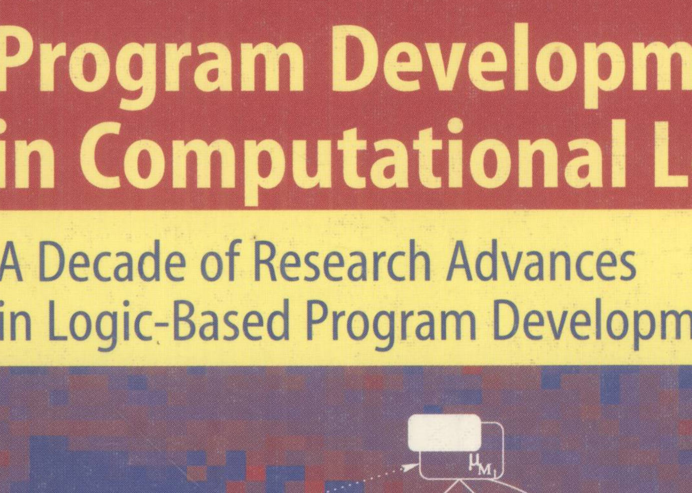
State-of-the-Art Survey

LNCS 3049

Maurice Bruynooghe
Kung-Kiu Lau (Eds.)

Program Development in Computational Logic

A Decade of Research Advances in Logic-Based Program Development



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Library of Congress Control Number: 2004107507

CR Subject Classification (1998): F.3.1, D.1.1, D.1.6, I.2.2, F.4.1, D.2, D.3

ISSN 0302-9743
ISBN 3-540-22152-2 Springer-Verlag Berlin Heidelberg New York

Typesetting: Camera-ready by author, data conversion by Boller Mediendesign
Printed on acid-free paper SPIN: 11012061 06/3142 5 4 3 2 1 0

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Preface

The tenth anniversary of the LOPSTR[1] symposium provided the incentive for this volume. LOPSTR started in 1991 as a workshop on logic program synthesis and transformation, but later it broadened its scope to logic-based program development in general, that is, program development in computational logic, and hence the title of this volume.

The motivating force behind LOPSTR has been the belief that declarative paradigms such as logic programming are better suited to program development tasks than traditional non-declarative ones such as the imperative paradigm. Specification, synthesis, transformation or specialization, analysis, debugging and verification can all be given logical foundations, thus providing a unifying framework for the whole development process.

In the past 10 years or so, such a theoretical framework has indeed begun to emerge. Even tools have been implemented for analysis, verification and specialization.

However, it is fair to say that so far the focus has largely been on programming-in-the-small. So the future challenge is to apply or extend these techniques to programming-in-the-large, in order to tackle software engineering in the real world.

Returning to this volume, our aim is to present a collection of papers that reflect significant research efforts over the past 10 years. These papers cover the whole development process: specification, synthesis, analysis, transformation and specialization, as well as semantics and systems.

We would like to thank all the authors for their valuable contributions that made this volume possible. We also thank the reviewers for performing their arduous task meticulously and professionally: Annalisa Bossi, Nicoletta Cocco, Bart Demoen, Danny De Schreye, Yves Deville, Sandro Etalle, Pierre Flener, John Gallagher, Samir Genaim, Gopal Gupta, Ian Hayes, Patricia Hill, Andy King, Vitaly Lagoon, Michael Leuschel, Naomi Lindenstrauss, Nancy Mazur, Mario Ornaghi, Dino Pedreschi, Alberto Pettorossi, Maurizio Proietti, CR Ramakrishnan, Sabina Rossi, Abhik Roychoudhury, Salvatore Ruggieri, Tom Schrijvers, Alexander Serebrenik, Jan-Georg Smaus, Wim Vanhoof and Sofie Verbaeten.

April 2004 Maurice Bruynooghe and Kung-Kiu Lau

[1] http://www.cs.man.ac.uk/~kung-kiu/lopstr/

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Specifying Compositional Units for Correct Program Development in Computational Logic

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Abstract. In order to provide a formalism for defining program correctness and to reason about program development in Computational Logic, we believe that it is better to distinguish between specifications and programs. To this end, we have developed a general approach to specification that is based on a model-theoretic semantics. In our previous work, we have shown how to define specifications and program correctness for open logic programs. In particular we have defined a notion of correctness called *steadfastness*, that captures at once modularity, reusability and correctness. In this paper, we review our past work and we show how it can be used to define compositional units that can be correctly reused in modular or component-based software development.

1 Introduction

In software engineering, requirements analysis, design and implementation are distinctly separate phases of the development process [18], as they employ different methods and produce different artefacts. In requirements analysis and design, *specifications* play a central role, as a frame of reference capturing the requirements and the design decisions. By contrast, data and programs only appear in the implementation phase, towards the end of the development process. There is therefore a clear distinction between specifications and programs.

In Computational Logic, however, this distinction is usually not maintained. This is because there is a widely held view that logic programs are executable specifications and therefore there is no need to produce specifications before the implementation phase of the development process. We believe that undervaluing specifications in this manner is not an ideal platform for program development. If programs are indistinguishable from specifications, then how do we define program correctness, and how do we reason about program development? We hold the view that the meaning of correctness must be defined in terms of something other than logic programs themselves. We are not alone in this, see e.g., [17, p. 410]. In our view, the specification should axiomatise all our relevant knowledge of the problem context and the necessary data types, whereas, for complexity reasons, programs rightly capture only what is strictly necessary for computing. In the process of extracting programs from specifications, a lot of knowledge is lost, making programs much weaker axiomatisations. This suggests that specifying and programming are different activities, involving different methodological aspects. Thus, we take the view that specifications should be clearly distinguished from programs, especially for the purpose of program development. Indeed, we have shown (in [28,29]) that in Computational Logic, not only can we maintain this distinction, but we can also define various kinds of specifications for different purposes. Moreover, we can also define correctness with respect to these specifications.

Our semantics for specification and correctness is model-theoretic. The declarative nature of such a semantics allows us to define *steadfastness* [34], a notion of correctness that captures at once modularity, reusability and correctness. *Open* programs are incomplete pieces of code that can be (re)used in many different *admissible* situations, by *closing* them (by adding the missing code) in many different ways. *Steadfastness* of an open program P is pre-proved correctness of the various closures of P, with respect to the different meanings that the specification of P assumes in the admissible situations. For correct reuse, we need to know when a situation is admissible. This knowledge is given by the *problem context.* We have formalised problem context as a *specification framework* [27], namely, a first-order theory that axiomatises the problem context, characterises the admissible situations as its (intended) models, and is used to write specifications and to reason about them.

In this paper, we review our work in *specification* and *correctness* of logic programs, including steadfastness. Our purpose is to discuss the role of steadfastness for correct software development. In particular, we are interested in modularity and reuse, which are key aspects of software development. Our work is centred on the notion of a *compositional unit.* A compositional unit is a *software component*, which is commonly defined as a unit of composition with contractually specified interfaces and context dependencies only [46]. The interfaces declare the imported and exported operations, and the context dependencies specify the constraints that must be satisfied in order to correctly (re)use them. Throughout the paper, we will not refer to compositional units as software components, however, for the simple reason that as yet there is no standard definition for the latter (although the one we used above [46] is widely accepted). So we prefer to avoid any unnecessary confusion. In our compositional units, the interfaces and the context dependencies are declaratively specified in the context of the specification framework $\mathcal{F}$ axiomatising the problem context. $\mathcal{F}$ gives a precise semantics to specifications and allows us to reason about the *correctness* of programs, as well as their *correct reuse.* Thus, in our formalisation, a compositional unit has a three-tier structure, with separate levels for framework, specifications and programs.

We introduce compositional units in Section 2, and consider the three levels separately. We focus on model-theoretic semantics of frameworks and specifications, and on steadfastness (i.e., open program correctness).

In Section 3, we show how the proposed formalisation of compositional units can be used to support correct reuse. Our aim is to highlight the aspects related to specifications, so we consider only the aspects related to the framework and the specification levels, while assuming the possibility of deriving (synthesising) steadfast programs from specifications.

At the end of each section we briefly discuss and compare our results with related work, and finally in the conclusion we comment on future developments.

2 Compositional Units

In our approach, compositional units represent correctly reusable units of *specifications and correct open programs.* Our view is that specifications and programs are not stand-alone entities, but are always to be considered in the light of a problem context. The latter plays a central role: it is the *semantic context* in which specifications and program correctness assume their appropriate meaning, and it contains the necessary knowledge for *reasoning* about correctness and correct reuse. This is reflected in the three-tier structure (with model-theoretic semantics) of a compositional unit, as illustrated in Figure 1.

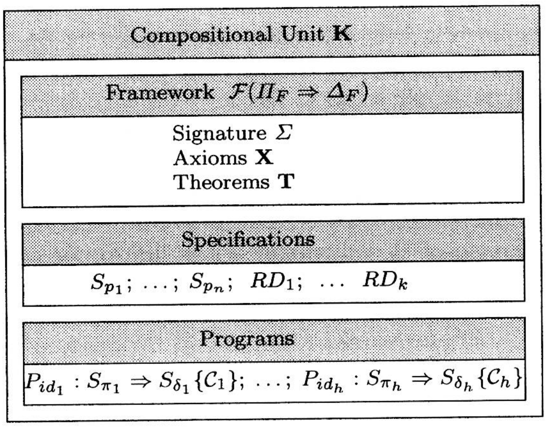
Compositional Unit **K**
Framework $\mathcal{F}(\Pi_F \Rightarrow \Delta_F)$
Signature Σ
Axioms **X**
Theorems **T**
Specifications
$S_{p_1}; \ldots; S_{p_n}; RD_1; \ldots RD_k$
Programs
$P_{id_1} : S_{\pi_1} \Rightarrow S_{\delta_1}\{C_1\}; \ldots; P_{id_h} : S_{\pi_h} \Rightarrow S_{\delta_h}\{C_h\}$

Fig. 1. A three-tier formalism.

At the top level of a compositional unit **K**, we have a *specification framework* $\mathcal{F}$, or *framework* for short, that embodies an axiomatisation of the problem context. $\mathcal{F}$ has a signature Σ, a set **X** of *axioms*, a set **T** of *theorems*, a list Π_F of *open symbols*, and a list Δ_F of *defined symbols*. The syntax $\Pi_F \Rightarrow \Delta_F$ indicates that the axioms of $\mathcal{F}$ fix (the meaning of) the symbols Δ_F whenever $\mathcal{F}$ is composed with frameworks that fix Π_F. The defined and open symbols belong to the signature Σ, which may also contain *closed symbols*, namely symbols defined completely by the axioms (i.e., independently from Π_F). Frameworks are explained in Section 2.1, and framework composition is explained in Section 3.1.

In the middle, we have the *specification section.* Its role is to bridge the gap between the framework $\mathcal{F}$ and the chosen *programming language.* So far, we have considered only logic programs, and the corresponding specification formalism is explained in Section 2.2. The specification section contains the specifications $S_{p_1}, \ldots, S_{p_n}$ of the program predicates occurring in the program section. It may also contain a set of *specification reduction theorems* theorems $RD_1, \ldots, RD_k$, that are useful to reason about correct reuse. Specification reduction is explained in Section 3.2.

At the bottom, we have the *program section.* Programs are open logic (or constraint logic) programs. An open program $P_{id_i} : S_{\pi_i} \Rightarrow S_{\delta_i} \ \{C_i\}$ $(1 \leq i \leq h)$ has an identifier id_i, an *interface specification* $S_{\pi_i} \Rightarrow S_{\delta_i}$ and a set $\{C_i\}$ of *implementation clauses.* S_{π_i} and S_{δ_i} are lists of specifications defined in the specification section. An interface specification contains all the information needed to *correctly reuse* a *correct* program. Programs and correctness are explained in Section 2.3. Correct reuse is explained in Section 3.3.

2.1 Specification Frameworks

A specification framework $\mathcal{F}$ is defined in the context of first-order logic, and contains the *relevant knowledge* of the necessary concepts and data types for building a model of the application at hand.

We distinguish between *closed* and *open* frameworks. A *closed framework* $\mathcal{F} = \langle \Sigma, \mathbf{X}, \mathbf{T} \rangle$ has a signature Σ, a set $\mathbf{X}$ of axioms, and a set $\mathbf{T}$ of theorems. It has no open and defined symbols, that is, all the symbols of Σ are closed.

Example 1. An example of closed framework is first-order arithmetic $\mathcal{NAT} = \langle \Sigma_{Nat}, \mathbf{X}_{Nat}, \mathbf{T}_{Nat} \rangle$, introduced by the following syntax:[3]

Framework $\mathcal{NAT}$;

$$\begin{array}{lll}
\text{DECLS:} & & Nat : sort; \\
& & 0 : [\,] \to Nat; \\
& & s : [Nat] \to Nat; \\
& & \_+\_, \_*\_ : [Nat, Nat] \to Nat; \\
\text{AXS:} & & Nat : construct(0, s : Nat); \\
& + : & i + 0 = i; \\
& & i + s(j) = s(i + j); \\
& : & i * 0 = 0; \\
& & i * s(j) = i * j + i; \\
\text{THMS:} & & i + j = j + i; \\
& & \ldots
\end{array}$$

[3] In all the examples, we will omit the outermost universal quantifiers, but their omnipresence should be implicitly understood.

The signature Σ_{Nat}, introduced in the declaration section DECLS, is the signature of Peano's arithmetic. The axioms $\mathbf{X}_{Nat}$, introduced in the AXS section, are the usual ones of first-order arithmetic. 0 and s are the *constructors* of *Nat* and their axioms, which we call the *constructor axioms* for *Nat*, are collectively indicated by $construct(0, s : Nat)$. The latter contains Clark's equality theory [35] for 0 and s, as well as all the instances of the first-order induction schema. $\mathcal{NAT}$ has been widely studied, and there are a lot of known theorems (in section THMS), including for example the associative, commutative and distributive laws.

Theorems are an important part of a framework. However, they are not relevant in the definitions that follow, so we will not refer to them explicitly here.

For closed frameworks we adopt isoinitial semantics, that is, we choose the intended model of $\mathcal{F} = \langle \Sigma, \mathbf{X} \rangle$ to be a *reachable isoinitial model*, defined as follows:

Definition 1 (Reachable Isoinitial Model [5]). *Let* $\mathbf{X}$ *be a set of* Σ*-axioms. A* Σ*-structure* I *is an* isoinitial model *of* $\mathbf{X}$ *iff, for every model* M *of* $\mathbf{X}$*, there is a unique isomorphic embedding* $i : \mathrm{I} \longrightarrow \mathrm{M}$.

A model I *is* reachable *if its elements can be represented by ground terms.*

Definition 2 (Adequate Closed Frameworks [30]). *A closed framework* $\mathcal{F} = \langle \Sigma, \mathbf{X} \rangle$ *is* adequate *iff there is a reachable isoinitial model* I *of* $\mathbf{X}$ *that we call 'the' intended model of* $\mathcal{F}$.

In fact I is one of many intended models of $\mathcal{F}$, all of which are isomorphic. So I is unique up to isomorphism, and hence our (ab)use of 'the'.

As shown in [5], adequacy entails the computability of the operations and predicates of the signature.

Example 2. $\mathcal{NAT}$ is an adequate closed framework. Its intended model is the standard structure $\mathcal{N}$ of natural numbers ($\mathcal{N}$ is a reachable isoinitial model of $\mathbf{X}_{Nat}$). $\mathcal{N}$ interprets *Nat* as the *set of natural numbers*, and $s, +$ and $*$ as the *successor*, *sum* and *product* function, respectively.

The adequacy of a closed framework is not a decidable property. We have the following useful proof-theoretic characterisation, which can be seen as a "richness requirement" implicit in isoinitial semantics [31]:

Definition 3 (Atomic Completeness). *A framework* $\mathcal{F} = \langle \Sigma, \mathbf{X} \rangle$ *is* atomically complete *iff, for every ground atomic formula* A*, either* $\mathbf{X} \vdash A$ *or* $\mathbf{X} \vdash \neg A$.

Theorem 1 (Adequacy Condition [38]). *A closed framework* $\mathcal{F} = \langle \Sigma, \mathbf{X} \rangle$ *is adequate iff it has at least one reachable model and is atomically complete.*

Closed adequate frameworks can be built incrementally, starting from a closed adequate kernel, by means of *adequate extensions*.

Definition 4 (Adequate Extensions [30]). *An* adequate extension *of an adequate closed framework $\mathcal{F} = \langle \Sigma, \mathbf{X} \rangle$ is an adequate closed framework $\mathcal{F}_\delta = \langle \Sigma \cup \delta, \mathbf{X} \cup D_\delta \rangle$ such that:*

a) D_δ is a set of $(\Sigma \cup \delta)$-axioms, axiomatising a set of new *(i.e., not in Σ) symbols δ;*
b) the Σ-reduct $\mathrm{I}|\Sigma$ of the intended model I of $\mathcal{F}_\delta$ is the intended model of $\mathcal{F}$.

The notions of *reduct* and *expansion* are standard in logic [4]. The Σ-reduct $\mathrm{I}' = \mathrm{I}|\Sigma$ forgets the interpretation of the symbols not in Σ, in our case the new symbols δ. Conversely, I is said to be a $(\Sigma \cup \delta)$-*expansion* of I', that is, a $(\Sigma \cup \delta)$-expansion is a $(\Sigma \cup \delta)$-interpretation that preserves the meaning of the old Σ-symbols, and interprets the new δ arbitrarily.

In Definition 4, by b), the intended model I of an adequate extension is an expansion of the old intended model, that is, adequacy entails that the meaning of the old symbols is preserved.

If the axioms D_δ of an *adequate* extension are explicit definitions, we say that they are *adequate explicit definitions.* Since they are important in our approach, we briefly recall them.

An explicit definition of a new relation r has the form $\forall \underline{x} \bullet r(\underline{x}) \leftrightarrow R(\underline{x})$, where $\underline{x}$ indicates a tuple of variables and (as usual) "$\bullet$" extends the scope of a quantifier to the longest subformula next to it. The explicit definition of a new function f has the form $\forall \underline{x} \bullet F(\underline{x}, f(\underline{x}))$, where $R(\underline{x})$ and $F(\underline{x}, y)$ are formulas of the framework that contain free only the indicated variables. The explicit definition of f has the *proof obligation* $\mathbf{X} \vdash \forall \underline{x} \bullet \exists! y \bullet F(\underline{x}, y)$, where $\mathbf{X}$ are the framework axioms (as usual, $\exists! y$ means unique existence). $R(\underline{x})$ is called the *definens* (or *defining formula*) of r, and $F(\underline{x}, y)$ the *definiens* (or *defining formula*) of f.

Explicit definitions have nice properties. They are *purely* declarative, in the following sense: they define the new symbols *purely in terms of the old ones*, that is, in a *non-recursive* way. This declarative character is reflected by the following *eliminability* property, where Σ is the signature of the framework and δ are the new explicitly defined symbols: the extension is conservative (i.e., no new Σ-theorem is added) and every formula of $\Sigma + \delta$ is provably equivalent to a corresponding formula of the old signature Σ. Moreover, if we start from a sufficiently expressive kernel, most of the relevant relations and functions can be explicitly defined. Finally, we can prove:

Proposition 1. *If the definiens of an explicit definition is quantifier-free, then the definition is adequate.*

If the definiens is not quantifier-free, adequacy must be checked. To state the adequacy of closed frameworks and of explicit definitions, we can apply proof methods based on logic program synthesis [26,27] or constructive logic [38].

Example 3. The kernel $\mathcal{NAT}$ of Example 1 is sufficiently expressive in the following sense. Every recursively enumerable relation r can be introduced by an