(\lambda[i], F_A(\lambda[0,i]))$

- $out(s, F_A)$ the set of all computations λ consistent with F_A that start from s

- $\lambda \in out(s, F_A)$ is b-consistent with F_A iff, for every $i \geq 0$, for every $a \in A$,

$$\sum_{j=0}^{j=i-1} tot(F_a(\lambda[0,j])) + b_a \geq cons(F_a(\lambda[0,i]))$$

  where $F_a(\lambda[0,j])$ is a's action as part of the joint action returned by F_A for the sequence of states $\lambda[0,j]$; $tot(\sigma) = prod(\sigma) - cons(\sigma)$

Uniform strategies

- a strategy is uniform if, after epistemically indistinguishable histories, agents select the same actions
- two states s and t are epistemically indistinguishable by agent a, denoted by $s \sim_a t$, if a has the same local state (knows the same formulas) in s and t: $s \sim_a t$ iff $s_a = t_a$
- $\sim_a$ can be lifted to sequences of states in an obvious way
- a strategy for A is uniform if it is uniform for every agent in A

Coalition uniform strategies

- for a coalition A, indistinguishability $s \sim_A s'$ means that A as a whole has the same knowledge in the two states
- various notions of coalitional knowledge can be used to define $\sim_A$, for example:
  - $s \sim_A t$ iff $\bigcup_{a \in A} s_a = \bigcup_{a \in A} t_a$ (the distributed knowledge of A in s and t is the same)
  - another possible definition of $s \sim_A t$ is $\forall a \in A(s_a = t_a)$
- a strategy for A is coalition uniform with respect to $\sim_A$ if it assigns agents in A the same actions in any two histories indistinguishable in $\sim_A$
- The model-checking problem for RB$\pm$ATSEL with coalition-uniform strategies, with respect to any decidable notion of $\sim_A$, is decidable.

Truth definition for standard models

- $M, s \models p$ iff $p \in s_e$
- boolean connectives have standard truth definitions
- $M, s \models \langle\langle A^b \rangle\rangle \bigcirc \phi$ iff $\exists$ coalition-uniform b-strategy F_A such that for all $\lambda \in out(s, F_A)$: $M, \lambda[1] \models \phi$
- $M, s \models \langle\langle A^b \rangle\rangle \phi \mathcal{U} \psi$ iff $\exists$ coalition-uniform b-strategy F_A such that for all $\lambda \in out(s, F_A)$, $\exists i \geq 0$: $M, \lambda[i] \models \psi$ and $M, \lambda[j] \models \phi$ for all $j \in \{0, \ldots, i-1\}$
- $M, s \models \langle\langle A^b \rangle\rangle \Box \phi$ iff $\exists$ coalition-uniform b-strategy F_A such that for all $\lambda \in out(s, F_A)$ and $i \geq 0$: $M, \lambda[i] \models \phi$.
- $M, s \models K_a \phi$ iff $\phi \in s_a$

Alternative definition for K_a

- $M, s \models K_a\phi$ iff $\phi \in s_a$: a knows ϕ iff ϕ is in a's state
- more general definition: let alg_a be any algorithmic (terminating) procedure that produces a's knowledge when applied to s_a
- for example, alg_a could be computing the largest subset of some finite set of formulas that is derivable from s_a in a particular logic

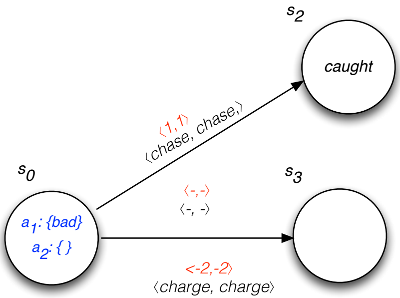
Model-checking problem for RB±ATSEL

- given a model *M* of RB±ATSEL and a RB±ATSEL formula ϕ, return the set of states of *M* where ϕ is true
- the model-checking problem for ATL with perfect recall and uniform strategies is undecidable (because RB±ATSEL is an extension of ATL with perfect recall)

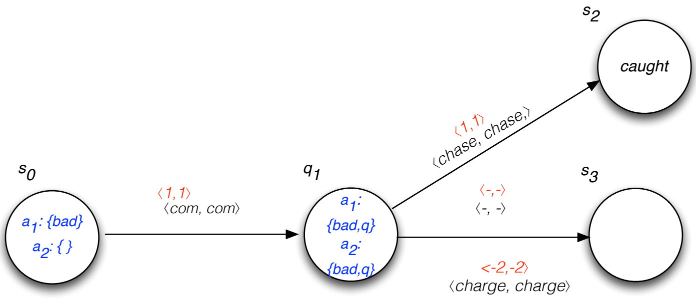
Adding explicit communication step

- coalition uniformity presupposes that agents can select actions based on the knowledge of other agents in the coalition
- to make this assumption realistic, we add an explicit communication step, with associated costs

Original model (fragment)



Communication model (fragment)



Communication models

- precise definition of communication models is in LAMAS 2017 paper
- main points:
  - two disjoints sets of states, action states and communication states
  - in action states, only communication actions of the form $com(s_a, A)$ (send the contents of state of a to all agents in A) are available
  - the effect of communication action is adding communicated formulas of s_a to the state of every agent in A
  - we changed the truth definition of ‘next’ for communication states (to look two steps ahead)

Model checking for communication models

- Model checking RB±ATSEL over communication models is decidable for perfect recall uniform strategies
- model checking algorithm is obtained by modifying the algorithm for RB±ATSEL for coalition-uniform strategies (for the special case where $\sim_A$ is equivalence of distributed knowledge)
- the algorithm has an added check for the type of each state that is encountered in the search
- in action states, each agent $a \in A$ executes $com(s_A, A)$ which results in a state where all agents in A have the same knowledge
- the choice of $com(s_A, A)$ results in a uniform strategy because each agent in A always communicates the same information to other agents in A when it has the same local state.

The cost of communication

- The $com(s_A, A)$ action can be assigned a cost based e.g., on the number of agents in A and the number of formulas in s_a

Why communicate all formulas?

- The decidability result still holds if agents communicate not all knolwedge, but only some specified 'public formulas'
- 'coalitional knolwedge equivalence' then is simply re-defined to refer to only 'public formulas'
- another possibility is to keep track of which formulas are 'visible' to which agents in the coalition; those do not need to be communicated

Conclusions and future work

- the model-checking problem for ATL with uniform strategies and perfect recall is undecidable
- however, it is decidable for strategies uniform with respect to e.g., distributed knowledge of the whole coalition
- it is also decidable if agents can communicate (and make distributed knowledge their individual knowledge)
- in future work, we plan to investigate realistic communication protocols rather than protocols aimed at achieving the same individual knowledge