Algebraic and Coalgebraic Models in Software Development

MAP-I — 2010-11

Summary

This document describes a proposal for the course Fundamentals of Computing *for the 2010-11 MAP-I edition. The proposal is supported by a team from Aveiro University (Dep. of Mathematics) and Minho University (Dep. of Informatics) to be included on the MAP-I.*

1 Context and Objectives

An increasing number of computer based systems rely on the cooperation of distributed, heterogeneous components or services organised into open software architectures that, moreover, can survive in loosely-coupled environments and be easily adapted to changing application requirements. Such is the case, for example, of applications designed to take advantage of the increased computational power provided by massively parallel systems or of the whole business of Internet-based software development. In order to develop such systems in a systematic way, the focus of development methods has switched, along the last decade, from functional to architectural issues: both data and processes are encapsulated into software units which are connected into large systems resorting to a number of techniques intended to support reusability and modifiability. This encapsulation principle is essential to both the *object-oriented* and the more recent *component-based* software engineering paradigms.

This entails the need for semantic techniques able to cope either with *date structuring* and *prescription of functionality*, as well as with specification and analysis of (externally observable) *behaviour*.

If on data-intensive applications the main element to tackle is the *structure* of information and its transformations, in dynamic, reactive computing the focus is placed on system's behaviours and their interactions. Quoting Robin Milner, in his Turing Award Lecture, computing science has become a *structural theory of interaction*: *Thus software, from being a prescription for how to do something — in Turing's terms a "list of instructions" — becomes much more akin to a description of behaviour, not only programmed on a computer, but occurring by hap or design inside or outside it.*

Both *initial* algebras and *final* coalgebras provide abstract descriptions of a variety of phenomena in programming, in particular of *data* and *behavioural* structures, respectively. As universal properties, they both entail definitional and proof principles, *i.e.*, a basis for the development of program calculi directly based on (actually driven by) type specifications. Moreover, such properties can be turned into programming *combinators* and used, not only to calculate programs, but also to program with. In functional programming the role of such universals has been fundamental to a whole discipline of algorithm derivation and transformation. On the oher hand, *coalgebraic modelling* of dynamical systems and reasoning by *coinduction* has recently emerged as active area of research.

This course explores the role of such algebraic and coalgebraic structures, and corresponding logics, in program development. As expected, *initial* algebras turn out to be *inductive data types*, *i.e.*, abstract descriptions of data structures. Dually, *final* coalgebras entail a notion of *coinductive*, *behaviour types*, representing the dynamics of systems. Therefore, the course will cover the core ideas, techniques and results in

- Algebraic specification, induction and equational logic
- Coalgebraic specification, coinduction and modal logic for coalgebras

In both cases exposition will resort to suitable tool support (namely, OBJ, BOBJ and Circus).

To provide a common background to formulate and discuss the topics above, the course will also include a brief

- Introduction to category theory

A particular emphasis will be placed on *observational* semantics. As a matter of fact, there are several phenomena in computing which are hardly definable (or even simply not definable) in terms of a complete set of constructors and in an essentially finitary process. Such is the case of, for example, processes, transition systems, objects, stream-like structures used in lazy programming languages, 'infinite' or non well-founded objects arising in semantics. Such 'systems' are inherently dynamic, do possess an observable behaviour, but their internal configurations remain hidden and have therefore to be identified if not distinguishable by observation. Therefore, the study of behavioural satisfaction refinement of algebraic specifications, and coalgebraic methods, will be particularly targeted in the course.

The course will build a *roadmap* to the broad area of algebraic and coalgebraic methods in software development, not only by providing an introductory survey, but also by exposing students to cutting-edge research topics and open problems, eventually leading to the formulation of a few specific research plans.

2 Learning outcomes

- Familiarity with the main topics, research questions and scientific challenges in the covered area (algebraic and coalgebraic methods);
- Ability to apply them to building and reasoning about, abstract models for software, its functionality, behaviour and composition.
- Ability to extract information from scientific papers in the area.
- Enhanced technical writing and presentation skills.

3 Pre-requisites

The course is almost self-contained, assuming only familiarity with elementary discrete mathematics at undergraduate level. Some previous experience on semantics of programming languages will help.

4 Format

Tutorial module, supported with demos and experimental lab work.

5 Grading

Assessment on base of an individual report on a research paper and a set of written exercises.

6 Course Contents

Plan

1. Introduction to category theory for computer science
   (a) Universal properties; categories; isomorphism; monomorphisms and epimorphisms.
   (b) Constructions in categories: duality, products, sums, limits and colimits.
   (c) Functors and natural transformations
   (d) The Yoneda lemma
   (e) Adjoint functors and adjoint functor theorems
   (f) Cartesian closed cateories and λ-calculus
2. Algebras and algebraic specification
   (a) Signatures, models
   (b) Equational logic
   (c) Signature morphisms
   (d) Refinements
   (e) Introduction to the theory of institutions
   (f) Behavioural specifications
3. Coalgebras and coalgebraic specification
   (a) Coalgebras
   (b) Bisimulation
   (c) Coinduction, final coalgebras
   (d) Logics for coalgebras
   (e) Applications

Textbooks and Reading Material

On category theory : [3, 30, 18, 2]

On algebraic specification : [11, 13, 12, 8, 29]

On coalgebraic modelling and coinduction : [28, 16, 17, 1]

7 Team

Luis Soares Barbosa (Coordinator) is Associate Professor, with tenure, at the Department of Informatics of Minho University, and a researcher at CCTC (area of *Theory and Formal Methods*). His research interests are related to program semantics and calculi applied to systems understanding and rigorous software construction. A particular application area concerns the development of formal models and calculi for software components, services and architectures. On this topic he has published over the past 4 years more than 15 papers in several journals and conferences. He has supervised 2 PhD thesis (1 in the area of the current proposal) and is currently supervising 5 PhD projects (2 in the area of the current proposal). *Selected relevant publications* on coalgebraic modelling and coinductive reasoning: [4, 5, 25, 27, 6, 26, 7, 23, 22].

Dirk Hofmann is Assistant Professor at Department of Mathematics at the University of Aveiro, and researcher at the Center for Research and Development in Mathematics and Applications. His main interests of research focus on the development and application of categorical methods in Mathematics, more specifically in algebra, topology and domain theory. On this topic he has published more than ten papers in several journals over the past 4 years. He has supervised 4 Msc thesis and is currently supervising 1 PhD project. *Selected relevant publications* on category theory: [15, 9, 10, 14].

Manuel António Martins is Assistant Professor at the Department of Mathematics of Aveiro University, and a researcher at the Center for Research and Development in Mathematics and Applications. His research interests are related to Abstract Algebraic Logic (AAL) and Algebraic Specification of abstract data types; namely on the application of tools and results of AAL to the specification and verification of software systems. On this topic he has published 6 papers in international journals. He has supervised 4 MSc thesis (2 in the area of the current proposal) and is currently supervising 2 PhD projects (1 in the area of the current proposal). *Selected relevant publications* on specification and verification of software systems: [19, 24, 20, 21, 23, 22].

References

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[4] L. S. Barbosa. Process calculi *à la* Bird-Meertens. In *CMCS'01*, volume 44.4, pages 47–66, Genova, April 2001. Elect. Notes in Theor. Comp. Sci., Elsevier.

[5] L. S. Barbosa and J. N. Oliveira. Coinductive interpreters for process calculi. In *Proc. of FLOPS'02*, pages 183–197. Springer Lect. Notes Comp. Sci. (2441), 2002.

[6] L. S. Barbosa and J. N. Oliveira. Transposing partial components: an exercise on coalgebraic refinement. *Theor. Comp. Sci.*, 365(1-2):2–22, 2006.

[7] L. S. Barbosa, J. N. Oliveira, and A. M. Silva. Calculating invariants as coreflexive bisimulations. In J. Meseguer and G. Rosu, editors, *Algebraic Methodology and Software Technology, 12th International Conference, AMAST 2008, Urbana, IL, USA, July 28-31, 2008, Proceedings*, pages 83–99. Springer Lect. Notes Comp. Sci. (5140), 2008.

[8] M. Bidoit and R. Hennicker. Proving behavioral refinements of col-specifications. In *Essays Dedicated to Joseph A. Goguen*, pages 333–354, 2006.

[9] Maria Manuel Clementino and Dirk Hofmann. Lawvere completeness in Topology. *Appl. Categ. Structures*, 17, 2009.

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[14] Dirk Hofmann. Topological theories and closed objects. *Adv. Math.*, 215(2):789–824, 2007.

[15] Dirk Hofmann. Injective spaces via adjunction. *J. Pure Appl. Algebra*, 2010 (accepted).

[16] B. Jacobs and J. Rutten. A tutorial on (co)algebras and (co)induction. *EATCS Bulletin*, 62:222–159, 1997.

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[20] M. A. Martins. Closure properties for the class of behavioral models. *Theor. Comput. Sci.*, 379(1-2):53–83, 2007.

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[22] M. A. Martins, A. Madeira, and L. S. Barbosa. Refinement by interpretation. In *7th IEEE International Conference on Software Engineering and Formal Methods (SEFM'09)*. IEEE Computer Society Press, 2009.

[23] M. A. Martins, A. Madeira, and L. S. Barbosa. Refinement by interpretation in a general setting. In J. Derrick E. Boiten and S. Reeves, editors, *Proc. Refinement Workshop 2009*, pages 105–121. Elsevier, 2009.

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[26] Sun Meng and L. S. Barbosa. A coalgebraic semantic framework for reasoning about UML sequence diagrams. In Hong Zhu, editor, *Proceedings of the Eighth International Conference on Quality Software, QSIC 2008, 12-13 August 2008, Oxford, UK*, pages 17–26. IEEE Computer Society, 2008.

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CURRICULUM VITÆ

I Personal Data

Name: Manuel António Gonçalves Martins
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University of Aveiro
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E-mail: martins@ua.pt
Webpage: `www.mat.ua.pt/martins/`

II Academic Data

- PhD in Mathematics, area of Algebra, Logic and Foundations, University of Lisbon, 2004.

III Current Position

- Auxiliar Professor, Department of Mathematics, University of Aveiro, since 2004.

IV Research

Main Research Area:

- Algebraic logic.
- Algebraic specification of abstract data types.
- Supported teaching and Elearning.

Affiliation. I am a member of the Center for Research and Development in Mathematics and Applications of the Department of Mathematics of the University of Aveiro.

Refereeing. I have refereed for Studia logica.

V PhD Supervisions

V.1 On-going

- PhD: Alexandre Madeira, co-supervision with Luís S. Barbosa, Department of Informatics, Minho University. Theme: *Behavioural Certification of Evolving Software Requirements* (Feb 2009).
- PhD: Jacinta Poças, co-supervision with Carlos Caleiro, IST, Technical University of Lisbon. Theme: *Semantics for Behavioural Abstract Algebraic Logic* (Jan 2010).

VI MSc Supervisions

VI.1 Concluded

- Ângela Ribau, co-supervision with Luís Descalço, Maths Dep., Univ. Aveiro. Theme: *Máquinas algébricas* (concluded at 16 December 2009).
- Jacinta Poças, Maths Dep., Univ. Aveiro. Theme: *Leibniz Hierarchy* (concluded at 13 July 2009).
- Nilde Barreto, co-supervision with David Vieira, Theme: *Análise estruturada e formal das provas* (concluded at 9 July 2009).
- Sandra Ramos, co-supervision with Luís Descalço, Theme: *Monóide bicíclico* (concluded at 9 July 2008).
- Alexandre Madeira, co-supervision with Luís Descalço, Theme: *Equivalência Comportamental; uma perspectiva algébrica*(concluded at 11 June 2008).

VII Member of Funded Projects

- [PTDC/MAT/68723/2006] KLog: Kleistic Logic (KLog: Lógica para Segurança).
- [PTDC/EIA-CCO/108302/2008] Mondrian - Foundations for architectural design: Service certification, dynamic reconfiguration and self-adaptability (Fundamentos para arquitecturas de serviços: certificação, reconfiguração dinámica e auto-adaptabilidade)
- Completeness Notions. Principal investigator: María Manzano, University of Salamanca, Spain (2010-13).

VIII Publications

VIII.1 Jornal papers

- L. Descalço, M.A. Martins. *On the injectivity of the Leibniz operator*. Bull. Sect. Log., Univ. Lódz, Dep. Log. 34, No. 4, 203-211, 2005.
- M.A. Martins. *Behavioral institutions and refinements in generalized hidden logics*. Journal of Universal Computer Science, Springer, vol. 12(8), 1020-1049, 2006.
- M.A. Martins, Don Pigozzi. *Behavioural reasoning for conditional equations*. Mathematical Structures in Computer Science, vol. 17 (5), 1075-1113, 2007.
- M.A. Martins. *Closure properties for the class of behavioral models*. Theoretical Computer Science, vol. 370(1-2), 53-83, 2007.
- M.A. Martins. *On the behavioral equivalence between k-data structures*. Computer Journal, vol. 51(2) 181-191, 2008.
- I. Andrade, L. Descalço, M.A. Martins. *Automatic structures for semigroup constructions.* Semigroup Forum. vol. 76, 239-255, 2008.
- C. Caleiro, R. Gonçalves, M.A. Martins. *Behavioral algebraization of logics.* Studia Logica, vol. 91, 63-111, 2009.
- S. Babenyshev and M.A. Martins. *Admissible equivalence systems*, Bull. Sect. Log., Univ. Lódz, Dep. 39 1/2, 17-33, 2010.

VIII.2 Conference Papers

- E.G. Hernández-Manfredini and M.A. Martins. *To prove a tautology.* In Proceedings of the Conference - ICMSE'06, 11 a 14 de Junho 11-14, Departamento de Matemática, Universidade de Aveiro, pág. 193-198, 2006.
- E.G. Hernández-Manfredini and M.A. Martins and P. Cruz. *A teaching aid for building proofs in propositional calculus.* In Proceedings of the Second International Congress on Tools for Teaching Logic, 26 a 30 de Setembro, Universidade de Salamanca, 51 - 56, 2006.
- M.A. Martins. *Applying abstract algebraic logic to behavioral reasoning.* In Proceedings of the Second International Congress on Tools for Teaching Logic, 26 a 30 de Setembro, Universidade de Salamanca, 111 - 115, 2006.
- M.A. Martins, A. Madeira and L. S. Barbosa. *Refinement via interpretation in a general setting* . In Proc. of the Refinement Workshop REFINE09, Eindhoven, Netherlands (co-located with Formal Methods 2009). Electr. Notes Theor. Comput. Sci., vol 259, pp 105–121, 2009.
- M.A. Martins, A. Madeira and L. S. Barbosa. *Refinements via interpretations* , In Proceedings of the SEFM'09 (7th IEEE Inter. Conf. on Software Engineering and Formal Methods), Hanoi, Vietnam, pp 250–259, IEEE Computer Society Press, 23-27 Nov 2009.
- L. Descalço, A. Madeira, M.A. Martins, *Applying Abstract Algebraic Logic to Classical Automata Theory: an exercise*; In Proc. of CiE10-computing in Europe, Azores, Portugal, June 2010 (Accepted).

VIII.3 Other papers

- E. H. Manfredini, M.A. Martins. Algumas aplicações do cálculo proposicional (in Portuguese) Boletim da Sociedade Portuguesa de Matemática, N 48, May 2003, 37-52.
- M.A. Martins, Alexandre Madeira and L. S. Barbosa. The role of logic interpretation on program development. Technical Report TR-10-02, U. Minho, 2010.

VIII.4 Editor of proceedings

- Proceedings of the International Conference in Mathematics, Sciences and Science Education - ICMSE'06 (editor with A. Breda and R. Duarte). 11 – 14 June, 2006, Aveiro, ISBN : 972-789-187-X, Portugal.

IX Communications in conferences

- *Behavioral reasoning for conditional equations*, Recent Trends in Algebraic Development Techniques, 16th International Workshop, WADT 2002, Frauenchiemsee, Germany, September (2002)
- *To prove a tautology* (joint work E.G. Hernández-Manfredini), International Conference in Mathematics, Sciences and Science Education - ICMSE'06, University of Aveiro, 12 June, 2006.
- *Axiomatization of the class of behavioral models via abstract algebraic logic*, British Logic Colloquium - BLC'06, University of Oxford, 9 September, 2006.

- *Applying abstract algebraic logic to behavioral reasoning*, Second International Congress on Tools for Teaching Logic University of Salamanca, 29 September, 2006.
- *Behavioral algebraization*, Second World Congress on Universal Logic - UNILOG'07, Northwestern Polytechnical University, Xi'an - China, 21 August, 2007.
- *Observational stepwise refinement process* (joint work with A. Madeira), Days in Logic08, Instituto Superior Técnico, Lisbon, Portugal. 17 January, 2008; (presented by A. Madeira)
- *Automata theory within abstract algebraic logic* (joint work with A. Madeira and L. Descalço), SATA 2008, School on Algebraic Theory of Automata, Lisbon, Portugal. 3 September 2008; (presented by A. Madeira)
- *Refinement by interpretation in a general setting* (joint work with A. Madeira and L. S. Barbosa) Refinement Workshop, Eindhoven, Netherlands. 3 November 2009. (presented by A. Madeira)
- *Refinement via interpretation* (joint work with A. Madeira and L. S. Barbosa)7th IEEE Int. Conf. on Software Engineering and Formal Methods, Hanoi, Vietnam, November, 2009. (presented by A. Madeira)
- *Interpretations on formal software development* (joint work with A. Madeira and L. S. Barbosa), Days in Logic10, DCC U.Porto, Porto, Portugal. 29 January, 2010; (presented by A. Madeira)
- *Interpretation as coalgebra morphisms* (joint work with A. Madeira and L. S. Barbosa), CMCS10-coalgebraic methods on computer science, (co-located with ETAPS 2010) Paphos, Cyprus, 27 March, 2010. (presented by A. Madeira)
- *Abstract algebraic logic approach to algebraic specification.* Third World Congress on Universal Logic - UNILOG10, Estoril, Lisboa, Portugal, 25 April, 2010.

CURRICULUM VITÆ

I Personal Data

Name:	**Luís Manuel Dias Coelho Soares Barbosa**
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URL:	`www.di.uminho.pt/~lsb/`
Affiliations	FME (Formal Methods Europe Association)
	EATCS (European Association for Theorectical Computer Science)

II Current Position

- Associate Professor (with tenure), School of Engineering, U. Minho, since 2007.
- Deputy Head of Department, Informatics Department, U. Minho, since 2002.

III Previous Positions

- Invited Lecturer, *Department of Engineering Mathematics*, Bristol University, UK (1992 – 2004).
- Assistant Professor, School of Engineering, U. Minho, since 2001 (with tenure since 2006).

IV Reserach

Main Research Area. Program semantics and calculi applied to systems understanding and rigorous software construction.

Other Scientific Interests.

- Reactive programming.
- Mathematical modelling and proof. Problem solving.

V PhD Supervisions

V.1. – Concluded

- *Sun Meng*, on *Coalgebra Theory and its Application to Component Software*. Co-supervision with *Dr. Berhnard Aichernig* (IIST/UNU, Macau) and *Prof. Zhang Naixiao* (School of Mathematical Sciences, Peking University, China), concluded 7th September 2009 on 12 November 2004.
- *Nuno Miguel Feixa Rodrigues*, on *Slicing Techniques Applied to Architectural Analysis of Legacy Software*, concluded on 9 February, 2009.
- *Marco Antnio Castro Barbosa*, on *A Refinement Calculus for Software Components and Architectures*, concluded 7th September 2009

V.2. – On-going

- *Joo Fernando Peixoto Ferreira*, on *Algorithmic Problem Solving: Principles and Applications* cosupervision with *Prof. Roland Backhouse* (School of Computer Science and Information Technology, University of Nottingham, UK), started December 2005.
- *Alexandra Martins Silva* on *Kripke coalgebras*. Co-supervision with *Prof. J. J. M. M. Rutten* (CWI andVrije Universiteit Amsterdam, Amsterdam), started May 2006.
- *Alexandre Madeira* on *Behavioural Certification of Evolving Software Requirements*. Co-supervision with *Prof. Manuel Antonio Martins* (Mathematics Department of Aveiro University) started January 2009.
- *Alejandro Sanchez* on *A Calculusof Coordination Patterns*. started September 2009.

VI Coordination of Funded Projects

starting January, 2010
Principal researcher of **Foundations for architectural design** — MONDRIAN. FCT (contract PTDC/EIA-CCO/108302/2008).

starting January, 2010
Researcher of **An Infrastructure for Certification and Re-engineering of Open Source Software** — CROSS. FCT (contract PTDC/EIA-CCO/108995/2008).

starting January, 2009
Principal researcher of **Reinvigorating Mathematics for the Information Society** — MATISSE. FCT (contract PTDC/EIA/73252/2006).

2005 – 2008
Coordinator of the Portuguese Hub of LERNET, ALFA Network for Joint European - Latin American PhD Programme in **Language Engineering and Rigourous Software Development**.

2005 – 2008
Coordinator of **Formal Foundations for Component-based Programming**, Technological and Scientific Cooperation between Portugal and the P. R. of China (contract GRICES-00342).

2003 – 2006
Principal researcher of **Program Understanding and Re-engineering: Calculi and Applications** — PURE. FCT (contract POSI/CHS/44304/2002).

VII Selected Publications relevant to the present proposal

(1) L. S. Barbosa and Sun Meng. A coalgebraic semantic framework for reasoning about interaction designs. In Jifeng He and Zhiming Liu, editors, *UML2 Semantics and Applications*, John Wiley and Sons, Inc., pp 249-279, 2009.

(2) L. S. Barbosa and M. A. Barbosa. A perspective on service orchestration. *Science of Computer Programming, Elsevier*, volume 74 (9), pp 671-687, 2009.

(3) L. S. Barbosa and Sun Meng. Bringing class diagrams to life. *Innovations in Systems and Software Engineering, a NASA Journal, Springer*, (to appear), 2009.

(4) L. S. Barbosa and J. N. Oliveira. Transposing partial coalgebras: An exercise on coalgebraic refinement. *Theoretical Computer Science, Elsevier*, 365 (1-2), pp 2-22, 2006.

(5) P. R. Ribeiro, L. S. Barbosa, and M. A. Barbosa. Generic Process Algebra: A Programming Challenge. *Journal of Universal Computer Science*, Special Issue with Selected papers from Xth SBLP, M. Bigonha (Guest Editor), 12 (7), pp 922-937, 2006.

(6) A. M. Cruz, L. S. Barbosa, and J. N. Oliveira. From Algebras to Objects: Generation and Composition. *Journal of Universal Computer Science*, Special Issue on *Compositional Construction and Reasoning Techniques for Software*, F. Arbab and J. Kok (Guest Editors), 11 (10), pages 1580–1613, December, 2005.

(7) M. Sun and L. S. Barbosa. Components as coalgebras: the refinement dimension. *Theoretical Computer Science, Elsevier*, 351, pp 276-294, 2005.

(8) Sun Meng and L. S. Barbosa. A coalgebraic semantic framework for reasoning about UML sequence diagrams. Proc. of QSIC'08 (IEEE 8th International Conference on Quality Software International) *IEEE Press*, pp 17-26, 2008.

(9) L. S. Barbosa, J. N. Oliveira, A. Silva. Calculating invariants as coreflexive bisimulations. In J. Meseguer and G. Rosu, editors, Proc. of AMAST'08, pages 83–99, July, 2008. *Springer Lect. Notes Comp. Sci.* (5140).

(10) Shuling Wang, L. S. Barbosa and J. N. Oliveira. A relational model for confined separation logic. Proc. of TASE'08, June, Nanjing. *IEEE CS Press*, pp 263-270, 2008.

(11) P. Barbosa, L. S. Barbosa and Shuling Wang. An exercise on transition systems. Proc. of TTSS'07, Macau. *Elect. Notes in Theor. Comp. Sci.*, Elsevier, 207: 89-106, 2007.

(12) M. Sun, Z. Naixiao, and L. S. Barbosa. On semantics and refinement of UML statecharts: A coalgebraic view. In J. Cuellar and Z. Liu, editors, *Proc. of 2nd IEEE Int. Conf. on Software Engineering and Formal Methods*, pages 164–173, Beijing, China, September 2004. IEEE Computer Society Press.

(13) M. Sun, B. K. Aichernig, L. S. Barbosa, and Z. Naixiao. A coalgebraic semantic framework for component based development in UML. In L. Birkedal, editor, *Proc. Int. Conf. on Category Theory and Computer Science (CTCS'04)*, Elect. Notes in Theor. Comp. Sci., Elsevier, 122: 229-245, 2005.

(14) L. S. Barbosa and J. N. Oliveira. Coinductive interpreters for process calculi. In Z. Zhenjiang Hu and M. Rodrıiguez-Artalejo, editors, *Proc. of FLOPS'02*, pages 183–197, Aizu, Japan, September 2002. Springer Lect. Notes Comp. Sci. (2441).

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1. Education

Ph.D. in Mathematics. University of Bremen, Germany, June 1999.
Supervisor: Prof. Dr. Hans-Eberhard Porst.
Thesis: *Natürliche Dualitäten und das verallgemeinerte Stone-Weierstraß Theorem* (Natural Dualities and the generalised Stone-Weierstraß Theorem).
The thesis project was supported by a grant of the foundation "Ernst A.C. Lange".

M.Sc. (Diplom) in Mathematics. University of Bremen, Germany, October 1995.
Supervisor: Prof. Dr. Horst Herrlich.
Thesis: *Ringe stetiger Funktionen* (Rings of continuous functions).

2. Work Experience

2001 – present. Assistant Professor (Professor Auxiliar), Department of Mathematics, University of Aveiro, Portugal.

2000 – 2001. Assistant Professor (Assistente Convidado), Department of Mathematics, University of Coimbra, Portugal.

1999 – 2000. Postdoctoral Fellow, Department of Mathematics, University of Coimbra, Portugal.

1996 – 1999. Doctoral Fellow, Department of Mathematics, University of Bremen, Germany.

3. Research

Affiliation. I am a member of the research center Mathematics and Applications of the Department of Mathematics of the University of Aveiro. I am also collaborator of the research center Center for Mathematics of the department of Mathematics of the University of Coimbra.

Conference Organisation. I was member of the Organisation Comitee of IV Congresso Ibero-Americano de Topologia e suas Aplicações, University of Coimbra, Portugal, April 18 – 21, 2001.

Refereeing. I have refereed for Proceedings of the American Mathematical Society, Mathematical Structures in Computer Science, Topology and its Applications, Fuzzy Sets and Systems, Algebra Universalis, Theory and Applications of Categories and Applied Categorical Structures. I also serve as a Reviewer for Zentralblatt Math.

Conference Presentations.

- Workshop on Categorical Topology, Ponta Delgada, Azores, March 18 – 20, 2010; where I was invited speaker and presented the talk *Duality-TV* (`http://www.mat.uc.pt/~catop/`).
- Aspects of contemporary topology IV, University of Antwerp, Belgium, December 14 – 19, 2009; where I presented the talk *Quantitative domain theory*.
- PSSL 89 – Peripatetic Seminar on Sheaves and Logic, Louvain-la-Neuve, Belgium, December 12 – 13, 2009; where I presented the talk *More on completely distributive spaces*.
- VI Portuguese Category Seminar, University of Coimbra, July 23, 2009; where I presented the talk *An unnatural duality*.
- 24st Summer Conference on Topology and its Applications, Brno, Czech Republic, July 14 – 17, 2009; where I was invited speaker and presented the talk *'Distributors at work' in Topology* (`http://www.vutbr.cz/SUMTOPO2009`).
- CT 2009 – International Category Theory Conference, Capetown, South Africa, June 29 – July 4, 2009; where I presented the talk *Completely Distributive Spaces*.
- CIC '09, Coinduction, Interaction and Composition, Braga, Portugal, May 7 – 8, 2009; where I presented the talk *Quantitative domain theory*.
- Domains IX, Brighton, United Kingdom, September 22 – 24, 2008; where I presented the talk *Continuous* V*-categories*.
- CT 2008 – International Category Theory Conference, Calais, France, June 22 – 28, 2008; where I presented the talk *Injective spaces via adjunction*.
- UltraMath 2008 – Applications of Ultrafilters and Ultraproducts in Mathematics, University of Pisa, Italy, June 1 – 7, 2008; where I presented the talk *Some aspects of ultrafilter convergence in Topology*.
- Aspects of contemporary topology III, University of Antwerp, Belgium, December 10 – 15, 2007; where I presented the talk *Completion of Remarks about Completeness*.
- Categorical Methods in Algebra, Topology and Computer Science (workshop in honour of Jiří Adámek and Walter Tholen, on the occasion of their sixtieth birthday), University of Coimbra, Portugal, October 26 – 28, 2007; where I presented the talk *Cocomplete* $\mathcal{T}$*-categories, injectivity, and Kan-extensions*.
- 22st Summer Conference on Topology and its Applications, Universidad Jaume I de Castellón, Spain, July 24 – 27, 2007; where I presented the talk *A unified treatment of function space structures*.
- CT 2007 – International Category Theory Conference, Carvoeiro, Algarve, Portugal, June 18 – 23, 2007; where I was invited speaker and presented the talk *Topological spaces, categorically* (`http://www.mat.uc.pt/~categ/ct2007`).
- IV Portuguese Category Seminar, University of Coimbra, December 11, 2006; where I presented the talk *Categorical notions in* $\mathcal{T}$*-categories*.
- 21st Summer Conference on Topology and its Applications, Georgia Southern University, Statesboro, GA, July 6 – 9, 2006; where I presented the talk *Completeness, Duality, and Injectivity*.
- CT 2006 – International Category Theory Conference, White Point, Nova Scotia, June 25 – July 1, 2006; where I presented the talk *Lax-algebraic theories and closed objects*.
- Aspects of contemporary topology II, University of Antwerp, Belgium, December 11 – 17, 2005; where I presented the talk *Incomplete remarks about completeness*.
- Categorical Methods in Algebra, Topology and Logic, University of Coimbra, Portugal, April 8 and 15, 2005; where I presented the talk *Axioms for sequential convergence*.
- 19th 'Summer' Conference on Topology and its Applications, Capetown, South Africa, July 5 – 9, 2004; where I presented the talk *Exponentiation for (weak) transitive structures*. (The participation was supported by a grant of the foundation "Calouste Gulbenkian".)

- II Portuguese Category Seminar, University of Coimbra, June 18, 2004; where I presented the talk *Exponentiability in topology*.
- Aspects of contemporary topology, University of Antwerp, Belgium, December 14 – 20, 2003; where I presented the talk *From preorders to topological spaces and further*.
- European Category Theory Meeting, Haute-Bodeux, Belgium, September 7 – 13, 2003; where I presented the talk *On lax extensions of monads*.
- V Congresso Ibero-Americano de Topologia e suas Aplicações, Lorca, Spain, June 10 – 14, 2003; where I presented the talk *Topological quotient maps via ultrafilters*.
- Workshop on Algebraic homotopy, Galois theory and Descent, University of Coimbra, January 22, 2003; where I presented the talk *Regular epimorphisms of lax algebras*.
- Workshop on Categorical Structures for Descent and Galois Theory, Hopf Algebras and Semiabelian Categories, Fields Institute, Toronto, Canada, September 23 – 28, 2002; where I presented the talk *Descent Theory for Lax Algebras*.
- 5th Annual Workshop on Applications and Generalisations of Complex Analysis, University of Coimbra, Portugal, March 16, 2002; where I presented the talk *Natural Dualities*.
- 9th Prague Topological Symposium, Prague, Czech Republic, August 19 – 25, 2001; where I presented the talk *Lax algebras*.
- IV Congresso Ibero-Americano de Topologia e suas Aplicações, University of Coimbra, Portugal, April 18 – 21, 2001; where I presented the talk *Topological features of lax algebras*.
- CatMAT 2000 – Categorical Methods in Algebra and Topology, University of Bremen, Germany, August 21 – 25, 2000; where I presented the talk *Ultrarelational spaces and triquotient maps*.
- CT99 – International Category Theory Meeting, University of Coimbra, Portugal, July 19 – 24, 1999; where I presented the talk *Natural dualities*.
- Norddeutsches Kategorienseminar, University of Braunschweig, Germany, February 20 – 21, 1999; where I presented the talk *Stone-type dualities*.
- II Encontro Projecto ACL Algebraic Combination of Logics, Figueira da Foz, Portugal, June 22 – 23, 1998; where I presented the talk *Generalised Stone dualities*.
- International Symposium on Applications of Categorial Methods, University of Antwerp, Belgium, March 23 – 27, 1998; where I presented the talk *New Proofs for Old Duality Theorems*.

Colloquia and Seminars.

- *Álgebra em Computação: Introdução à teoria de di-álgebras*, University of Aveiro, March – June 2009.
- *Triquotient maps via ultrafilter convergence*, Georgia Southern University, Statesboro, USA, April 28, 2008.
- *Continuous* V*-categories*, University of Coimbra, Portugal, April 22, 2008.
- *Variações sobre um lema de Yoneda* (Variations about a Lemma of Yoneda), University of Lisbon, Portugal, March 28, 2008.
- *De Álgebras a Co-álgebras* (From Algebras to Coalgebras), University of Aveiro, Portugal, April 10 and April 23, 2007.
- *The Yoneda Lemma in Topology*, Vrije Universiteit Brussel, Belgium, March 14, 2007.
- *Isbell Duality and Compactness*, York University, Toronto, Canada, February 20, 2007.
- *Towards a notion of* $\mathcal{T}$*-frame*, University of Coimbra, Portugal, January 31, 2007.
- *About Yoneda in* $\mathcal{T}$*-categories*, University of Coimbra, Portugal, November 13, 2006.
- *Was ist ein Cauchy-vollständiger topologischer Raum?* (What is a Cauchy-complete topological space?), University of Bremen, Germany, June 7, 2005 (Kolloquium).
- *Folgenbestimmte Räume und ihre Folgen* (Sequential spaces and their (con)sequences), University of Bremen, Germany, June 7, 2005.
- *Einige (unvollständige) Bemerkungen zur Vollständigkeit* (Some incomplete remarks about completeness), University of Bremen, Germany, January 4, 2005.
- *On categories of unitary structures*, York University, Toronto, Canada, May 18, 2004.

- *Mais notas sobre exponenciabilidade* (More remarks about exponentiability), University of Coimbra, Portugal, April 14, 2004.
- *Algumas notas sobre exponenciabilidade* (Some remarks about exponentiability), University of Aveiro, Portugal, November 21, 2003.
- *Eine Beschreibung lokaler Homöomorphismen mittels Ultrafiltern* (A description of local homeomorphism via ultrafilters), University of Bremen, Germany, May 14, 2003.
- *Topologia sob o ponto de vista da Álgebra* (Topology under the point of view of Algebra), University of Aveiro, April 4, 2003.
- *Quotient maps between lax algebras*, York University, Toronto, Canada, February 6, 2003.
- *Various classes of effective descent maps in categories of lax algebras*, University of Coimbra, Portugal, June 11, 2002.
- *Sobre uma caracterização de aplicações quociente em termos de ultrafiltros* (On a characterisation of quotient maps via ultrafilters), University of Coimbra, Portugal, January 15, 2002.
- *Lax algebras*, University of Antwerp, Belgium, June 11, 2001.
- *Topological examples of lax algebras*, University of Coimbra, Portugal, February 14, 2001.
- *A generalisation of the Duality Compactness Theorem*, University of Lisbon, Portugal, January 18, 2001.
- *Limit stability of classes of quotient maps*, University of Coimbra, Portugal, September 20, 2000.
- *Characterisations of special classes of quotient maps via convergence II*, University of Coimbra, Portugal, May 10, 2000.
- *On a generalised Stone-Weierstrass theorem and its application to natural dualities*, University of Coimbra, Portugal, February 10, 2000.
- *Natural Dualities*, University of Braunschweig, Germany, November 10, 1998.
- *Duality Theory and the Stone-Weierstrass Theorem II*, University of Coimbra, Portugal, May 13, 1998.
- *Duality theory and the Stone-Weierstrass Theorem I*, University of Coimbra, Portugal, May 6, 1998.
- *Concrete dualities*, University of Coimbra, Portugal, April 17, 1998.

4. PUBLICATIONS

Articles in Books.

MARIA MANUEL CLEMENTINO E DIRK HOFMANN (2007), On some special classes of continuous maps, in ELLIOTT PEARL, editor, *Open Problems in Topology II*, chapter 4, pages 367–376, Elsevier.

Articles in Journals (accepted).

DIRK HOFMANN (2010), Injective spaces via adjunction, *accepted for publication in J. Pure Appl. Algebra,* arXiv:math.CT/0804.0326.

DIRK HOFMANN AND WALTER THOLEN (2008), Lawvere completion and separation via closure, *Accepted for publication in Appl. Categ. Structures,* arXiv:math.CT/0801.0199.

Articles in Journals (published).

MARIA MANUEL CLEMENTINO, DIRK HOFMANN AND ISAR STUBBE (2009), Exponentiable functors between quantaloid-enriched categories, *Appl. Categ. Structures* **17** (1), 91–101, arXiv:math.CT/0604569.

MARIA MANUEL CLEMENTINO AND DIRK HOFMANN (2009a), Lawvere completeness in Topology, *Appl. Categ. Structures* **17**, 175–210, arXiv:math.CT/0704.3976.

MARIA MANUEL CLEMENTINO AND DIRK HOFMANN (2009b), Relative injectivity as cocompleteness for a class of distributors, *Theory Appl. Categ.* **21**, No. 12, 210–230, arXiv:math.CT/0807.4123.

GONÇALO GUTIERRES AND DIRK HOFMANN (2009), Sequential convergence via Galois correspondences, *Acta Math. Hungar.* **123** (1-2), 187–202.

ERALDO GIULI AND DIRK HOFMANN (2009), Affine sets: the structure of complete objects and duality, *Topology Appl.* **156** (12), 2129–2136.

Gonçalo Gutierres and Dirk Hofmann (2007), Axioms for sequential convergence, *Appl. Categ. Structures* **15** (5-6), 599–614.

Dirk Hofmann (2007), Topological theories and closed objects, *Adv. Math.* **215** (2), 789–824.

Maria Manuel Clementino and Dirk Hofmann (2006), Exponentiation in V-categories, *Topology Appl.* **153** (16), 3113–3128.

Dirk Hofmann (2006), Exponentiation for unitary structures, *Topology Appl.* **153** (16), 3180–3202.

Dirk Hofmann and Walter Tholen (2006), Kleisli compositions for topological spaces, *Topology Appl.* **153** (15), 2952–2961.

Maria Manuel Clementino, Dirk Hofmann and George Janelidze (2005), Local homeomorphisms via ultrafilter convergence, *Proc. Amer. Math. Soc.* **133** (3), 917–922.

Dirk Hofmann (2005), An algebraic description of regular epimorphisms in topology, *J. Pure Appl. Algebra* **199** (1-3), 71–86.

Maria Manuel Clementino and Dirk Hofmann (2004a), Effective descent morphisms in categories of lax algebras, *Appl. Categ. Structures* **12** (5-6), 413–425.

Maria Manuel Clementino and Dirk Hofmann (2004b), On extensions of lax monads, *Theory Appl. Categ.* **13**, No. 3, 41–60.

Maria Manuel Clementino, Dirk Hofmann and Walter Tholen (2004), One setting for all: metric, topology, uniformity, approach structure, *Appl. Categ. Structures* **12** (2), 127–154.

Maria Manuel Clementino, Dirk Hofmann and Walter Tholen (2003a), The convergence approach to exponentiable maps, *Port. Math. (N.S.)* **60** (2), 139–160.

Maria Manuel Clementino, Dirk Hofmann and Walter Tholen (2003b), Exponentiability in categories of lax algebras, *Theory Appl. Categ.* **11**, No. 15, 337–352.

Maria Manuel Clementino and Dirk Hofmann (2003), Topological features of lax algebras, *Appl. Categ. Structures* **11** (3), 267–286.

Dirk Hofmann (2002a), A generalization of the duality compactness theorem, *J. Pure Appl. Algebra* **171** (2-3), 205–217.

Dirk Hofmann (2002b), On a generalization of the Stone-Weierstrass theorem, *Appl. Categ. Structures* **10** (6), 569–592.

Maria Manuel Clementino and Dirk Hofmann (2002a), Triquotient maps via ultrafilter convergence, *Proc. Amer. Math. Soc.* **130** (11), 3423–3431.

Maria Manuel Clementino and Dirk Hofmann (2002b), On limit stability of special classes of continuous maps, *Topology Appl.* **125** (3), 471–488.

Submitted Articles.

Dirk Hofmann and Isar Stubbe (2010), Towards Stone duality for topological theories, Technical report, `arXiv:math.CT/1004.0160`.

Dirk Hofmann and PawełWaszkiewicz (2010), Approximation in continuous V-categories, Technical report, `arXiv:math.CT/1004.2228`.