Reasoning about Contracts

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Introduction

- What are contracts, and are they different from properties or specifications?
  - Actual vs. ideal behaviour
  - Looking at contracts as first class entities
- The sort of questions one would like to answer are:
  - Does a system satisfy a contract? To what extent?
  - Is a contract stricter than another for a particular party?
  - Are two contracts compatible together?

Contracts

- Basic building blocks of contracts:
  - Obligation to perform x related to the property *'action taken must include x'*
  - Prohibition from performing x related to the property *'action taken may not include x'*
  - But what are permission to perform x? Actions may include x? What are violations?
- Add combinators to handle temporal modalities, logical combinators and reparations.
- Contracts are by definition an agreement between two or more *interacting* parties but most formal studies regulate the parties independently.

Contract clause #1

"John is permitted to withdraw cash."

- John may choose to perform an action *'withdraw cash'*,
- which the bank is bound to engage with.
- John may also choose not to perform the action.
- but if he does and the bank does not allow *the bank has violated the contract*.

Contract clause #2

"John is obliged to pay an annual fee."

- John should perform an action *'pay annual fee'*,
- If John chooses not to perform the action, he has violated the contract.
- But the bank is bound to engage with John's action to allow him to satisfy the contract.

Interacting Systems

- Interaction has a long history in computer science providing tools such as *communication* and *synchronisation* which allow the modelling of directed modalities in a two-party contract setting.
- We formalise two-party contracts modelling interaction using *synchronous composition with multiset-actions*.

Synchronous Composition over Multisets of Actions

- The synchronous composition of two automata $S_i = \langle Q_i,\ q0_i,\ \rightarrow_i \rangle$ synchronising over alphabet G, is written $S_1 \|_G S_2$, is defined to be $\langle Q_1 \times Q_2,\ (q0_1, q0_2), \rightarrow \rangle$.

$$\frac{q_1 \xrightarrow{A}_1 q_1'}{(q_1, q_2) \xrightarrow{A} (q_1', q_2)}\ A \cap G = \emptyset \qquad \frac{q_2 \xrightarrow{A}_2 q_2'}{(q_1, q_2) \xrightarrow{A} (q_1, q_2')}\ A \cap G = \emptyset$$

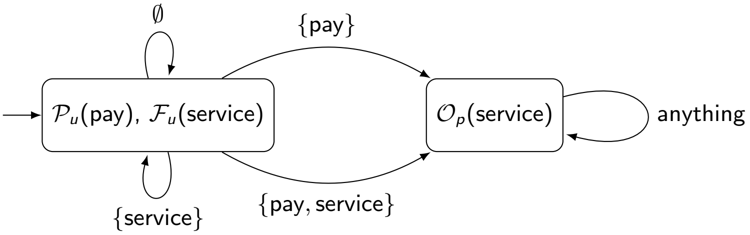
$$\frac{q_1 \xrightarrow{A}_1 q_1' \qquad q_2 \xrightarrow{B}_2 q_2'}{(q_1, q_2) \xrightarrow{A \cup B} (q_1', q_2')}\ A \cap G = B \cap G \neq \emptyset$$

But What About the Contract?

- Contracts are also encoded as automata with states tagged with the contract clauses that will be in force at that point.

Contract

"Initially, the user (party *u*) is forbidden from using the *service* but permitted to *pay* after which the provider (party *p*) is obliged to provide the *service*."



Contract Automata

- A *contract clause* is one of the following:

$$\text{Clause} ::= \mathcal{O}_p(a) \mid \mathcal{O}_p(!a) \mid \mathcal{P}_p(a) \mid \mathcal{P}_p(!a)$$

- A contract automaton is a normal automaton with an additional function $Q \to 2^{\text{Clause}}$.
- The transition relation of contract automata is always total to ensure no deadlock, *even after a violation occurs*.

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Prohibition

Prohibition $\mathcal{F}_p(a)$ is just $\mathcal{O}_p(!a)$.

Regulated Two-Party Systems

- A *regulated two-party system* synchronising over the set of actions G consists of three parts: (i) the interacting systems S_1 and S_2 and (ii) the contract $\mathcal{A}$.
- By composing the contract automaton $\mathcal{A}$ with the parties' behaviour we can then identify what clauses are in force and when, hence allowing analysis for contract violation: $(S_1 \|_G S_2) \|_\Sigma \mathcal{A}$.

Contract Violation

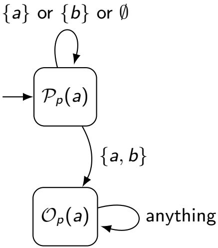
- Given a regulated two-party system, we can now analyse the system automata with respect to the contract clauses and tag violations and the responsible party.
- Violations can occur on:
  - **Transitions:** e.g. a transition which contains an action which is prohibited at that point.
  - **States:** e.g. a state in which a party does not permit (allow) the other party to perform an action which should be permitted.

Example of Semantics: Permissions

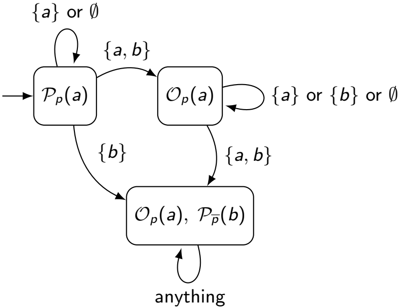
- If party p is permitted to perform shared action a, then the other party $\overline{p}$ must provide p with at least one viable outgoing transition which contains a but does not include any forbidden actions.
- Violations of a permission occur when no appropriate action is possible, and is thus a property of a state not a transition.
- We give a semantics that tags as a violation a state in which one party is permitted to perform an action, while the other provides no way of actually doing so.

Comparing Contracts

- Breach-incapability:
  - A regulated system gives an automaton of all potential behaviours when composed.
  - It is breach-incapable if no violating states and/or transitions are reachable from the initial state.
  - This is stronger than being compliant for one specific run.
- Ordering of contracts based on leniency:
  - A contract $\mathcal{A}$ is more lenient than another contract $\mathcal{A}'$ for a particular party p ($\mathcal{A} \sqsubseteq_p \mathcal{A}'$) if any system behaviour of p which may violate $\mathcal{A}$ may also violate $\mathcal{A}'$.
  - This definition allows us to characterise the notion of contract equivalence for a particular party or even for all parties.



$\sqsubseteq_p$

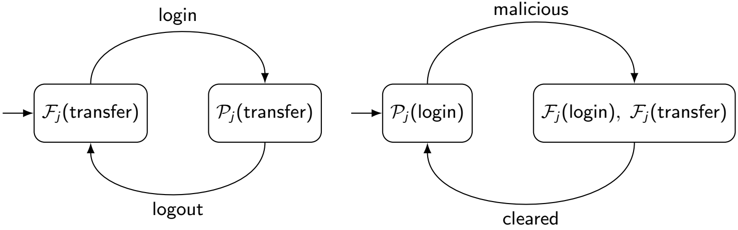


Conflicts in Contracts

Axiom 1: Opposite permissions conflict: $\vdash \mathcal{P}_p(x) \maltese\ !\mathcal{P}_p(x)$.
Axiom 2: Obligation to perform mutually exclusive actions is a conflict: $a \bowtie b \vdash \mathcal{O}_p(a) \maltese \mathcal{O}_p(b)$.
Axiom 3: Conflicts are closed under symmetry: $C \maltese C' \vdash C' \maltese C$.
Axiom 4: Conflicts are closed under increased strictness: $C \maltese C' \wedge C' \sqsubseteq C'' \vdash C \maltese C''$.

John and his Bank

The contract says that (i) whenever he is logged into his Internet banking account, he is to be permitted to make money transfers; and (ii) if a malicious attempt to log in to his account is identified, logging in and making transfers will be prohibited until the situation is cleared.



Note what happens after {login, malicious} in the composition of these contracts.

Discussion

- By keeping the contract as a separate automaton:
  - We share the same formalism and theory as for systems;
  - We are able to reason about contracts independently of the system — e.g. compose contracts using synchronous composition
- Although we can reduce a regulated system to a single automaton, by keeping the original systems and contract as automaton we keep the system behaviours separate and intact. Permission can only be deduced with this unadulterated behaviour.

Conclusions

- Until now we have focussed on:
  - A formalisation of the meaning of directed deontic operators in a two-party setting;
  - The use of standard techniques from computer science, namely communication and synchronisation, to analyse contracts regulating two parties.
- Practically all the work done on directed obligations and permissions introduces new modalities such as intention, causality, etc.
- Ongoing work:
  - Implicitly-enforced and implicitly-satisfied contracts;
  - The notion of violations *within* the contracts so as to allow satisfactory handling of notions such as *contrary-to-duty* clauses;
  - Dealing with multi-party ($n > 2$) systems.