Part B

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MARIE SKŁODOWSKA–CURIE ACTIONS

Individual Fellowships (IF)
Call: H2020-MSCA-IF-2017

PART B

"CARBS"

"Compositional Approximate Reasoning via Bialgebraic Semantics"

This proposal is to be evaluated as:

[**EF-ST**]

List of Participating Organisations

Participants	Legal Entity Short Name	Academic (tick)	Non-academic (tick)	Country	Dept. / Division / Laboratory	Supervisor	Role of Partner Organisation
Beneficiary							
University College London	UCL	*		UK	Department of Computer Science	Alexandra Silva	

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1 Excellence

1.1 Quality and credibility of the research/innovation action (level of novelty, appropriate consideration of inter/multidisciplinary and gender aspects)

Programming languages with probabilistic features are abound in computer science, for instance to deal with uncertainty in modelling hardware or software systems, and for quantitative analysis such as performance modelling or risk assessment. A motivating example for the current project is ProbNetKAT,[1] a probabilistic language for describing randomised protocols and analysing quantitative properties in networks such as throughput or chance of failure. Other prominent examples are probabilistic modelling languages, and the wide range of probabilistic programming languages for machine learning that are currently under very active development.[2]

To analyse programs in such quantitative languages, a fundamental question is whether two programs behave "approximately" or "probably" the same. This question underlies many correctness properties: whether two implementations of a randomised protocol behave the same, whether such a protocol behaves as expected, or whether it has a very low probability of failure, for instance. Reasoning *approximately* about such questions is crucial in the context of quantitative systems, as it is robust under minor variations.[3] Having effective methods for proving approximate equivalence is thus an important challenge in the study of quantitative systems.

CARBS takes a foundational approach to this challenge, with the overall aim of developing a general mathematical framework of compositional proof techniques for approximate equivalence. In developing this framework, I will focus on two essential features:

- *General applicability*: there exist a wide range of probabilistic languages and models,[4] and this active area of research will certainly continue to generate new and perspectives in the future. Many of these languages however share common aspects, and it is a major aim of this project to develop foundational techniques that are widely applicable.
- *Compositionality*: properties of a larger system can be inferred from properties of its components. This is crucial for mastering the complexity of large-scale systems. One of the aims is to *integrate* compositionality within proof techniques for approximate reasoning.

The resulting proof techniques will be applied to approximate equivalence of ProbNetKAT programs, allowing me to immediately evaluate the resulting methods in practical case studies.

The CARBS approach is based on leveraging proven technology for behavioural equivalence to the quantitative setting of approximate reasoning. More precisely, the core technical ingredients are the theory of *coalgebras* (to cover a wide range of different models of computation), *bialgebraic semantics* (to study compositionality in quantitative languages) and *enhanced coinduction* (to effectively and compositionally reason about these calculi). The applicant is an expert in these areas.[5] This is complemented by the expertise of the host in quantitative systems and network calculus: Alexandra Silva is one of the main people behind ProbNetKAT.

[1] N. Foster, D. Kozen, K. Mamouras, M. Reitblatt, and A. Silva. "Probabilistic NetKAT". in: *ESOP 2016*. 2016, pp. 282–309; S. Smolka, P. Kumar, N. Foster, D. Kozen, and A. Silva. "Cantor meets Scott: semantic foundations for probabilistic networks". In: *POPL 2017*. 2017, pp. 557–571.

[2] http://probabilistic-programming.org

[3] A. Giacalone, C.-C. Jou, and S. A. Smolka. "Algebraic reasoning for probabilistic concurrent systems". In: *IFIP TC2 Conference*. Citeseer. 1990; J. Desharnais, V. Gupta, R. Jagadeesan, and P. Panangaden. "Metrics for labelled Markov processes". In: *TCS* 318.3 (2004), pp. 323–354; F. van Breugel and J. Worrell. "A behavioural pseudometric for probabilistic transition systems". In: *TCS* 331.1 (2005), pp. 115–142.

[4] F. Bartels, A. Sokolova, and E. P. de Vink. "A hierarchy of probabilistic system types". In: *TCS* 327.1-2 (2004), pp. 3–22.

[5] J. Rot. "Enhanced Coinduction". PhD thesis. Leiden University, Oct. 2015.

Overview and key objectives CARBS proposes an extension of bialgebraic semantics to quantitative systems, providing on the one hand fundamental insights about quantitative coalgebras and compositionality, and on the other hand concrete, effective proof techniques for approximate reasoning. Overall, the key objectives of this project are (1) A bialgebraic framework for the specification and analysis of quantitative calculi and behavioural metrics; (2) A general toolkit of enhanced coinduction for compositional approximate reasoning, and (3) The application to approximate reasoning in ProbNetKAT.

Behavioural metrics There is a vast literature on proof techniques for behavioural equivalence, with bisimilarity of processes as a well-known example from concurrency theory. Approximate reasoning requires to move from behavioural equivalence to *behavioural metrics*, formalising how far apart two programs are.[6] While (exact) equivalence is by now fairly well understood, behavioural metrics require different tools and techniques, posing significant research challenges. This has led to a range of algorithms and techniques for probabilistic models.[7] However, many of these existing approaches apply primarily to specific formalisms and in particular to (finite) state-based systems rather than quantitative *languages*, which require understanding compositionality. There are several recent studies of compositional programming constructs in certain kinds of probabilistic calculi,[8] which however do not yet develop (enhanced) coinductive proof techniques.

While enhanced coinduction has been mainly applied for (exact) behavioural equivalence, first steps towards their application to behavioural metrics have been proposed recently;[9] this is an important inspiration for the project. However, a general theory of enhanced coinduction for approximate reasoning is still missing. I will develop a more general framework of up-to techniques based on coalgebraic foundations (mentioned explicitly as an open problem in *loc. cit.* and by Baldan et al.[10]), applicable to different systems and different behavioural metrics. In particular, this enables the application to probabilistic network calculus.

Coalgebraic modelling. Behavioural metrics are fundamentally coinductive: they generalise the classical notion of bisimulation to the quantitative setting. Coinduction is studied systematically in the theory of *coalgebras*, the framework of choice to model state-based systems and their semantics in a general and uniform manner.[11] The theory of coalgebras has provided new perspectives and results in such diverse areas as modal logic, operational semantics, probabilistic systems, infinite data structures, automata theory and, most recently, networking. The framework of coalgebras provides generic notions of *behavioural equivalence*, *bisimulation* and *coinduction* to reason about systems and their behaviour.

It was first shown by van Breugel and Worrell how to capture behavioural metrics for probabilistic systems coalgebraically, in the category PMet of pseudometric spaces.[12] The coalgebraic

[6] Desharnais, Gupta, Jagadeesan, and Panangaden, "Metrics for labelled Markov processes".

[7] F. van Breugel and J. Worrell. "Approximating and computing behavioural distances in probabilistic transition systems". In: *TCS* 360.1-3 (2006), pp. 373–385; D. Chen, F. van Breugel, and J. Worrell. "On the Complexity of Computing Probabilistic Bisimilarity". In: *FOSSACS 2012.* 2012, pp. 437–451; G. Bacci, G. Bacci, K. G. Larsen, and R. Mardare. "On-the-Fly Exact Computation of Bisimilarity Distances". In: *TACAS 2013.* 2013, pp. 1–15; G. Bacci, G. Bacci, K. G. Larsen, and R. Mardare. "On the Metric-Based Approximate Minimization of Markov Chains". In: *ICALP 2017.* 2017, 104:1–104:14.

[8] D. Gebler, K. G. Larsen, and S. Tini. "Compositional Metric Reasoning with Probabilistic Process Calculi". In: *FoSSaCS 2015.* 2015, pp. 230–245; D. Gebler and S. Tini. "Compositionality of Approximate Bisimulation for Probabilistic Systems". In: *EXPRESS/SOS 2013.* 2013, pp. 32–46.

[9] K. Chatzikokolakis, C. Palamidessi, and V. Vignudelli. "Up-To Techniques for Generalized Bisimulation Metrics". In: *CONCUR 2016.* 2016, 35:1–35:14.

[10] P. Baldan, F. Bonchi, H. Kerstan, and B. König. "Behavioral Metrics via Functor Lifting". In: *FSTTCS 2014.* 2014, pp. 403–415.

[11] J. Rutten. "Universal coalgebra: a theory of systems". In: *TCS* 249.1 (2000), pp. 3–80; B. Jacobs. *Introduction to Coalgebra. Towards Mathematics of States and Observations.* Cambridge Tracts in TCS. Cambridge University Press, 2016.

[12] Breugel and Worrell, "A behavioural pseudometric for probabilistic transition systems".

presentation was recently extended by Baldan et al.[13] as an instance of the abstract framework of coinduction in fibrations, providing abstract notions of quantitative models, where classical metrics such as those based on the Kantorovich lifting form a special case. As such, this is a good starting point for the aim of an general theory of proof techniques for approximate reasoning.

Research methodology and approach. The overall aim of effective, general reasoning about approximate equivalence will be realised through the aforementioned three key objectives (1), (2) and (3). The *bialgebraic framework* (1) provides the mathematical foundation for systematically studying compositionality in approximate calculi, and the subsequent application to the *development of compositional proof techniques* (2). The result of these proof techniques will be evaluated and *applied to ProbNetKAT* (3). These objectives translate directly into three work packages WP1–3. Below we explain each of these work packages in detail, including the relevant background on bialgebraic semantics, enhanced coinduction and ProbNetKAT.

WP1: Bialgebraic foundations of behavioural metrics. Bialgebraic semantics, a categorical generalisation of structural operational semantics,[14] is a modern, generic and systematic approach to semantics that comes with a powerful toolkit for reasoning about important properties such as compositionality. Formally, the structure or syntax of such calculi is modelled by algebras, and the behaviour by coalgebras.[15] The semantics of the language is defined in terms of the interplay between algebra and coalgebra, formalised by the categorical notion of distributive law. Instantiating the theory to concrete types of coalgebra yields rule formats for calculi that are guaranteed to be compositional, i.e., for which behavioural equivalence is a congruence.[16]

The application of the bialgebraic framework for approximate reasoning, however, is entirely open. In WP1 **I will develop a quantitative bialgebraic framework for approximate reasoning** by combining the aforementioned coalgebraic theory of behavioural metrics with the theory of *quantitative algebras*,[17] which was introduced recently with the specific aim of approximate reasoning. The main steps are to identify suitable distributive laws to represent quantitative calculi, and the basic modelling of approximate equivalence in the bialgebraic setting. Based on this bialgebraic presentation, **I will extract concrete syntactic rule formats that characterise compositional quantitative languages.**

WP2: Enhanced coinduction for approximate reasoning. The combination of algebra and coalgebra in bialgebraic semantics enables the application of *enhanced coinduction*. In particular, *coinduction up to context* improves the coinductive proof technique by extending the *circularity* provided by coinduction and coalgebraic modelling with *compositionality* provided by algebraic modelling. These techniques can drastically reduce the size of proofs needed.[18] The presentation of enhanced coinduction in terms of algebras and coalgebras is part of a recent line of research partially developed by the applicant,[19] which enables the application to a wide variety of systems and properties. Enhanced coinduction originates from concurrency theory,[20]

[13] Baldan, Bonchi, Kerstan, and König, "Behavioral Metrics via Functor Lifting".

[14] D. Turi and G. Plotkin. "Towards a Mathematical Operational Semantics". In: *LICS 1997.* 1997, pp. 280–291; L. Aceto, W. Fokkink, and C. Verhoef. "Structural Operational Semantics". In: *Handbook of Process Algebra.* Elsevier Science, 2001, pp. 197–292.

[15] Turi and Plotkin, "Towards a Mathematical Operational Semantics".

[16] F. Bartels. "On generalised coinduction and probabilistic specification formats". PhD thesis. CWI, Amsterdam, Apr. 2004; B. Klin. "Bialgebras for structural operational semantics: An introduction". In: *TCS* 412.38 (2011), pp. 5043–5069.

[17] R. Mardare, P. Panangaden, and G. D. Plotkin. "Quantitative Algebraic Reasoning". In: *LICS '16.* 2016, pp. 700–709.

[18] D. Pous and D. Sangiorgi. "Enhancements of the bisimulation proof method". In: *Advanced Topics in Bisimulation and Coinduction.* Cambridge University Press, 2012, pp. 233–289; Rot, "Enhanced Coinduction".

[19] Rot, "Enhanced Coinduction"; J. Rot, F. Bonchi, M. Bonsangue, D. Pous, J. Rutten, and A. Silva. "Enhanced Coalgebraic Bisimulation". In: *Math. Struct. Comput. Sci.* (2015), pp. 1–29; J. Rot, M. Bonsangue, and J. Rutten. "Coalgebraic Bisimulation-Up-To". In: *SOFSEM 2013.* 2013, pp. 369–381; F. Bonchi, D. Petrisan, D. Pous, and J. Rot. "Coinduction up-to in a fibrational setting". In: *CSL-LICS 2014.* 2014, p. 20.

[20] Pous and Sangiorgi, "Enhancements of the bisimulation proof method"; D. Sangiorgi. "On the bisimulation

but is increasingly applied in other areas: a highlight is a recent efficient algorithm for language equivalence of non-deterministic automata featured on the cover of the Journal of the ACM.[21]

Based on the bialgebraic foundation of WP1, **I will apply the abstract framework of enhanced coinduction to derive compositional proof techniques** for approximate equivalence in quantitative calculi. That framework relies on bialgebras and distributive laws, hence the result of WP1 is a suitable starting point. As a result of applying the abstract framework, I will obtain a range of sound proof techniques. **I will subsequently use these proof techniques to develop generically applicable algorithms for approximate equivalence.**

WP3: Approximate reasoning in probabilistic network calculus. An intended application of my approach comes from the world of *software-defined networking* (SDN), which rose to prominence and widespread industrial use in the last years. SDN separates control of the network from the devices that implement packet processing, and forwarding rules are expressed in standardised, open protocols. This enables the development of a range of high-level languages for networking. *NetKAT* is such a language, based on solid, mathematical principles. In fact, its *coalgebraic* presentation forms the basis for a decision procedure of behavioural equivalence.[22]

In this project, I will focus on the aforementioned *ProbNetKAT*, an extension of NetKAT with probabilistic features, that was designed to reason about randomised protocols and probability of, e.g., failure or congestion in the network. Based on the tools developed in this project, I will develop approximate reasoning about equivalence of ProbNetKAT programs. The envisaged proof techniques have previously been successfully applied by the applicant in the context of (exact) behavioural equivalence of regular expressions, on which NetKAT is based.[23] For WP3, the expertise of the host, one of the main people behind of ProbNetKAT and the coalgebraic theory of NetKAT, will be invaluable. This will be further strengthened by a research visit to the NetKAT founders at Cornell University, allowing to immediately incorporate the developed techniques in current research on decision procedures[24] and apply it to concrete case studies.

The first step in WP3 is to **extend the coalgebraic theory of NetKAT to a bialgebraic presentation**, by adapting the bialgebraic theory of regular expressions.[25] The next step is to move to the quantitative setting of ProbNetKAT, putting the latter in the context of the framework developed in WP1, and **apply the developed proof techniques developed in WP2 to ProbNetKAT to obtain compositional algorithms for approximate equivalence**.

Originality and innovative aspects of the research programme. CARBS proposes for the first time a bialgebraic framework for behavioural metrics and approximate reasoning, providing a new, foundational perspective on the interplay between behavioural metrics and quantitative algebra. This will lead to abstract specification formats for compositional calculi generalising aforementioned proposals for specific instances. Further, the project will extend enhanced coinduction to behavioural metrics at the bialgebraic level, leading to a fully general framework of efficient proof techniques for approximate reasoning. Finally, the application of these proof techniques for probabilistic network programs provides for a real need: approximate reasoning about probabilistic network programs.

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proof method". In: *Math. Struct. Comput. Sci.* 8.5 (Oct. 1998), pp. 447–479.

[21] F. Bonchi and D. Pous. "Hacking nondeterminism with induction and coinduction". In: *Comm. ACM* 58.2 (2015), pp. 87–95.

[22] N. Foster, D. Kozen, M. Milano, A. Silva, and L. Thompson. "A Coalgebraic Decision Procedure for NetKAT". in: *POPL 2015*. 2015, pp. 343–355.

[23] J. Rot, M. M. Bonsangue, and J. Rutten. "Proving language inclusion and equivalence by coinduction". In: *Inf. Comput.* 246 (2016), pp. 62–76.

[24] S. Smolka, D. Kahn, P. Kumar, N. Foster, D. Kozen, and A. Silva. "Deciding Probabilistic Program Equivalence in NetKAT". in: *CoRR* arXiv:1707.02772 (2012).

[25] B. Jacobs. "A Bialgebraic Review of Deterministic Automata, Regular Expressions and Languages". In: *Essays Dedicated to Joseph A. Goguen*. Ed. by K. Futatsugi, J.-P. Jouannaud, and J. Meseguer. Vol. 4060. LNCS. Springer, 2006, pp. 375–404.

Interdisciplinary aspects. The project lies within the intersection of mathematics and computer science, applying and developing mathematical techniques to reason accurately and effectively about models of computation. It further involves the field of networking and systems in WP3.

New collaboration opportunities. The innovative research is expected to lead to various new collaboration opportunities and increase my international visibility. My expertise on bialgebraic semantics is crucial for the succesful execution of this project, making the fellowship attractive for the host institute. I will obtain valuable new expertise on both quantitative systems and network programming, which are at the forefront of international research and will continue to be a major focus in the areas of programming languages and theoretical computer science.

The *Programming Principles, Logic and Verification* group at UCL is an ideal base for this project, recognised as being at the top of international research in programming languages and verification. London is currently one of the best places for theoretical computer science, with numerous leading universities in the area, including UCL, Queen Mary and Imperial college, but also the *Quantitative Analysis and Verification* group at nearby Oxford university, which is highly relevant to the innovative research. I will be able to benefit from this through participation in local seminars, research visits and ensuing collaborations. At UCL, I will have access to the expertise of the *Communications and Information Systems* group, which will be instrumental for the innovative applications to networking. The project is further strengthened by research visits to McGill University and Cornell University, allowing to expand my international network and visibility in the areas of quantitative systems and network programming languages, beyond what would otherwise be possible. Overall, the results of this project will form an excellent basis for joint grant proposals, to consolidate and continue these collaborations after the fellowship.

1.2 Quality and appropriateness of the training and of the two way transfer of knowledge between the researcher and the host

Training programme With only half a year of postdoc experience after my PhD I obtained a tenure track position at Radboud University. The overall training objective is to further broaden my scientific portfolio and expand my network and visibility, by devoting a year purely to this ambitious research project in collaboration with internationally leading researchers. The project enables me to be involved and contribute to new areas of research that are very active internationally (quantitative systems and network programming), thereby significantly increasing my chances of receiving the necessary funding in the next years to build an own research group. The training programme is thus designed to strengthen my scientific track record, portfolio and network, and provide me with invaluable transferrable skills for managing research projects, obtaining funding and leading a group.

Scientifically, the fellowship gives me unique possibilities for expanding my knowledge, collaboration and research network in the areas of quantitative systems and network programming languages. This is achieved in the first place by collaboration with Prof. Silva and her research group, structured through weekly research meetings. Further, as mentioned in the last paragraph in the previous section, UCL is ideally situated for interacting with experts in the broad area of this project at neighbouring groups and universities. About three months into the fellowship, I will visit Prof. Panangaden at McGill University, a leading authority on probabilistic systems and founder of the algebraic techniques underlying the proposal. About two months before the end of the fellowship, I will visit Prof. Kozen at Cornell University, an authority in computer science and one of the founders of the network calculus forming an integral part of this proposal. Both visits are expected to lead to continued collaborations after the fellowship.

I will benefit from the extensive programme in transferrable skills offered at UCL[26], by taking courses such as *Becoming a Principal Investigator or Research Leader* and *Writing Targeted*

[26] http://www.ucl.ac.uk/hr/od/index.php

Grant Proposals. These courses will help further strengthening the project management, supervision and acquisition skills that are crucial at this stage of my career. Simultaneously, I will develop these skills in practice, by assisting in the supervision of a PhD student in Prof. Silva's group. This supervision is planned to continue after the fellowship through mutual visits.

Transfer of knowledge to the host I am an expert on coinductive proof techniques and bialgebraic specification. These research skills and knowledge will be transferred to the host institute in the first place by collaboration with Prof. Silva and her group, the joint supervision of a PhD student, and by giving regular talks at local seminars. In the beginning of the fellowship I will organise a PhD school on bialgebraic semantics, advertised broadly at universities in London and Oxford, further increasing visibility of the research group at UCL as a leading group in coalgebraic semantics and proof techniques. This visibility is further strengthened by the organisation of a workshop towards the end of the fellowship, in order to disseminate the results and discuss future perspectives and collaborations.

1.3 Quality of the supervision and of the integration in the team/institution

1.3.1 Qualifications and experience of the supervisor(s)

Professor Silva is a leading expert in coalgebra and semantics of programming languages, witnessed by her numerous publications (>50) on these topics at top-tier venues, for instance at the A-ranked conference series POPL, LICS, and RTA including the Best Paper award at RTA in 2015. She was the recipient of the Dutch government's Veni grant and of an European Research Council Starting grant. The topic of the latter is core to the present proposal - quantitative analysis of network behaviour. She was recently promoted to a full professor at UCL. She has graduated 2 PhD students, currently supervises 4 PhD students and 4 postdocs, all in topics related to semantics and theory. Two of the current PhD students and two post-docs work on quantitative network verification. She is one of the main organisers of the programming language mentoring workshop (at POPL, 2017 and 2018) and initiated the Logic mentoring workshop (at LICS). She thus has an excellent track record in guiding and mentoring young researchers.

1.3.2 Hosting arrangements

In the 2014 Research Excellence Framework (REF) evaluation UCL was ranked in first place for Computer Science, out of 89 Universities assessed, and considerably ahead of other Institutions. The Programming Principles, Logic, and Verification (PPLV) group was the highest ranked research group in the evaluation. PPLV has outstanding connections with cutting-edge industry and excellent connections with other groups at UCL, including Systems and Networks, Information Security, and Software Systems Engineering. There are regular seminars and working groups where knowledge can be shared and collaborations formed. During the fellowship I will have weekly meetings with Prof. Silva to assess scientific progress and address practical matters. Being in the same corridor, we will also be able to discuss informally at any time, and I will collaborate directly with her on certain aspects of this project. I will complete a Career Development Plan with Prof. Silva early in the fellowship and we will revisit this quarterly.

1.4 Capacity of the researcher to reach or re-enforce a position of professional maturity/independence

I have shown the ability to independently carry out research as well as collaborate internationally with leading experts in different fields. I am an expert on coinductive techniques: my PhD thesis on this topic was awarded a cum laude qualification and a national research school award. While I defended my PhD less than two years ago, my scientific output includes well over 30 peer-reviewed papers in journals and proceedings of conferences, including top-tier venues such as LICS, CAV, ICALP, CONCUR and FoSSaCS, in topics ranging from abstract coalgebraic theory to concrete case studies in program verification.

Besides my thesis I have collaborated to a broad range of topics in coalgebra including automata minimisation (during a postdoc at ENS Lyon), duality in automata theory, coalgebraic foundations of types in object-oriented programming and coalgebraic logic for trace semantics (during a four month research visit to the University of Warsaw). More recently, I have co-invented (with Damien Pous) a novel concept in the theory of coalgebras that immediately got published at a prestigious venue and opens up a new direction of research in coinductive semantics. Besides my work on the theory of coalgebras, I have been active in theoretical and practical aspects of verification. A highlight is my involvement in the verification of a concrete sorting algorithm, which highlighted a bug in the Java standard library. This generated widespread attention both from a scientific and non-scientific audience: a blog post on the topic received over 200.000 unique page views in the first few days, and led to intense discussions on message boards and news sites.

My scientific independence, potential and capability of generating new ideas is further recognised by the tenure track position at a very good university that I received in less than one year from my defence. The fellowship would allow me to further expand and broaden my scientific portfolio, network and recognition in the community, which will be invaluable for my trajectory of building an own research agenda and group, and becoming a leading independent researcher.

2 Impact

2.1 Enhancing the potential and future career prospects of the researcher

After the fellowship I will return to Radboud University to proceed with my tenure track, with a significantly strengthened scientific profile and highly increased chances for obtaining tenure. Being awarded a prestigious MSCA fellowship would show my ability to attract research funding, a major criterion for tenure. The overall strengthening of my CV will increase my chances of obtaining financing for building up a group, such as a Dutch VIDI grant or an ERC starting grant, for which I will have a very good profile by the end of the fellowship. For the succesful execution of such projects, the transferrable skills learned during this fellowship, in particular project management, supervision and acquisition, will be crucial.

The fellowship will be instrumental for my overall professional aims in the following years to establish an internationally recognised and competitive scientific agenda as an independent researcher, obtaining tenure and leading a research group. Scientifically, I will strengthen my profile with both theoretical and applied aspects of quantitative systems and network programming languages, which are very active fields of research and provide ample opportunities both for collaboration and attracting research funding in the near future. The project allows me to devote a year of dedicated research, further strengthen my publication and dissemination record and increase my standing in the community through the innovative research and the collaboration with leaders in the field.

2.2 Quality of the proposed measures to exploit and disseminate the action results

The results of the project will be published in top-tier international conferences such as POPL, LICS or FoSSaCS and in leading journals such as LMCS, as well as to specialised venues such as CALCO and CMCS. I will support further dissemination by frequently speaking at local seminars at various universities (including but not limited to those mentioned at the end of Section 1.1) about the results of the project. These visits will be planned during the fellowship, taking advantage of the extensive network of Prof. Silva complemented by my own network. To foster international collaboration and communication of the main results, we will organise a workshop on quantitative systems and coalgebraic methods towards the end of the fellowship.

I will aim to publish open-access as much as possible, to guarantee general availability of the results of this project; this is fully supported by UCL.[27] The fundamental nature of the research makes it unlikely that intellectual property issues will arise. However, in case of doubt, I will immediately contact the *UCL Innovation and Enterprise*[28] office.

2.3 Quality of the proposed measures to communicate the action activities to different target audiences

The overall plan for communication to different audiences is tailored towards two main objectives: dissemination of the results of the project itself to a broad audience, and more personal communication of the experience of an MSCA fellowship and carrying out an ambitious scientific project in general. To support both objectives, I will write (approximately monthly) blog posts both on my personal experience of the fellowship and on the concrete results and applications of the project addressed to a broad audience. I have previously been involved in practical experiments in verification of Java programs, which we published in a similar manner[29], receiving widespread attention (over 200.000 unique page views in a few days) and, most importantly, elaborate and frequently sophisticated discussions on online platforms, mainly among programmers. The current project, including applications to network programming, has a similar potential leading to direct feedback from the networking and programming languages communities.

Early in the fellowship, I will organise a PhD school on bialgebraic semantics (see Section 1.2). Further, certain results of the project will be incorporated in courses that I teach at Radboud University when I return (e.g., *Coalgebra*). At a very different level, I will contribute to the active programme of UCL in developing materials and giving scientific talks at high schools. Other public outreach opportunities, such as speaking at open days, will arise during the fellowship.

3 Quality and Efficiency of the Implementation

3.1 Coherence and effectiveness of the work plan

The proposed work is organised according to the methodology described in Section 1.1, in terms of the three overall scientific work packages **WP1**, **WP2** and **WP3**. These work packages are each divided in two main tasks. Each of these tasks will result in a scientific paper or report. For quick dissemination of these results, most of it will be presented at conferences or workshops. The results of WP1.2 will be submitted to a journal, consolidating also the outcome of WP1.1. The **tasks and deliverables** are listed below.

	Description	Output
WP1.1	Bialgebras and distributive laws in PMet	Conference
WP1.2	Rule formats for compositional quantitative calculi	Journal
WP2.1	Enhanced coinduction for compositional approximate reasoning	Report
WP2.2	Application to algorithms for approximate equivalence	Conference
WP3.1	Bialgebraic semantics of (Prob)NetKAT	Workshop
WP3.2	Algorithms for approximate equivalence of ProbNetKAT	Conference

WP1, and in particular WP1.1, is at the core of the project: both WP2 and WP3 depend on WP1.1, and WP3 depends on WP2.1. The estimated time planning is presented in Figure 3.1. The chart also includes major training and dissemination activities. Other activities, including local seminars and research visits, workshops, writing blog posts and other public outreach events are more difficult to plan in advance and hence are not included. Similarly, I plan to

[27] http://www.ucl.ac.uk/library/open-access
[28] http://www.ucl.ac.uk/enterprise
[29] http://www.envisage-project.eu/proving-android-java-and-python-sorting-algorithm-is-broken-and-how-to-fix-it/

take courses at UCL on several days around the middle of the fellowship, but exact planning will depend on the course schedule.

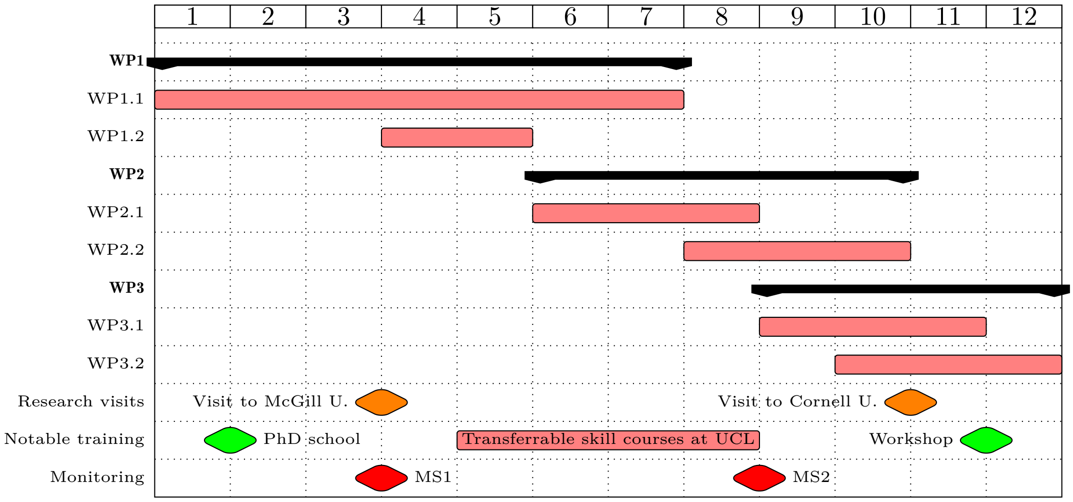

Figure 1: Gantt chart of the work plan

Milestones There are two major milestones, at which the overall scientific progress and trajectory will be thoroughly assessed, and adapted if needed. The first milestone **M1** is planned after **three months**: I should have understood and developed the basics of the quantitative bialgebraic framework. The second milestone **M2** is planned after **eight months**: I should have developed the enhanced coinductive proof techniques well developed enough in order to continue with the application to probabilistic networking languages.

3.2 Appropriateness of the allocation of tasks and resources

The work packages and deliverables described in the previous section constitute the overall scientific work of the project, for which I will be principally responsible. This work involves research for–and writing of–three conference publications, a journal paper and at least an extended abstract for a workshop. This is an ambitious output for a one-year project, but fully consistent with my production rate throughout my career. Weekly meetings are consistent with the workload of Prof. Silva.

The three work packages have been designed in a flexible manner and scheduled with the crucial dependencies in mind, to minimise the effect of (unexpected) problems (described in detail in the next section). In particular, both WP3 and WP2 depend strongly on the success of WP1. This is why the first half year is fully devoted to WP1; with my expertise in bialgebraic semantics WP1.1 is expected to be completed well in time, allowing plenty of time for the remaining work. Moreover, the two research visits have been planned ideally to boost WP1 and WP3, respectively. The other training activities are spread evenly throughout the year.

The costs for research visits, organisation of the workshop and other visits to conferences and workshops will be covered by the Research, Training and Networking Costs budget. This research does not require further resources, so this budget is expected to be fully sufficient.

3.3 Appropriateness of the management structure and procedures, including risk management

Organisation, management structure and progress monitoring to ensure objectives are reached
I will work on a Career Development Plan at the beginning of the fellowship according to the training goals and long-term career aims outlined above. This will be reviewed and reassessed

quarterly together with Prof. Silva. Training and scientific progress will be monitored during regular meetings, and reassessed extensively around the two milestones (Section 3.1). My principal responsibility for the management of the project is an integral part of the training programme.

Risk analysis This is an ambitious research project, and naturally involves several risks. The three most important risks, together with suitable countermeasures, are identified below.

WP1: *delay in development of bialgebraic framework and rule formats (low risk).* The bialgebraic framework of WP1 is crucial for the project: it is the foundation of WP2 and WP3. However, given my expertise on bialgebras combined with the expertise of the host institute (as well as McGill university) on quantitative systems, this is likely to succeed. In any case, WP1 does not require full development for continuing with WP2 and WP3: in the unlikely case that the bialgebraic approach causes major difficulties, my understanding of the coalgebraic and algebraic approaches to quantitative systems will have developed to a sufficient extent to allow continuation with the remaining work packages on proof techniques and applications.

WP3.2: *limited applicability of developed proof techniques to probabilistic network calculus (medium/high risk).* The problem of equivalence of probabilistic network programs has been shown to be very challenging, making WP3.2 risky, but also very high-gain, even in case of only partial completion. Moreover, the research visit to Cornell university has been planned strategically to seek help from world-leading experts during the development of WP3. Finally, in case of failure, a successful execution of only WP1, WP2 (and possibly WP3.1) would already be a solid contribution, encompassing many of the innovative aspects mentioned in Section 1.1. Given my strong background in bialgebraic semantics and enhanced coinduction, it is very likely that I will successfully complete WP1, WP2 and WP3.1.

Overall risk: *the research plan may prove too ambitious and time-consuming for full completion (medium risk).* This risk is mitigated by the very nature of WP1.2 and WP2: they both aim to be applicable to a very general scope, but the actual range of results is flexible, and in case of severe time pressure can be adapted accordingly. This inherent flexibility is also important to deal with unforeseen issues.

3.4 Appropriateness of the institutional environment (infrastructure)

The hosting group will provide me with office space with the usual equipment (whiteboard, desktop computer etc.). I will have weekly meetings with Prof. Silva for collaboration, guidance and project management. My office will be in the same corridor as Prof. Silva's office, making it easy to interact with her and the other members of the group. My integration in the group is further strengthened by weekly group meetings, collaborations on parts of the project and through supervision of a PhD student.

I will have access to the extensive physical and electronic libraries of UCL. While the project is theoretical in nature and does not require advanced computational resources for the most part, if high performance computing is needed for the experiments in WP3 I will have access to UCL's dedicated configurable departmental cluster of 3000 cores. The host will support my commitment to publishing open access. UCL has extensive experience in hosting MSCA fellows, with 70 fellowship in the last two years. Practical and administrative support will be provided by the UCL Human Resources Division. I will benefit from the assistance of UCL's Accommodation Service with moving to London, and the Employee Assistance Service to provide guidance on personal and work-related issues.

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