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Axiomatizing Lüttgen & Vogler's ready simulation for finite processes in CLL_R ☆

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A B S T R A C T

In the framework of logic labelled transition systems, a variant of weak ready simulation has been presented by Lüttgen and Vogler. It has been shown that such behavioural preorder is the largest precongruence w.r.t. parallel and conjunction composition satisfying some desirable properties. This paper offers a ground-complete axiomatization for this precongruence over processes containing no recursion in the calculus CLL_R. Compared with the usual inference systems for process calculi, in addition to axioms about process operators, such system contains a number of axioms to characterize the interaction between process operators and logical operators.

1. Introduction

It is well-known that process algebra and temporal logic take different standpoints for looking at specifications and verifications of reactive and concurrent systems, and offer complementary advantages [25]. To take advantage of these two paradigms when designing systems, a few theories for heterogeneous specifications have been proposed, e.g., [8,9,11,12,15,17,19–21,24]. Among them, Lüttgen and Vogler propose the notion of logic labelled transition system (Logic LTS or LLTS for short), which combines operational and logical styles of specification in one unified framework [19–21]. In particular, a variant of weak ready simulation has been presented in [20], which is adopted to capture a refinement relation between processes in the presence of logical operators. It has been shown that such simulation preorder is the largest precongruence w.r.t. parallel and conjunction satisfying the desirable property that an inconsistent specification can only be refined by inconsistent ones [20]. Moreover, in addition to the usual process operators (e.g., CSP-style parallel composition, hiding, etc.) and logic operators (disjunction and conjunction), some standard temporal logic

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operators, such as "always" and "unless", are also integrated into this framework [21]. In summary, Lüttgen and Vogler offer a framework which allows one to freely mix operational and logic operators when designing systems.

Lüttgen and Vogler's approach is entirely semantic, and doesn't provide any kind of syntactic calculus. Recently, the first three authors of this paper explore recursive operations over LLTS in a pure process-algebraic style. An LLTS-oriented process calculus CLL_R[1] is presented, and the uniqueness of solutions of equations of the form $X = t_X$ in CLL_R is established under the hypothesis that X is strongly guarded and does not occur in the scope of any conjunction in t_X [26].

Axiomatizing behavioural congruences is one of the classic topics in concurrency theory. For example, Milner gives an axiomatization for observational congruence over the regular fragment of CCS [23]; Baeten and Bravetti extend Milner's this work and provide an axiomatization over $\mathrm{TCP}+\mathrm{REC}_f$ [2], where $\mathrm{TCP}+\mathrm{REC}_f$ is a fragment of TCP + REC which is a generic process language that embodies features of the classical process algebras CCS, CSP and ACP; Lin offers complete inference systems for late and early weak bisimulation equivalences for processes without involving recursion in the π-calculus [18]; Aceto et al. explore the axiomatization of weak simulation semantics systematically over BCCSP (without recursion) [1]. Although Lüttgen and Vogler's original paper [20] mentions some sound laws, they have not provided an axiomatization for the weak ready simulation preorder considered in Logic LTS. As the main contribution of this paper we intend to provide a proof system for such behavioural relation over CLL_R-processes with finite behaviour, and demonstrate its soundness and ground-completeness.

The rest of this paper is organized as follows. The notion of Logic LTS and the calculus CLL_R are recalled in the next section. The inference system is presented in Section 3, along with the soundness proof. Section 4 demonstrates that the inference system is ground-complete for processes with finite behaviour. The paper is concluded with Section 5, where we discuss the axiomatization of ready simulation over the regular fragment of CLL_R.

2. Preliminaries

The purpose of this section is to fix our notation and terminology, and to introduce some concepts that underlie our work in all other parts of the paper.

2.1. Logic LTS and ready simulation

Let Act be the set of visible action names ranged over by a, b, etc., and let Act_τ denote $Act \cup \{\tau\}$ ranged over by α and β, where τ represents invisible actions. A labelled transition system with predicate is a quadruple $(P, Act_\tau, \rightarrow, F)$, where P is a set of states, $\rightarrow \subseteq P \times Act_\tau \times P$ is the transition relation and $F \subseteq P$.

As usual, we write $p \stackrel{\alpha}{\rightarrow}$ if $\exists q \in P.p \stackrel{\alpha}{\rightarrow} q$, otherwise we write $p \stackrel{\alpha}{\not\rightarrow}$. The ready set $\{\alpha \in Act_\tau \mid p \stackrel{\alpha}{\rightarrow}\}$ of a given state p is denoted by $\mathcal{I}(p)$. A state p is stable if $p \stackrel{\tau}{\not\rightarrow}$. A number of useful decorated transition relations are given:

$p \stackrel{\alpha}{\rightarrow}_F q$ iff $p \stackrel{\alpha}{\rightarrow} q$ and $p, q \notin F$;

$p \stackrel{\epsilon}{\Rightarrow} q$ iff $p(\stackrel{\tau}{\rightarrow})^* q$, where $(\stackrel{\tau}{\rightarrow})^*$ is the transitive and reflexive closure of $\stackrel{\tau}{\rightarrow}$;

$p \stackrel{\alpha}{\Rightarrow} q$ iff $\exists r, s \in P.p \stackrel{\epsilon}{\Rightarrow} r \stackrel{\alpha}{\rightarrow} s \stackrel{\epsilon}{\Rightarrow} q$;

$p \stackrel{\gamma}{\Rightarrow} |q$ iff $p \stackrel{\gamma}{\Rightarrow} q \stackrel{\tau}{\not\rightarrow}$ with $\gamma \in Act_\tau \cup \{\epsilon\}$;

$p \stackrel{\epsilon}{\Rightarrow}_F q$ iff there exists a sequence of τ-transitions from p to q such that all states along this sequence, including p and q, are not in F; the decorated transition $p \stackrel{\alpha}{\Rightarrow}_F q$ may be defined similarly;

$p \stackrel{\gamma}{\Rightarrow}_F |q$ iff $p \stackrel{\gamma}{\Rightarrow}_F q \stackrel{\tau}{\not\rightarrow}$ with $\gamma \in Act_\tau \cup \{\epsilon\}$.

[1] CLL_R is a shorthand of A Calculus of Logic LTS. Here the index R is used to emphasize that this calculus contains recursion.