Synthetic Scientific Report

on the implementation of the project PN-II-ID-PCE-2011-3-0439

September 16, 2016

The implementation of the project *Universal Logic Methods in Computer Science* was performed between October 2011 and October 2016 within the three objectives specified in the project proposal:

1. Foundations of structured specifications;
2. Universal approach to formal verification; and
3. Institution-theoretic approach to logic combination.

The results obtained have been published in 25 international publications (from which 11 are in ISI Web of Science indexed journals). In addition to that, there have been a number of 24 presentations in international conferences, and 2 PhD theses emerged from the project. Some of the project achievements have also been reported in the *Internet Encyclopedia of Philosophy* entry [Dia16a].

1 Foundations of structured specifications

This project objective has been achieved through the following research themes: (*1*) structured institutions, (*2*) translations of structured specifications, (*3*) structured behavioural specifications, (*4*) views for parameterized specifications. An overview presentation of some of the results developed during the project for this objective constitutes one of the main subjects of [Dia15b; Dia15c].

1.1 Structured institutions

Research under this theme has focused on the introduction of a new approach to the theory of structured specifications that is based on a new level of abstraction, and that includes the study of technical fundamental properties that are necessary for the structuring of programs and specifications. The results obtained have been published in [Dia12; Ţuţ14]. The main technical contributions are as follows:

1. The definition of the concept of *abstractly structured institution* as a special case of the concept of institution morphism [GB92]. This represents a general framework for the theoretical study of structured specifications and of software that provides both independence of any particular choice of structuring operators (hence this is applicable to a wide range of structuring formalisms) and the unification of the two major theoretical approaches to structuring: Goguen and Burstall's, which is property oriented [GB92], and that of Sannella and Tarlecki, which is model oriented [ST88; ST12].
2. Theorems concerning the existence of colimits and of model amalgamation by lifting from the level of the base (logical) institution to the level of the institution of abstract specifications. These are the two technical properties that bear the greatest importance in the theory of structured specifications.
3. Development of the concept of *normal form* for abstract structured specifications, and based on the existence of normal forms (see [ST12]), the development of lifting results of important logical properties from the base institution to that of the structured specifications; these include compactness, interpolation, and complete proof systems.
4. The development of the concept of *pushout-style parameterization with sharing* (the body of the the parameterized specification and the instance of the parameter may have a non-empty intersection) within abstractly structured institutions; this generalizes the respective concept developed in [DŢ11].

5. The generalization of the concept of *inclusion system* [DGS93] to *quasi-inclusions* by relaxing the partial-order condition to a preorder; this allows their lifting from the level of the category of signatures of the base institution to that of the category of abstract specifications, i.e. the category of signatures of the abstractly structured institution. The main reason for this development is the impossibility of a similar lifting when working with inclusion systems.
6. The study of *free extensions* of morphisms (of signatures) along quasi-inclusions. These constitute the main technical tool in the study of instantiations of multi-parametric specifications with 'sharing'.
7. The study of parameterized objects and their instantiations in categories with a distributive system of quasi-inclusions.
8. The study of functors for parameterization in abstractly structured institutions so as to lift colimits and quasi-inclusion systems.
9. Theorem of isomorphism between the results of *sequential instantiations* and of *parallel instantiations* for multi-parametric abstractly structured specifications. This is a double-extension of the main result of [DŢ11]: (*1*) extension to the abstractly structured institutions, introduced in [Dia12], and (*2*) extension of the concept of 'sharing' to allow 'sharing' situations between different parameters for multi-parametric specifications.

1.2 Translations of structured specifications

The research under this theme has focused on the study of the translations of structured specifications within institution theory. This issue occurs in the heterogeneous specification paradigm [DF02; Mos05; Sch04] that has recently witnessed an important development. The results obtained have been published in [Ţuţ13a; Dia15a]. The main contributions are as follows:

1. The introduction of the concept of *comorphism of abstractly structured institutions* by extending the well-known concept of comorphism of institutions [GR02]. This formalizes the intuitive idea of coding a theory of structuring specifications (such as that of Goguen and Burstall) into another structuring theory (such as that of Sannella and Tarlecki), the latter being supposed to be more complex. It is this defined a category of abstractly structured institutions, whose role is essential for the development of heterogeneous specification languages that can vary both the core logic and also at the level of the structuring mechanism; the second dimension of the structuring of specifications is not considered, for example, in heterogeneous languages such as CafeOBJ [DF98] and HetCasl [Mos04a].
2. The development of an automatic construction of 'simple' comorphisms of institutions from comorphisms of abstractly structured institutions, as well as the investigation of some of the most important properties of these encodings: conservativeness, amalgamation of models [Bor02] and liberality [KM95; Dia98].
3. The development of a general existence theorem on translating structured specifications based on a set of general conditions with a rather broad applicability. The translations of structured specifications are formalized as comorphisms between abstractly structured institutions (see [Ţuţ13a]).

1.3 Structured behavioural specifications

The research under this theme has focused on the foundations for structuring behavioural specifications, a case that poses some specific technical issues and that are not fully covered by the structuring-specifications theory in general. The results obtained have been published in [DŢ14; ŢD16].

1. Existence theorem for pushouts of morphisms of signatures in the institution of hidden-sorted algebras (called *HA*). The existence of pushouts in the category of signatures is the most fundamental property in order to have a structuring-specification system based on that logic.
2. Theorem of existence of an inclusion system for the category of *HA* signatures by lifting the strong inclusion system of the category of signatures of the institution of many-sorted algebras (denoted *MSA*). Based on this, development of a concept of *import of modules* for structured behavioural specifications as well as several constructions and properties that are fundamental for parameterization such as the preservation of signatures by signature morphisms and the existence of free extensions.
3. The proof of idempotency, commutativity and of associativity of the union of signatures in *HA*, all of which are partial algebraic rules because of the partiality of the union of signatures in *HA*.

4. Proof of the distributivity of union over intersection for $\underline{HA}$ signatures as a partial algebraic conditional rule.
5. The development of the concept of *abstract behavioural specification* based on the concept of abstractly structured institution [Dia12] over $\underline{HA}$. This ensures a concept of behavioural specification general enough to not depend on any particular choice of a set of structuring operators, making it applicable to a wide range of structuring formalisms for behavioural-specification languages.
6. The proof of partial algebraic rules for abstractly structured behavioural specifications based on the algebraic properties of the union of signatures in $\underline{HA}$.
7. The development of a concept of *(pushout style) parameterized behavioural specification* in the general setting of abstract structured specifications and its corresponding parameter instantiation mechanism.
8. The development of a general result relating the sequential and the parallel instantiation of multiple parameters in the behavioural setting.

1.4 Views for parameterized specifications

The research under this objective has focused on the study of the semantics of *views* used in instantiations of parameterized specifications. This represents a theoretic and methodological concept that is very important in the context of formal structured specifications (e.g. [DF98; Mos04b], etc.) and that has not been sufficiently clarified in the literature. The results obtained have been published in [Diabm]. The main contributions are as follows:

1. A clear mathematical definition for first-order views, including their compositions. This turns to be a Kleisli category for a monad of *derived* first-order signatures.
2. A semantics for first-order views that has two components, a view determining both a syntactic translation and a model reduct that are mutually compatible via a *satisfaction condition*. Crucially, this semantics is shown to be functorial.
3. An inclusion system for the category of first-order views.
4. The explanation of parameter instantiation as a pushout in the category of views. This explanation is based upon a result giving the existence of suitable pushouts of appropriate spans of first-order views. ('Suitable' here refers to a specific property that supports proper multiple-parameter instantiations and that has been formulated in [DŢ11; Ţuţ14].)
5. A model-amalgamation result for the pushouts mentioned at the above item, that provides consistency for the parameter-instantiation process.

2 Universal approach to formal verification

Research under this objective has had so far two main directions: the lifting of the logic-programming paradigm (in its conventional form, as implemented for example in Prolog) to service-oriented computing, and the study of formal verification of systems specified in hybridized logics by translation to first-order logic.

2.1 Institution-independent logic programming

Under this theme, research has focused on the study of a new approach to abstract logic programming and on the implementation and evaluation of the developed theory both for the classical paradigm of logic programming and for service-oriented computation. The results obtained are the subject of the works [ŢF13; Ţuţ13b; ŢF15a; ŢF15c; ŢF15b] and were presented at the *5th and 6th Conference on Algebra and Coalgebra in Computer Science (CALCO 2013 and 2015)* [ŢF13; ŢF15b], at the *22nd International Workshop on algebraic Development Techniques (WADT 2014)* [ŢF14a; Vis+15], and at the *22nd meeting of the group IFIP WG1.3* [ŢF14b]. In addition, they are also part of the PhD thesis [Ţuţ15] defended at Royal Holloway, University of London. The main contributions are as follows:

1. The definition of appropriate algebraic structures for the study of the so-called service modules that are specific to the service-oriented-computing paradigm [FLB11] – both from the static perspective, referring to the structure of the modules, and from the dynamic perspective, referring to the manner in which modules interact (by means of mechanisms of service discovery, selection, and binding).

2. A parameterized construction (by an arbitrary logic) of an institution of *asynchronous relational networks* that supports the definition of service specifications, of models of such specifications – corresponding to *orchestrations* of software components that depend on external services or resources – and of the processes of searching for services and of connecting their corresponding modules to the applications executed by clients.
3. Establishing a rigorously founded theoretical analogy between service-oriented computing [FLB11; FL11] and classical logic programming [Llo84]. This analogy involves the development of a general theory of logic programming through which we can identify (*1*) the concept of Herbrand universe with the class of *ground orchestrations*, which have no external requirements, (*2*) variables with the so-called service requirements, (*3*) terms with service delivery through 'ports', (*4*) clauses with modules corresponding to services, (*5*) queries with applications executed by clients, (*6*) logic programs with service repositories, and (*7*) derivation by resolution with the mechanism dedicated to discovering services and connecting them to the applications.
4. The introduction of the concepts of *substitution system* and *generalized substitution system* (see [ŢF15a]). These extend the notion of institution through constructions that allow the capture of (explicit) variables and substitutions – fundamental elements for defining the operational semantics of logic programming – with the aim of integrating the logic-programming semantics of services from [ŢF13] with the institution-theoretic study of the foundations of logic programming from [Dia04].
5. The study of quantified sentences within the abstract framework of generalized substitution systems, highlighting the role of the model-amalgamation property in ensuring the invariance of their satisfaction relative to the change of signature – the link between these two concepts has been investigated since the 1980s within the context of the theory of formal specifications (see, for example [BPP85; ST88; DGS93] and also more recent works [Tar00; Bor02] devoted to the study of heterogeneous specifications).
6. Generalization of the *Herbrand theorems* of [Dia04] to logical systems in which variables cannot be captured faithfully using morphisms of signatures – the main exponent in this case being the logic of asynchronous relational networks (which underlines the service-oriented-computing paradigm) described in [ŢF13].
7. A novel study on the institutional foundations of logic programming that revise the original study of [Dia04]. This subsumes (*1*) the examination of a class of substitution systems whose variables are defined through extensions of signatures (of a given institution), and whose substitutions correspond to the institution-independent notion of substitution, (*2*) the investigation of the translation of variables along signature morphisms and the identification of a set of sufficient conditions under which an institution can give rise to a generalized substitution system, and (*3*) new proofs of the institution-independent versions of Herbrand's fundamental theorem that make use of the generalization put forward in [ŢF15a].
8. Definition of a mathematical concept of *logic-programming language* and of an abstract form of *resolution* (as a rule of inference) that generalizes both the classical resolution (specific to relational logic programming) and paramodulation and narrowing (specific to equational logic programming). These enable the introduction of a general procedure for solving a logic-programming problem. We have shown the soundness of this procedure and have identified sufficient conditions for its completeness also.
9. The study of problem solving in logic programming (using the procedure discussed above) in the context of structured, modular logic programs, which may be build using a variety of structuring operators (see [ŢF14a]). This includes an investigation of the preservation of solutions over morphisms of logic programs (imports) and the possibility of reducing the context (set of clauses) against which one tries to solve a problem.
10. The application of the general theory of logic programming from [ŢF15a] for service-oriented systems. The category-theoretic concept of *orchestration scheme* introduced in [ŢF15c] enables the study of models of the dynamic computations that are performed over networks of service modules; this study is independent of the local computational model involved – which may be based, for example, upon the Hoare calculus [Hoa69] or the asynchronous relational networks discussed in [FL13].
11. The definition of a full operational semantics of services (see [Vis+15]) by characterizing the execution of a service application (which is assumed to be dynamic, in the sense of accepting possible reconfigurations of the network that supports it) as traces of a dedicated transition system. This refines the operational semantics proposed in [ŢF13] (based on logic-programming concepts) by making explicit the local computation and communication steps of asynchronous relational networks. In addition, by the derivation of transition systems that are equivalent (from the perspective of the operational semantics) to asynchronous relational networks, it is facilitated the use of *model-checking* techniques for the formal verification of service applications.

2.2 Formal verification by translation

The following results are shared with the objective *Institution-theoretic approach to logic combination* and have been published in [DM16]:

1. Encoding abstract hybridized institutions into first order logic ($\underline{FOL}$) by lifting abstract comorphisms $\mathcal{I} \to \underline{FOL}^{\text{pres}}$ (where $\underline{FOL}^{\text{pres}}$ means the institution of $\underline{FOL}$ theories) to comorphisms $\mathcal{HI} \to \underline{FOL}^{\text{pres}}$ (where $\mathcal{HI}$ means a hybridization of $\mathcal{I}$). If $\mathcal{HI}$ means a logic combination between traditional hybrid logic [ABD01] and the logic/institution $\mathcal{I}$, then the resulting comorphism $\mathcal{HI} \to \underline{FOL}^{\text{pres}}$ is a combination of the encoding given by the initial comorphism $\mathcal{I} \to \underline{FOL}^{\text{pres}}$ and the standard encoding [Bra11] of traditional hybrid logic into $\underline{FOL}$.
2. Theorem lifting the conservativeness property of the base comorphism $\mathcal{I} \to \underline{FOL}^{\text{pres}}$ to a comorphism $\mathcal{HI} \to \underline{FOL}^{\text{pres}}$. The main implication of this result is the ability to shift a formal verification in $\mathcal{HI}$ to one in $\underline{FOL}$, with the advantage of using highly developed technologies for formal verification in $\underline{FOL}$.
3. Case study of a formal specification in a hybridization of partial algebras containing both the translation in first-order logic and the formal verification of some properties of the specification through encoding in first-order logic and by using the theorem provers [Wei+02] and Darwin [Bau+07].

3 Institution-independent approach to logic combination

The research under this objective was to study hierarchical combinations of logical systems, as well as their semantic (model-theoretic) and proof-theoretic properties. This was done on the directions of *hybridized logics* and of *many-valued logics*. Another distinct research theme under this objective that is related to the former theme is that of *stratified institutions*.

3.1 Hybridized institutions

The results obtained in this theme have been published in [Dia16b; DM16]. The main technical contributions are as follows:

1. New definition of the combination between hybrid logic and any other logic by internalizing the concepts of hybrid logic at the level of abstract institutions. This process, called *hybridization* of institutions is developed both at the syntactic and the semantic levels. It extends the internalisation of Kripke semantics developed in [DS07; Mar+11] with the concept of constrained *models*, which is axiomatized as a subfunctor (satisfying some specific properties of rather general nature) of the model functor in the hybridized institution with unconstrained models. Hybridized institutions with constrained models accommodate a large class of hybrid logics from the literature in which different types of 'sharing' between semantic entities are considered. An important parameter of the process of hybridization consists of an axiomatization of the quantification space, a general approach that, due to the concept of constrained models, includes a great diversity of kinds of quantification from the literature.
2. The proof of the *satisfaction condition* for hybridized institutions with constrained models.
3. Definition of the concept of *quasi-variety* for categories of models in hybridized institutions, a process that has two aspects: (*1*) the definition of the concept of sub-model in hybridized institutions based on the concept of *inclusion system*. (the inclusion systems for categories of models in the base institution are lifted up to the hybridization by means of a flattening construction of the Grothendieck category kind); (*2*) the construction of direct products of models in hybridized institutions from the direct products of models in the base institution.
4. Preservation results (of the satisfaction relation between models and sentences) by submodels and direct products in hybridized institutions.
5. The derivation of a general result of existence of initial models of theories in hybridized institutions. This result allows for a specification methodology based on initial semantics in a variety of combinations between hybrid logic and other logics.
6. The development of concrete examples of hybridization that can be used in formal specifications of dynamic systems. These examples include both traditional and new examples of hybrid logic, such as hybridization of logics with partial functions.

3.2 Many-valued institutions

The results obtained in this theme have been published in [Dia13; Dia14b; Dia15d]. The main technical contributions are as follows:

1. The definition of a general abstract framework (called $\mathcal{I}(L)$) for the description of many-valued semantics. In $\mathcal{I}(L)$ the residuated lattice L of the truth values is fixed but considered abstract, the atomic syntax (the signatures category and the functor of the atomic sentences) is also considered completely abstract, while the model categories and the satisfaction relation $\models$ are defined generically. From the perspective of the problem of combining logical systems, $\mathcal{I}(L)$ can be considered a combination of traditional many-valued logic [Hájek98] (called $\underline{MVL}$) with different logics whose atomic syntax is an instance of the abstract atomic syntax of $\mathcal{I}(L)$.
2. Proof that $\mathcal{I}(L)$ is an institution [GB92]; in particular the proof of the *satisfaction condition* for $\mathcal{I}(L)$.
3. Theorem of a conservative embedding of $\underline{MVL}$ into $\mathcal{I}(L)$, the main implication is that, for L fixed, the semantic-deduction relation of $\underline{MVL}$ coincides with that of $\mathcal{I}(L)$, which allows for the replacement of the traditional semantics of $\underline{MVL}$ with the categorical one of $\mathcal{I}(L)$.
4. Definition of fuzzy multi-algebras as a fuzzy extension of classical multi-algebras [WM97]; this allows for a fuzzy approach to algebraic non-determinism.
5. Theorem of a conservative embedding of the logic of fuzzy multi-algebras into $\mathcal{I}(L)$. As in the case of the embedding of $\underline{MVL}$, the main implication of this result is the possibility of the replacement of the semantics of fuzzy multi-algebras with the categorical semantics of $\mathcal{I}(L)$.
6. Proof that $\mathcal{I}(L)$ has model amalgamation. In general, this is one of the fundamental properties that assist the development of a model theory for an institution, in this case $\mathcal{I}(L)$.
7. Proof that $\mathcal{I}(L)$ admits the method of diagrams [Dia08]. Overall, this is one of the fundamental properties that ensures the development of a model theory for an institution, in this case $\mathcal{I}(L)$.
8. The definition of a graded concept of deductive system extending Tarski and Scott's concept of classic deductive system from the binary to the many-valued case.
9. The generalization of the concept of institution to the many-valued case. Proof that this determines a Galois connection between the syntax and the semantics.
10. Interpretation of many-valued institutions as graded deductive systems, and proof that this construction corresponds to a retract. The inverse of this retract is a technical artefact that allows for semantic arguments in purely deductive situations.
11. Theorem of transfer of soundness from inference rules to graded proofs.
12. Definition of many-valued closure systems. Definition of two interpretations of graded deductive systems as many-valued closure systems, the first as many-valued interpretation of *modus ponens* and the second corresponding to a semantic closure. While in the binary case these two interpretation are identical, in the many-valued case we show that the former is weaker than the latter.
13. Study of the logic of graded consequence by introducing the concepts of logical connectors and quantifiers at two distinct levels: the deductive level and the semantic level. Sufficient conditions in which their presence at the semantic level induces their presence at the deductive level.
14. Preservation theorem of the soundness property by logical connectors and by quantifiers.
15. Generalization of the concept of compactness from binary deductive systems to graded deductive systems. Proof that systems of finitary graded rules generate compact graded deductive systems and of the fact that compactness is preserved by logical connectors and quantifiers.
16. Definition of *opposition squares* [Ari84; BD12] and *hexagons* [Bla66] in lattices. Study of their fundamental algebraic properties.
17. Definition of a concept of *many-valued consequence* by weakening the concept of graded consequence of [Cha88; Cha95; EH10; Dia14b].
18. The generation of non-Boolean opposition squares via many-valued consequences.
19. The generation of many-valued consequences by many-valued abstract semantics of a similar kind of institution theory (in a generalized many-valued sense).

3.3 Stratified institutions

Under this theme we have proposed the *stratified institutions* of [AD07] as a fully abstract model theoretic approach to modal logic. This allows for a uniform treatment of model-theoretic aspects across the great multiplicity of contemporary modal-logic systems. Moreover, Kripke semantics (in all its manifold variations) is captured in an implicit manner free from the sometimes bulky aspects of explicit Kripke structures, also accommodating other forms of concrete semantics for modal-logic systems. The conceptual power of stratified institutions is illustrated with the development of a modal ultraproducts method that is independent of the concrete details of the actual modal logical systems by employing the institution-independent concept of ultraproduct of [Dia03; Dia08]. Consequently, a wide array of compactness results in concrete modal logics may be derived easily. This was the subject of the paper [Diai1]. The main technical contributions are as follows:

1. Upgrade of the concept of stratified institution of [AD07].
2. Two general interpretations of stratified institutions as ordinary institutions that represent high abstractions of the concepts of local and global satisfaction from modal logic, respectively.
3. A series of examples of stratified institutions that include both conventional and eccentric modal-logic systems. The former category includes propositional and first-order modal logic, possibly with hybrid and polyadic modalities features, while the latter includes the double hybridization of [DM16] and a first-order valuation semantics for first-order modal logic that is based upon the 'internal stratification' example introduced in [AD07].
4. An extension of the well-known institution-theoretic semantics of the Boolean connectives $\wedge$, $\neg$, etc., and of the quantifiers $\forall$, $\exists$ to the more refined level of stratified institutions, and a study of the relationship with their correspondents from the local and the global institutions associated to the stratified institution.
5. A semantics for modalities and for hybrid features in abstract stratified institutions.
6. Extension of the institution-theoretic method of ultraproducts [Dia03; Dia08] to stratified institutions. The core contributions here consist of a series of general preservation results across the abstract semantics for Boolean connectives, quantifiers, modalities, nominals, @.
7. Derivation of compactness properties for the local and the global institutions associated to a stratified institution via ultraproducts.

3.4 Synthesis contributions

The general methods employed towards the implementation this objective have been the subject of the synthesis works [Dia14a] (paper invited to *International Colloquium on Theoretical Aspects of Computing 2014*) and [DMT14]. The methods presented are:

1. Morphisms of signatures versus language extensions.
2. Local approach on logical variables and on quantifications; the concept of quantification space.
3. Generalized institution-theoretic interpolation and definability.
4. The institution-theoretic method to determine the scope of a logic theorem.

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