Model Checking Contracts
A case study

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Contracts

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This deed of Agreement is made between:
1. [name], from now on referred to as Provider and
2. the Client.

INTRODUCTION
3. The Provider is obliged to provide the Internet Services as stipulated in this Agreement.
4. DEFINITIONS
   a) Internet traffic may be measured by both Client and Provider by means of Equipment and may take the two values high and normal.

OPERATIVE PART
1. The Client shall not supply false information to the Client Relations Department of the Provider.
2. Whenever the Internet Traffic is high then the Client must pay [price] immediately, or the Client must notify the Provider by sending an e-mail specifying that he will pay later.
3. If the Client delays the payment as stipulated in 2, after notification he must immediately lower the Internet traffic to the normal level, and pay later twice (2 * [price]).
4. If the Client does not lower the Internet traffic immediately, then the Client will have to pay 3 * [price].
5. The Client shall, as soon as the Internet Service becomes operative, submit within seven (7) days the Personal Data Form from his account on the Provider’s web page to the Client Relations Department of the Provider.
Contracts

- We call the above a conventional contract
- An e-contract is a machine-readable contract

Two scenarios:

1. Obtain an e-contract from a conventional contract
   - Context: legal (e.g. financial) contracts
2. Write the e-contract directly in a formal language
   - Context: web services, components, OO, etc

Definition

A contract is a document which engages several parties in a transaction and stipulates their (conditional) obligations, rights, and prohibitions, as well as penalties in case of contract violations.

- A better name: ‘deontic’ e-contracts
Contracts

- We call the above a *conventional contract*
- An *e-contract* is a machine-readable contract

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A contract is a document which engages several parties in a transaction and stipulates their (conditional) obligations, rights, and prohibitions, as well as *penalties in case of contract violations*.

- A better name: ‘deontic’ e-contracts
Aim and Motivation

- Use **deontic e-contracts** to ‘rule’ services exchange

1. Give a **formal language** for specifying/writing contracts
2. Analyze contracts “internally”
   - Detect contradictions/inconsistencies statically
   - Determine the obligations (permissions, prohibitions) of a signatory
   - Detect superfluous contract clauses
3. Develop a **theory of contracts**
   - Contract composition
   - Subcontracting
   - Conformance between a contract and the governing policies
   - *Meta-contracts* (policies)
4. Monitor contracts
   - Run-time system to ensure the contract is respected
   - In case of contract violations, act accordingly
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Outline

1. The Contract Language $\mathcal{CL}$

2. Model Checking Contracts

3. Final Remarks
Outline

1. The Contract Language $CL$

2. Model Checking Contracts

3. Final Remarks
The Contract Specification Language $\mathcal{CL}$

Contract $:=$ $D ; C$

$C$ $:=$ $C_O | C_P | C_F | C \land C | [\alpha]C | \langle \alpha \rangle C | C U C | \bigcirc C | \Box C$

$C_O$ $:=$ $O(\alpha) | C_O \oplus C_O$

$C_P$ $:=$ $P(\alpha) | C_P \oplus C_P$

$C_F$ $:=$ $F(\alpha) | C_F \lor [\alpha]C_F$

- $O(\alpha)$, $P(\alpha)$, $F(\alpha)$ specify obligation, permission (rights), and prohibition (forbidden) over actions
- $\alpha$ are actions given in the definition part $D$
  - $+$ choice
  - $\cdot$ concatenation (sequencing)
  - $\&$ concurrency
  - $\phi?$ test
- $\land$, $\lor$, and $\oplus$ are conjunction, disjunction, and exclusive disjunction
- $[\alpha]$ and $\langle \alpha \rangle$ are the action parameterized modalities of dynamic logic
- $U$, $\bigcirc$, and $\Box$ correspond to temporal logic operators
The Contract Specification Language $\mathcal{CL}$


text content

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The Contract Specification Language $\mathcal{CL}$

$\text{Contract} \quad ::= \quad D ; C$

$C \quad ::= \quad C_O \mid C_P \mid C_F \mid C \land C \mid [\alpha]C \mid \langle \alpha \rangle C \mid C \cup C \mid \bigcirc C \mid \Box C$

$C_O \quad ::= \quad O(\alpha) \mid C_O \oplus C_O$

$C_P \quad ::= \quad P(\alpha) \mid C_P \oplus C_P$

$C_F \quad ::= \quad F(\alpha) \mid C_F \lor [\alpha]C_F$

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The Contract Specification Language $\mathcal{CL}$

\begin{align*}
\text{Contract} & := \quad D ; C \\
C & := \quad C_O \mid C_P \mid C_F \mid C \land C \mid [\alpha]C \mid \langle \alpha \rangle C \mid C \cup C \mid \lozenge C \mid \square C \\
C_O & := \quad O(\alpha) \mid C_O \oplus C_O \\
C_P & := \quad P(\alpha) \mid C_P \oplus C_P \\
C_F & := \quad F(\alpha) \mid C_F \lor [\alpha]C_F
\end{align*}

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- $\alpha$ are actions given in the definition part $D$
  - $+$  choice
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The Contract Specification Language $\mathcal{CL}$

$$\text{Contract} \ := \ \mathcal{D} \ ; \ \mathcal{C}$$

$$\mathcal{C} \ := \ \mathcal{C}_O \mid \mathcal{C}_P \mid \mathcal{C}_F \mid \mathcal{C} \land \mathcal{C} \mid [\alpha]\mathcal{C} \mid \langle \alpha \rangle \mathcal{C} \mid \mathcal{C} \cup \mathcal{C} \mid \bigcirc \mathcal{C} \mid \square \mathcal{C}$$

- $O(\alpha)$, $P(\alpha)$, $F(\alpha)$ specify obligation, permission (rights), and prohibition (forbidden) over actions
- $\alpha$ are actions given in the definition part $\mathcal{D}$
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- $\mathcal{U}$, $\bigcirc$, and $\square$ correspond to temporal logic operators
Expressing contrary-to-duty (CTD)

\[ O_C(\alpha) = O(\alpha) \land [\overline{\alpha}]C \]
More on the Contract Language

CTD and CTP

Expressing **contrary-to-duty** (CTD)

\[ O_C(\alpha) = O(\alpha) \land [\overline{\alpha}]C \]

Expressing **contrary-to-prohibition** (CTP)

\[ F_C(\alpha) = F(\alpha) \land [\alpha]C \]
Translation into a variant of $\mu$-calculus ($C\mu$)

The syntax of the $C\mu$ logic

$$\varphi ::= P \mid Z \mid P_c \mid T \mid \neg \varphi \mid \varphi \land \varphi \mid [\gamma] \varphi \mid \mu Z. \varphi(Z)$$

Main differences with respect to the classical $\mu$-calculus:

1. $P_c$ is set of propositional constants $O_a$ and $F_a$, one for each basic action $a$

2. Multisets of basic actions: i.e. $\gamma = \{a, a, b\}$ is a label
**CL Semantics**

Cμ – A variant of the modal μ-calculus

- Translation into a variant of μ-calculus (Cμ)
- The syntax of the Cμ logic

\[ \varphi ::= P | Z | P_c | \top | \neg \varphi | \varphi \land \varphi | [\gamma] \varphi | \mu Z. \varphi(Z) \]

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Obligation

\[ f^T (O(a \& b)) = \langle \{a, b\} \rangle (O_a \land O_b) \]
Obligation

\[ f^T(O(a \& b)) = \langle \{a, b\}\rangle (O_a \land O_b) \]
Outline

1. The Contract Language $\mathcal{CL}$

2. Model Checking Contracts

3. Final Remarks
1. Model the conventional contract (in English) as a $CL$ expression
2. Translate the $CL$ specification into $C_\mu$
3. Obtain a Kripke-like model (LTS) from the $C_\mu$ formulas
4. Translate the LTS into the input language of NuSMV
5. Perform model checking using NuSMV
   - Check the model is ‘good’
   - Check some properties about the client and the provider
6. In case of a counter-example given by NuSMV, interpret it as a $CL$ clause and repeat the model checking process until the property is satisfied
7. In some cases rephrase the original contract
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7. In some cases rephrase the original contract
1. The **Client** shall not:
   a) supply false information to the Client Relations Department of the **Provider**.
2. Whenever the Internet Traffic is **high** then the **Client** must pay [price] immediately, or the **Client** must notify the **Provider** by sending an e-mail specifying that he will pay later.
3. If the **Client** delays the payment as stipulated in 2, after notification he must immediately lower the Internet traffic to the **normal** level, and pay later twice (2 * [price]).
4. If the **Client** does not lower the Internet traffic immediately, then the **Client** will have to pay 3 * [price].
5. The **Client** shall, as soon as the Internet Service becomes operative, submit within seven (7) days the Personal Data Form from his account on the **Provider**’s web page to the Client Relations Department of the **Provider**.
6. **Provider** may, at its sole discretion, without notice or giving any reason or incurring any liability for doing so:
   a) Suspend Internet Services immediately if **Client** is in breach of Clause 1;
1. The **Client** shall not:
a) supply false information to the Client Relations Department of the **Provider**.

2. Whenever the Internet Traffic is **high** then the **Client** must pay \([price]\) immediately, or the **Client** must notify the **Provider** by sending an e-mail specifying that he will pay later.

3. If the **Client** delays the payment as stipulated in 2, after notification he must immediately lower the Internet traffic to the **normal** level, and pay later twice \((2 \times [price])\).

4. If the **Client** does not lower the Internet traffic immediately, then the **Client** will have to pay \(3 \times [price]\).

5. The **Client** shall, as soon as the Internet Service becomes operative, submit within seven (7) days the Personal Data Form from his account on the **Provider**’s web page to the Client Relations Department of the **Provider**.

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Case Study
Translating into $CL$ syntax

1. $\Box F(f_i)$

2. Whenever the Internet Traffic is high then the Client must pay $[price]$ immediately, or the Client must notify the Provider by sending an e-mail specifying that he will pay later.

3. If the Client delays the payment as stipulated in 2, after notification he must immediately lower the Internet traffic to the normal level, and pay later twice $(2 \times [price])$.

4. If the Client does not lower the Internet traffic immediately, then the Client will have to pay $3 \times [price]$.

5. The Client shall, as soon as the Internet Service becomes operative, submit within seven (7) days the Personal Data Form from his account on the Provider’s web page to the Client Relations Department of the Provider.

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a) Suspend Internet Services immediately if Client is in breach of Clause 1;
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Translating into $CL$ syntax

1. $\square F(f_i)$

2. Whenever the Internet Traffic is high then the Client must pay $[price]$ immediately, or the Client must notify the Provider by sending an e-mail specifying that he will pay later.
3. If the Client delays the payment as stipulated in 2, after notification he must immediately lower the Internet traffic to the normal level, and pay later twice $(2 \ast [price])$.
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   a) Suspend Internet Services immediately if Client is in breach of Clause 1;
Case Study
Translating into $CL$ syntax

1. $\Box F_{P(s)}(fi)$

2. Whenever the Internet Traffic is high then the Client must pay [price] immediately, or the Client must notify the Provider by sending an e-mail specifying that he will pay later.

3. If the Client delays the payment as stipulated in 2, after notification he must immediately lower the Internet traffic to the normal level, and pay later twice ($2 \times [price]$).

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Case Study
Translating into $\mathcal{CL}$ syntax

1. $\square F_{P(s)}(f_i)$

2. $\square[h](\phi \Rightarrow O(p + (d\&n)))$

3. If the Client delays the payment as stipulated in 2, after notification he must immediately lower the Internet traffic to the normal level, and pay later twice $(2 \times [\text{price}])$.

4. If the Client does not lower the Internet traffic immediately, then the Client will have to pay $3 \times [\text{price}]$.

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1. $\Box F_{P(s)}(fi)$

2. $\Box[h](\phi \Rightarrow O(p + (d\&n)))$

3. $\Box([d\&n](O(I) \land [I]O(p\&p)))$

4. If the **Client** does not lower the Internet traffic immediately, then the **Client** will have to pay $3 \times [price]$.  
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Case Study
Translating into \( \mathcal{CL} \) syntax

1. \( \square F_{P(s)}(fi) \)

2. \( \square [h](\phi \Rightarrow O(p + (d\&n))) \)

3. \( \square ([d\&n](O(l) \land [l]\diamond O(p\&p))) \)

4. \( \square ([d\&n \cdot \bar{l}]\diamond O(p\&p\&p)) \)

5. The **Client** shall, as soon as the Internet Service becomes operative, submit within seven (7) days the Personal Data Form from his account on the **Provider**’s web page to the Client Relations Department of the **Provider**.
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Translating into $\mathcal{CL}$ syntax

1. $\Box F_{P(s)}(fi)$

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3. $\Box([d\&n](O(l) \land [l]\Diamond O(p\&p)))$

4. $\Box([d\&n \cdot \bar{I}]\Diamond O(p\&p\&p))$

5. $\Box([o]O(sfD))$
Case Study
Handcrafting the model

$\phi = \text{the Internet traffic is high}$

$f_i = \text{client supplies false information}$
  to Client Relations Department

$h = \text{client increases Internet traffic}$
  to high level

$p = \text{client pays [price]}$

$d = \text{client delays payment}$

$n = \text{client notifies by e-mail}$

$l = \text{client lowers the Int. traffic}$

$s f D = \text{client sends the Personal}$
  Data Form to Client Relations Department

$o = \text{provider activates the Internet}$
  Service (it becomes operative)

$s = \text{provider suspends service}$
\( \phi = \) the Internet traffic is high

\( f_i = \) client supplies false information to Client Relations Department

\( h = \) client increases Internet traffic to high level

\( p = \) client pays [price]

\( d = \) client delays payment

\( n = \) client notifies by e-mail

\( l = \) client lowers the Internet traffic

\( sfD = \) client sends the Personal Data Form to Client Relations Department

\( o = \) provider activates the Internet Service (it becomes operative)

\( s = \) provider suspends service
Case Study
Checking the contract on the model

1. $\square F_{P(s)}(fi)$
2. $\square[h](\phi \Rightarrow O(p + (d\&n)))$
3. $\square([d\&n](O(\bar{l}) \land [\bar{l}]\diamond O(p\&p)))$
4. $\square([d\&n \cdot \bar{l}]\diamond O(p\&p\&p))$
5. $\square([o]O(sfD))$
Case Study
Checking the contract on the model

1. $\square F_{P(s)}(fi)$
2. $\square [h](\phi \Rightarrow O(p + (d\&n)))$
3. $\square ([d\&n](O(l) \land [l]O(p\&p)))$
4. $\square ([d\&n \cdot \bar{l}]O(p\&p\&p))$
5. $\square ([o]O(sfD))$

1, 2, and 4: OK
Case Study
Checking the contract on the model

1. □\(F_{P(s)}(fi)\)
2. □[h](\(\phi \Rightarrow O(p + (d\&n))\))
3. □([d\&n](O(l) \land [l] O(p\&p)))
4. □([d\&n \cdot \bar{l}] O(p\&p\&p))
5. □([o] O(sfD))

1, 2, and 4: OK
3 and 5: FAIL!
**Case Study**

Checking the contract on the model (cont.)

**Failure of 3.** It fails since there is a dependency with clause 2
- We need to combine clauses 2 and 3: it model checks!
Failure of 3. It fails since there is a dependency with clause 2
  - We need to combine clauses 2 and 3: it model checks!

Failure on our formalization in $\mathcal{CL}$!
Failure of 3. It fails since there is a dependency with clause 2

- We need to combine clauses 2 and 3: it model checks!

**Failure on our formalization in $\mathcal{CL}$!**

Failure of 5. ($\Box([o]O(sfD)))$

- The system should become operative only once
Case Study

Checking the contract on the model (cont.)

Failure of 3. It fails since there is a dependency with clause 2

- We need to combine clauses 2 and 3: it model checks!

Failure on our formalization in $CL$!

Failure of 5. ($\square([o]O(sfD)))$

- The system should become operative only once

1. We rewrite the original contract
2. This is formulated in $CL$, written in NuSMV, and it model checks!
Case Study
Checking the contract on the model (cont.)

Failure of 3. It fails since there is a dependency with clause 2
  - We need to combine clauses 2 and 3: it model checks!
  Failure on our formalization in $C\mathcal{L}$!

Failure of 5. ($\Box([o]O(sfD)))$
  - The system should become operative only once
    - We rewrite the original contract
    - This is formulated in $C\mathcal{L}$, written in NuSMV, and it model checks!

'Failure' on the original contract!
Case Study
Verifying a property about client obligations

“It is always the case that whenever the Internet traffic is high, if the clients pays immediately, then the client is *not* obliged to pay again immediately afterward”
Case Study
Verifying a property about client obligations

• “It is always the case that whenever the Internet traffic is high, if the clients pays immediately, then the client is not obliged to pay again immediately afterward”

• It fails!
Case Study
Verifying a property about client obligations

- “It is always the case that whenever the Internet traffic is high, if the clients pays immediately, then the client is not obliged to pay again immediately afterward”
- It fails!
- We get a counter-example
  - Problem: state s4
Case Study
Verifying a property about client obligations

“It is always the case that whenever the Internet traffic is high, if the clients pays immediately, then the client is not obliged to pay again immediately afterward”

It fails!

We get a counter-example
- Problem: state s4

We modify the original contract to capture the above more precisely
Case Study
Verifying a property about payment in case of increasing Internet traffic

“It is always the case that whenever Internet traffic is high, if the client delays payment and notifies, and afterward lowers the Internet traffic, then the client is forbidden to increase Internet traffic until he pays twice”
Case Study
Verifying a property about payment in case of increasing Internet traffic

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It fails!
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Counter-example: From $s_4$ ($\phi$ holds), after $d \& n \cdot l$, it is possible to increase Internet traffic in state $s_7$, so neither $F(h)$ nor $\text{done}_{p} \& p$ hold
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- Add to the original contract the clause above!
Outline

1. The Contract Language $CL$

2. Model Checking Contracts

3. Final Remarks
Model Checking Contracts

- Initial ideas on how to model check contracts

Based on:

- A formal specification language for contracts with semantics based on a variant of $\mu$-calculus
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Use of model checking for reasoning about contracts:

1. We use model checking to increase our confidence in the correctness of the model with respect to the original natural language contract
2. By finding errors in the model, we identify problems in the original natural language contract or its interpretation in $\mathcal{CL}$
3. We enable the signatories to safeguard their interests by ensuring certain desirable properties hold (and certain undesirable ones do not)
Currently:

- Direct semantics: “Normative” automata
- Redesign $\mathcal{CL}$
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Further work:
- Develop a proof system
- Internal vs external operations
- Add time
- Case studies
- Explore how to extract a contract monitor (?!)
Thank you!
Links and Papers


- COSoDIS: “Contract-Oriented Software Development for Internet Services” – A Nordunet3 project (http://folk.uio.no/gerardo/nordunet3/index.shtml)

- FLACOS’07 – 1st Workshop on Formal Languages and Analysis of Contract-Oriented Software (http://www.ifi.uio.no/flacos07/)
  - Oslo, 9-10 October 2007