Collaborative Planning with Privacy

Protocol eXchange

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Context

- Many examples of collaboration
  - Between distributor and retailer
  - Between hospitals and insurance companies
  - Distributed databases
  - Social networking sites (MySpace, Facebook)
- *Temporary* alignment of interests
- Information sharing is necessary to collaborate, but full disclosure is not desired.

Our Work

- We provide a model of collaboration at an abstract level.
- We can model a large class of collaborations while being able to make conclusions about privacy.
- Focus is on the interplay between protecting and releasing information.

Our Work

- We draw on
  - Planning from AI literature
  - State transition systems and multiset rewriting
- We consider systems with well-balanced actions
- It is PSPACE-complete to decide the existence of a collaborative plan, and if the system preserves the privacy of all agents.

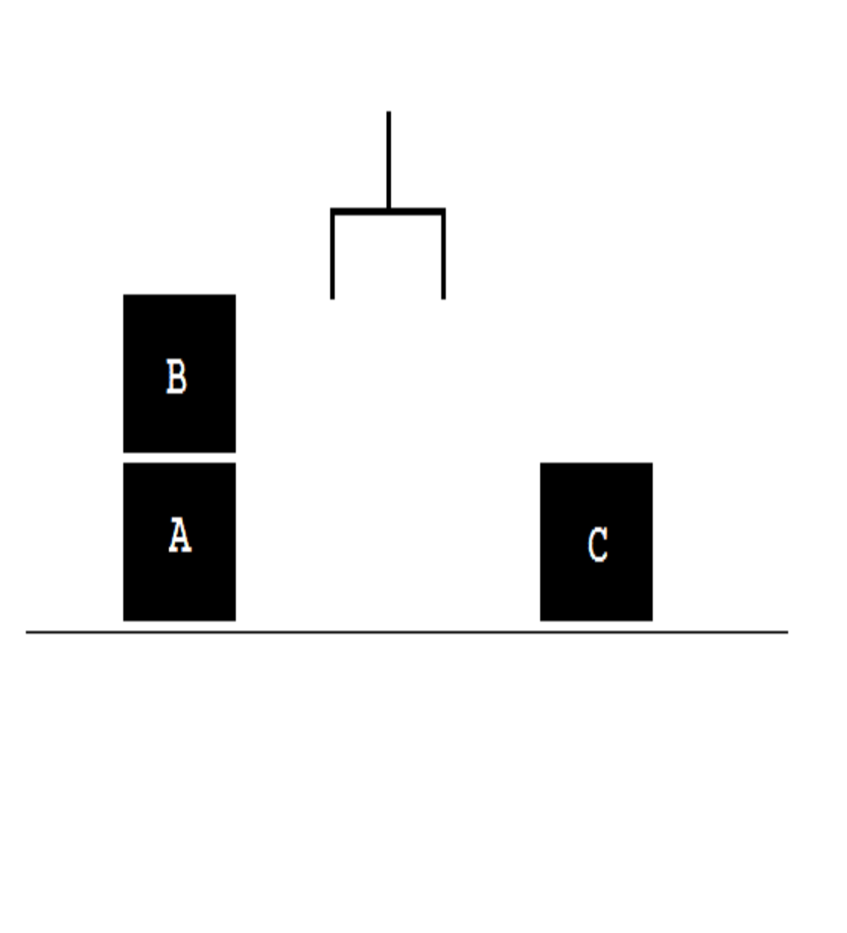
Outline

- Motivations from Classical Planning
- Our formalism: Local state transition systems
- Privacy in collaboration
- Complexity results and foundation in logic
- Related and future work

Classical Planning

- A robot manipulating its environment
- Description of the environment
  - Objects
  - Relations between the objects
- Actions
- Initial configuration
- Goal configuration

Initial State



{ONTABLE(A),
ON(B,A), CLEAR(B),
ONTABLE(C),
CLEAR(C),
HANDEMPTY}

Actions

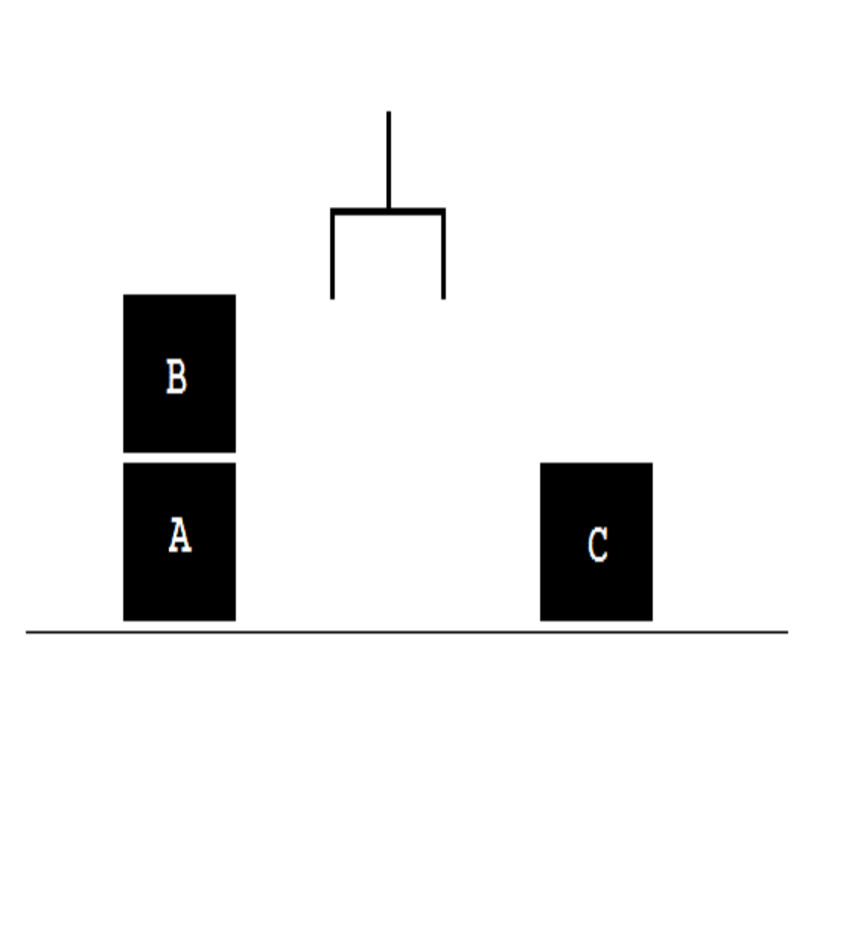
- take(x): {HANDEMPTY, CLEAR(x), ONTABLE(x)}
  → {HOLDS(x)}

- remove(x,y): {ON(x,y), HANDEMPTY, CLEAR(x)}
  → {HOLDS(x), CLEAR(y)}

- stack(x,y): {HOLDS(x), CLEAR(y)}
  → {HANDEMPTY, CLEAR(x), ON(x,y)}

- put(x): {HOLDS(x)}
  → {ONTABLE(x), CLEAR(x), HANDEMPTY}

Blocks World: Plan



remove(B,A)

put(B)

take(A)

stack(A,C)

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Collaboration and Planning

- Multiple agents: $A_1, \ldots, A_n$
- Each has private data $P_A(t)$ and public data $P'(u)$
- Each has a set of actions
- Initial state
- Goal state
- Find a sequence of actions leading from initial state to goal state

Local State Transition Systems

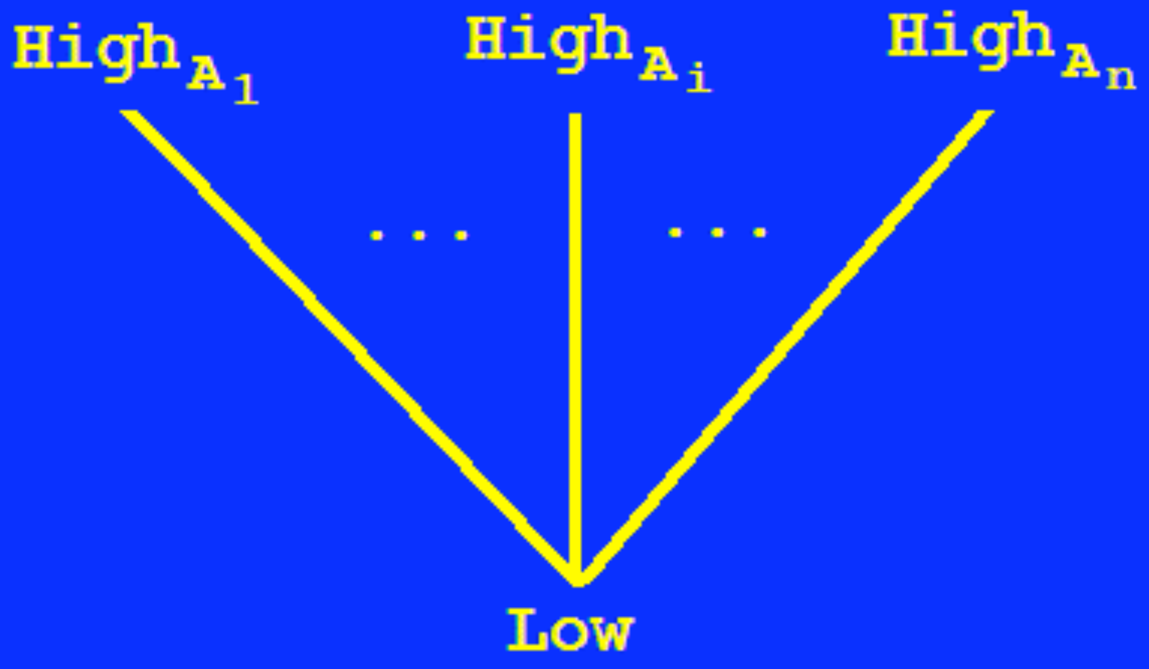
- A local state transition system is a triplet $T = (\Sigma, I, R_T)$ where
  - Σ is a signature of predicate symbols and terms (currently only constants and variables)
  - I is a set of agents
  - R_T is a set of (local) actions

Local State Transition Systems

- A *fact* is a closed atomic predicate over multi-sorted terms
- A syntactic convention distinguishes between private and public facts:

Private	Public/Group
$P_A(t)$	$P'(u)$

Security Labels



System Configurations

- A *state* or *configuration* of the system is a multiset of private and public facts

$$X_{A_1}, X_{A_2}, \ldots, X_{A_n}, X'$$

- Each agent can affect only their own private data and the public data.

Actions

- Replace X_A and X' by Y_A and Y'

$$r : X_A X' \rightarrow_A Y_A Y'$$

Transforms $W = VX_A X'$ into $U = VY_A Y'$

- System transformation is written as

$$W \; \mathbb{B} \;\; _r \, U$$

- Reachability from a set R of actions is denoted by

$$W \; \mathbb{B} \;\; _R{}^* \, U$$

Partial Goals

- The goal need not describe the complete configuration.
- Partial reachability is defined by

  $W \text{Ã}_{R}^{*} Z$ iff $W \mathbb{B}_{R}^{*} ZU$ for some U

So with $r : X_A X' \rightarrow_A Y_A Y'$ we find that

$UX_A X' \text{Ã}_{r} Y_A Y'$

Collaborative Plans

A *collaborative plan* based on the action set R which leads from W to the partial goal Z is a labeled, non-branching tree satisfying:

- Edges are labeled with actions from R, and nodes are labeled with states
- The label of each node enables the label of the outgoing edge
- The label of the root is W
- The label of the leaf is ZU for some U

There exists a collaborative plan based on R, leading from W to the partial goal Z if and only if $W \to_{R}^{*} Z$

Abstract Example

- Alice's actions include

$$r_1 : P_A(t) \rightarrow_A P_A(t)P'(t')$$

$$r_2 : P_A(t) \rightarrow_A P_A(t)P''(t'')$$

- Bob's actions include

$$r_3 : Q_B(u)Q'(v)P'(t')P''(t'') \rightarrow_B Q_B(t)Q'(v')$$

- When $R = \{r_1, r_2, r_3\}$ then

$$P_A(t)Q_B(u)Q'(v) \;\text{Ã}\; {}_{R}^{*}\, Q_B(t)$$

An Example

- Example:
  - r_1 : $P_A(15\_A\_Pwd)\ S_A(7\_B\_Share) \rightarrow_A$

    $P_A(21\_A\_Pwd)\ S_A(7\_B\_Share)\ P'(8\_A\_Share)$
  - r_2 : $Q_B(7\_B\_Share)\ P'(8\_A\_Share) \rightarrow_B Q_B(15\_A\_Pwd)$

An Example

- Example:
  - $r_1 : P_A(15\_A\_Pwd)\ S_A(7\_B\_Share) \rightarrow_A$
    $P_A(21\_A\_Pwd)\ S_A(7\_B\_Share)\ P'(8\_A\_Share)$
  - $r_2 : Q_B(7\_B\_Share)\ P'(8\_A\_Share) \rightarrow_B Q_B(15\_A\_Pwd)$

$P_A(15\_A\_Pwd)\ S_A(7\_B\_Share)\ Q_B(7\_B\_Share)$

An Example

- Example:
  - $r_1 : P_A(15\_A\_Pwd)\ S_A(7\_B\_Share) \rightarrow_A$
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  - $r_2 : Q_B(7\_B\_Share)\ P'(8\_A\_Share) \rightarrow_B Q_B(15\_A\_Pwd)$

$P_A(15\_A\_Pwd)\ S_A(7\_B\_Share)\ Q_B(7\_B\_Share)$ B r_1
$P_A(21\_A\_Pwd)\ S_A(7\_B\_Share)\ P'(8\_A\_Share)\ Q_B(7\_B\_Share)$

An Example

- Example:
  - $r_1 : P_A(15\_A\_Pwd)\ S_A(7\_B\_Share) \rightarrow_A$
    $P_A(21\_A\_Pwd)\ S_A(7\_B\_Share)\ P'(8\_A\_Share)$
  - $r_2 : Q_B(7\_B\_Share)\ P'(8\_A\_Share) \rightarrow_B Q_B(15\_A\_Pwd)$

$P_A(15\_A\_Pwd)\ S_A(7\_B\_Share)\ Q_B(7\_B\_Share)\ \mathbb{B}\ r_1$
$P_A(21\_A\_Pwd)\ S_A(7\_B\_Share)\ P'(8\_A\_Share)\ Q_B(7\_B\_Share)\ \mathbb{B}\ r_2$
$P_A(21\_A\_Pwd)\ S_A(7\_B\_Share)\ Q_B(15\_A\_Pwd)$

An Example

- Example:
  - $r_1 : P_A(15\_A\_Pwd)\ S_A(7\_B\_Share) \rightarrow_A$
    $P_A(21\_A\_Pwd)\ S_A(7\_B\_Share)\ P'(8\_A\_Share)$
  - $r_2 : Q_B(7\_B\_Share)\ P'(8\_A\_Share) \rightarrow_B Q_B(15\_A\_Pwd)$

$P_A(15\_A\_Pwd)\ S_A(7\_B\_Share)\ Q_B(7\_B\_Share)$ B r_1
$P_A(21\_A\_Pwd)\ S_A(7\_B\_Share)\ P'(8\_A\_Share)\ Q_B(7\_B\_Share)$ B r_2
$P_A(21\_A\_Pwd)\ S_A(7\_B\_Share)\ Q_B(15\_A\_Pwd)$

- In this case we see
  $P_A(15\_A\_Pwd)\ S_A(7\_B\_Share)\ Q_B(7\_B\_Share)$
  Ã R^* $Q_B(15\_A\_Pwd)$

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Privacy Concerns

- If Alice starts with a secret term *t*, she wants to make sure it stays secret.
- Protect the secret from all possible behavior of other participants.
- Requires a global condition on reachable configurations.

Privacy Condition

- Local state transition system in initial configuration $\mathcal{W}$, protects the privacy of agent A if every term t which, in the initial configuration $\mathcal{W}$, occurs only in private predicates of A, also occurs only in private predicates of A in any reachable configuration.

- Partial goals of the form $\mathcal{Q}'(t)$ or $\mathcal{Q}_B(t)$ are not reachable from the initial configuration.

Remarks on Privacy

- Local state transition systems define a space of plans or protocols.
- Privacy condition is global condition on entire space.
- Other participants may be viewed as a type of adversary.
- Provides a guarantee that if others don’t follow plan, or perform extra local computations then secrets are not revealed.

Remarks on Privacy

- Can express notions of knowledge of *current* information.

- Alice's action may change her password, rendering the old password obsolete.

- Knowledge of old password without knowledge of current password may be useless.

The Collaborative Planning Problem with Privacy

Given a local state transition system, and given an initial state *W* and a partial goal *Z*, does there exist a plan which leads from *W* to *Z*, and does the system protect the privacy of all agents?

Well-Balanced Actions

- Actions are restricted to have the same number of facts in the pre- and post-conditions.

- Intuitively, actions serve to update fields and they do not create new ones.

- Introduce a special constant symbol to indicate an empty field: *P(*)*

- Not as restrictive as it seems.

Example Revisited

- Example:
  - $r_1 : P_A(15\_A\_Pwd)\ S_A(7\_B\_Share)\ P'(*) \rightarrow_A$
    $P_A(15\_A\_Pwd)\ S_A(7\_B\_Share)\ P'(8\_A\_Share)$
  - $r_2 : Q_B(7\_B\_Share)\ P'(8\_A\_Share) \rightarrow_B Q_B(15\_A\_Pwd)\ P'(*)$

$P_A(15\_A\_Pwd)\ S_A(7\_B\_Share)\ P'(*)\ Q_B(7\_B\_Share)$ B r_1
$P_A(15\_A\_Pwd)\ S_A(7\_B\_Share)\ P'(8\_A\_Share)\ Q_B(7\_B\_Share)$ B r_2
$P_A(15\_A\_Pwd)\ S_A(7\_B\_Share)\ P'(*)\ Q_B(15\_A\_Pwd)$

- We still find that
  $P_A(15\_A\_Pwd)\ S_A(7\_B\_Share)\ P'(*)\ Q_B(7\_B\_Share)$
  Ã R^* $Q_B(15\_A\_Pwd)$

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Complexity Results

- The Collaborative Planning Problem with Privacy, with well-balanced actions, is PSPACE-complete.
  - It is polynomial with respect to the following parameters:
    - The size of a program recognizing the actions
    - The number of facts in the initial configuration
    - The number of closed facts in the (finite) signature

Complexity Results

- For a *fixed* finite signature, the Collaborative Planning Problem with privacy, with well-balanced actions, is solvable in polynomial time.
  - It is polynomial with respect to the parameters:
    - The size of a program recognizing the actions
    - The number of facts in the initial configuration

(The number of closed facts in the signature is now viewed as a constant.)

Logical Foundation

- Linear logic is a resource-sensitive refinement of traditional logic.
- Linear implication mimics actions well by "consuming" antecedents.
- We translate local state transition systems into a variant of linear logic called affine logic.

Logical Foundation

- Theorem: Local state transition systems are sound and complete with respect to (our translation into) affine logic.

- Benefits include:
  - Possible insights from well established formalism
  - Use of already existing tools

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Related Work

- **Multiset Rewriting and the Complexity of Bounded Security Protocols** [N. Durgin, P. Lincoln, J. Mitchell, A. Scedrov 2004]
- **A Linear Logic of Authorization and Knowledge** [D. Garg, L. Bauer, K. D. Bowers, F. Pfenning, M. K. Reiter 2006]
- **Security Policies and Security Models** [J. A. Goguen and J. Meseguer '82]
- **Conditional Rewriting Logic as a Unified Model of Concurrency** [J. Meseguer '92]

Related Work

- **Enforcing Robust Declassification and Qualified Robustness** [A. C. Myers, A. Sabelfeld, S. Zdancewic 2004]
- **ORCHESTRA: Rapid, Collaborative Sharing of Dynamic Data** [Z. G. Ives, N. Khandelwwal, A. Kapur, M. Cakir 2005]

Future Work

- Extend to a richer language of functional terms.
- Explore the use of existentials in affine logic to model fresh values.
- Investigate behavior in the presence of actions with nondeterministic effects.
- Determine if our formalism provides traceability.

Future Work

- Investigate more completely the ability to distinguish between obsolete and current secrets.
- Explore the use of utility functions weighing the relative importance of protecting or releasing information.
- Explore a more complicated structure for security labels.

Summary

- Introduced local state transition systems
- Discussed notions of privacy in collaboration
- Formalized the collaborative planning problem with privacy
- Determined PSPACE-completeness in the well-balanced case
- Discussed foundation in logic

Thank You!

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