Professor Neil Ghani
Google Deep Mind, Univ. Strathclyde

Personal Details:

Name: Prof. Neil Ghani
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Academic Qualifications:

- *Adjoint Rewriting*, Ph.D. in Computer Science, University of Edinburgh. 1990-1995.
- M.Sc. in Computation, Balliol College, University of Oxford. 1989-1990.
- B.A. Hons in Mathematics, Pembroke College, University of Oxford. 1985-1988.

Recent Positions:

- Google Deep Mind, October 24 — .
- Head of Department of Computer and Information Sciences, Univ. of Strathclyde. Aug 2017 to July 2023.
- Assoc. Dean (Research), Fac. of Science, Univ. of Strathclyde, Glasgow, Scotland. Nov 2014 to August 2017
- Prof. of Computer Science, Univ. of Strathclyde, Glasgow, Scotland. July 2008 —

Significant Academic/Non-Academic Projects

- A Correct by Construction Approach to Approximate Computation. EPSRC 2023-2027. Co-Investigator. Grant Value 700,000 pounds. Code EP/Y000455/1.
- Dependent Types For Trustworthy Tools. National Physical Laboratory 2019-2023. Co-Investigator. Grant Value 600,000 pounds. **Non-academic Funder**
- Homotopy Type Theory: Programming and Verification. EPSRC 2015-2019. Principal Investigator. Total Grant Value: 1.2M pounds. Code EP/M016951/1.
- Logical Relations for Program Verification. EPSRC 2013-2017. Sole Investigator. Grant Value: 442,000 pounds. Code EP/K023837/1.
- Categorical Foundations of Indexed Programming. EPSRC 2010-2013. Co-Investigator. Grant Value: 342,000 pounds. Code EP/G068917/1.
- Reusability and Dependent Types. EPSRC 2009-2012. Principal Investigator. Grant Value: 148,000 pounds. Code EP/G034699/1.
- Theory and Applications of Induction Recursion. EPSRC 2009-2013. Principal Investigator. Grant Value: 311,000 pounds. Code EP/G033056/1.
- Theory and Applications of Containers. EPSRC 2005-2008. Principal Investigator. Grant Value: 206,000 pounds. Code EP/C511964/2.
- Kan - A Categorical approach to Computer Algebra. EPSRC 2001 - 2004. Sole Investigator. Grant Value: 130,000 pounds. Code GR/R29604/01. End of grant IGR assessment: Tending to Outstanding.

Academic Leadership: I have significant personal and leadership skills which enable me to deliver an ambitious and transformative agenda. These skills arose from my time as Head of Department and Associate Dean of Science. Staff development lies at the very heart of these roles. I regard staff as our most prized asset and so communicate, persuade and listen to staff at both a rational and an emotional level; and continuously reflect and refine what we do to achieve the best outcomes possible. This requires team leadership which I achieve by i) agreeing with team members a specific remit to ensure they take ownership of that remit; ii) offering operational autonomy so people can bring their own creativity and innovation to bear on their remit; and iii) giving team members continuous support and oversight. I am particularly heartened by the number of staff taking on senior roles in the Department and University, and by those who have had significant research success after not having any for some time.

Concretely, I have been HoD of Computer and Information Sciences (CIS) for 5.5 years, running a Department with over 100 full time staff and an annual turnover of over £10m. I have led a remarkable transformation of CIS: i) grant income has more than doubled; ii) our PGR cohort has doubled; iii) our REF return almost doubled in size with an associated increase in quality leading to an improvement of 19 places in the recent REF; iv) in 2019 CIS came 5th in UK for the National Student Survey and in 2021 we came 8th; v) we launched two highly innovative Graduate Apprenticeships (GAs) attracting over 100 students; vi) PGT numbers increased from 50 in 2017/18 to 400 in 2022/3; vii) we launched 3 highly successful new PGT courses including an advanced MSc in Artificial Intelligence and another conversion MSc in AI and Applications; viii) we secured our first Knowledge Transfer Partnerships (KTPs) and are aiming at 4 KTPs next year; ix) two new research groups were successfully launched including one in Artificial Intelligence; x) we transformed a deficit of £500K into a surplus of £2m.

I am thus capable of i) training and developing staff to improve performance; ii) managing complex projects with multiple/diverse stakeholders involving significant financial and human resources; iii) developing strategic learning activities for non-academics; iv) providing

leadership across not just Computer Science, but Science in general — and ranging from fundamental research through to impactful knowledge exchange.

Scientific Contributions: I have a world-leading track record using category theory and type theory to create formal mathematical models appropriate for formal proof. I use category theory to understand the structure of computation and then reflecting that structure into new type systems to enable formal proof. The application of category theory and type theory to machine learning and data science is what I have recently been focussing on. Below, I highlight 5 papers with ideas for taking them forward. But I have a lot more ideas not mentioned below.

Categorical foundations of gradient-based learning [1]: This paper creates a lens-theoretic model of machine learning where diverse features such as back propagation, different gradient descent algorithms, reverse differentiation, different error functions and parameter update are uniformly modelled by lenses. The unifying power of the framework was demonstrated by showing the model covered not just learning in continuous domains, but also discrete domains such as boolean circuits where gradient descent might be thought to not apply. A Python implementation showed its use for programming languages tools. It has been picked up by other authors using it as a basis for their research. This underpins my ideas going forward to use category theory/type theory to articulate both i) the learning of structured phenomena; and ii) the structure of learning itself.

Compositional Game Theory [2,3,4]: Games are often used as a model of learning. Until these papers, games were defined as stand alone entities unable to interact with other games. These papers solved this problem by allowing games to be glued together to form more complex games such that the equilibria of the larger games can be inferred from the equilibria of their smaller components. Such a "lego-brick" approach to decision making has transformative potential. They led to an EPSRC Fellowship and a software implementation used by the Ethereum Foundation and 20 Squares to model financial contracts. As game theory and ML are interlinked, I will use these ideas to develop Compositional AI so complex learning agents can be built by gluing simpler ones together. Another idea is to extend sheaves for data integration to sheaves for decision integration.

Containers: Constructing Strictly Positive Types [5]: This paper provided a new, syntax-independent, foundation for concrete data structures. It has been hugely influential with numerous academics across the world working on containers and polynomial functors (an extension). It led to a large EPSRC grant, and an implementation is now part of the standard Agda library. I will use containers and similar structures to i) form the natural dependently typed generalisation of lenses to augment learners with extra correctness information; ii) model the architecture of learning (NN-layers laid out in list, grid, tree, networks etc); and iii) create a core language for interfacing the interaction between AI-agents.

A relationally parametric model of dependent type theory [5]: Reynolds' theory of parametricity captures the invariance of polymorphically typed programs under change of data representation. Extending this to dependent type theories had proven extremely difficult due to their sophisticated interweaving of types and terms. This paper solved the problem, thereby extending properties such as invariance and symmetries to dependent types — thus parametericity becomes available for formal proof. I am currently using these ideas at Google Deep Mind to generalise Geometric Deep Learning beyond equivariances to other forms of uniformity.

Models for Polymorphism over Physical Dimension [6]: The Mars Rover famously crash-landed costing over $\$100$m. Investigations showed that a computation added a measurement in feet to a measurement in length. To prevent such errors from re-occurring, I used category theory to extend type systems to cover units of measure. These powerful type systems can then formally verify the correct handling of units within computation. This formed the basis of a £600K joint project with NPL aimed at introducing digital units of measure into standard engineering practice.

Selected Research Publications

1 Categorical Foundations of Gradient-Based Learning. G. Cruttwell, B. Gavranovic, N. Ghani, P. Wilson and F. Zanasi. *European Symposium on Programming* 2022.

2 Compositional game theory N. Ghani, J. Hedges, V. Winschel and P. Zahn *Logic in Computer Science* 2018.

3 Infinite horizon extensive form games, coalgebraically. M. Capucci, N. Ghani, C. Kupke, J. Ledent and F. Nordvall Forsberg. *Journal of Mathematics for Computation.* 2022

4 Compositional game theory with mixed strategies: probabilistic open games using a distributive law. N. Ghani, C. Kupke, A. Lambert and F. Nordvall Forsberg, F. *Applied Category Theory* 2019.

5 Containers - Constructing Strictly Positive Types. N. Ghani, M. Abbott and T. Altenkirch. *J. of Theoretical Computer Science*, Volume 341(1), pages 3-27, 2005.

6 Models for polymorphism over physical dimensions R. Atkey, N. Ghani, F. Nordvall Forsberg, T. Revell, and S. Staton. *Typed Lambda Calculi and Applications*. 2015.

7 A Relationally Parametric Model of Dependent Type Theory. N. Ghani, R. Atkey and P. Johann. *Principles of Programming Languages*, 2014