Riccardo Poli's Curriculum Vitae

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Synopsis

Born: May 31, 1961 **Nationality:** Italian **Resident:** United Kingdom

Work Address: School of Computer Science and Electronic Engineering, University of Essex, Wivenhoe Park, Colchester CO4 3SQ, UK.

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Research Interests: Bio-inspired Artificial Intelligence and Machine Learning, Evolutionary computation, Neural Networks, Genetic Programming, Swarm Algorithms, Brain Computer Interfaces, Computer Vision, Biomedical Engineering.

Academic Qualifications: In 1993, PhD on Computer Vision Systems for Medical Images (awarded the prize for the best Italian PhD thesis in Biomedical Engineering), University of Florence, Italy. In 1989, Laurea in Electronic Engineering with *Summa Cum Laude*, University of Florence, Italy.

Employment: 2001–present Full Professor of Computer Science, School of Computer Science and Electronic Engineering, University of Essex, UK; 1999–2001 Reader in Evolutionary and Emergent Behaviour, Intelligence, and Computation, School of Computer Science, Birmingham University, UK; 1994–1999 Lecturer in Artificial Intelligence (same institution); 1993–1994 Research Fellow, Department of Electronic Engineering, University of Florence, Italy. 1992–1994 consultant Advantage Medical Research, Florence, Italy.

Teaching: *Current:* Large-Scale Software Systems; Evolutionary Computation and Genetic Programming. *Past:* Genetic Programming and its Applications; Procedural Programming and Mathematics for Engineering; Intelligent Problem Solving; AI Programming; Evolutionary Computation; Image Understanding; Introduction to AI and Cognitive Science; AI Elective; Neural Networks; Computer Vision; Special Topics in Artificial Intelligence.

Supervision: *Current:* 2 full-time PhD students and 1 postdoctoral visiting researcher. *Past:* 15 PhD students (all completed) and 8 researchers.

Grants: 27, approximately worth £2.2 million

Publications (1989–present): 3 authored books, 21 edited books/special issues, 23 chapters of books, 62 journal articles and 202 conference/workshop papers for a total of 311 refereed publications.

External Recognition: Associate editor, advisory board or editorial board member of 6 international journals; tutorial/keynote speaker at 28 international conferences and Summer schools; programme committee member of 78 international workshops and conferences; reviewer for 15 journals; fellow of the International Society for Genetic and Evolutionary Computation (ACM's SIG-EVO since 2005); member of ACM's SIG-EVO executive committee (2007-2013); recipient of EvoStar award for Outstanding Contributions to the Field of Evolutionary Computation; organiser and/or technical chair of 18 international events; winner of best PhD, 7 best paper and one best software awards; invited seminars in major UK universities and abroad; external examiner for 14 PhDs in the UK and abroad; college member for Engineering and Physical Sciences Research Council (EPSRC); international assessor for grant proposal.

Membership: ACM.

Contents

1 Academic Career

1.1 Summary in Reverse Chronological Order

2001–present Professor of Computer Science, School of Computer Science and Electronic Engineering, University of Essex, UK. Research topics: theory of genetic programming and genetic algorithms, applications of genetic programming, vision, image analysis, brain computer interfaces, models of feature integration and visual attention, swarm intelligence, halting probability.

1999–2001 Reader in Evolutionary and Emergent Behaviour Intelligence and Computation, School of Computer Science, University of Birmingham, UK. Research topics: theory of genetic programming and genetic algorithms, applications of genetic programming, image analysis, neural networks.

1994–1999 Lecturer in Artificial Intelligence, School of Computer Science, University of Birmingham, UK. Research topics: evolutionary computation, image analysis, signal processing, neural networks, probabilistic logic, biomedical applications, AI search.

1993–1994 Research fellow, Department of Electronic Engineering, University of Florence (Italy). Research topics: neural architectures, genetic algorithms, computer vision, medical imaging.

1993 PhD in Biomedical Engineering (awarded the prize for the best Italian PhD thesis in the field), University of Florence, Italy. Thesis title: *Computer Vision Systems for Medical Images: Theory, Methods and Applications.* Research topics: computer vision, neural networks, biomedical applications

1992–1994 Advantage Medical Research, Florence, Italy: part-time consultant on neural networks and digital signal processing for "DayPress" project.

1992–1993 Contract consultant, Department of Electronic Engineering, University of Florence. Research topics: genetic algorithms and neural nets for medical image and signal analysis.

1989 Laurea in Electronic Engineering with Summa Cum Laude, University of Florence, Italy. Thesis topic: an expert system for the analysis of blood vessels in X-ray images. Research topics: AI, computer vision (particularly Marr's theory), cell membrane potential.

1.2 First Degree

- I received the Laurea in Electronic Engineering in July 1989 *Summa Cum Laude* (the highest mark that can be awarded) with specialisation in biomedical engineering.[1]
- My final year project was an expert system (implemented in C and Prolog) for the automatic interpretation of X-ray angiographic images based on computer vision techniques for building high level image representations. During my project I became very interested in artificial intelligence.
- In the period 1987–88 I collaborated with biologists and doctors in the Institute of General Pathology of the University of Florence and produced a mathematical model of the variations of the membrane potential of leukaemia cells.
- By the end of my first degree I had two papers accepted for publication in international journals.

1.3 PhD

- In 1989 I was awarded a PhD studentship for research in biomedical engineering at the Department of Electronic Engineering of the University of Florence.[2]

- My PhD work was on machine vision techniques and neural-network architectures for medical image and signal understanding. The main contributions of my work were in the area of segmentation and 3–D representations.
- In July 1993 I passed the *viva voce* national examination.
- I won the prize for the best Italian PhD thesis in Biomedical Engineering of its year.[3]
- During my PhD I visited the MIT Media Lab for two weeks.
- During my PhD I also collaborated with doctors at the Institute of Clinical Medicine of the University of Florence on the problem of detecting and treating hypertension. This work resulted in the development of an expert system (largely based on artificial neural networks).[4]
- Towards the end of my PhD I became also interested in genetic algorithms and genetic programming.
- By the end of my PhD I had co-authored more than 20 papers, of which 10 were journal papers and one was a chapter of a book.

1.4 PhD/Research Fellowship Interim Period

- From November 1992 to November 1993 I was employed as an external consultant at the Department of Electronic Engineering of the University of Florence. My main research was on genetic algorithms for the optimisation of the topology on neural networks for medical image and signal processing.
- During that period I also performed research on artificial-life-inspired automata for image segmentation which led to my first publication in the area of evolutionary computation.[5]
- From June 1992 until February 1994 I worked part-time for Advantage Medical Research, Florence, Italy, as a consultant on neural networks and biomedical signal processing for the development of a portable, neural-network-based intelligent blood pressure monitor (DayPress).[6]

1.5 Research Fellowship

- In December 1993 I applied and obtained funding from the Italian National Research Council to continue my research at the Department of Electronic Engineering of the University of Florence.[7]
- My work was primarily on genetic algorithms and genetic programming for the optimal filtering and detection in medical images/signals and for the discovery of the optimal topology of neural networks.[8]

1.6 Lectureship

- I was appointed Lecturer in Artificial Intelligence in School of Computer Science of the University of Birmingham at the end of August 1994.[9]
- I was hired as a computer vision person. However, in the first year or so I also became interested in other areas:
  - I worked with A. Sloman and D. Davis on (and with) the SIM_AGENT agent programming toolkit. This work resulted in one of my most cited publications.
  - I collaborated with M. Brayshaw and A. Sloman on a rule-based system where rules could learn how to map conditions into actions over time.
  - I worked with M. Ryan, A. Sloman, and M. Kerber on minimum polynomial logic and its generalisations.[10]
  - I also worked with B. Logan on route planning.

- Naturally, I also kept working on vision, for example, collaborating with colleagues in Italy (in Florence) and North America (at MIT's Whitaker College).
- In addition, over a period of some years my interest for evolutionary computation grew considerably and eventually I founded the EEBIC (Evolutionary and Emergent Behaviour Intelligence and Computation) group, I was able to attract numerous PhD students and I had a grant from the Defence and Evaluation Research Agency (DERA) which allowed me to employ an outstanding research fellow (Bill Langdon).
- Four years after my joining the school, Birmingham was an internationally recognised centre of excellence in the area of genetic programming, one of the branches of evolutionary computation.

1.7 Readership

- I was promoted Reader in mid 1999.
- In that period I worked to increase the visibility of the EEBIC group and to attract high quality applicants in my research area for various job openings in the School. My objective was to create a world-class research group in evolutionary computation at Birmingham.
- In the following three years we hired Xin Yao (now Fellow of IEEE and former editor-in-chief of the IEEE Transactions on Evolutionary Computation), Julian Miller (one of the leaders in Evolvable Hardware) and Jon Rowe (a world-class genetic-algorithm theorist). We also had two temporary lecturers, 12 PhD students and two research fellows. This placed us among the then largest and strongest groups in evolutionary computation worldwide.
- During 2000 and 2001 I wrote with Bill Langdon the book "Foundations of Genetic Programming" (260 pages) which appeared in March 2002.[11] The book is the first and, so far, only book on the theory of genetic programming. The book has a five-star rating in amazon.com and has gathered an average of 58 citations per year.

1.8 Professorship

- I moved to Essex for a professorship in computer science in October 2001.
- In the approximately 10 years with the department I have published, with my students and collaborators, over 210 refereed papers, while at the same time putting a substantial effort into acquiring grants to fund my research (see Section 7).
- Most of my research during this period has been in Evolutionary Computation, Swarm Intelligence and Brain Computer Interfaces. About half of the work we do is of a theoretical nature. The other half is about improving technology and applying it.
- In 2003–2004, I joined forces with Lakany, Sepulveda and Gan to create the Brain Computer Interfaces (BCI) group at Essex (see `http://cswww.essex.ac.uk/Research/BCIs/`).[12] In 7 years of activity many more people have joined the group and we have published near 140 peer-reviewed publications in the most important journals and conferences relevant to BCIs, received frequent coverage in the media (see `http://cswww.essex.ac.uk/Research/BCIs/Essex_BCIs_media.html` and also `http://www.youtube.com/watch?v=28-eeouhkME`), become one of the main European centres for BCI research, and received more EPSRC funding in BCIs than all other UK-based labs combined. Our 70-square-meter lab (thanks to a successful bid for a £274,000 SRIF 3 infrastructure grant) comprises four experimental areas (one shielded) and has state-of-the-art equipment including: 8 EEG systems, a 24-channel near infra-red system, a 16-channel Nexus EMG system, a Jazz eye tracker, a MagStim BitStim transcranial magnetic stimulator, four Bionics electrically-controlled

medical chairs, a dedicated 182-processor Viglen/Rocks cluster, and much more. Our aim is to expand the current limits of BCI technology using non-invasive means and also to carry out more fundamental psychophysiology and neuro-engineering studies which will enable future more powerful technologies. What is particular about our team is its multidisciplinarity: we have computer scientists, psychologists, electrical engineers, and biomedical engineers all interacting. One of our major achievements has been the realisation of a genetically-designed BCI 2–D pointing device (effectively a brain-controlled mouse), which is currently the best of those that can be used by users without requiring weeks or months of training (see below).

- In 2004 we obtained funding for a large 5-site EPSRC project entitled "Extended Particle Swarms (XPS)" coordinated by myself. The aim of this multidisciplinary research project was to systematically explore the extension of particle swarm optimisers (PSOs). We achieved this by including strategies from a wide range of collective behaviours in biology, by extending the physics of the particles, by generating an extensive set of engineering problems and a flexible simulation engine, and by providing a solid theoretical and mathematical basis for the understanding and problem-specific design of new particle swarm algorithms. International collaborators in the project included: Jim Kennedy, Marco Dorigo, Maurice Clerc, Chris Stephens and Thiemo Krink.

- In the Autumn and Winter 2007–2008, I have co-authored with William B. Langdon and Nicholas F. McPhee a book entitled "A Field Guide to Genetic Programming" (250 pages), which we decided to make freely available on the Internet in PDF form (`http://www.lulu.com/content/2167025`) and available at cost in printed form. With this strategy our objective was to maximise the diffusion of the ideas and techniques in the book. So, far this strategy has produced the desired result (see page 13).

- A project that is now reaching an end, after 5 years from its start, has been the writing of a much more substantial theory book with Christopher R. Stephens entitled "Taming the Complexity of Evolutionary Dynamics: From microscopic models to schema theory and beyond", which gathers and integrates all of the work Prof Stephens and I have done independently and together on the analysis of evolutionary systems via a technique known as coarse-graining in physics. We are under contract with Springer for the publication of the book in two of its series: the Natural Computation series and the Complexity series. We have a draft of over 700 pages at the moment which we are actively revising. We expect the book to be out sometime in early 2012.

- In 2008–2011, I obtained a large grant (£364,770, with Francisco Sepulveda) from EPSRC to extend the preliminary research we had done since 2004 on an analogue BCI mouse. The objective of this project was the development of the technology and related scientific basis for the creation of usable hands-free BCI mice. Our guiding vision was that brains are analogue devices that should communicate whenever possible without the restrictions imposed by traditional BCIs, which rely on a discrete classification. Instead, our BCI mice are logically analogue, contrary to previous BCI design wisdom. So, the 2-D motion of the mouse pointer is not in discrete steps, but gradual ones which are proportional to the amplitude of particular electrical waves, known as P300s, produced by the brain. P300 waves are only produced if a user sees particular patterns appear on the computer screen and his/her attention is fully devoted to those stimuli. Nobody knows what visual patterns are best for generating P300s and what's the best way of keeping users interested in such patterns. So, developing a BCI mouse did not only mean solving signal processing and machine learning problems: importantly it also meant to find the best way of interacting with the mind of users. This required an interdisciplinary approach where technical solutions were compatible or even exploited the cognitive and perceptual limits of the human mind. We achieved this by employing a psychologist (Caterina Cinel) in addition to computer scientists (Luca Citi and Mathew Salvaris).

2 Academic Collaborations

During my career I have collaborated with tens of different researchers.[13] Below is a list of my main external collaborations in the last decade:

1. Professors Chris Stephens, at UNAM, Mexico (research collaboration);
2. Prof Nic McPhee, from the University of Minnesota (research collaboration);
3. Prof Alden Wright, from the University of Montana (research collaboration);
4. Dr Jon Rowe, from the University of Birmingham (research collaboration);
5. Dr Ela Claridge, from the University of Birmingham (co-supervision and co-authorship of articles);
6. Prof John Koza, from Stanford University (co-authored book chapters and conference tutorial, co-organising two conferences, EPSRC project collaborator, and Human-Competitive Result competition);
7. Prof Stefano Cagnoni, from the University of Parma (co-editing special issue and research collaboration);
8. Dr W. B. Langdon from University College London (research collaboration, co-organising events and joint conference tutorials) who is now here at Essex;
9. Prof Rob Smith, from University of West of England (joint grant proposal);
10. Prof Edmund Burke, from Nottingham (EPSRC project collaborator);
11. Dr Graham Kendal, from Nottingham (EPSRC project collaborator);
12. Prof Wolfgang Banzhaf, from Dortmund University now at Memorial University of Newfoundland in Canada (joint EU grant proposal, EPSRC project collaborator, conference co-organisation);
13. Dr Joao Pujol, from the centre for the applications of nuclear energy in Brazil (research collaboration and grant proposals);
14. Dr Tim Blackwell, Goldsmith College (EPSRC project collaborator);
15. Dr Alex Freitas, Kent University (EPSRC project collaborator);
16. Dr Colin Johnson, Kent University (EPSRC project collaborator);
17. Prof David Broomhead, Manchester University (EPSRC project collaborator);
18. Dr Jens Krause, Leeds University (EPSRC project collaborator);
19. Dr Iain Couzin, Oxford University and Princeton University (EPSRC project collaborator);
20. Dr Paul Marrow, BT Exact (EPSRC project collaborator);
21. Dr. Alexei Skourikhine at Los Alamos National Laboratory (joint DARPA grant proposal);
22. Prof Glyn Humphreys in the School of Psychology of the University of Birmingham (multi-site grant proposal and joint research paper);
23. Prof Kalyanmoy Deb, Department of Mechanical Engineering Indian Institute of Technology, Kanpur (joint grant proposal Air Force Office of Scientific Research and conference co-organisation);

24. Prof David Goldberg, Department of General Engineering, University of Illinois at Urbana-Champaign (joint grant proposal Air Force Office of Scientific Research and conference co-organisation);

25. Jim Kennedy (research collaborator)

26. Maurice Clerc (research collaborator)

27. Thiemo Krink (research collaborator)

28. Marco Dorigo (XPS project visiting researcher, co-organisation of conference, collaborated in launching the Swarm Intelligence journal)

29. Eric Bonabeau, Icosystem Corporation, Cambridge, MA 02138 (co-editorship of two special issues)

30. David Corne, Heriot-Watt University (co-organisation of conferences, co-editing of an edited book and two special issues)

31. Joshua Knowles, University of Manchester (co-edited one special issue)

32. Paolo Di Chio, Aquila University, Italy (three joint conference papers)

33. Luca Citi, Post-doctoral Research Fellow at the Department of Anesthesia, Critical Care and Pain Management at Massachusetts General Hospital, Harvard Medical School, and Research Affiliate at the Brain and Cognitive Sciences Department at MIT (several joint articles).

34. Many other people with whom I have co-organised events.

At Essex, I have also interacted with several other members of the Department and of the University. These include:

1. Prof Edward Tsang (with whom I have written grants proposals and collaborate in an EPSRC project)

2. Dr Simon Lucas (with whom I have collaborated for the organisation of GECCO 2004 and in a joint grant proposal);

3. Dr Quingfu Zhang (joint grant proposal)

4. Prof Owen Holland (joint multi-site grant proposal);

5. Dr Adrian Clark of the department of Electronic Systems Engineering (with whom I have written an EPSRC grant proposal);

6. Prof Elaine Fox of the Department of Psychology (joint multi-site grant proposal);

7. Drs John Gan, Heba Lakani and Francisco Sepulveda (with whom I have produced several grant proposals for the creation of a brain computer interfaces group at Essex);

8. Dr Sheri Markose (with whom I have written one grant proposal).

9. Prof Massimo Poesio (joint Leverhulme Trust grant proposal).

3 Teaching

I enjoy teaching. Like many, I tend to prefer advanced courses in my areas of research, but I am also very happy to teach programming and software design courses and other introductory courses.

A summary of my teaching experience follows:

Current Courses: I am currently involved in the teaching of two courses:

Large-Scale Software Systems: This is a third-year course which introduces the most modern software development techniques for large systems, focusing in particular on the Extreme Programming methodology.[14] I taught the course with the help of two teaching assistants. Teaching material: lecture and lab handouts both printed and on the web, software demonstrations and sources on the web, plus Trac and Subversion systems.

Evolutionary Computation and Genetic Programming: This is an advanced third-year undergraduate and MSc-level course on evolutionary algorithms with particular emphasis on genetic programming. This is itself an evolution of the "GP and its applications" course mentioned below. Teaching material: lecture handouts and class handouts both printed and on the web, software demonstrations and source on the web, spreadsheets on the web.

Previously Taught Subjects:

Genetic programming and its applications: This was an advanced third-year undergraduate course, which was also offered as an MSc course, on genetic programming techniques and applications. I've introduced and taught this course for the first time during the 2003–2004 academic year. This was a course unique in the world. I was the sole person responsible for its teaching. Teaching material: lecture handouts and class handouts both printed and on the web, software demonstrations and source on the web, spreadsheets on the web. The course won a student-union "apple for the teacher" award and was amongst the highest ranking in the department in terms of student satisfaction.

Procedural Programming and Mathematics for Engineering: This was a first-year full-year course for electrical engineers which introduces continuous mathematics using Matlab and also the C Programming Language with applications in mathematics (including numerical integration and differentiation and symbolic manipulations). I taught the C Programming part. Teaching material: lecture, lab and class handouts both printed and on the web, software demonstrations and sources on the web.

Intelligent Problem Solving: this was a second year course which first introduced the Prolog AI programming language and then introduced a variety of problem solving techniques and illustrated their implementation in Prolog. This course was taken by between 40 and 80 students. Teaching material: lecture handouts, on-line teaching material, lab handouts. In 2002-2003 I've been responsible for 100% of the teaching of this course, while in 2001-2002 and 2003-2004 I shared it with Prof E. Tsang.

Special topics: this was an MSc small-group-teaching type of course, where the students developed research skills, presentation skills and technical writing skills. Main AI topics were introduced and discussed in the course. For several years I taught a group of around 5 students in this course.

A Practical Introduction to AI When at Birmingham I taught this elective course for a couple of years. The course included a mixture of topics from my introduction to AI and AI programming courses.

Introduction to AI and Cognitive Science (for 1st year students of the BSc degree in AI and Computer Science at Birmingham) The course covered core problems in AI and surveyed some areas of current research. The core problems discussed included philosophical issues, knowledge

representation and computation. The survey of current research covered areas such as vision, natural language processing, logic, search, planning, neural networks and evolutionary computation. The course included lectures and weekly tutorials. The lectures were given by the School's experts in each AI sub-discipline. I was responsible for the organisation of the course, for the marking, for running 2 weekly tutorial groups and for approximately 1/3 of the lectures. The course was taken by about 50 students. Teaching material: lecture handouts, tutorial handouts with exercises.

AI programming (for 1st year students of the BSc degree in AI and Computer Science at Birmingham) This module introduced general procedural and functional programming techniques as well as basic AI programming styles (including list manipulation and pattern matching) using the AI language Pop-11. This course was taken by about 50 students. Teaching material: lecture handouts, on-line teaching material (e.g. exercises), workshop handouts.

Evolutionary Computation (for all 3rd year students and MSc students at Birmingham) The course gave an introduction to the main techniques and theory in evolutionary computation (genetic algorithms, genetic programming, classifier systems, etc.) and discussed the applications of evolutionary algorithms to problems of parameter and combinatorial optimisation and to machine learning. The course was quite popular, and it was taken on average by 40 students. Teaching material: around 200 transparencies (distributed as handouts), tutorial material (e.g. exercises). When I firstly introduced this course, it was one the very few and one of the most advanced undergraduates course of its kind in the world. Its syllabus was published among those of the 29 other courses of this kind in the booklet *University Courses on Genetic Algorithms 1995* edited by Prof. J. R. Koza (Stanford University).

Other While at the Department of Electronic Engineering of the University of Florence I contributed to the courses taught by my supervisor with series of seminars (each series lasting between 3 and 7 hours) on the following topics: *Computer Vision* (an introduction to David Marr's theory of vision), *Neural Networks* (including an introduction to the most important kinds of neural networks and supervised and unsupervised learning algorithms) and *Evolutionary Computation* (an introduction to genetic algorithms and their applications).

Curriculum Development I redeveloped the Intelligent Problem solving course and developed from scratch the Genetic Programming and its Applications course and its successor (Evolutionary Computation and Genetic Programming). Last year I also completely redesigned of the "Large Scale Software Systems" course to introduce the most modern software development techniques, including the innovative Extreme Programming methodology. In 2008-09 and 2009-10 I taught a new full-year course to first year students (CE-132, Procedural Programming and Mathematics for Engineering) with Nigel Newton. I was responsible for designing and delivering the "procedural programming" part of the course (in C). I have also been involved in the shaping of a new MSc degree on Brain Computer Interfaces. While at Birmingham I developed from scratch the course in Evolutionary Computation. I was responsible of organising the first year, first semester teaching for the AI&CS BSc. I was also involved in shaping two other degrees: a new BSc in Bioinformatics and a new MSc in Natural Computation which started in October 2001. This MSc was the result of a successful EPSRC Master Training Programme proposal of which I was a co-proposer (with X. Yao and J. Miller). This degree was unique in its kind in the UK. The curriculum included the following courses: Introduction to Molecular and Quantum Computation, Introduction to Neural Computation, Introduction to Evolutionary Computation, Nature Inspired Optimisation, Nature Inspired Learning, Nature Inspired Design, plus two research-based mini-projects and a summer project.

4 Supervision

UG/MSc Supervision: Typically, every year I supervise between 2 and 10 UG and MSc students in all areas of CS and AI in their projects. In several cases these projects led to scientific publications.

PhD Supervision:

Past PhD students: Since 1995 I have had 15 PhD students completing (none of the students I've supervised has ever withdrawn or failed to get the PhD so far). Their research has been in the following areas:

- Genetic programming techniques for the evolution of learning rules for neural networks.
- Evolutionary algorithms for the efficient evolution of the topology and weights of neural networks.
- Logic-based polynomial neural networks.
- Role of the primitive set in genetic programming
- Continual robot learning.
- Hardware implementations of genetic programming.
- Morphological image analysis with genetic programming.
- Theoretical foundations of evolutionary computation in relation to classical geometry and topology.
- The theoretical analysis of the performance of evolutionary algorithms.
- The effects of neutrality in genetic algorithms and genetic programming.
- The evolution of control rules for particle swarm optimisers as their application as a modelling tool for biological swarms.
- Programme length distributions, crossover biases and allele diffusion in genetic programming.
- The application of genetic programming as a hyperheuristic for the evolution of solvers for combinatorial optimisation problems (particularly, SAT).
- The applications of genetic programming in the area of lossless compression.
- Models of performance for genetic programming, algorithm portfolios and taxonomies in GP.

Current PhD students:

- Behrooz Koohestani, from Iran, is doing research on using genetic programming both as a metaheuristic and a hyperheuristic to solve graph bandwidth- and envelope-minimisation problems.
- Mikdam Turkey, from Iraq, is doing research on new evolutionary optimisation approaches inspired by the evolution of social behaviour.

Postdoctoral Supervision:

1996–1998 I was responsible for the supervision of Dr Bill Langdon who was the research fellow on my DERA grant.

2003–2004 I was responsible for Joao Pujol 10-month Leverhulme Trust Visiting Fellowship.

2003–2004 With Drs H. Lakany, F. Sepulveda and J. Gan I was responsible for Shang-Ming Zhou, a part time research assistant funded by the University for one year and working on brain computer interfaces.

2004–2006 Bill Langdon (principal research officer on the EPSRC Extended Particle Swarms grant).

2004–2007 Luca Citi (part time research officer on BCI workpackage of EPSRC XPS project).

2005–2008 Robert Keller[15] on an EPSRC project entitled "An investigation of the role of Genetic Programming in a Hyper-Heuristic Framework".

2008–2011 Luca Citi (replaced by Mathew Salvaris in October 2009) and Caterina Cinel, on the EPSRC project entitled "Analogue Evolutionary Brain Computer Interfaces".

2011–2014 Caterina Cinel, visiting researcher.

5 Administration

At Essex, I am (or have been) a member of the following committees:

- the Department Strategy Group
- the Research Strategy Group
- the Postgraduate Degree Schemes Management Committee
- the Research Student Progress Committee
- the Postgraduate Curriculum Committee
- the University's Senate Staffing Committee which decides on all promotions (except to professor), probation cases, pay increments, etc. for the whole university[16]
- the Curriculum Strategy Committee (invited member)
- the advisory/supervisory board of tens of PhD students

In addition:

- I have been postgraduate area director for the MSc in Robotics and Embedded Systems and the MSc in Computer Science.
- In 2003 I was deputy director of graduate studies and deputy Head of Department (for Research). In these two roles I led the creation of various schemes (e.g. journal publication incentives and a grant proposers club) which have improved significantly the output of the department in terms of number and quality of journal publications, number and quality of grant proposals submitted and quality of PhD student supervision.

At Birmingham I was:

- Course director for the BEng/MEng in Electronic and Software Engineering
- a member of the Research Committee
- chair of the Research Committee
- member of the Research Students Monitoring Committee
- member of several PhD student advisory groups
- organiser for the weekly seminars of the EEBIC group which I also coordinated

In addition I contributed to open days and admission days with talks and demos.

Finally, during my 17 years or so of service in UK universities, I have been in several appointment committees for research officers/fellows, lecturers and senior lecturers.

6 External Recognition

"Foundations of Genetic Programming" This book is well cited (537 citations in Google Scholar: average 58 per year) and successful. The book has a five-star rating in amazon.com.

"A Field Guide to Genetic Programming" This book is freely available from the Internet. In just over three years it has been cited in approximately 330 times (averaging nearly 100 citations per year) and has been adopted by approximately 15 universities worldwide.[17] Reviews of the book refer to it as "the best introductory book about genetic programming", "destined to become the standard reference to the field", "awesome book for the beginner", and "an invaluable starting point for the new GP researcher or practitioner". In the first two years since its publication in March 2008, the book had over 54,000 genuine downloads from the official web site. The book has also sold 2167 paper copies. Searching Google for "field guide to genetic programming" produces over 140,000 hits. The book is mentioned in the Wikipedia pages on artificial intelligence, genetic programming, genetic algorithms, machine learning, search algorithms, etc. in over 10 languages.

EvoNet I have been a member of the management board EvoNet, the the EU European Network of Excellence in Evolutionary Computation, until its end. I was also a co-chair of EvoGP, the working group on Genetic Programming of EvoNet. The working group included all the most prominent European genetic programming researchers. I was one of the proposers and former coordinator of EvoIASP, the EvoNet working group on Evolutionary Image Analysis and Signal Processing.

ISGEC/ACM SIG-EVO I was a member of ISGEC (the International Society for Genetic and Evolutionary Computation) which became the ACM special interest group SIG-EVO in 2005. I've been elected member of SIG-EVO's executive committee (2007-2013). Within ISGEC I was also a member of the council of authors and I was the 2002–2003 chair of the council of conferences.

ISGEC Fellowship In June 2003 I was elected by my peers *Fellow of ISGEC* "in recognition of sustained and significant contribution to the field and the community" [from the Fellow plaque]. There were only 14 other people in the world with the rank of Fellow or Senior Fellow. Only one other person in the UK (Dr Bill Langdon) has received this honour.

EvoStar Prize EvoStar is a composite European event including three European conferences (EuroGP, EvoCOP and EvoBio) and eight European workshops. At the EvoStar 2007 banquet I received the EvoStar award for Outstanding Contributions to the Field of Evolutionary Computation. I was presented with a gold pocket watch. As a winner I then became part of the award committee which decides on the awards every year.

Programme committee membership: Portuguese conference on Artificial Intelligence 1995; Second (1997), Third (1998) and Fourth (1999) Online World Conference on Soft Computing; Genetic Programming Conference 1997 and 1998; AISB Workshops on Evolutionary Computation 1997; Foundations of Genetic Algorithms (FOGA-5) Workshop 1998; EuroGP'98 (First European Workshop on Genetic Programming); Parallel Problem Solving from Nature (PPSN'98); EuroGP'99; EvoIASP'99 (the first European workshop on Evolutionary Image Analysis and Signal Processing); Genetic and Evolutionary Computation Conference (GECCO'99); GECCO'99 Workshop on Foundations of Genetic Programming; GECCO'99 Workshop on Methodology, Pedagogy and Philosophy; IEEE Congress on Evolutionary Computation (CEC'99); Third International Conference on Knowledge-based Intelligent Information Engineering Systems (KES'99); Third International Conference on Evolvable Systems: From Biology to Hardware (ICES2000); The First International Workshop on Computational Intelligence in Economics and Finance (CIEF 2000); EuroGP 2000; EvoIASP 2000; Foundations of Genetic Algorithms (FOGA-6) Workshop 2000; GECCO 2000; CEC 2000; PPSN 2000; EuroGP 2001; EvoIASP 2001; CEC 2001; GECCO-2001; CEC 2002; PPSN 2002; EuroGP 2002; GECCO 2002; EvoIASP 2002; UK-CI 2002; FOGA-7 (2002); Irish Conference on Artificial Intelligence and Cognitive Science (AICS) 2002; EuroGP 2003; EvoIASP 2003; GECCO 2003; Towards Intelligent Mobile Robots (TIMR) 2003; EvoIASP 2004; EuroGP 2004; EvoIASP 2005; EuroGP 2005; FOGA 2005; European Conference on Artificial Life (ECAL) 2005; International Workshop on Parallel Bioinspired Algorithms 2005; GECCO 2005; CEC 2005; Giornata di Studio Italiana di Calcolo Evoluzionistico (GSICE) workshop 2005; Genetic Programming Theory and Practice (GPTP) workshop 2005;

Foundations of Genetic Algorithms (FOGA) 2005 EuroGP 2006; Workshop on Evolutionary Computation of the European Conference on Artificial Intelligence (EC)^{2}AI 2006; FOGA 2007; GPTP 2007; Fourth International Conference on Fuzzy Systems and Knowledge Discovery (FSKD'07) to held in Haikou, China in August 2007; EvoIASP 2007; EuroGP 2007; EvoTheory 2008; EuroGP 2008; GPTP 2008; EuroGP 2009; GECCO 2009; EvoIASP 2009; Genetic and Evolutionary Computation Summit (GECS) 2009; GPTP 2009; EuroGP 2010; EvoIASP 2010; GECCO 2010; GPTP 2010; GPTP 2011; EvoIASP 2011; EuroGP 2011; FOGA 2011; Italian Workshop on Artificial Life and Evolutionary Computation (WIVACE) 2012; EuroGP 2012.

Reviewer for: IEEE Transactions on Evolutionary Computation, IEEE Transactions on Pattern Analysis and Machine Intelligence, IEEE Transactions on Neural Networks, Knowledge Engineering Review, IEEE Transactions on System Man and Cybernetics, Parallel Algorithms and Applications, Neurocomputing Journal, International Journal of System Science, Computational and Mathematical Organization Theory, Neural Computing & Applications, Trends in Genetics, Proceedings A of the Royal Society, International Journal of Neural Systems, Theoretical Computer Science C, Pattern Analysis and Applications, Journal of Neural Systems, Swarm Intelligence. Book proposal reviewer for Kluwer Academic Publishers.

Editorial roles: I was an associate editor of the Evolutionary Computation Journal (MIT Press), the oldest journal in the field of evolutionary algorithms, for many years. I then became a member of the Advisory Board of the journal in 2009. I am also an associate editor of the Journal of Genetic Programming and Evolvable Machines (Kluwer/Springer). I was the associate editor for Europe and I'm now a member of the advisory board of the International Journal of Computational Intelligence Research (IJCIR). I am a member of the editorial board of Swarm Intelligence (Springer) and of the International Journal of Applied Metaheuristic Computing. I was a member of the advisory board of the Journal of Artificial Evolution and Applications (Hindawi) until the board resigned *en masse* in 2010.

Guest Editorships: I've also edited a number of special issues: (1) a special issue of the EURASIP Journal of Applied Signal Processing on Genetic and Evolutionary Computation for Signal Processing and Image Analysis with S. Cagnoni (2003); (2) a special issue of the Evolutionary Computation Journal (MIT Press) on the Best of GECCO with Marc Schoenauer (2006); (3) a special issue (co-edited with Yossi Borenstein and Thomas Jansen) of the Evolutionary Computation Journal on Bridging Theory and Practice in Evolutionary Algorithm Research (2007); (4) a special issue of the Journal of Artificial Evolution and Applications entitled "Particle Swarms: the Second Decade", with Jim Kennedy, Tim Blackwell and Alex Freitas (2008); (5) a special issue (with Jim Kennedy and Andries Englebrecht) on Particle Swarm Optimisation of the Swarm Intelligence journal (2009); (6) a special issue (with Eric Bonabeau, David Corne and Joshua Knowles) entitled "Swarm Intelligence Theory: A Snapshot of the State of the Art" of the Theoretical Computer Science series C (2010); (7) a special issue (with Eric Bonabeau and David Corne) of Natural Computing on "Swarm intelligence: the state of the art" (2010); (8) a special issue (with Julian Miller) entitled "10 years of Genetic Programming and Evolvable Machines" for the tenth anniversary of the Genetic Programming and Evolvable Machines journal (2010).

Session Chair Initially I kept a record of the sessions I chaired: GP'96 conference, Special Genetic Programming session organiser for the second on-line workshop on Evolutionary Computation, Panel and Session Chair for the AISB Workshop on Evolutionary Computing'97, Session Co-chair at the Third Online World Conference on Soft Computing (WSC3). However, in later years I've effectively been invited to chair sessions in virtually all conferences I've attended (including EuroGP, GECCO and CEC) and so I've lost count.

Conference/Workshop Chair I was a programme co-chair of EUROGP'98 and EuroGP'99, the first and second European Workshops on Genetic Programming (held in Paris and Goteborg). I was pro-

gramme co-chair of EuroGP 2000, which was then turned into an international conference (of which I am a member of the steering committee). Also, I co-chaired EvoIASP'99 and the Foundations of Genetic Programming (FOGP'99) Workshop of the GECCO'99 conference, the largest conference in evolutionary computation. I co-chaired the Dynamics of Evolutionary Algorithms Workshop at GECCO-2002. I was programme chair at GECCO 2002 for the genetic programming track. I was programme co-chair for the prestigious and highly selective Foundations of Genetic Algorithms (FOGA) 2002 workshop. I was local chair at EuroGP 2003, which was held at Essex. I was the general chair for GECCO 2004 held in Seattle. I was the first non-US chair ever for this conference. The conference included 16 workshops, 13 tracks, 32 tutorials, over 450 papers submitted and reviewed through 14 track chairs and over 350 reviewers. The conference was financially very successful. I was part of the conference's business committee for the 2005 edition of GECCO. This advisory body is responsible for all the decisions of major financial relevance. I was competition chair for GECCO 2006, technical co-chair of the IEEE-sponsored ANTS (Ant Colony Optimisation and Swarm Intelligence) 2006, and a co-chair of the workshop of the Parallel Problem Solving from Nature (PPSN) conference 2006 on Bridging Theory and Practice in Evolutionary Algorithm Research. I was programme chair at GECCO 2007 for the genetic programming track, and a co-organiser of the GECCO 2007 workshop on "Particle Swarms: the Second Decade". I was programme co-chair at GECCO 2009 for the Theory track. I was the chair of the Graduate Student workshop at GECCO 2010.

Tutorial/Keynote Speaker I gave a tutorial on genetic programming at the PPSN'98 international conference (Amsterdam) with Bill Langdon. I gave a tutorial on the theoretical foundations of genetic programming at GECCO 2000 (Las Vegas). I gave, with Bill Langdon, a 4-hour tutorial on the same topic at GECCO 2001 (San Francisco) and GECCO 2002 (New York). I gave a tutorial on genetic programming at EuroGP 2001 (Como, Italy) and a tutorial on schema theories at IEEE Congress on Evolutionary Computation (CEC) 2001 (Seoul). I gave a 4-hour tutorial on the theoretical foundations of genetic programming at GECCO 2003 (Chicago) jointly with Bill Langdon, and a tutorial (jointly with Prof John Koza, from Stanford) at the 1st Multidisciplinary International Conference on Scheduling: Theory and Applications (MISTA 2003) held in Nottingham. I gave a tutorial on the foundations of genetic programming at the IEEE Congress on Evolutionary Computation 2004 (Portland, Oregon). I gave an tutorial at the workshop of the Italian Artificial Intelligence (AI*IA 2005) conference, Milan, September 2005. I gave a tutorial at GECCO 2006 and ANTS (Ant Colony Optimisation and Swarm Intelligence) 2006. I gave a tutorial at GECCO 2007 and CEC 2007, and two tutorials GECCO 2008. I was an invited speaker at the Workshop on Hyperheuristics of the Parallel Problem Solving from Nature (PPSN) conference held in Dortmund (Germany) in 2008. I gave a tutorial at Genetic and Evolutionary Computation Summit 2009, two tutorials (one lasting two hours, the other lasting four hours with Bill Langdon) at GECCO 2009, and one at CEC 2009. I gave a 2-hour invited tutorial on the theory of genetic programming at the GECCO 2010 conference held in Portland. I gave an invited keynote presentation at 2nd International Symposium on Search Based Software Engineering to held in Italy in September 2010. I will give an invited talk at the Italian Workshop on Artificial Life and Evolutionary Computation (WIVACE) 2012. Over the years I've also been a panelist in a number of panel discussions, particularly at the EuroGP conference.

School/Summer Schools I was one of the senior tutors (with all expenses paid) at the COIL (Computational Intelligence and Learning) summer school in Limerick, Ireland (Aug 2000). My group of (postgraduate and postdoctoral) students won the best paper award. I've been invited to five Dagstuhl Schools on the Theory of Evolutionary Computation (2000, 2002, 2004, 2006, 2008 and 2010), taking part in four. I have been a senior tutor (with all expenses paid) at the EvoNet summer school on evolutionary computation held in Parma (Italy) is the Summer 2003. My project proposal there were so successful that eventually the organisers had to assign two groups of students to me. I have also given a tutorial on genetic programming at an international Summer School in Erice Italy in 2004. I have given a tutorial on GP in the 3rd BCS Summer School on Pattern Recognition in July 2005.

Awards Best PhD thesis award. EuroGP 2001 best paper award (for my work with Nic McPhee on the schema theory for genetic programming). EvoIASP 2003 best paper award (with Marcos Quintana and Ela Claridge). Best Academic Standard Award for EEBIC Group and runner-up Best Overall Paper Award, the 2nd On-line Word Conference on Soft Computing in Engineering Design and Manufacturing. Runner up for best paper awards at GECCO 2002 and EuroGP 2003. My implementation of genetic programming won the TinyGP competition of the Genetic and Evolutionary Computation Conference (GECCO-2004), Seattle, USA, June 26-30 2004. Best paper award at the "Giornata di Studio Italiana di Calcolo Evoluzionistico" (GSICE) workshop of the Italian Artificial Intelligence (AI*IA 2005) conference. Best Paper Awards at the European Conference on Genetic Programming (EuroGP2007) and the European Workshop on Evolutionary Image Analysis and Signal Processing (EvoIASP2007). Best paper award for GECCO's 2007 Genetic Algorithms track (the largest). Best paper award for GECCO's 2008 Genetic Programming track. Also, I've had many nominations for best paper awards over the years. Additionally, as mentioned above, I also won the EvoStar award.

External Examiner I have been the external examiner of 14 PhD students at University College London, Bristol, City University London, University of Kent, Coventry, Universitad de Extremadura (Spain), Switzerland (University of Lausanne), Nottingham, York, Ireland (Limerick), Goldsmith College, University of Coimbra, Universitat Ramon Llull (Barcelona).

Grant Proposal Assessor I am a college member for Engineering and Physical Sciences Research Council. I was an expert reviewer for the EU Cognitive Systems initiative. I have also refereed grant proposals for the Italian, Swiss and Irish governments.

Citations/Bibliometrics The analysis of Google Scholar performed by the program "Publish or Perish" (`http://www.harzing.com/`) indicates that I have an H-index of 41 (as of August 2011), a G-index of 75 and over 8,000 citations overall. I'm in Prof Palsberg's list of the 500 computer scientists with the highest H-index (widely used index of research impact) ever (`http://www.cs.ucla.edu/~palsberg/h-number.html`). This list includes one Nobel Laureate, 27 Turing Award winners, 108 IEEE Fellows and 194 ACM Fellows. I'm also in the list of the most prolific authors in DBLP (one of the largest computer science bibliographies) with 187 publications (as of August 2011, see `http://www.informatik.uni-trier.de/~ley/db/indices/a-tree/prolific/index.html`). I'm also one of the top three authors in the Genetic Programming Bibliography (first for number of co-authored publications, third in weighted order) at `http://www.cs.bham.ac.uk/~wbl/biblio/gp-html/index.html`. Also, I'm in the list of Top Italian Scientists (`http://www.topitalianscientists.org/Top_italian_scientists_VIA-Academy.aspx`), within which I rank 30th among the best ever Italian computer scientists (by H-index). Microsoft Academic Search places me at the 18th position in the list of the top authors in Artificial Intelligence in the last 5 years (`http://academic.research.microsoft.com/RankList?entitytype=2&topdomainid=2&subdomainid=5&last=5`) (8th position in the last 4 years). Also, my 2007 article entitled "Particle Swarm Optimisation" is listed as the 8th top publications in Artificial Intelligence in the last 5 years (`http://academic.research.microsoft.com/RankList?entitytype=1&topDomainID=2&subDomainID=5&last=5&start=1&end=100`)

Other I have been the assessor for tenure and promotion for many US and European universities. I'm also a regular assessor for cases of promotion for UK universities. I have been guest of the Santa Fe institute of complex systems and gave a seminar there in July 2000. I have been a panel member and judge in the student workshop at GECCO 2000, 2001, 2002, 2003 and 2005. I was also a panel member at the workshop on standards at GECCO 2002. I was invited (with all expenses paid) by Prof Chris Stephens to do research for one week and give a seminar on genetic programming at UNAM in Mexico City, the largest university in the world, in September 2003. I've been a judge for the Human-competitive Results competition (endowed with a total of $ 10,000 in prizes) at GECCO 2004, 2005, 2006, 2007, 2008, 2009 and 2010.

7 Grants

In my career I have contributed to securing 27 grants for a total of around £2.2M (approx £1.4M as principal investigator – PI). Below I list the grants I obtained:

2008–2011 Engineering and Physical Sciences Research Council (EPSRC) grant "Analogue Evolutionary Brain Computer Interfaces", (PI, £364,770). Two post-docs.

2011 A departmental Research Innovation Fund grant for preliminary research on communication (PI, £3,751).

2010 A departmental Research Innovation Fund grant for preliminary research on sleep (PI, £4,195).

2010 A departmental Research Innovation Fund grant to extend the aforementioned preliminary research on sleep (PI, £2,823).

2005–2008 EPSRC joint grant with Nottingham, "An investigation of the role of Genetic Programming in a Hyper-Heuristic Framework", total value approx £470,000 (PI, £247,000 for Essex). I am also a co-investigator in the Nottingham side of the grant.

2008 EPSRC Visiting Fellowship "Bringing contemporary biology into Evolutionary Computation: Plasticity, hierarchy, and genetic re-use" (PI, £39,000).

2008 5 day research consultancy for QinetiQ (formerly known as DERA — Defence and Evaluation and Research Agency) on the application of Particle Swarm Optimisers in the analysis of social networks in relation to defence strategy (£7,500).

2005–2007 Leverhulme visiting professorship (for Prof Chris Stephens), approx £22,000.

2005–2007 SRIF 3 funding of £274,000 for equipment and refurbishment of brain computer interfaces laboratory (co-PI).

2004–2007 A multi-site EPSRC grant entitled "Extended Particle Swarms" for over £980,000 (of which around £280,000 for Essex) plus an indirect contribution of £70,000 from BT Exact. This project involves physicists, mathematicians, biologists and computer scientists at the 5 sites, and also 6 international leaders in the area of swarm intelligence. I'm the PI at Essex and the coordinator for the whole proposal. This project is the result of membership of the EPSRC cluster on Novel Computation in Swarm Intelligence.

2001–2006 EPSRC Master Training Programme (with X. Yao and J. Miller, grant GR/N29969/01, £534,923) for an MSc in Natural Computation at Birmingham. Co-investigator.

2006 European Space Agency ARIADNA (interaction with European universities on advanced research topics) grant, EUR 15,000 (co-PI), 2 month pilot study entitled "Critical review and future perspectives of non-invasive brain-machine interfaces" jointly held with Universitá Campus Biomedico (Rome) and Scuola Superiore Sant'Anna (Pisa).

2006 Research Promotion Fund grant on Advanced Evolutionary Methods for Learning Finite State Machines (£5,000). Co-principal investigator.

2005 EPSRC visiting fellowship: "Coarse Grain in Complex Adaptive Systems" (for Prof. Chris Stephens), approx £45,000.

2003–2004 Leverhulme Trust Visiting Fellowship (£15,320) which paid for one of my ex-PhD students, Dr Joao Pujol from Brazil, to spend 10 months here at Essex working with me on a genetic-programming-based parameter mapping approach to optimisation problems. Principal investigator.

2003–2004 Essex University Research Promotion Fund grant to build up Brain Computer Interface research at Essex (with Lakany, Sepulveda and Gan, approx £3,900). This paid for a PhD student acting as a part time research assistant.

2004 $10,000 grant from the Air Force Office of Scientific Research to support travel studentships for GECCO 2004.

2003 Royal Society travel grant (approx £1,100)

2003 Membership of EPSRC cluster on Novel Computation in Swarm Intelligence (refunded travel expenses for myself and collaborators, approx £700).

2003 Departmental pump priming to purchase equipment for Brain Computer Interface research (with Lakany, Sepulveda and Gan, approx £3,000)

2002 EPSRC visiting fellowship on the Theory of Evolutionary Computation (GR/R47394/01, £39,149). Co-investigator.

2002 Research Promotion Fund for completion of an EPSRC grant proposal (£500). Principal investigator.

2001 Royal Society visiting fellowship (£1,500)

1996–1998 Defence and Evaluation and Research Agency (DERA) Malvern (grant CSM/428/UA, £89,000), including equipment and a research fellow, for fundamental research on evolutionary computation and its role in the design of autonomous intelligent agents. Principal investigator.

1996–1998 British-Council/MURST CRUI (travel grant ROM/889/95/87, approx £3,000) for a long-distance collaboration with the University of Florence on evolutionary techniques for image analysis

1995 5-day consultancy on Evolutionary Algorithms for Defence and Evaluation Research Agency (DERA) (£1,500)

1995 Faculty of Science pilot grant for research on evolutionary computation (£1,500)

8 Scientific Contributions

My main contributions to science have been in the field of Evolutionary Algorithms (EAs) and allied disciplines – more specifically, in the areas of Genetic Programming, Genetic Algorithms and Particle Swarm Optimisation – and Brain-Computer Interfaces (BCI), although I would also like to think that my earlier work in vision was also significant.

8.1 Genetic programming

In the area of Genetic Programming (GP) – the evolution of computer programs – my work has led to the development of *strong theoretical foundations* for the technique and well as numerous technical improvements and some applications.

My theoretical work on GP started with the formulation of evolution equations, known as schema theorems, which provide probabilistic descriptions of how an evolutionary system explores a search space. Initially we were able to obtain only lower-bound equations for GP with a particular form of genetic recombination (e.g., Poli and Langdon, 1997; Poli and Langdon, 1998; Poli, Langdon and O'Reilly, 1998). Although these results generalised John Holland's famous schema theorem for genetic algorithms, their inexact nature made them unsatisfactory. However, later these results were improved and extended, obtaining exact evolution equations for GP with that particular form of recombination (Poli, 2000; Poli, 2001) and then exact equations for GP and a large class of GP recombinations, including the standard from used in virtually all GP implementations (Poli, 2001; Poli and McPhee, 2001; Poli and McPhee, 2003) and even

all standard forms of mutation (Poli and McPhee, 2001; McPhee, Poli, and Rowe, 2001). This work models the most widespread forms of GP and, effectively, gives a definitive answer to the quest, started as early as 1992 and continued throughout the 1990s, for a comprehensive theory for GP.

Traditionally, in the genetic algorithm literature, the alternative to schema theory models has been Michael Vose's Markov chain model. For many years schema theory and Vose's model were believed to be independent and irreconcilable theories. However, in (Poli, McPhee and Rowe, 2001; Poli, McPhee and Rowe, 2004) we were able to first derive an exact schema theory for a very general class of evolutionary systems, including both GP and most genetic algorithms operating on either variable-length or fixed-length representations, and to then use it to derive a Markov chain model for these same evolutionary systems. This formally linked for the first time these two theoretical approaches while at the same time providing the first, and so far only, Markov chain model of GP.

The work mentioned above led to the realisation that GP is a much more general EA than people thought. It proved that other EAs operating on fixed-length representations are just special forms of GP, thereby allowing the *unification* of these two forms of EA (e.g., see Stephens and Poli, 2004). A consequence of this is that our GP theory is a *generalisation of previous EA theory.*

The definition of exact mathematical models of GP (and various types of GAs), however, was not an end, but a means to understand the dynamics of evolutionary systems.

For example, the schema theory led to the formulation of a size-evolution equation (Poli, 2001; Poli and McPhee, 2003), which states the exact conditions under which average program size can change. This is important because it provided a framework within which to explain the well-know tendency of programs do grow during evolution without any clear fitness benefit (a phenomenon known as bloat).

All non-trivial search algorithms explore the search space in some particular order or giving preference to certain particular areas. This tendency is termed *search bias.* Search biases are crucially important in determining the performance of an algorithm on a problem (or a class of problems). In fact, a well-known consequence of the no-free lunch theorems for search is that, only if the search bias of the algorithm is well-matched to the fitness landscape being explored, performance can be better than that of random search. However, despite their being ubiquitous and important, the exact nature of the biases of search algorithms is only known for very few cases. Therefore, for the greatest majority of cases, nobody knows what is required to match an algorithm to a problem.

In the case of evolutionary algorithms, the search bias is the result of the interaction of the search biases of the operators of selection, crossover and mutation. It is, therefore, only by understanding the biases of these operators and their interactions that one can understand where evolution in heading. However, only the search bias of selection and particularly simple forms of crossover and mutation for fixed-length linear genomes (such as those used in the simple GA) were known in the 1990s and early 2000s. Nothing was known about the search biases of recombination and mutation operators for variable size representations (such as GP program trees).

So, after the definition of our exact mathematical models of GP, the challenge was to try and use them to *understand the search biases of GP and variable-size GAs.* Since standard selection was well-understood (being selection representation independent, theoretical models of selection developed for GAs apply to GP as well), we concentrated on understanding the biases of recombination and mutation. This is no easy task however. Exact models of evolutionary systems include zillions of non-linear difference equations (e.g., Vose's model for a simple GA with a tiny population of 5 individuals and a tiny genome of 5 bits has 376,992 equations). In the case of GP and variable-length GAs, being the search space infinite, exact probabilistic models must include infinitely many equations! So, simulation and analysis are fraught with difficulties even if one is able to express the calculations in the best possible basis (Poli and Stephens, 2005).

Perhaps the most informative way of characterising the bias of genetic operators is to determine where a particular genetic operator would push a population if it was repeatedly applied to the population in the absence of other operators. That is, one is interested in the fixed points for the evolution equations corresponding to these conditions. In the case of fixed-length GAs, thanks to their similarity with well-studied systems modelled in theoretical population genetics, the evolutionary fixed point for a crossover-

only system has been known for decades and goes under the various names of *linkage equilibrium, Robbins' proportions or Geiringer manifold*. Finding the Geiringer manifold for GP and variable length GAs was, therefore, our primary objective.

Initially, we were able to study in detail only the case of variable-length linear structures (Poli and McPhee, 2001; McPhee and Poli, 2001; McPhee, Poli, and Rowe, 2001; Poli, Rowe, Stephens and Wright, 2002; Poli, Stephens, Wright, and Rowe, 2002; Poli, Stephens, Wright and Rowe, 2003). Recently, however, we have been able to extend the study of bias to the case of standard tree-based GP (Poli, Langdon and Dignum, 2007; Dignum and Poli, 2007). This led to discovering that GP recombination attempts to produce a particular, highly asymmetric, program-size distributions, which we proved to be a discrete Gamma for linear GP and have shown to be a Lagrange distribution of the second kind in the more general case of tree-based GP. We also discovered that GP recombination produces a previously unsuspected diffusive bias. In the case of linear structures this pushes the population towards a distribution where each instruction is equally likely to be found at any available locus. For such structures, we now have a complete characterisation of where crossover directs evolution, i.e., of GP's Geiringer manifold. Recently we were also be able to complete the characterisation of the Geiringer manifold for general tree-based GP (Dignum and Poli, 2008; Dignum and Poli, 2010).

The above characterisations of the Geiringer manifold for GP have profound implications. For example, knowing that the size distribution fixed-point is a rapidly decreasing distribution allows one to explain in very simple terms the reasons for bloat (Dignum and Poli, 2007; Poli, McPhee and Vanneschi, 2008), thereby, at last, ending the search for an explanation for bloat – a phenomenon that has been studied for over a decade without any theoretical explanation ever becoming universally accepted.

Another recent effort, which was initially motivated by GP but that is also generating interest among theoretical computer scientists, has been the development of a *Markov chain model of program execution and halting* for Turing complete machine code languages (Poli and Langdon, 2006; Langdon and Poli, 2007). The model is able to predict with great accuracy and in minutes the halting probability of programs with sizes ranging from a few instructions to tens of millions of instructions, that is, over seven orders of magnitude.

My most recent theoretical contribution to the area of genetic programming has been the analysis of the relationships between program induction and the no-free lunch theorem of Wolpert and Macready. The results of this analysis have been particularly interesting: in general the no-free lunch theory does not apply to program induction, and this includes the evolution of computer programs (Poli, Graff and McPhee, 2009) as well as the evolution of neural networks (Poli and Graff, 2009). The theory tells us also what limits the no-free lunch imposes on hyper-heuristics and on computer scientists (Poli and Graff, 2009).

Naturally, a lot of my work in GP has also been aimed at *improving and applying GP technology* itself. In some cases, these improvements are a direct result of a deeper theoretical understanding of GP. For example, thanks to the derivation of size-evolution equation (Poli, 2001; Poli and McPhee, 2003) it became possible, for the first time, to remedy bloat with theoretically sound recipes (Poli, 2003). Also, the knowledge of the limiting distribution produced by GP crossover (Poli, Langdon and Dignum, 2007) can be used to correct the undesirable features of GP's crossover bias using theoreically sound algorithms (Dignum and Poli, 2007; Dignum and Poli, 2008).

Over the years, with my students and collaborators, I have also proposed numerous powerful representations, operators and speedup techniques, including: a method which allows the evolution of parallel and distributed programs, finite state machines, as well as neural and recursive transition networks (Poli, 1996; Poli, 1997; Poli, 1999; Pujol and Poli, 1998; Pujol and Poli, 1999); a method to speedup the evaluation of Boolean expressions by nearly *two orders of magnitude* (Poli and Langdon, 1999; Poli, 1999; Poli, Page and Langdon, 1999; Poli and Page, 2000); a method which allows to run GP in *backward chaining* mode thereby making it possible to know the future of a run without having to compute all previous generations (Poli, 2005; Poli and Langdon, 2005; Poli and Langdon, 2006, more on this below), etc.

In the area of the applications of GP and EAs, I made significant contributions in the area of *evolving operators, filters and detectors for image and signal processing* (Poli and Valli, 1993; Cagnoni, Dobrzeniecki,

Yanch and Poli, 1994; Poli, Cagnoni, and Valli, 1995; Poli, 1996; Poli and Cagnoni, 1997; Johanson and Poli, 1998; Cagnoni, Dobrzeniecki, Poli, and Yanch, 1999; Quintana, Poli and Claridge, 2002; Quintana, Poli and Claridge, 2003; Citi, Poli, Cinel and Sepulveda, 2004; Citi, Poli and Sepulveda, 2004; Quintana, Poli and Claridge, 2006; Citi, Poli and Cinel, 2006; Citi, Poli, Cinel and Sepulveda, 2007). With one of my students, I also pioneered the use of GP to evolve learning rules for artificial neural networks (Radi and Poli, 1998; 1999; 2003) and the use of GP as a function optimiser (Pujol and Poli, 2004; Pujol and Poli, 2007). In addition, we have recently used GP to evolve solvers and search algoritms (rather than solutions) for problems. Domains have included Particle Swarm Optimisation (PSO, more on this below), satisfiability (Bader-El-Den and Poli, 2007 and 2008), TSP (Keller and Poli, 2007 and 2008), bin packing (Poli, Woodward and Burke, 2007), as well as graph and matrix bandwidth- and envelope-minimisation problems (Koohestani and Poli, 2010 and 2011).

We have also obtained excellent results in the applications of genetic programming in the area of lossless compression (Kattan and Poli, 2008, 2009, 2010 and 2011) and in constructing practical models that allow one to predict the performance of genetic programming systems without actually running the system (Graff and Poli, 2008, 2009, 2010 and 2011).

8.2 Genetic algorithms

My initial interest in the schema theory was primarily aimed at giving a solid theoretical foundation to GP. However, in getting deeper and deeper into the subject I was able to make several contributions also in the theory of genetic algorithms, in addition to the aforementioned clarification of the relationship between GP and GAs.

One limit of the traditional form of schema theory is that the r.h.s. of the evolution equations represents an expectation. This prevents the iteration of the equations except under the infinite-population approximation. In my studies on the schema theorem I realised that it was possible to do without the expectation operator, by introducing confidence intervals and making use of Chebychev inequality (Poli, 1999). This made it possible to derive a new form of schema theory that would allow one to make predictions over multiple generations (the conditional recursive schema theorem) and indicated a possible route to proving GA convergence (Poli, 2000).

In the late 1990s, in a sequel of three theoretical papers, including one in IEEE Transactions on Evolutionary Computation, by Drs Fogel and Ghozeil, strong doubts were cast on the applicability of schema theories when the fitness function is noisy and when, as is typically the case, stochastic effects are present in a genetic algorithm. If confirmed, these results would have effectively put an end to the hope to model GAs with schema theorem type results. I proved conclusively that the interpretations put forward by Fogel and Ghozeil were incorrect (Poli, 2000).

The vast majority of theoretical work in biology and in evolutionary computation has been centered on homologous recombination. In the latter, a position (locus) in the offspring can only be filled using gene values (alleles) from the same position in one of the parents. In nature, though, there are many more ways of combining parental genetic material into an offspring than just homologous crossover. With Chris Stephens, I proposed, modelled and studied theoretically a general notion of recombination where homologous recombination, inversion, gene duplication, gene deletion, diploidy, etc. are just special cases (Poli and Stephens, 2006; Poli and Stephens, 2007; Stephens and Poli, 2008). For the first time this work allows the study of a huge variety of natural and artificial phenomena within a unified framework. The Geiringer manifold for this model was also derived as was an explicit solution for a two-locus system.

A fundamental question in evolutionary computation has always been whether population-based search (as opposed, for example, to a (1+1) evolutionary strategy or a stochastic hill-climber) had something special to offer, i.e., for example, whether the interactions between individuals would create a whole that is more than the sum of its parts and whether all population-based algorithms could be seen as having some common emergent properties. The same question can be asked in relation to natural swarms, fish shoals, etc. To address these questions, I formulated a model of emergent coordinated behaviour for a population of interacting entities (Langdon and Poli, 2006). This is a modified spring mass model where masses can

perceive the environment and generate external forces. One can prove mathematically that in certain conditions the population behaves like a single organism. This emergent organism, however, does not live in the original landscape, but one resulting from the application of a low-pass filtering kernel. To test to what extent this model would apply to genetic algorithms and particle swarm optimisers, we identified the sensing kernels of the model's masses that provided the best fit between the spring-mass model to these two population-based search algorithms. In both cases, the best kernels were low-pass (smoothing) filters. They provided an excellent fit for many generations.

This suggested that we should search for the origins of low-pass filtering behaviours in these systems. One important step in this direction was obtained in (Poli, Wright, McPhee and Langdon, 2006), were we provided a mathematical proof that for a GA, on any problem and for any crossover operator, the effect of crossover is that of reducing the amplitude of the derivatives (slopes) of the population distribution. This implies that a GA perceives an effective fitness landscape which is a smoothed, low-pass filtered version of the original. A low-pass filtering bias of GA crossover had never been reported before. The search for a low-pass filtering bias in PSO is still ongoing.

Another contribution that I consider valuable is the definition and theoretical analysis of a measure of difficulty for GAs called the *fitness-proportional negative slope coefficient* (*fpncs*) (Poli and Vanneschi, best paper award at GECCO 2007; Vanneschi, Valsecchi and Poli, 2008) which it is strongly linked to the notion of evolvability and Fisher's fundamental theorem of natural selection (yet it is different from both).

Another scientific contribution which I consider significant is what I called *Backward-chaining Evolutionary Algorithms* (Poli 2005; Poli and Langdon, 2005; Poli and Langdon, 2006). This line of research started from the detection of a previously-unknown source of inefficiency in a popular selection method EAs – tournament selection. This led us to rethink the order in which operations are performed within EAs, and to derive an algorithm that avoids the inefficiencies associated with tournament selection. Reordering operations inside the EA made it then possible to notice a totally unexpected similarity between our evolutionary algorithm and traditional AI rule-based systems. This led us to further modify the order of operations in the EA, effectively turning the evolutionary search into an inference process operating in backward-chaining mode. The resulting backward-chaining EA creates and evaluates individuals recursively, backward from the last generation to the first, using depth-first search and backtracking. This algorithm has four unique features: (a) it is provably statistically equivalent to a standard EA, (b) operations are ordered in such as way that, provably, the backward-chaining algorithm finds fitter solutions sooner, i.e., it is a faster algorithm, (c) the algorithms is general and can be applied to any form of population based search, any representation, any fitness function, any crossover and mutation, provided tournament selection is used, (d) a full theoretical characterisation of the algorithm is available, which predicts exactly what savings one should expect by using the backward-chaining strategy. In fact, this work is unusual from this point of view in that, unusually, here the theory preceded implementation: first we studied tournament-selection's inefficiencies theoretically using Markov chain theory and computed exactly the speedup and savings provided by an ideal EA without such inefficiencies, and only then did we try to find implementations that achieved such benefits.

Another recent contribution to GA research has also to do with selection. In most forms of selection, when multiple individuals are needed for an operation, these are drawn independently from the population. So, for example, in the case of crossover, the probability of a particular pair of parents being selected is given by the product of the selection probabilities of each parent. This form of selection has been studied extensively in the literature. In fact, theoretical studies appeared to have completely characterised selection, fundamentally making it a largely understood process. However, all studies have neglected the more general and interesting form of selection where pairs of parents are not selected independently, therefore, leaving it a totally unchartered terrain. In (Graff, Poli and Moraglio, 2007) started filling this theoretical gap, investigating theoretically (with empirical validation), a particular form of dependent selection, linear selection. In particular, we proved that this leads a genetic algorithm with homologous crossover to become very similar to a genetic algorithm with standard (independent) selection and headless chicken crossover, i.e., it turns crossover into a type of mutation. We also showed the theoretical connections between this form of selection and Holland's original selection method.

Finally, I would like to mention my work on the finite-element analysis of stochastic optimisers. While Markov chains are important in the theoretical analysis of evolutionary algorithms operating on discrete search spaces, they have been of little to no use for EAs searching on continuous spaces. So, a variety of other analysis tools have been used, but, generally, making theoretical progress in the continuous domain has proven to be extremely difficult, and often success has been limited to very special cases (e.g., sphere functions, absence of randomness, etc.). So, there is a large gap between theory and practice for continuous optimisers. In (Poli, Langdon, Clerc and Stephens, 2007) we proposed an idea which has the potential to radically improve the situation. The idea is to deal with the continuous optimiser as one would deal with a mechanical system, i.e., via the finite-difference or the finite-element methods. These divide continuous systems into elements. The elements are sufficiently small that the behaviour of each can safely be modelled by a numerically simple function and so the whole system is accurately modelled by simply combining all its elements. That is, instead of constructing an approximate theory for continuous optimisers, we discretise the optimiser and its fitness function, we derive an exact theory for the discrete system (a Markov chain), and we then study the behaviour of such as system. If the discretisation mesh is fine enough, this behaviour will closely match the behaviour of the continuous optimiser. This gives us an effective general technique to produce discrete Markov chain models of continuous stochastic optimisers that, in principle, can approximate them on continuous problems to arbitrary precision, for arbitrary fitness functions and for an arbitrary number of generations. We turned these ideas into practice applying the approach to real-valued GAs, (1+1) evolution strategies, and bare-bone particle swarm optimisers (more on this below), obtaining very accurate predictions of behaviour, success probability, convergence probability and run-time.

8.3 Particle Swarm Optimisation

Particle swarm optimisers (PSOs) — a field closely related to evolutionary computation, but drawing inspiration from natural swarms, shoals and flocks — has been another area where I feel I have recently made good contributions.

For stochastic optimisation algorithms (such as PSOs, GAs, etc.), knowing the probability distribution with which an algorithm allocates new samples in the search space is very important, since this explains how the algorithm really works and is a prerequisite to being able to match algorithms to problems. This is the only way to beat the limitations highlighted by the no-free lunch theory. Yet, the sampling distribution of PSOs – the "holy grail" of PSO research – has remained a mystery until now, i.e., for over a decade of intense PSO research. The main reason for this is that the many theoretical analyses of the dynamics of particle swarms offered in the literature in the past invariably relied on substantial simplifications, and on the assumption that particles are deterministic. Naturally, these simplifications then made it impossible to derive an exact characterisation of the sampling distribution of the PSO.

In (Poli, 2007; Poli and Broomhead, 2007; Poli, 2008; Poli, 2009) we changed all this. There we proposed a method that allows one to exactly determine all the characteristics of a PSO's sampling distribution and explain how and why it changes over time during stagnation (i.e., while particles are in search for a better personal best) for a large class of PSOs. The method allows one also to study and compare the stability of the sampling distribution (via moment analysis) as a function of the PSO's parameters, making it possible, for the first time, for PSO users to choose parameters knowing how the PSO behaviour will be affected. The method is general. For example, in (Poli, Bratton, Blackwell and Kennedy, 2007) we applied the same type of analysis to derive the stability regions of a simpler form of velocity-based PSO.

Another important contribution was the application of the finite-element analysis technique developed in (Poli, Langdon, Clerc and Stephens, 2007) and described in the previous section to bare-bones PSOs with different sampling distributions. Bare-bone PSOs are based on the idea of doing without the notion of particle velocity, and instead draw the new positions of particles from a predefined class of sampling distributions (e.g., Gaussian, Cauchy or Levy distributions). Although many proposals for BB-PSOs are present the literature, no accurate theoretical analysis of their behaviour was available. Thanks to the application of our finite-element analysis method, we were able to derive the first ever Markov chain

models for these type of PSOs. In (Poli and Langdon, 2007), we then went on to compare, for the first time, BB-PSOs with 8 different distributions, showing, for example, which classes of distributions guarantee asymptotic convergence to the global optimum and which don't, how convergence time is affected by the distribution and initial conditions, etc.

While initially in PSO research the communication topology (or social networks) of the particles was limited to two fixed topologies (fully connected and ring), in recent years it has become apparent that the topology has a major impact on PSO performance, and a number of studies have started looking at the effects of different topologies. Unfortunately, the focus of previous research on PSO social networks has mostly been on PSO performance, not PSO behaviour. However, it is clear behaviour is what matters, since performance comes from behaviour rather than the other way around. Performance on a problem is the result of coupling the features of that problem with the natural behaviour of that particular PSO. If the mode of exploration fits the features of a problem, we expect good performance and vice versa. To rectify the situation, in (Poli, Langdon, Marrow, Kennedy, Clerc, Bratton and Holden, 2006, nominated for a best paper award at ANTS 2006) we investigated the properties of social networks as systems for reaching consensus (e.g., about which area of the search space to explore). A particular aim was to investigate whether and how consensus is reached and groupings of individuals are formed in different settings and with different forms of interaction and leadership. To this end, we proposed an executable model of PSO communication where the details of the dynamics and the optimum seeking behavior of PSOs were put in the background. Despite these simplifications, however, the model predicted a variety of behaviours, some of which, for example, deception and origin seeking dynamics, have previously been reported in real PSOs.

8.4 Brain Computer Interfaces

The keyboard and mouse provide us with reliable, but unnatural forms of input, being primitive transducer of muscular movement. Wouldn't it be nice some day to be able to replace them with Brain-Computer Interfaces (BCIs) capable of directly interpreting the intentions of computer users?

Around 7 years ago I started looking into the possibility of applying bio-inspired techniques to the area of BCI. This led to the creation of the Essex BCI group, which is now one of the strongest in Europe (see page 5).

BCI systems measure specific (intentionally and unintentionally induced) signals of brain activity and translate them into device control signals. Many factors limit their performance. These include: the natural variability and noise in the brain signals measured; the limitations of the recording and signal processing methods that extract signal features and of the algorithms that translate these features into device commands; the quality of the feedback provided to the user; the lack of motivation, tiredness, limited degree of understanding, age variations, handedness, etc. in users.

Since in BCI the human is part of the system, we started looking at the ways in which the natural limitations of the human perceptual system can affect performance (e.g., in Cinel, Poli, Citi, 2004). This led us to understand that in many cases a deeper knowledge of how the human perceptual system works can lead to reinterpreting amplitude and shape variations in brain waves as important sources of information which can be exploited to the benefit of BCI. BCI researchers, instead, typically consider such variations as noise. This psychology-informed approach was exploited to develop the prototype of a unique analogue system for the control of 2–D pointers (mouse) (Citi, Poli and Cinel, 2006; Poli, Cinel, Citi, Sepúlveda, 2007; Citi, Poli, Cinel, Sepúlveda, 2008).

In 2008 I obtained funding for a project (see page 6) aimed at turning these ideas and prototypes into systems for practical use outside the lab. The objective of this project was the development of the technology and related scientific basis for the creation of usable hands-free BCI mice. Results with our holistic and interdisciplinary approach (Poli, Citi, Sepulveda, and Cinel, 2009) were extremely promising. We carried out fundamental research to understand how the shape and amplitude of P300 waves varies depending on the type and timing of the visual stimuli used and this also required developing better ways of recording and averaging such waves (Poli, Cinel, Citi and Sepulveda, 2010; Citi, Poli, and Cinel, 2009). Also, in the exploration of visual stimuli (Salvaris, Cinel, Poli, Citi, Sepulveda, 2010; Salvaris, Cinel and

Poli, 2011), we found a totally innovative protocol, which uses periodic, and thus predictable, sequences of stimuli instead of the traditional random sequences. This goes against all the psychophysiology literature on the generation of P300s, yet, with an appropriate mental task for users, we found that periodic sequences produced much stronger and more widely distributed P300s than traditional sequences. Correspondingly, this produced a marked increase in performance in our mouse. Also, in using genetic programming to aid the design of our BCI mice (Poli, Salvaris and Cinel, 2011 and 2011), we discovered that it devoted much attention to minimising the effects of muscular artifacts (such as eye blinks or swallowing) on the mouse trajectories. When we combined our new periodic stimulation patterns with the best machine learning technology and the best evolved system for artifact rejection, we obtained excellent results. Subjects were able to use the mouse in both controlled conditions and in a standard Windows environment with very good accuracy only minutes after wearing the electrode cap and with no previous training.

Our analougue mouse is currently the best P300-based BCI mouse in the literature by far, performing one movement every 100ms. In addition, we were able to exploit the newly acquired knowledge on P300 variability beyond our BCI mouse, building a matrix speller that provides a significant improvement in accuracy over the top-performing algorithm in the literature to date (Citi, Poli and Cinel, 2009 and 2010).

8.5 Computer Vision

I believe I also made good contributions to science in the area of computer vision and neural networks during and after my PhD. In particular, I formulated a *computational theory of shape from density* from single X-ray (projective) images and proposed two mathematical methods for its practical implementation (Poli and Valli, 1997). I proposed a *multi-scale method for the segmentation of projective images* which relaxed the standard notion that regions cannot overlap (Poli and Valli, 1996; Poli and Valli, 2003). The method defined the segmentation task as an optimisation problem which was solved by the relaxation of a Hopfield recurrent neural network. Finally, I constructed a *spherical counter-part of the classical thin plate model*, which allowed the representation of complex 3–D shapes (Poli, Coppini and Valli, 1994; Coppini, Poli and Valli, 1995). Because of its physical nature, following Alex Pentland's original ideas, the model allowed the decomposition (and recognition) of shapes via the free vibrational modes of the surface.

9 Publications

9.1 Summary of Publications by Year

Year	Publications Histogram
1989	(2)
1990	(3)
1991	(6)
1992	(6)
1993	(4)
1994	(2)
1995	(5)
1996	(9)
1997	(13)
1998	(17)
1999	(21)
2000	(7)
2001	(9)
2002	(10)
2003	(14)
2004	(14)
2005	(20)
2006	(25)
2007	(32)
2008	(35)
2009	(21)
2010	(20)
2011+	(16)

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2. Riccardo Poli, William B. Langdon and Nicholas Freitag McPhee, *A Field Guide to Genetic Programming*, Lulu.com, freely available under Creative Commons Licence from `www.gp-field-guide.org.uk`, March 2008.

3. Riccardo Poli and Christopher R. Stephens, Taming the Complexity of Evolutionary Dynamics: From microscopic models to schema theory and beyond, Springer, Natural Computation series and Complexity series, approx 700 pages, forthcoming, 2012.

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the First European Workshop on Evolutionary Computation in Telecommunications - EuroECTel'99, Goteborg, May, 1999 Springer-Verlag.

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9. S. Cagnoni and R. Poli, editors, Special issue of the EURASIP Journal of Applied Signal Processing on Genetic and Evolutionary Computation for Signal Processing and Image Analysis, issue 8, July 2003.

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12. R. Poli and M. Schoenauer, Special Issue of the Evolutionary Computation Journal (MIT Press) on the Best of GECCO, Issue 1 of 2006.

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4. J. C. F. Pujol and R. Poli, Synthesis of neural networks by a two-dimensional approach, Invited Chapter in L. C. Jain (Ed), *Evolutionary Computing Techniques in System Design*, CRC Press, 1999.

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191. Stephen Dignum and Riccardo Poli. Sub-Tree Swapping Crossover and Arity Histogram Distributions. In Anna Isabel Esparcia-Alcazar, Aniko Ekart, Sara Silva, Stephen Dignum and A. Sima Uyar editors, Proceedings of the 13th European Conference on Genetic Programming, EuroGP 2010, volume 6021, pages 38-49, Istanbul, 2010. Springer.

192. Ahmed Kattan and Riccardo Poli, Evolution of Lossless Compression Algorithms with GP-ZIP3, IEEE World congress on computational intelligence, Barcellona, pp. 1-8, July 2010.

193. Riccardo Poli: Genetic programming theory. Genetic and Evolutionary Computation Conference (GECCO) (Companion), ACM, pp. 2473-2502, 2010.

194. Behrooz Koohestani, Riccardo Poli: A Genetic Programming Approach to the Matrix Bandwidth-Minimization Problem. Parallel Problem Solving from Nature, pp. 482-491, 2010.

195. Poli, R., Citi, L., Salvaris, M., Cinel, C., & Sepulveda, F. Eigenbrains: the Free Vibrational Modes of the Brain as a New Representation for EEG. 32nd Annual International Conference of the IEEE Engineering in Medicine and Biology Society August 31 - September 4, 2010 Buenos Aires Sheraton Hotel, Buenos Aires, Argentina, pp. 6011-6014.

196. Salvaris, M., Cinel, C., Poli, R., Citi, L., & Sepulveda, F. Exploring Multiple Protocols for a Brain-Computer Interface Mouse. 32nd Annual International Conference of the IEEE Engineering in Medicine and Biology Society August 31 - September 4, 2010 Buenos Aires Sheraton Hotel, Buenos Aires, Argentina, pp. 4189-4192.

197. Riccardo Poli, Mathew Salvaris and Caterina Cinel, Evolution of a Brain-Computer Interface Mouse via Genetic Programming, Proceedings of Genetic Programming - 14th European Conference, EuroGP, Torino, Italy, April 27-29, 2011, Lecture Notes in Computer Science 6621, Springer, pp. 203-214.

198. Riccardo Poli, Mathew Salvaris and Caterina Cinel, Evolutionary Synthesis of a Trajectory Integrator for an Analogue Brain-Computer Interface Mouse, Proceedings of Applications of Evolutionary Computation (EvoApplications), Torino, Italy, April 27-29, 2011, Lecture Notes in Computer Science 6624, Springer, pp. 214-223.

199. Mario Graff and Riccardo Poli, Models of Performance of Evolutionary Program Induction Algorithms Based on Problem Difficulty Indicators, Proceedings of Genetic Programming - 14th European Conference, EuroGP, Torino, Italy, April 27-29, 2011, Lecture Notes in Computer Science 6621, Springer, pp. 118-129.

200. M. Salvaris, C. Cinel and R. Poli, Novel Sequential Protocols for a ERP Based BCI Mouse, 5th International IEEE EMBS Neural Engineering Conference, forthcoming, 2011.

201. Riccardo Poli, Caterina Cinel, Luca Citi and Mathew Salvaris, A Genetic Programming Approach to Detecting Artifact-generating Eye Movements from EEG in the Absence of Electro-oculogram, 5th International IEEE EMBS Neural Engineering Conference, forthcoming, 2011.

202. Behrooz Koohestani and Riccardo Poli, A Hyper-Heuristic Approach to Evolving Algorithms for Bandwidth Reduction Based on Genetic Programming, AI-2011 Thirty-first SGAI International Conference on Artificial Intelligence, Cambridge, 13-15 December 2011, forthcoming.

9.7 Other Output

1. I produced a 8 technical reports before 1995 while in Italy, I have coauthored 63 technical reports between March 1995 and May 2001 while at Birmingham, and I've produced tens more technical reports at Essex. Since most of these reports have later become journal or conference publications, I've chosen not to provide their lengthy list here. Also I don't normally consider them in my publication count.

2. I have submitted the following short paper to the "Mathematics: History and Overview" section of arXiv.org:

   Riccardo Poli and William B. Langdon, A simple reformulation of Riemann Zeta function, `arXiv:math/0701160v1 [math.HO]`, January 2007.

3. I produced a 40 minute video with Bill Langdon on genetic programming and the halting problem available in Google Videos. I have also produced an 11 minute video on our Brain Computer Interfaces work at the University of Essex available in Goolge Videos.

4. In conjunction with the "Field Guide to Genetic Programming" book, I've released a software implementation called "TinyGP". There is also a blog and a Google group associated to the book.

5. I have invented an intelligent adaptive control system for computer mice and pointing devices. A patent application sponsored by the University and the Iceni Seedcorn Fund LLP was filed in February 2004 (GB0403416.1). This was turned into an international patent application in February 2005, but later the University decided to let it expire for some reason.

10 Main Invited Tutorials, Talks, etc.

- Aston University, Hopfield neural nets for medical image segmentation, 1995.
- University of Sussex, Minimal polynomial logic, 1996.
- University of Edinburgh, Genetic Programming for image analysis, 1996.
- Queen and Mary Westfield College London, On the relations between Search and Evolutionary Computation, 1996.
- University of Oxford, Genetic Programming, 1997.
- University of Reading, Parallel distributed genetic programming, 1998.

- University of Parma (Italy), Genetic Programming, 1998.
- Amsterdam, PPSN-V international conference, Tutorial on Genetic Programming, 1998.
- City University (London), Genetic Programming, 1998.
- Invited presentation at the Workshop on Evolutionary Computation Teaching in the CEC'99 conference (Washington, USA), 1999.
- Invited partecipant and presenter at the Dagstuhl School on the Theory of Evolutionary Computation (Feb 2000).
- Invited speaker (with Wolfgang Banzhaf) for the one-day seminar on genetic programming jointly organised by the University of Geneva and the University of Lausanne, April 2000.
- University College London (UCL), Exact Schema Theories and Effective Fitness in Genetic Programming and Genetic Algorithms, May 2000.
- Tutorial speaker at GECCO 2000. Title: Foundations of Genetic Programming. July 2000.
- The Santa Fe Institute for Complex Systems. Topic: exact schema theory. July 2000.
- Senior tutor at the Computational Intelligence and Learning (COIL) Summer School, Limerick, Ireland, September 2000.
- Istituto Dalle Molle di Studi sull'Intelligenza Artificiale (IDSIA), Lugano, Switzerland, Exact Schema Theories and Effective Fitness in Genetic Programming and Genetic Algorithms, April 2001.
- Tutorial Speaker at the EuroGP 2001 Conference (Como, Italy), April 2001. Introduction to Genetic Programming.
- Tutorial Speaker at the CEC 2001 conference (Seoul), May 2001. Schema theorems for GAs and GP.
- Tutorial Speaker at the GECCO 2001 conference, San Francisco, July 2001. Foundations of genetic programming.
- Invited partecipant and presenter at the Dagstuhl School on the Theory of Evolutionary Computation (Jan 2002).
- Invited panel member for the discussion on the future of evolutionary computation at EUROGEN 2001, Athens, September 2001.
- Invited panel member for the final discussion at the ISGEC Workshop on Standards held at GECCO 2002, New York, July 2002.
- Tutorial Speaker at the GECCO 2002 conference, New York, July 2002. Foundations of genetic programming.
- Tutorial Speaker at the GECCO 2003 conference, Chicago, July 2002. Foundations of genetic programming.
- Tutorial Speaker Multidisciplinary International Conference on Scheduling: Theory and Applications (MISTA 2003), Nottingham, August 2003. Introduction to Genetic Programming.
- Senior tutor EvoNet Summer School on evolutionary computation, Parma (Italy), Summer 2003.
- Invited keynote speaker (all expenses paid) at the SEMINAL (Software Engineering with Metaheuristic INnovative ALgorithms) Network workshop (Sep 2003).

- Seminar at University College London (March 2004).
- Seminar at Royal Holloway (March 2004).
- Seminar on Constrained Molecular Dynamics at BT Exact (Adastral Park, Ipswich), May 2004.
- Invited tutor (all expenses paid) International School of Mathematics "G. Stampacchia" on "Evolution: from biology to statistical modelling", Ettore Majorana Centre, Erice (Sicily), Italy (July 2004): 2.5 hour tutorial on the foundations of genetic programming.
- Tutorial speaker at CEC 2004 (Portland, June 2004).
- Tutorial speaker BCS School on Pattern Recognition, Plymouth, July 2005.
- Invited keynote speaker at the UK-Computationa Intelligence (UKCI 2005) workshop, London, September 2005. Talk title: Surfing the waves of artificial intelligence.
- Invited tutorial speaker at the "Giornata di Studio Italiana di Calcolo Evoluzionistico" workshop of the Italian Artificial Intelligence (AI*IA 2005) conference, Milan, September 2005.
- Tutorial speaker at the GECCO 2006 conference, Seattle, July 2006.
- Invited partecipant and presenter at the Dagstuhl School on the Theory of Evolutionary Computation (2006).
- Tutorial speaker at the GECCO 2007 conference.
- Tutorial speaker at the CEC 2007 conference.
- Panel member at EuroGP 2008 debate.
- Doubly tutorial speaker at the GECCO 2008 conference (GP theory and Particle Swarm Optimisation).
- Invited speaker PPSN 2008 workshop on Hyperheuristics, Germany.
- Invited partecipant and presenter at the Dagstuhl School on the Theory of Evolutionary Computation (2008).
- Panel member at EuroGP 2009 discussion.
- Tutorial speaker at Genetic and Evolutionary Computation Summit (GECS), Shanghai, 2009 (theory of genetic programming).
- Two invited tutorials at ACMs GECCO 2009 conference in Montreal in July 2009. The first was a 2-hour tutorial introduction to genetic programming (jointly with Prof N. F. McPhee). The second was a 4-hour tutorial on the theory of genetic programming (jointly with Dr W.B. Langdon).
- Tutorial speaker at the CEC 2009 conference, Norway (Theory and Practice of Genetic Programming).
- Panel member at EuroGP 2010 discussion.
- A 2-hour invited tutorial on the theory of genetic programming at the GECCO 2010 conference held in Portland in July 2010.
- Invited keynote presentation at 2nd International Symposium on Search Based Software Engineering held in Benevento, Italy in September 2010.
- Senior in EuroGP 2011 "Speed Dating" session (where students where given a chance about their career prospects with senior figures in the field).

- Invited talk at the Italian Workshop on Artificial Life and Evolutionary Computation (WIVACE), February 2012.

A Summary of PhD Thesis

The title of the thesis was "Computer Vision Systems for Medical Images: Theory, Methods and Application". Below is its summary.

Medical imaging techniques produce images containing a lot of information about the anatomical structures being investigated. This information is valuable for making correct diagnoses, choosing the most adequate therapy, and so on.

The analysis of medical images has always been performed visually by physicians. Only recently a strong impulse has been given to develop automated or semi-automated systems capable of assisting physicians in this task. The reason is probably that the number of images per exam as well as the number of exams is quickly growing so that visual inspection of medical images is becoming a more and more tiring task. In addition physicians have also a strong desire of quantizing a number of anatomical and functional parameters, useful for diagnosis and therapy, which can be evaluated only qualitatively by human beings. However, the presence of noise and of masking structures, the variability of biological shapes and tissues, imaging system anisotropy, etc. make the automated analysis of medical images a very hard task.

The approach to overcome these problems has always be a) to simplify the objective of the analysis as much as possible and b) to exploit some kind of *a priori* information about the imaged structures. To simplify the objective of the analysis usually means to restrict the analysis to a single image modality (e.g. MR, CT or echo), to a single anatomical district (e.g. the thorax or the head), to a single structure inside a district (e.g. the brain, the lungs), to a single kind of view, and so on. *A priori* information about the structures to be analyzed can be anatomical knowledge about their typical apparence (shape, gray levels) and position, or knowledge about statistical properties of the gray levels of the tissues included in those structures. In any case the knowledge which can be embedded in automated analysis methods represents an specific, oversimplified model of reality. As a result, in spite of any efforts, present systems are not reliable, useful or fast enough for a practical use. Actually, only enhancement and interactive-measurement techniques have been implemented on medical imaging devices and therefore have had a real diffusion.

In this thesis a new approach to the analysis of medical images is described. It differs from the other ones for two reasons.

First, the analysis of medical images is here considered as a visual task. Vision is the cognitive process by which the information implicitly contained in the images is transformed into explicit descriptions of the shape, the dimensions, the motion etc. of the three-dimensional structures been observed. Computer vision (CV) is the field of computer science whose aim is to design programs or devices capable of analyzing a visual input so as to build a 3-D scene-description useful for object recognition and action planning. As such CV is the ideal framework for building automated analysis systems for medical images. To give a clear idea of the field, Chapter 2 of this thesis has been devoted to biological and artificial vision. The chapter includes a description of the basic anatomic, physiologic and psychologic mechanisms of human vision, a brief history of computer vision along with a description of pre-Marr approaches, an extensive description of Marr's computational theory of vision, and a summary of the most recent advances in computer vision.

The second distinguishing point of this thesis is related to the adopted processing architectures. In fact most of the methods here reported are based on artificial neural networks (ANN), and so they can have a parallel, distributed, fine-grained implementation like the one of biological vision systems. The reason for using this kind of architectures is twofold. First, ANNs are capable of learning from examples to perform complex tasks and generalize what they have learned so as to perform correctly even in the presence of unknown or degraded inputs. Second, ANNs are fault tolerant so that large scale hardware implementation at reasonable costs will be soon possible. Therefore, the integration of neural architectures and computer vision techniques seems to be the right strategy to overcome the reliability and speed problems encountered in developing automated systems for the analysis of medical images. Given the numerous references to ANNs in the rest of the thesis, Chapter 3 and 4 have been devoted to a description of the basic ANN paradigms and to the most important neural architectures for computer vision reported in literature, respectively. This completes Part 1 of the thesis; Part 2 reports the theory, the methods and

the applications developed by the author.

As already mentioned, in this work the automated analysis of medical images is seen as a problem of machine vision. However, it should not be thought that to build such systems one has simply to consult computer vision literature and select methods freely. In fact, as pointed out in Chapter 5, only extremely robust and flexible methods are adequate to face the noise and the variability of medical images. Unfortunately, only few CV algorithms have these features. Therefore, when developing CV systems for medical images one has often to discar, adapt or redevelop CV algorithms. However, as discussed in the chapter, in doing that the most important difference between natural imagery and medical images, i.e. the process of image generation, must be kept in mind. This difference changes the assumptions on which many CV methods, in particular 3-D recovery algorithms, are based. As a consequence methods for computer vision of medical images must be developed or, if possible, adapted from CV on the ground of a new computational theory for medical-image vision which specifies which representations should be built, why and how. The other chapters of Part 2 describe the methods and the applications which have been designed on the basis of this theory.

Under the title pre-processing, Chapter 6 collects a number of different techniques which are used as a first step by modules described in the following chapters. In particular the chapter reports on methods for image normalization and linearization, on interpolation and decimation techniques, on a deconvolution algorithm, on linear and neural filtering for signal enhancement, on ANNs for shape-representation, on a neural architecture for attention focusing, and on an ANN-based pattern recognition method.

The problem of texture analysis in medical images is discussed in Chapter 7 with particular attention paid to projective imaging. The chapter reports on some mathematical results about fractal dimension and other statistical texture-descriptors for medical images.

Chapter 8 describes some techniques for the detection and analysis of the boundaries of biological structures. In particular it reports on: algorithms for edge detection and linking, methods of contour analysis based on differential geometry, symbolic boundary descriptors, and hybrid symbolic/neural analysis techniques.

In Chapter 9 the dual approach, i.e. region growing for medical images, is discussed. First, a brief description of simple segmentation techniques, which are used in the case of noiseless images or as a final step of other segmentation methods, is given. Then, the chapter describes a segmentation system based on multiple ANNs trained with the backpropagation algorithm, a symbolic segmentation/recognition system for X-ray angiograms, an Hopfield ANN for multi-scale segmentation of 2-D and 3-D tomographic images, and its extension to X-ray ones.

Methods for 3-D recovery in medical imaging are discussed in Chapter 10. The goal of these methods is to construct basic 3-D representations of the scene from boundaries, regions or any other kind of 2-D representation of the input image(s). After a brief discussion on such methods for the case of tomographic images, the chapter reports on the computational theory of shape from density for X-ray images and on two mathematical methods for its practical implementation.

Chapter 11 describes 3-D representations for biological structures. After a brief discussion on the advantages and disadvantages of volumetric 3-D representations, the chapter extensively reports on two new representations based on physical models of thin elastic surfaces. These representations are extremely suitable for fast 3-D rendering, for shape and motion analysis, and for recognition of biological structures.

Chapter 12 draws some final conclusions and describes future perspectives of computer vision systems for medical images.

B Notes

[1]The Italian "Laurea" in Electronic Engineering was a 5-year degree followed by a substantial project (at the time, typically requiring an additional 10 to 12 months).

[2]These studentships were awarded on the basis of a written exam and an interview on a national basis (I had to compete with candidates from Rome, Naples, Bologna, Ancona and Florence). I was ranked first.

[3]This prize is equivalent to a distinguished dissertation award in the UK.

[4]The work was described in a paper published in *IEEE Computer*.

[5]The automata were controlled by recurrent neural networks trained by a genetic algorithm.

[6]Advantage Medical Research was a company producing medical instruments. The DayPress project was very successful leading to a spinoff company called Neural Instruments.

[7]I resulted first (out of 200+ candidates) in a national competition for one-year research fellowships.

[8]During my one-year fellowship I tried to obtain further funding and participated to various selections for permanent academic jobs in Italy. However, because of the peculiarities of the Italian academia, I did not manage to find any reasonable way to support my research. Then my only option was to start applying abroad.

[9]This was a permanent position, for which I finished the customary probation period in the Summer 1997.

[10]This is a type of propositional logic we invented, where expressions are represented by polynomials having a probabilistic interpretation.

[11]The book is highly regarded: it has attracted over 500 citations and has sold very well (over 3000 copies of which 1200 in the first year) considering its highly technical focus. The first print ran out at the end of 2004. A second edition has been printed in March 2005. The table of contents of the book and its first chapter are available from `http://www.cs.ucl.ac.uk/staff/W.Langdon/FOGP/`.

[12]BCI is a rapidly growing area of research involving detecting brain responses and converting these into appropriate signals for applications in various disciplines, from virtual reality to hands-free control of augmentative communication technologies for individuals with disabilities.

[13]A list of my 116 coauthors is available at the bottom of my DBLP bibliography page at `http://www.informatik.uni-trier.de/~ley/db/indices/a-tree/p/Poli:Riccardo.html` .

[14]This involved creating from scratch 400 slides, setting up, configuring and managing 5 Trac servers (for cooperative team communication and bug tracking) and as many Subversion servers (for cooperative software development), creating new marking schemes (one for group work evaluation, one for peer evaluation and one for teaching assistant individual evaluation) and the software to automatically integrate them into a single report which is also automatically emailed to each student. The course is unique in that students work for 6 weeks on a group project (with demos every 3 weeks) but any work they do is electronically monitored (via the Trac system and the Subversion revision control system) and counts towards their course work mark. While marking this has required big innovations, it has led to a more realistic situation where students are assessed exactly like they would if they were developers in an extreme programming team working in a real project. Labs were initially used to familiarise the students to the techniques required for the team work, but later they were almost entirely managed by the students for group coordination and pair programming. Myself and the teaching assistants acted as the "clients" for the software projects.

[15]Robert Keller is a co-author with Wolfgang Banzhaf, Peter Nordin and Frank Francone of the only university textbook book on Genetic Programming.

[16]This is probably one of the biggest administrative jobs in the university.

[17]These include: Brook University and Waterloo University in Canada, Missouri University of Science and Technology, California State University Los Angeles, University of Colorado at Colorado Springs, University of Minnesota, University of Genoa, University of Pavia, King Saud University, Arizona State University, University College Dublin and Carnegie Mellon.