

Complete Lattices and Up-to Techniques

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- **Bisimilarity**: a behavioural equivalence associated with a proof technique: **bisimulation**.

"To prove that p and q are bisimilar, it suffices to show that p and q are related by a relation which is a bisimulation".

- Up-to techniques, "bisimulation up-to":

*"To prove that p and q are bisimilar, it suffices to show that p and q are related by a relation which is **almost** a bisimulation".*

- Not only for π -calculus: growing interest in bisimulation proof methods for extensions of the λ -calculus.

Outline

1. A concrete toy example to get started,
2. General and abstract theory of up-to techniques,
3. A new method for validating up-to context techniques.

A typical bisimulation proof

- Bisimilarity is the largest symmetric relation such that the following diagram holds:

$$\begin{array}{ccc} p & \sim & q \\ \alpha \downarrow & & \downarrow \alpha \\ p' & \sim & q' \end{array}$$

- Suppose we have an LTS, with a replication operator (!), defined by the following rule:

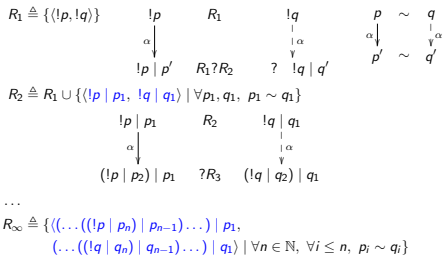
$$\frac{p \xrightarrow{\alpha} p'}{!p \xrightarrow{\alpha} !p \mid p'}$$

let's prove that bisimilarity is preserved by this operator:

$$p \sim q \Rightarrow !p \sim !q$$

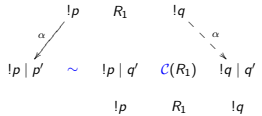
A typical bisimulation proof, cont.

Assuming that $p \sim q$, we have to find a relation that contains $\langle !p, !q \rangle$ and satisfies the previous diagram.



A typical bisimulation up-to proof

- Start again with the singleton relation: $R_1 \triangleq \{ \langle !p, !q \rangle \}$



- R_1 is a **bisimulation up to** the map $R \mapsto \sim \mathcal{C}(R) \sim$.
- This up-to technique is actually correct, we have proved that $R_1 \subseteq \sim$.

A Theory of Up-to Techniques

Challenge 1: modularity

- Other examples of up-to techniques:
 - based on diagram chasing arguments:
 - $R \mapsto \sim R \sim$ (more modular proofs)
 - $R \mapsto R^*$ (small and local candidates)
 - $R \mapsto \sim R \approx$ (patch for the weak case)
 - based on the structure of processes:
 - \mathcal{C} (keep small processes)
 - σ "injective substitution" (work with fewer names)
- Some of these techniques they may be delicate to obtain.
- We often want to combine these techniques, to obtain a powerful one.

Challenge 2: abstraction

- ▶ Several kinds of bisimilarity:
 1. several kinds of transition systems (π , λ , ...)
 2. strong (\sim), weak (\approx), expansion (\gtrsim), coupled...
 3. labelled, barbed, hedged, typed, with environments...
- ▶ The notion of LTS give the first level of abstraction: we don't need to fix the set of processes.
- ▶ The theory of up-to techniques can be defined at the abstract level of **complete lattices**; In doing this, we will reason about **coinduction** in general, rather than about a specific form of bisimilarity.

(we will actually use this gain of generality)

 - ▶ We enrich the complete lattice with a monoid structure to define bisimilarity, and diagram based techniques
 - ▶ For up-to context techniques, we need to work with concrete relations, however.

Up-to techniques

- ▶ A diagram becomes a simple inclusion:

$$\begin{array}{ccc}
 p & R & q \\
 \alpha \downarrow & & \downarrow \alpha \\
 p' & R & q' \\
 R \subseteq s(R) & & R \subseteq s(f(R))
 \end{array}$$

- ▶ A map f is **correct** if any simulation up to f is contained in similarity, or equivalently, if

$$\nu(s \circ f) \subseteq \nu s .$$

- ▶ Different maps may generate the same similarity, and some of them are easier to work with; we would like to find the "largest" one.
- ▶ **Problem with correct maps**: they are not always preserved by composition or lubs.

Coinduction

- ▶ Assume a complete lattice $\langle X, \subseteq, \bigcup \rangle$ (elements of X (R, S, \dots) intuitively represent binary relations)
- ▶ Knaster-Tarski theorem ensures that any order preserving map $s : X \rightarrow X$ has a greatest fixpoint, obtained as the lub of its post-fixpoints:

$$\nu s \triangleq \bigcup \{R \in X \mid R \subseteq s(R)\} .$$

- ▶ We introduce the following terminology:
 - ▶ νs is called the **similarity**,
 - ▶ a **simulation** is an element R s.t. $R \subseteq s(R)$,
 "similarity is the greatest simulation"
 (almost all notions of bisimilarity can be defined in this way)
 - ▶ a **simulation up to f** is an element R s.t. $R \subseteq s(f(R))$,

Compatible maps

- ▶ An order-preserving map f is **compatible** (with s) if

$$f \circ s \subseteq s \circ f .$$

Proposition.

- ▶ *Compatible maps are correct maps.*
- ▶ *Compatible maps are closed under composition and lubs.*
- ▶ In the case of strong/weak bisimilarity, all known up-to techniques can be expressed by means of compatible maps [San98]...
- ▶ **except for recent ones**, that go beyond the "up to expansion" technique by using termination hypotheses [Pou05].

Combining correct and compatible maps

These recent techniques being only correct, they could not be combined for free, even with standard (compatible) techniques.

The following theorem gives a sufficient condition for such a combination to remain correct:

Composition Theorem.

Let g be *correct* and f be *compatible*.

If f is *compatible* with g , then $g \circ f$ is *correct*.

(surprisingly, the sufficient condition is a compatibility property)

An application of the composition theorem

Complex technique. Let \succ be a relation. If $\succ^+ \cdot \tau^+$ is strongly normalising, then the following map is *correct*

$$t_{\succ} : R \mapsto (R \cap \succ)^* \cdot R.$$

Standard technique. The following map is *compatible*

$$f : R \mapsto \mathcal{C}(R)^= \cdot \approx.$$

To combine both techniques, it suffices that f be compatible with t_{\succ} . A sufficient condition for that is $\mathcal{C}(\succ) \subseteq \succ$.

Combined, scary technique. If $\succ^+ \cdot \tau^+$ is strongly normalising, and $\mathcal{C}(\succ) \subseteq \succ$, then any symmetric relation satisfying the following diagram is contained in \approx :

$$\begin{array}{ccccc} p & & R & & q \\ \alpha \downarrow & & & & \Downarrow \hat{\alpha} \\ p' & & ((\mathcal{C}(R) \cup \approx) \cap \succ)^* \cdot \mathcal{C}(R)^= \cdot \approx & & q' \end{array}$$

Transition

Up to context techniques

► The following situation may appear in a bisimulation game:

$$\begin{array}{ccccc} & p & R & q & \\ \alpha \swarrow & & & & \searrow \alpha \\ c[p'] & & \mathcal{C}(R) & & c[q'] \\ p' & & R & & q' \end{array}$$

- We have an abstract setting that allows one to combine up-to techniques in an easy way.
- We need some techniques to start with...
 - Standard diagram based techniques, for weak and strong bisimilarities. (in the paper)
 - "Up-to context": we propose a new method for proving their validity. (rest of this talk)

- In this case, we would like to reason "up to context", and just remove the context part of the processes.
- These techniques generally fall in the scope of compatible maps; however, proving this usually requires us:
 - in most cases, to consider polyadic contexts;
 - to reason by induction on the structure of these contexts.

Consider the case of CCS:

$$p, q ::= \mathbf{0} \mid (\nu a)p \mid \alpha.p \mid p \mid q \mid !p$$

- ▶ A polyadic context c is a process whose occurrences of $\mathbf{0}$ are numbered; $c[p_1 \dots p_n]$ is the term obtained by replacing numbered occurrences; we associate to each context the following map over relations:

$$[c] : R \mapsto \{ \langle c[p_1, \dots, p_n], c[q_1, \dots, q_n] \rangle \mid \forall i, p_i R q_i \}$$

- ▶ The **context closure** is the map $\mathcal{C} \triangleq \bigcup_c [c]$.
- ▶ Proving the compatibility of \mathcal{C} directly requires a tedious structural induction.

- ▶ Define the following **initial contexts**:

$$\begin{array}{lll} \mathbf{0} : \emptyset \mapsto \mathbf{0} & (\nu a) : p \mapsto (\nu a)p & \alpha. : p \mapsto \alpha.p \\ & & ! : p \mapsto !p \\ & & \mid : p, q \mapsto p \mid q \end{array}$$

- ▶ By iterating over these contexts, we can reach the previous definition of context closure:

Proposition.

$$\mathcal{C} = \left(\text{id} \cup \bigcup_{c \text{ initial}} [c] \right)^\omega.$$

- ▶ Therefore, it should suffice to prove that maps $[c]$ are compatible, where c is initial. **Unfortunately**, $[\!|\!]$ is not compatible by itself (\mathcal{C} is, don't worry...).

Up-to techniques for compatibility

- ▶ Recall that f is compatible if $f \circ s \subseteq s \circ f$.
- ▶ This property can be defined **coinductively**, by working in the **function space** (which is a complete lattice): there exist a second-order map φ s.t.:

$$f \subseteq \varphi(g) \iff f \circ s \subseteq s \circ g \quad (\text{notation: } f \overset{s}{\mapsto} g).$$

- ▶ We have a theory of up-to techniques for compatibility!

Theorem. If $f \overset{s}{\mapsto} f^\omega$, then f^ω is compatible.

Theorem. If g is compatible, and $f \overset{s}{\mapsto} g \circ f^\omega$, then $g \circ f^\omega$ is compatible.

(in both cases, under some uninteresting technical conditions on f and g , easily satisfied in practise)

The initial contexts method

- ▶ We want to prove that \mathcal{C} is compatible, i.e., that $\mathcal{C} \overset{s}{\mapsto} \mathcal{C}$.
- ▶ Proving $[c] \overset{s}{\mapsto} [c]$ for any initial context is sufficient, but may not always be possible;
- ▶ Thanks to the “up to iteration” technique, it suffices to prove $[c] \overset{s}{\mapsto} \mathcal{C}$ for any initial context. This amounts to checking a **simple condition** between **each syntactic construction** of the language and the map that generates the bisimilarity we consider.
- ▶ This method is complete; in CCS, in the strong case, we have:

$$[\!|\!] \overset{s}{\mapsto} [\!|\!]^\omega \circ ([\!|\!] \cup \text{id}) \subseteq \mathcal{C}$$

- ▶ in the weak case, we found a mistake in the standard proof [SW01]: \mathcal{C} itself is not compatible, we have to reason modulo unfolding of replications.

- ▶ A general theory of up to techniques for coinduction: compatible and correct maps that can be composed.
- ▶ A theory of up to techniques for compatibility,
- ▶ used to define a method for validating up to context techniques in an easy way (initial contexts)
- ▶ More in the paper:
 - ▶ going from one-sided games to two-sided games, at the abstract level.
 - ▶ proof of the scary technique based on termination guarantees;
 - ▶ detailed proofs for up to context in CCS,
 - ▶ a counter-example for an invalid combination of up to context and a restricted form of up to transitivity.

- ▶ We cannot encompass the recent “logical bisimulations” [SKS07a], but it seems that we can analyse the even more recent “environment bisimulations” [SKS07b].
- ▶ Up-to techniques relying on termination hypotheses can be proved at the abstract (point-free) level [DBvdW97].
- ▶ Parts of the theory presented here are formalised in the Coq proof assistant; in the long term, we would like to define a framework in which bisimulation proofs could be done formally and easily, in a semi-automatic way.
- ▶ Can SOS rule formats for congruence (tyft/tyxt, panth...) be turned into rule formats for up-to context techniques?

Thanks!