Genetic and Evolutionary Computation Conference 2014

Conference Program

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Advancing Computing as a Science & Profession

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Welcome

On behalf of the Organizing Committee, I would like to welcome you to Vancouver for the 2014 Genetic and Evolutionary Computation Conference (GECCO 2014). This year's GECCO is comprised of 20 tracks, including the new Artificial Immune Systems and Hot Off the Press (HOP) tracks. The latter offers authors of outstanding research recently published in journals and other conferences the opportunity to present their work to the GECCO community. Under the guidance of Editor-in-Chief Christian Igel, the Track Chairs and Program Committee have selected 180 out of the 544 submissions received in all tracks (excluding HOP) for oral presentation as full papers, resulting in an acceptance rate of 33%. Close to 100 short papers will be presented in the poster session.

Highlights of the conference include keynote talks by Yoshua Bengio on "Deep Learning and Cultural Evolution", and by Dario Floreano on "Bridging Natural and Artificial Evolution", as well as an invited talk by Sumit Gulwani in the Genetic Programming track. Altogether 32 tutorials cover topics ranging from broad and introductory to specialized and at the frontier of current research. GECCO also hosts fifteen workshops, including several new ones as well as at least one that predates GECCO itself. Further high points include the 11th Annual "Humies" Awards for Human-Competitive Results, which are again generously supported by John Koza, and five competitions, ranging from Art, Design, and Creativity to the Industrial Challenge. Finally, Evolutionary Computation in Practice continues to be an important and integral part of GECCO.

I would like to thank the entire Organizing Committee for their work and dedication over the past year. Thanks also go to the Track Chairs and the Program Committee for their careful reviewing of the large number of submissions received. Finally, thanks are due to Roxane Rose and Cara Candler from *Executive Events*, who have been in charge of logistical aspects and registration, Lisa Tolles and her team at *Sheridan Printing* for the production of the proceedings, Mark Montague and his team at *Linklings* for their conference management tool and support of the reviewing process, and Gerardo Valencia for artwork and website management.

I wish you all a productive and enjoyable conference.

Dirk Arnold
General Chair

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Majercik, Stephen, *Bowdoin College*
Malago, Luigi, *Università degli Studi di Milano–Bicocca*
Malo, Pekka, *Aalto University*
Mambrini, Andrea, *University of Birmingham*
Mancoridis, Spiros, *Drexel University*
Manderick, Bernard, *Vrije Universiteit Brussel*
Mandziuk, Jacek, *Warsaw University of Technology*
Manzoni, Luca, *Université Nice Sophia Antipolis*
Marchiori, Elena, *Radboud University Nijmegen*
Marinakis, Yannis, *Technical University of Crete*
Maringer, Dietmar, *University of Basel*
Marks II, Robert, *Baylor University*
Marmion, Marie-Eleonore, *Université Lille Nord de France*
Martin, Andrew, *University College London*
Martinez, Hector P., *IT University of Copenhagen*

Martinez, Ivette C., *Universidad Simon Bolivar*
Mascia, Franco, *Université Libre de Bruxelles*
Maslov, Igor V., *EvoCo Inc.*
Matsui, Shouichi, *Central Research Institute of Electric Power Industry, Japan*
Mauri, Giancarlo, *Università degli Studi di Milano–Bicocca*
Mayer, Helmut A., *University of Salzburg*
McDermott, James, *University College Dublin*
McEwan, Chris, *Microsoft Research*
McIntyre, Andrew Ryan, *Dalhousie University*
McKay, Bob, *Seoul National University*
McMinn, Phil, *University of Sheffield*
McPhee, Nicholas Freitag, *University of Minnesota, Morris*
Meignan, David, *University of Osnabrück*
Melab, Nouredine, *Université Lille Nord de France*
Melkozerov, Alexander, *Tomsk State University of Control Systems and Radioelectronics*
Mendes, Rui, *Universidade do Minho*
Mendiburu, Alexander, *University of the Basque Country*
Menzel, Stefan, *Honda Research Institute Europe*
Merelo-Guervós, Juan-Julián, *Universidad de Granada*
Mesejo Santiago, Pablo, *Université d'Auvergne*
Meyer, Bernd, *Monash University*
Meyer-Nieberg, Silja, *Universität der Bundeswehr, München*
Mezura-Montes, Efrén, *Universidad Veracruzana*
Miconi, Thomas, *The Neurosciences Institute*
Middendorf, Martin, *University of Leipzig*
Miettinen, Kaisa, *University of Jyväskylä*
Miikkulainen, Risto, *University of Texas, Austin*
Miklic, Damjan, *University of Zagreb*
Miller, Julian, *University of York*
Minai, Ali, *University of Cincinnati*
Minku, Leandro, *University of Birmingham*
Miramontes Hercog, Luis, *Self-Organizing Solutions*
Misir, Mustafa, *Singapore Management University*
Mitchell, George, *CCKF Ltd.*
Mjolsness, Eric, *University of California at Irvine*
Moen, Hans Jonas Fossum, *Norwegian Defence Research Establishment*
Mohan, Chilukuri K., *Syracuse University*
Montanier, Jean-Marc, *Norwegian University of Science and Technology*
Montemanni, Roberto, *IDSIA*
Moore, Jason, *Dartmouth College*
Mora, Antonio, *Universidad de Granada*
Moraglio, Alberto, *University of Birmingham*
Moses, Melanie, *University of New Mexico*
Möslinger, Christoph, *Karl-Franzens-Universität Graz*
Mostaghim, Sanaz, *Karlsruhe Institute of Technology*
Mouret, Jean-Baptiste, *Université Pierre et Marie Curie, CNRS*
Muelas, Santiago, *Universidad Politécnica de Madrid*
Müller, Christian Lorenz, *New York University*
Mumford, Christine Lesley, *Cardiff University*
Musliu, Nysret, *Technische Universität Wien*
Nagata, Yuichi, *Tokyo Institute of Technology*
Nakib, Amir, *Laboratoire LISSI*
Narukawa, Kaname, *Honda Research Institute Europe*
Nashed, Youssef, *Università degli Studi di Parma*
Naujoks, Boris, *Cologne University of Applied Sciences*
Nebro, Antonio, *Universidad de Málaga*
Neirotti, Juan, *Aston University*
Nejati, Shiva, *University of Luxembourg*
Neri, Ferrante, *University of Jyväskylä*
Neumann, Frank, *University of Adelaide*
Nguyen, Huy, *Misfit Wearables*
Nguyen Xuan, Hoai, *Hanoi University*
Nicolau, Miguel, *University College Dublin*
Nievola, Julio Cesar, *Pontifícia Universidade Católica do Paraná*
Nobile, Marco, *Universitàdegli Studi di Milano–Bicocca*
Nojima, Yusuke, *Osaka Prefecture University*
Noman, Nasimul, *University of Newcastle*
Ó Cinnéide, Mel, *National University of Ireland, Dublin*
O'Neill, Michael, *University College Dublin*
O'Riordan, Colm, *National University of Ireland, Galway*
Ochoa, Gabriela, *University of Stirling*
Ofria, Charles, *Michigan State University*
Oh, Choong Kun, *U.S. Naval Research Laboratory*
Okabe, Tatsuya, *Honda R&D Co., Ltd.*
Olhofer, Markus, *Honda Research Institute Europe*
Oliveira, Pedro N. F. P., *Universidade do Minho*
Oliveto, Pietro S., *University of Sheffield*
Oliwa, Tomasz, *University of Georgia*
Olmo, Juan Luis, *Universidad de Córdoba*
Ombuki-Berman, Beatrice, *Brock University*
Omran, Mohammed, *Gulf University for Science & Technology*
Ono, Isao, *Tokyo Institute of Technology*
Ortega, Julio, *Universidad de Granada*
Ouni, Ali, *Université de Montréal*
Özcan, Ender, *University of Nottingham*
Palafox, Leon, *University of Tokyo*
Pang, Wei, *University of Aberdeen*
Parque, Victor, *Toyota Technological Institute*
Pasquier, Philippe, *Simon Fraser University*
Pedro, Castillo, *Universidad de Granada*
Pellegrini, Paola, *Université Libre de Bruxelles*
Pereira, Francisco Baptista, *Instituto Superior de Engenharia de Coimbra*
Perez Caceres, Leslie, *Université Libre de Bruxelles*
Peña, Jose-Maria, *Universidad Polytécnica de Madrid*
Phelps, Steve, *University of Essex*
Philippides, Andrew, *University of Sussex*
Pibernat, Hugo, *King Games Inc.*
Polani, Daniel, *University of Hertfordshire*
Poles, Silvia, *EnginSoft*
Poloczek, Jendrik, *University of Oldenburg*
Pop, Petrica, *North University of Baia Mare*
Popovici, Elena, *Icosystem Corp.*
Porumbel, Daniel, *Université Lille Nord de France*

Pošík, Petr, *Czech Technical University in Prague*
Potter, Walter, *University of Georgia*
Poulding, Simon, *University of York*
Prandtstetter, Matthias, *Austrian Institute of Technology*
Prestwich, Steve, *University College Cork*
Preuss, Mike, *Technische Universität Dortmund*
Price, Kenneth
Puchinger, Jakob, *Austrian Institute of Technology*
Puente, Cesar, *Universidad Autónoma de San Luis Potosi*
Puerta, Jose Miguel, *Universidad de Castilla–La Mancha*
Punch, William F., *Michigan State University*
Purshouse, Robin, *University of Sheffield*
Qin, Kai, *RMIT University*
Randall, Marcus Christian, *Bond University*
Ranjithan, Ranji S., *North Carolina State University*
Rasheed, Khaled, *University of Georgia*
Ray, Tom, *University of Oklahoma*
Ray, Tapabrata, *University of New South Wales*
Read, Mark, *University of Sydney*
Reed, Patrick M., *Cornell University*
Reif, David, *U.S. Environmental Protection Agency*
Rhee, Phill Kyu, *Inha University*
Rhyd, Lewis, *Cardiff University*
Riff, Maria Cristina, *Universidad Técnica Federico Santa Maria*
Robert, Wille, *University of Bremen*
Robilliard, Denis, *Université Lille Nord de France*
Rohlfshagen, Philipp, *SolveIT Software*
Roper, Marc, *University of Strathclyde*
Ross, Brian J., *Brock University*
Ross, Peter, *Edinburgh Napier University*
Rothlauf, Franz, *Universität Mainz*
Rowe, Jonathan, *University of Birmingham*
Rudolph, Günter, *Technische Universität Dortmund*
Ruhul, Sarker, *University of New South Wales*
Ruiz, Ruben, *Universidad Polytécnica de Valencia*
Runkler, Thomas, *Siemens AG*
Ryan, Conor, *University of Limerick*
Sagarna, Ramon, *University of the Basque Country*
Sahin, Erol, *Middle East Technical University*
Sahraoui, Houari, *Université de Montréal*
Salem, Ziad, *Karl-Franzens-Universität Graz*
Sanchez, Luciano, *Universidad de Oviedo*
Santana, Roberto, *University of the Basque Country*
Santibáñez Koref, Iván, *Technische Universität Berlin*
Sarro, Federica, *University College London*
Sato, Hiroyuki, *University of Electro-Communications*
Sato, Yuji, *Hosei University*
Sawada, Hideyuki, *Kagawa University*
Schillaci, Massimiliano, *Dora S.p.A.*
Schoenauer, Marc, *INRIA Saclay*
Schütze, Oliver, *CINVESTAV-IPN*
Scully, Peter, *Aberystwyth University*
Segura, Carlos, *Universidad de La Laguna*
Sekanina, Lukas, *Brno University of Technology*
Semet, Yann, *Thales*
Sen, Sandip, *University of Tulsa*
Seppi, Kevin, *Brigham Young University*
Serpell, Martin, *University of the West of England*
Sevaux, Marc, *Université de Bretagne-Sud*
Shaheen, Fatima, *Loughborough University*
Shaker, Noor, *IT University of Copenhagen*
Shakya, Siddhartha, *British Telecom*
Shapiro, Jonathan Lee, *University of Manchester*
Shengxiang, Yang, *De Montfort University*
Shihab, Emad, *Rochester Institute of Technology*
Shukla, Pradyumn Kumar, *Karlsruhe Institute of Technology*
Siarry, Patrick, *Université Paris–Est Créteil*
Silva, Fernando, *Universidade de Lisboa*
Sim, Kevin, *Edinburgh Napier University*
Simões, Anabela, *Polytechnic Institute of Coimbra*
Sinha, Ankur, *Aalto University*
Sipper, Moshe, *Ben-Gurion University*
Skurikhin, Alexei N., *Los Alamos National Laboratory*
Smith, Jim, *University of the West of England*
Smith, Stephen L., *University of York*
Smith, Alice, *Auburn University*
Smyth, Tamara, *University of California at San Diego*
Snoek, Jasper, *Harvard University*
Solnon, Christine, *Institut National des Sciences Appliquées de Lyon*
Song, Andy, *RMIT University*
Sossa, Humberto, *Instituto Politécnico Nacional, México*
Souza, Jerffeson, *State University of Ceara*
Spector, Lee, *Hampshire College*
Spicher, Antoine, *Université Paris–Est Créteil*
Squillero, Giovanni, *Politecnico di Torino*
Standish, Russell, *High Performance Coders*
Stepney, Susan, *University of York*
Stibor, Thomas, *GSI Helmholtz Centre for Heavy Ion Research*
Stich, Sebastian, *ETH Zürich*
Stonedahl, Forrest, *Northwestern University*
Stouch, Daniel W., *Charles River Analytics*
Straccia, Umberto, *Istituto di Scienza e Tecnologie dell'Informazione*
Stracquadanio, Giovanni, *Johns Hopkins University*
Stradner, Jürgen, *Karl-Franzens-Universität Graz*
Sudholt, Dirk, *University of Sheffield*
Sun, Xiao-yan, *China University of Mining and Technology*
Sun, Yi, *Google Inc.*
Sun, Chaoli, *Taiyuan University of Science and Technology*
Sutton, Andrew Michael, *Friedrich-Schiller-Universität Jena*
Suzuki, Reiji, *Nagoya University*
Swan, Jerry, *University of Stirling*
Takadama, Keiki, *University of Electro-Communications*
Talbi, El-Ghazali, *INRIA Lille*
Tan, Ying, *Peking University*
Tanaka, Kiyoshi, *Shinshu University*
Tanev, Ivan, *Doshisha University*
Tang, Ke, *University of Science and Technology of China*
Tarantino, Ernesto, *Institute of High Performance Computing*

Schedule and Floor Plans

Schedule at a Glance

Saturday, July 12	Sunday, July 13	Monday, July 14	Tuesday, July 15	Wednesday, July 16
Tutorials and Workshops 8:30–10:20	Tutorials and Workshops 8:30–10:20	Opening 8:50–9:00		Paper Sessions 8:30–10:10
		Keynote Dario Floreano 9:00–10:10	Keynote Yoshua Bengio 9:00–10:10	
Coffee Break	Coffee Break	Coffee Break	Coffee Break	Coffee Break
Tutorials and Workshops 10:40–12:30	Tutorials and Workshops 10:40–12:30	Paper Sessions and Humies 10:40–12:20	Paper Sessions and EC in Practice 10:40–12:20	Paper Sessions 10:40–12:20
Lunch on Your Own	Lunch on Your Own	Lunch on Your Own	Lunch on Your Own	Lunch on Your Own
Tutorials and Workshops 14:00–15:50	Tutorials and Workshops 14:00–15:50	Paper Sessions and Humies 14:00–15:40	Paper Sessions and EC in Practice 14:00–15:40	SIGEVO Meeting and Awards 14:00–15:40
Coffee Break	Coffee Break	Coffee Break	Coffee Break	
Tutorials and Workshops 16:10–18:00	Tutorials and Workshops 16:10–18:00	Posters and Competitions 16:10–18:30	Paper Sessions and EC in Practice 16:10–17:50	
	Work/Life Panel 18:00–19:00		Conference Reception 18:00–21:00	

registration desk hours: Saturday and Sunday, 8:00-16:00
Monday and Tuesday, 8:00-16:30
Wednesday, 8:00-11:00

coffee breaks: Junior Pavilion Foyer

work/life balance panel: Junior Ballroom D

keynotes, posters and competitions, and SIGEVO meeting: Pavilion Ballroom

conference reception: Pavilion Ballroom or Fountain Square

Workshop and Tutorial Sessions, Saturday, July 12

	8:30–10:20	10:40–12:30	14:00–15:50	16:10–18:00
Junior Ballroom A	**Introduction to Genetic Algorithms** Goodman	**Blind No More** Whitley	**Decomposition and Cooperative Coevolution** Li	**Artificial Immune Systems for Optimisation** Jansen, Zarges
Junior Ballroom B	**Introduction to Evolution Strategies** Baeck	**Evolution Stategies and CMA–ES** Hansen, Auger	**Expressive Genetic Programming** Spector	**Self–Assembly** Bhalla, Bentley, Dorigo
Junior Ballroom C	**Introduction to Genetic Programming** O'Reilly	**Representations for Evolutionary Algorithms** Rothlauf	**Model–Based Evolutionary Algorithms** Thierens, Bosman	**Constraint–Handling Techniques Used with EAs** Coello Coello
Junior Ballroom D	**Evolutionary Multiobjective Optimization** Brockhoff	**Statistical Analysis for Evolutionary Computation** Wineberg	**Evolutionary Image Analysis and Signal Processing** Cagnoni	**Medical Applications of EC** Smith
Parksville	**International Workshop on Learning Classifier Systems (IWLCS)** p.24		**Evolutionary Computation Software Systems (EvoSoft)** p.26	
Port McNeill	**Student Workshop** p.24			**Visualisation Methods in GEC (VizGEC)** p.27
Port Hardy	**Evolutionary Computation and Multi–Agent Systems and Simulation (ECoMASS)** p.24		**Evolutionary Synthesis of Dynamical Systems (ESDS)** p.27	
Port Alberni	**Late Breaking Abstracts** p.25			

Tutorials

Workshops

Workshop and Tutorial Sessions, Sunday, July 13

	8:30–10:20	10:40–12:30	14:00–15:50	16:10–18:00
Junior Ballroom A	**Runtime Analysis of EAs: Basic Introduction** Lehre, Oliveto	**Bioinspired Comp. in Combinatorial Optimization** Witt	**Parameterized Complexity Analysis of EAs** Neumann, Sutton	**Black–Box Complexity** Doerr, Doerr
Junior Ballroom B	**Learning Classifier Systems: A Gentle Introduction** Lanzi	**Introduction to Evolutionary Game Theory** Tomassini	**Evolutionary Search Algorithms for Protein Modeling** Shehu, De Jong	**Cellular Genetic Algorithms** Alba
Junior Ballroom C	**Generative and Developmental Systems** Stanley	**Automatic (Offline) Configuration of Algorithms** Lopez–Ibanez, Stutzle	**Information Geometry in EC** Malago, Glasmachers	**Evolutionary Bilevel Optimization** Deb, Sinha
Junior Ballroom D	**Evolutionary Computation: A Unified Approach** De Jong	**Evolving Neural Networks** Miikkulainen	**Particle Swarm Optimization** Engelbrecht	**Theory of Swarm Intelligence** Sudholt
Parksville	**Green and Energy Efficient Applications of Evolutionary Computation (GreenGEC)** p.28		**Problem Understanding and Real–World Optimization (PURO)** p.30	
Port McNeill	**GEC in Defense, Security and Risk Mgmt (SecDef)** p.28	**Women@GECCO** p.29	**Evolutionary Computation for Big Data and Big Learning (ECBDL)** p.30	
Port Hardy	**Medical Applications of Genetic and Evolutionary Computation (MedGEC)** p.29		**Symbolic Regression and Modelling (SRM)** p.30	
Port Alberni	**Evolutionary Computation for the Automated Design of Algorithms (ECADA)** p.29		**Metaheuristic Design Patterns (MetaDeeP)** p.31	

Tutorials

Workshops

Parallel Sessions, Monday, July 14 through Wednesday, July 16

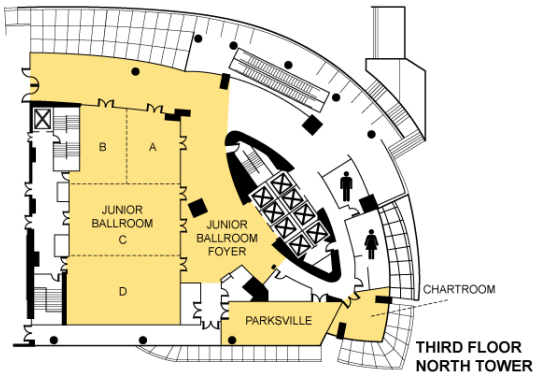
	Monday July 14 10:40–12:20	Monday July 14 14:00–15:40	Tuesday July 15 10:40–12:20	Tuesday July 15 14:00–15:40	Tuesday July 15 16:10–17:50	Wednesday July 16 8:30–10:10	Wednesday July 16 10:40–12:20
Junior Ballroom A	ALIFE1 p.42	ALIFE2 p.45	ALIFE3 p.48	ALIFE4/ PES2 p.51	HOP1 p.54	GDS1 p.57	GDS2/ DETA2 p.60
Junior Ballroom B	AIS p.42	SELF–*1 p.45	GP1 p.48	GP2 p.51	SBSE1 p.54	DETA1 p.57	SBSE2 p.60
Junior Ballroom C	ECOM1 p.42	ECOM2 p.45	ACO–SI1 p.48	ACO–SI2 p.51	ACO–SI3 p.54	GP4 invited talk (starts 9:00) p.35	HOP3 p.60
Junior Ballroom D	GA1 p.43	GA2 p.46	GA3 p.49	BP1 p.52	GP3 p.55	BP2 p.57	GA4 p.61
Parksville	THEORY1 p.43	THEORY2 p.46	THEORY3 p.49	IGEC1 p.52	ESEP/ IGEC2 p.55	EML1/ RWA6 p.58	EML2 p.61
Port McNeill	Humies p.38	Humies p.38	EMO1 p.49	EMO2 p.52	HOP2 p.55	EMO3 p.58	HOP4 p.61
Port Hardy	PES1 p.43	BIO1 p.46	ECiP1 p.40	ECiP2 p.40	ECiP3 p.40	EDA1 p.58	SELF–*2/ EDA2 p.62
Port Alberni	RWA1 p.44	RWA2 p.47	RWA3 p.50	RWA4 p.53	RWA5 p.56	ECOM3 p.59	ECOM4/ BIO2 p.62

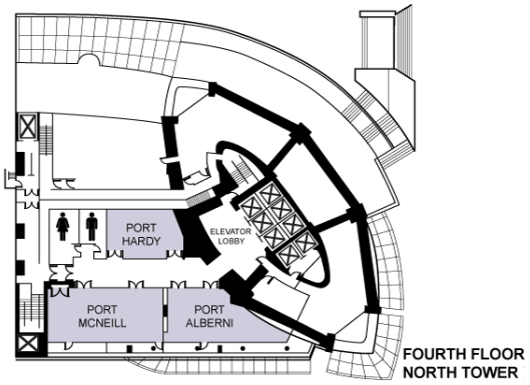
sessions with best paper nominees

BP1: best paper nominees DETA, EML, GDS, SBSE

BP2: best paper nominees AIS, ESEP, PES, THEORY

Floor Plans





Track List and Abbreviations

ACO-SI: Ant Colony Optimization and Swarm Intelligence

AIS: Artificial Immune Systems

ALIFE: Artificial Life, Robotics, and Evolvable Hardware

BIO: Biological and Biomedical Applications

DETA: Digital Entertainment Technologies and Arts

ECiP: Evolutionary Computation in Practice

ECOM: Evolutionary Combinatorial Optimization and Metaheuristics

EDA: Estimation of Distribution Algorithms

EML: Evolutionary Machine Learning

EMO: Evolutionary Multiobjective Optimization

ESEP: Evolution Strategies and Evolutionary Programming

GA: Genetic Algorithms

GDS: Generative and Developmental Systems

GP: Genetic Programming

HOP: Hot Off the Press

IGEC: Integrative Genetic and Evolutionary Computation

PES: Parallel Evolutionary Systems

RWA: Real World Applications

SBSE: Search Based Software Engineering

SELF-*: Self-* Search

THEORY: Theory

Tutorials

Intoductory Tutorials

Introduction to Genetic Algorithms
Erik D. Goodman, *Michigan State University*
Saturday, July 12, 8:30-10:20
Junior Ballroom A

Genetic Programming: A Tutorial Introduction
Una-May O'Reilly, *Massachusetts Institute of Technology*
Saturday, July 12, 8:30-10:20
Junior Ballroom C

Introduction to Evolution Strategies
Thomas Bäck, *Leiden University*
Saturday, July 12, 8:30-10:20
Junior Ballroom B

Evolutionary Computation: A Unified Approach
Kenneth De Jong, *George Mason University*
Sunday, July 13, 8:30-10:20
Junior Ballroom D

Evolutionary Multiobjective Optimization
Dimo Brockhoff, *INRIA Lille*
Saturday, July 12, 8:30-10:20
Junior Ballroom D

Representations for Evolutionary Algorithms
Franz Rothlauf, *Universität Mainz*
Saturday, July 12, 10:40-12:30
Junior Ballroom C

Statistical Analysis for Evolutionary Computation: An Introduction
Mark Wineberg, *University of Guelph*
Saturday, July 12, 10:40-12:30
Junior Ballroom D

Particle Swarm Optimization
Andries Engelbrecht, *University of Pretoria*
Sunday, July 13, 14:00-15:50
Junior Ballroom D

Learning Classifier Systems: A Gentle Introduction
Pier Luca Lanzi, *Politecnico de Milano*
Sunday, July 13, 8:30-10:20
Junior Ballroom B

Model-Based Evolutionary Algorithms
Dirk Thierens, *Universiteit Utrecht*
Peter A. N. Bosman, *Centrum Wiskunde & Informatica*
Saturday, July 12, 14:00-15:50
Junior Ballroom C

Runtime Analysis of Evolutionary Algorithms: Basic Introduction
Per Kristian Lehre, *University of Nottingham*
Pietro S. Oliveto, *University of Sheffield*
Sunday, July 13, 8:30-10:20
Junior Ballroom A

Evolving Neural Networks
Risto Miikkulainen, *University of Texas at Austin*
Sunday, July 13, 10:40-12:30
Junior Ballroom D

Advanced Tutorials

Evolution Strategies and CMA-ES (Covariance Matrix Adaptation)
Nikolaus Hansen, *INRIA Saclay*
Anne Auger, *INRIA Saclay*
Saturday, July 12, 10:40-12:30
Junior Ballroom B

Constraint-Handling Techniques Used with Evolutionary Algorithms
Carlos A. Coello Coello, *CINVESTAV-IPN*
Saturday, July 12, 16:10-18:00
Junior Ballroom C

Blind No More: Constant Time Non-Random Improving Moves and Exponentially Powerful Recombination
Darrell Whitley, *Colorado State University*
Saturday, July 12, 10:40-12:30
Junior Ballroom A

Expressive Genetic Programming
Lee Spector, *Hampshire College*
Saturday, July 12, 14:00-15:50
Junior Ballroom B

Parameterized Complexity Analysis of Evolutionary Algorithms
Frank Neumann, *University of Adelaide*
Andrew M. Sutton, *Friedrich-Schiller-Universität Jena*
Sunday, July 13, 14:00-15:40
Junior Ballroom A

Black-Box Complexity: From Complexity Theory to Playing Mastermind — Sunday, July 13, 16:10-18:00, Junior Ballroom A
Benjamin Doerr, *École Polytechnique de Paris*
Carola Doerr, *Université Pierre et Marie Curie, CNRS*

Bioinspired Computation in Combinatorial Optimization: Algorithms and Their Computational Complexity — Sunday, July 13, 10:40-12:30, Junior Ballroom A
Carsten Witt, *Technical University of Denmark*

Theory of Swarm Intelligence — Sunday, July 13, 16:10-18:00, Junior Ballroom D
Dirk Sudholt, *University of Sheffield*

Information Geometry in Evolutionary Computation — Sunday, July 13, 14:00-15:50, Junior Ballroom C
Luigi Malagò, *Università degli Studi di Milano*
Tobias Glasmachers, *Ruhr-Universität Bochum*

Specialized Tutorials

Cellular Genetic Algorithms — Sunday, July 13, 16:10-18:00, Junior Ballroom B
Enrique Alba, *Universidad de Málaga*

Artificial Immune Systems for Optimisation — Saturday, July 12, 16:10-18:00, Junior Ballroom A
Thomas Jansen, *Aberystwyth University*
Christine Zarges, *University of Birmingham*

Generative and Developmental Systems — Sunday, July 13, 8:30-10:20, Junior Ballroom C
Kenneth O. Stanley, *University of Central Florida*

Evolutionary Image Analysis and Signal Processing — Saturday, July 12, 14:00-15:50, Junior Ballroom D
Stefano Cagnoni, *Università degli Studi di Parma*

Decomposition and Cooperative Cooevolution Techniques for Large Scale Global Optimization — Saturday, July 12, 14:00-15:50, Junior Ballroom A
Xiaodong Li, *RMIT University*

Evolutionary Search Algorithms for Protein Modeling: From De Novo Structure Prediction to Comprehensive Maps of Functionally-Relevant Structures of Protein Chains and Assemblies — Sunday, July 13, 14:00-15:50, Junior Ballroom B
Amarda Shehu, *George Mason University*
Kenneth A. De Jong, *George Mason University*

Evolutionary Bilevel Optimization — Sunday, July 13, 16:10-18:00, Junior Ballroom C
Kalyanmoy Deb, *Michigan State University*
Ankur Sinha, *Aalto University*

Introduction to Evolutionary Game Theory — Sunday, July 13, 10:40-12:30, Junior Ballroom B
Marco Tomassini, *Université de Lausanne*

Medical Applications of Evolutionary Computation — Saturday, July 12, 16:10-18:00, Junior Ballroom D
Stephen L. Smith, *University of York*

Automatic (Offline) Configuration of Algorithms — Sunday, July 13, 10:40-12:30, Junior Ballroom C
Manuel López-Ibañez, *Université Libre de Bruxelles*
Thomas Stützle, *Université Libre de Bruxelles*

Self-Assembly — Saturday, July 12, 16:10-18:00, Junior Ballroom B
Navneet Bhalla, *Cornell University*
Peter J. Bentley, *University College London*
Marco Dorigo, *Université Libre de Bruxelles*

Workshops and Late Breaking Abstracts

IWLCS: 17th Annual International Workshop on Learning Classifier Systems

Organizers: Muhammad Iqbal, *Victoria University of Wellington*
Kamran Shafi, *University of New South Wales*
Ryan Urbanowicz, *Dartmouth College*

Time and Location: Saturday, July 12, 8:30-12:30, Parksville

Reusing Learned Functionality in XCS
Isidro M. Alvarez, Will N. Browne, Mengjie Zhang

Rule Networks in Learning Classifier Systems
Karthik Kuber, Stuart W. Card, Kishan G. Mehrotra, Chilukuri K. Mohan

ECoMASS: Eighth Annual Workshop on Evolutionary Computation and Multi-Agent Systems and Simulation

Organizers: Forrest Stonedahl, *Augustana College*
William Rand, *University of Maryland*

Time and Location: Saturday, July 12, 8:30-12:30, Port Hardy

Dynamic Learning of Heart Sounds with Changing Noise: An AIS-Based Multi-Agent Model Using Systemic Computation
Yiqi Deng, Peter J. Bentley

A Genetic Based Scheduling Approach of Real-Time Reconfigurable Embedded Systems
Hamza Gharsellaoui, Hamadi Hasni, Samir Ben Ahmed

The Effect of Communication on the Evolution of Cooperative Behavior in a Multi-Agent System
Sherri Goings, Emily P. M. Johnston, Naozumi Hiranuma

Modeling the Information Propagation in an Email Communication Network Using an Agent-Based Approach
Bin Jiang, Lei Wang, Chao Yang, Shuming Peng, Renfa Li

A Study on the Configuration of Migratory Flows in Island Model Differential Evolution
Rodolfo A. Lopes, Rodrigo Silva, Alan R. R. Freitas, Felipe Campelo, Frederico G. Guimarães

Student Workshop

Organizers: Tea Tušar, *Jošef Stefan Institute*
Boris Naujoks, *Cologne University of Applied Sciences*

Time and Location: Saturday, July 12, 8:30-15:50, Port McNeill

Effects of Personality Decay on Collective Movements
Jeremy Acre, Brent E. Eskridge, Nicholas Zoller

An Efficient Fitness-based Stagnation Detection Method for Particle Swarm Optimization
Hazem Radwan Ahmed

Selecting Evolutionary Operators Using Reinforcement Learning: Initial Explorations
Arina Buzdalova, Vladislav Kononov, Maxim Buzdalov

Improving the Quality of Supervised Finite-State Machine Construction Using Real-Valued Variables
Igor Buzhinsky, Daniil Chivilikhin, Vladimir Ulyantsev, Fedor Tsarev

Multi-Core GE: Automatic Evolution of CPU Based Multi-Core Parallel Programs
Gopinath Chennupati, R. Muhammad Atif Azad, Conor Ryan

Parameter Tuning in Quantum-Inspired Evolutionary Algorithms for Partitioning Complex Networks
Shikha Gupta, Naveen Kumar

Developing Morphological Computation in Tensegrity Robots for Controllable Actuation
Mark Khazanov, Julian Jocque, John Rieffel

A Reference Points-Based Evolutionary Algorithm for Many-Objective Optimization
Yiping Liu, Dunwei Gong, Xiaoyan Sun, Yong Zhang

Particles Types in a Swarm: Searching for Efficiency
Łukasz Rokita, Przemysław Ogrodowski

Flood Evolution: Changing the Evolutionary Substrate from a Path of Stepping Stones to a Field of Rocks
David Shorten, Geoff Nitschke

Consensus Costs and Conflict in Robot Swarms
Timothy Solum, Brent E. Eskridge, Ingo Schlupp

A Case Based Approach for an Intelligent Route Optimization Technology
Masaki Suzuki, Setsuo Tsuruta, Rainer Knauf, Takaaki Motomura, Taro Matsumaru, Yoshitaka Sakurai

A Niching Cumulative Genetic Algorithm with Evaluated Probability for Multimodal Optimization
Hongjun Yang, Yixu Song, Lihua Wang, Peifa Jia

A Quantitative Analysis of the Simplification Genetic Operator
Haoxi Zhan

Late Breaking Abstracts

Organizer: Dirk Sudholt, *University of Sheffield*

Time and Location: Saturday, July 12, 8:30-18:00, Port Alberni

NSGA-II Implementation Details May Influence Quality of Solutions for the Job-Shop Scheduling Problem
Maxim Buzdalov, Irina Petrova, Arina Buzdalova

Some Measurements on the Effects of the Curse of Dimensionality
Stephen Chen, James Montgomery, Antonio Bolufé-Röhler

A Fast Genetic Algorithm for the Flexible Job Shop Scheduling Problem
Marcin Cwiek, Jakub Nalepa

Genetic Algorithms for Evolving Deep Neural Networks
Omid E. David, Iddo Greental

A Modified Gravitational Search Algorithm for Continuous Optimization
Emerson Hochsteiner de Vasconcelos Segundo, Gabriel Fiori Neto, Andre Mendes da Silva, Viviana Cocco Mariani, Leandro dos Santos Coelho

Bat-Inspired Optimization Approach Applied to Jiles-Atherton Hysteresis Parameters Tuning
Leandro dos Santos Coelho, Viviana Cocco Mariani, Helon Vicente Hultmann Ayala, Andre Mendes da Silva, Nelson Jhoe Batistela, Jean Vianei Leite

Portfolio Optimization Using an Integer Genetic Algorithm
Javier Fernández-Rendón, Katya Rodríguez-Vázquez

Towards the Automated Generation of Term-Weighting Schemes for Text Categorization
Mauricio Garcia-Limon, Hugo Jair Escalante, Manuel Montes-y-Gomez, Alicia Morales-Reyes, Eduardo Morales

A Genetic Algorithm for Linear Ordering Problem Using an Approximate Fitness Evaluation
Jinhyun Kim, Byung-Ro Moon

ABC+ES: A Novel Hybrid Artificial Bee Colony Algorithm with Evolution Strategies
Marco Antônio Florenzano Mollinetti, Daniel Leal Souza, Otávio Noura Teixeira

Evolved Transforms for Improved Reconstruction of Lossy-Compressed NASA Images
Frank W. Moore, Brendan J. Babb

Adaptive Memetic Algorithm for the Vehicle Routing Problem with Time Windows
Jakub Nalepa

An Iterative Model Refinement Approach for MOEA Computation Time Reduction
Mathias Ngo, Raphaël Labayrade

A Study on the Efficiency of Neutral Crossover Operators in Genetic Algorithms Applied to the Bin Packing Problem
Eneko Osaba, Fernando Diaz, Roberto Carballedo, Idoia de la Iglesia, Enrique Onieva, Asier Perallos

A Study on the Impact of Heuristic Initialization Functions in a Genetic Algorithm Solving the N-Queens Problem
Eneko Osaba, Fernando Diaz, Roberto Carballedo, Enrique Onieva, Pedro Lopez

Improving Reconstructed Images Using Hybridization between Local Search and Harmony Search Meta-Heuristics
Ahlem Ouaddah, Dalila Boughaci

First Results of Performance Comparisons on Many-Core Processors in Solving QAP with ACO: Kepler GPU versus Xeon Phi
Mikiko Sato, Shigeyoshi Tsutsui, Noriyuki Fujimoto, Yuji Sato, Mitaro Namiki

Evaluation of Fitness Functions of GA Classification
Ming-Der Yang, Yeh-Feng Yang, Yi-Ping Chen

A Speed-Up and Speed-Down Strategy for Swarm Optimization
Haopeng Zhang, Fumin Zhang, Qing Hui

A Novel Genetic Clustering Algorithm with Variable-Length Chromosome Representation
Ming-An Zhang, Yong Deng, Dong-Xia Chang

A Novel Quantum Genetic Clustering Algorithm for Data Segmentation
Ming-An Zhang, Yong Deng, Dong-Xia Chang

EvoSoft: Evolutionary Computation Software Systems

Organizers: Stefan Wagner, *University of Applied Sciences Upper Austria*
Michael Affenzeller, *University of Applied Sciences Upper Austria*

Time and Location: Saturday, July 12, 14:00-18:00, Parksville

Scripting and Framework Integration in Heuristic Optimization Environments
Andreas Beham, Johannes Karder, Gabriel Kronberger, Stefan Wagner, Michael Kommenda, Andreas Scheibenpflug

Working with OpenCL to Speed Up a Genetic Programming Financial Forecasting Algorithm: Initial Results
James Brookhouse, Fernando E. B. Otero, Michael Kampouridis

Hyperion2: A Toolkit for {Meta-, Hyper-} Heuristic Research
Alexander E. I. Brownlee, Jerry Swan, Ender Özcan, Andrew J. Parkes

A Scalable Symbolic Expression Tree Interpreter for the HeuristicLab Optimization Framework
Simone Cirillo, Stefan Lloyd

Distributed Optimization on Super Computers: Case Study on Software Architecture Optimization Framework
Ramin Etemaadi, Michel R. V. Chaudron

A Genetic Programming Problem Definition Language Code Generator for the EpochX Framework
Claris Leroux, Fernando E. B. Otero, Colin G. Johnson

NodEO, a Multi-Paradigm Distributed Evolutionary Algorithm Platform in JavaScript
Juan Julián Merelo, Pedro A. Castillo, Antonio M. Mora, Anna I. Esparcia-Alcázar, Víctor Manuel Rivas-Santos

VizGEC: Visualisation Methods in Genetic and Evolutionary Computation

Organizers: David Walker, *University of Exeter*
Richard Everson, *University of Exeter*
Jonathan Fieldsend, *University of Exeter*

Time and Location: Saturday, July 12, 16:10-18:00, Port McNeill

EA Stability Visualization: Perturbations, Metrics and Performance
Matthew J. Craven, Henri C. Jimbo

On the Visualization of Trade-offs and Reducibility in Many-Objective Optimization
Alan R. R. Freitas, Rodrigo Silva, Frederico G. Guimarães

Initial Experiments in Visualization of Empirical Attainment Function Differences Using Maximum Intensity Projection
Tea Tušar, Bogdan Filipic

ESDS: Evolutionary Synthesis of Dynamical Systems

Organizers: Zhun Fan, *Shantou University*
Yaochu Jin, *University of Surrey*
Hod Lipson, *Cornell University*
Erik D. Goodman, *Michigan State University*

Time and Location: Saturday, July 12, 14:00-18:00, Port Hardy

A Probabilistic Pareto Local Search Based on Historical Success Counting for Multiobjective Optimization
Xinye Cai, Xin Cheng, Zhun Fan

Evolutionary Synthesis of Dynamical Systems: The Past, Current, and Future
Zhun Fan, Xinye Cai, Wenji Li, Huibiao Lin, Shuxiang Xie, Sheng Wang

Design Optimization of MEMS Using Constrained Multi-Objective Evolutionary Algorithm
Wenji Li, Zhun Fan, Xinye Cai, Huibiao Lin, Shuxiang Xie, Sheng Wang

Epsilon Constrained Method for Constrained Multiobjective Optimization Problems: Some Preliminary Results
Zhixiang Yang, Xinye Cai, Zhun Fan

GreenGEC: Green and Efficient Energy Applications of Genetic and Evolutionary Computation

Organizers: Peter A. N. Bosman, *Centrum Wiskunde & Informatica*
Alexandru-Adrian Tantar, *University of Luxembourg*
Emilia Tantar, *University of Luxembourg*

Time and Location: Sunday, July 13, 8:30-12:30, Parksville

Efficiency Enhancements for Evolutionary Capacity Planning in Distribution Grids
Ngoc Hoang Luong, Marinus O. W. Grond, Han La Poutré, Peter A. N. Bosman

Reinforcement Learning Based Energy Efficient LTE RAN
Joan Meseguer Llopis, Łukasz Rajewski, Sławomir Kukliński

Balancing Performance, Resource Efficiency and Energy Efficiency for Virtual Machine Deployment in DVFS-Enabled Clouds: An Evolutionary Game Theoretic Approach
Yi Ren, Junichi Suzuki, Chonho Lee, Athanasios V. Vasilakos, Shingo Omura, Katsuya Oba

A Survey on Sustainability in ICT: A Computing Perspective
Alexandru-Adrian Tantar, Emilia Tantar

SecDef: Workshop on Genetic and Evolutionary Computation in Defense, Security and Risk Management

Organizers: Anna I. Esparcia-Alcázar, *S2 Grupo*
Frank Moore, *University of Alaska Anchorage*

Time and Location: Sunday, July 13, 8:30-10:20, Port McNeill

Enforcing Corporate Security Policies via Computational Intelligence Techniques
Antonio M. García, Paloma De las Cuevas, Juan Julián Merelo, Sergio Zamarripa, Anna I. Esparcia-Alcázar

On Botnet Behaviour Analysis Using GP and C4.5
Fariba Haddadi, Dylan Runkel, A. Nur Zincir-Heywood, Malcolm I. Heywood

Evolutionary Based Moving Target Cyber Defense
David J. John, Robert W. Smith, William H. Turkett, Daniel A. Canas, Errin W. Fulp

On the Role of Multi-Objective Optimization in Risk Mitigation for Critical Infrastructures with Robotic Sensor Networks
Jamieson McCausland, Rami Abielmona, Rafael Falcon, Ana-Maria Cretu, Emil M. Petriu

Women@GECCO

Organizers: Una-May O'Reilly, *Massachusetts Institute of Technology*
Anna I. Esparcia-Alcázar, *S2 Grupo*
Anne Auger, *INRIA Saclay*
Carola Doerr, *Université Pierre et Marie Curie, CNRS*
Anikó Ekárt, *Aston University*
Gabriela Ochoa, *University of Stirling*

Time and Location: Sunday, July 13, 10:40-12:30, Port McNeill

MedGEC: Medical Applications of Genetic and Evolutionary Computation

Organizers: Stephen L. Smith, *University of York*
Stefano Cagnoni, *Università degli Studi di Parma*
Robert M. Patton, *Oak Ridge National Laboratory*

Time and Location: Sunday, July 13, 8:30-12:30, Port Hardy

Classification of EEG Signals Using a Novel Genetic Programming Approach
Arpit Bhardwaj, Aruna Tiwari, M. Vishaal Varma, M. Ramesh Krishna

Clarke and Parkes Error Grid Analysis of Diabetic Glucose Models obtained with Evolutionary Computation
J. Ignacio Hidalgo, J. Manuel Colmenar, Jose L. Risco-Martín, Esther Maqueda, Marta Botella, Jose Antonio Rubio, Alfredo Cuesta-Infante, Oscar Garnica, Juan Lanchares

An Evaluation of Particle Swarm Optimization Techniques in Segmentation of Biomedical Images
Salim Lahmiri, Mounir Boukadoum

Classification and Characterisation of Movement Patterns During Levodopa Therapy for Parkinson's Disease
Michael A. Lones, Jane E. Alty, Phillipa Duggan-Carter, Andrew J. Turner, Stuart Jamieson, Stephen L. Smith

Noise-Aware Evolutionary TDMA Optimization for Neuronal Signaling in Medical Sensor-Actuator Networks
Junichi Suzuki, Pruet Boonma

Data Based Prediction of Cancer Diagnoses Using Heterogeneous Model Ensembles
Stephan M. Winkler, Michael Affenzeller, Susanne Schaller, Herbert Stekel

ECADA: 4th Workshop on Evolutionary Computation for the Automated Design of Algorithms

Organizers: John R. Woodward, *University of Stirling*
Jerry Swan, *University of Stirling*
Earl Barr, *University College London*

Time and Location: Sunday, July 13, 8:30-12:30, Port Alberni

Automated Design of Algorithms and Genetic Improvement: Contrast and Commonalities
Saemundur O. Haraldsson, John R. Woodward

A Step Size Based Self-Adaptive Mutation Operator for Evolutionary Programming
Libin Hong, John H. Drake, Ender Özcan

A Problem Configuration Study of the Robustness of a Black-Box Search Algorithm Hyper-Heuristic
Matthew A. Martin, Daniel R. Tauritz

Benchmarks that Matter for Genetic Programming
John R. Woodward, Simon P. Martin, Jerry Swan

PURO: Workshop on Problem Understanding and Real-World Optimisation

Organizers: Kent McClymont, *University of Exeter*
Kevin Sim, *Edinburgh Napier Uniersity*
Gabriela Ochoa, *University of Stirling*
Ed Keedwell, *University of Exeter*

Time and Location: Sunday, July 13, 14:00-18:00, Parksville

A Real-World Employee Scheduling and Routing Application
Emma Hart, Kevin Sim, Neil Urquhart

A Comparison of Antenna Placement Algorithms
Abhinav Jauhri, Jason D. Lohn, Derek S. Linden

Hyper-Heuristic Genetic Algorithm for Solving Frequency Assignment Problem in TD-SCDMA
Chao Yang, Shuming Peng, Bin Jiang, Lei Wang, Renfa Li

Six Impossible Things Before Breakfast: Computational Intelligence in the SME (invited talk)
Anna I. Esparcia-Alcázar

Why Are There Not More Applications of Evolutionary Algorithms? (invited talk)
Darrell Whitley

ECBDL: Evolutionary Computation for Big Data and Big Learning

Organizers: Jaume Bacardit, *Newcastle University*
Ignacio Arnaldo, *Massachusetts Institute of Technology*
Kalyan Veeramachaneni, *Massachusetts Institute of Technology*
Una-May O'Reilly, *Massachusetts Institute of Technology*

Time and Location: Sunday, July 13, 14:00-18:00, Port McNeill

Evolving Relational Hierarchical Classification Rules for Predicting Gene Ontology-Based Protein Functions
Ricardo Cerri, Rodrigo C. Barros, Alex A. Freitas, André C. P. L. F. Carvalho

On the Application of GP to Streaming Data Classification Tasks with Label Budgets
Ali Vahdat, Aaron Atwater, Andrew R. McIntyre, Malcolm I. Heywood

SRM: Symbolic Regression and Modelling

Organizers: Steven Gustafson, *GE Global Research*
Ekaterina Vladislavleva, *Evolved Analytics*

Time and Location: Sunday, July 13, 14:00-18:00, Port Hardy

A Mathematical Model Of A Cold Rolling Mill By Symbolic Regression
Luis Alberto Alvarado-Yañez, Luis Martin Torres-Treviño, Fernando Gonzalez, Leonardo Nieves

Predict the Performance of GE with an ACO Based Machine Learning Algorithm
Gopinath Chennupati, R. Muhammad Atif, Conor Ryan

Genetic Programming with Data Migration for Symbolic Regression
Michael Kommenda, Michael Affenzeller, Bogdan Burlacu, Gabriel Kronberger, Stephan M. Winkler

Identification and Prediction Using Symbolic Regression Alpha-Beta: Preliminary Results
Luis M. Torres-Treviño

MetaDeeP: Workshop on Metaheuristic Design Patterns

Organizers: Jerry Swan, *University of Stirling*
Krzysztof Krawiec, *Poznan University of Technology*
John A. Clark, *University of York*
John R. Woodward, *University of Stirling*
Christopher L. Simons, *University of the West of England*

Time and Location: Sunday, July 13, 14:00-18:00, Port Alberni

Structural Stigmergy: A Speculative Pattern Language for Metaheuristics
Ben Kovitz, Jerry Swan

Tagging in Metaheuristics
Ben Kovitz, Jerry Swan

Metaheuristic Design Pattern: Candidate Solution Repair
Krzysztof Krawiec

Metaheuristics in Nature-Inspired Algorithms
Michael Lones

A Template for Designing Single-Solution Hybrid Metaheuristics
Manuel López-Ibáñez, Franco Mascia, Marie-Éléonore Marmion, Thomas Stützle

The 'Executable Experiments' Template Pattern for the Systematic Comparison of Metaheuristics
Geoffrey Kenneth Neumann, Jerry Swan, Mark Harman, John A. Clarke

Metaheuristic Design Pattern: Interactive Solution Presentation
Christopher L. Simons, Mark R. N. Shackelford

The 'Representative' Metaheuristic Design Pattern
Jerry Swan, Zoltan A. Kocsis, Alexei Lisitsa

Template Method Hyper-Heuristics
John R. Woodward, Jerry Swan

The 'Composite' Pattern in Metaheuristics
John R. Woodward, Jerry Swan, Simon Martin

Keynotes and Invited Talk

GECCO Keynote

Deep Learning and Cultural Evolution

Tuesday, July 15, 9:00-10:10
Pavilion Ballroom

Yoshua Bengio, *Université de Montréal*

We propose a theory and its first experimental tests, relating difficulty of learning in deep architectures to culture and language. The theory is articulated around the following hypotheses: learning in an individual human brain is hampered by the presence of effective local minima, particularly when it comes to learning higher-level abstractions, which are represented by the composition of many levels of representation, i.e., by deep architectures; a human brain can learn such high-level abstractions if guided by the signals produced by other humans, which act as hints for intermediate and higher-level abstractions; language and the recombination and optimization of mental concepts provide an efficient evolutionary recombination operator for this purpose. The theory is grounded in experimental observations of the difficulties of training deep artificial neural networks and an empirical test of the hypothesis regarding the need for guidance of intermediate concepts is demonstrated. This is done through a learning task on which all the tested machine learning algorithms failed, unless provided with hints about intermediate-level abstractions.

Biosketch: Yoshua Bengio received a PhD in Computer Science from McGill University, Canada in 1991. After two post-doctoral years, one at M.I.T. with Michael Jordan and one at AT&T Bell Laboratories with Yann LeCun and Vladimir Vapnik, he became professor at the Department of Computer Science and Operations Research at Université de Montréal. He is the author of two books and around 200 publications, the most cited being in the areas of deep learning, recurrent neural networks, probabilistic learning algorithms, natural language processing and manifold learning. He is among the most cited Canadian computer scientists and is or has been associate editor of the top journals in machine learning and neural networks. Since 2000 he holds a Canada Research Chair in Statistical Learning Algorithms, since 2006 an NSERC Industrial Chair, and since 2005 he is a Fellow of the Canadian Institute for Advanced Research. He is on the board of the NIPS foundation and has been program chair and general chair for NIPS. He has co-organized the Learning Workshop for 14 years and co-created the new International Conference on Learning Representations. His current interests are centered around a quest for AI through machine learning, and include fundamental questions on deep learning and representation learning, the geometry of generalization in high-dimensional spaces, manifold learning, biologically inspired learning algorithms, and challenging applications of statistical machine learning. In October 2013, Google Scholar finds more than 14500 citations to his work, yielding an h-index of 52.

GECCO Keynote

Bridging Natural and Artificial Evolution

Monday, July 14, 9:00-10:10
Pavilion Ballroom

Dario Floreano, *École Polytechnique Fédérale de Lausanne*

In this talk I will show how artificial evolution can be used to address biological questions and explain phenomena for which there is no fossil record or no experimental evidence, such evolution of behavior, altruism, and communication. I will give examples related to insects and plants. Central to this endeavor is how selection mechanisms are applied and interpreted. I will also show how selection pressure can be lifted in artificial evolution and lead to open-ended evolution in dynamic and changing environments.

Biosketch: Prof. Dario Floreano is Director of the Laboratory of Intelligent Systems at EPFL Switzerland and Director of the Swiss National Center of Robotics. His research focuses on the convergence of biology, artificial intelligence, and robotics. He has published more than 300 peer-reviewed papers, which have been cited more than 10K times, and four books on the topics of evolutionary robotics, bio-inspired artificial intelligence, and bio-mimetic flying robots with MIT Press and Springer Verlag. He is member of the World Economic Forum Council on robotics and smart devices, co-founder of the International Society of Artificial Life, Inc. (USA), co-founder of the aerial robot company senseFly, member of the editorial board of 10 professional journals, and board member of numerous professional societies in robotics and artificial intelligence. He is also active in the public understanding of robotics and artificial intelligence, delivered more than 150 invited talks worldwide, and started the popular robotics podcast Talking Robots (now The RobotsPodcast).

GP Track Invited Talk

Applications of Program Synthesis to End-User Programming and Intelligent Tutoring Systems

Wednesday, July 16, 9:00-10:10
Junior Ballroom C

Sumit Gulwani, *Microsoft Research*

Computing devices have become widely available to billions of end users, yet a handful of experts have the needed expertise to program these devices. Automated program synthesis has the potential to revolutionize this landscape, when targeted for the right set of problems and when allowing the right interaction model. The first part of this talk discusses techniques for programming using examples and natural language. These techniques have been applied to various end-user programming domains including data manipulation and smartphone scripting. The second part of this talk presents surprising applications of program synthesis technology to automating various repetitive tasks in Education including problem, solution, and feedback-generation for various subject domains such as math and programming. These results advance the state-of-the-art in intelligent tutoring, and can play a significant role in enabling personalized and interactive education in both standard classrooms and MOOCs.

Biosketch: Sumit Gulwani is a principal researcher at Microsoft Research, and an adjunct faculty in the Computer Science Department at IIT Kanpur. He has expertise in formal methods and automated program analysis and synthesis techniques. As part of his vision to empower masses, he has recently focused on cross-disciplinary areas of automating end-user programming (for systems like spreadsheets, smartphones, and robots), and building intelligent tutoring systems (for various subject domains including programming, math, logic, and automata). Sumit's programming-by-example work led to the famous Flash Fill feature of Microsoft Excel 2013 that is used by hundreds of millions of people. Sumit is a recipient of the ACM SIGPLAN Robin Milner Young Researcher Award. Sumit obtained his PhD in Computer Science from UC-Berkeley in 2005, and was awarded the ACM SIGPLAN Outstanding Doctoral Dissertation Award. He obtained his BTech in Computer Science and Engineering from IIT Kanpur in 2000, and was awarded the President's Gold Medal.

Humies, Competitions, and Evolutionary Computation in Practice

Human Competitive Results: 11th Annual Humies Awards

Presentations: Monday, July 14, 10:40-12:20 and 14:00-15:40
Port McNeill

Announcement of Awards: Wednesday, July 16, 14:00-15:40
Pavilion Ballroom

Judging Panel: Wolfgang Banzhaf, Erik D. Goodman, Una-May O'Reilly, Lee Spector, Darrell Whitley

Prizes: prizes totalling $10,000 to be awarded

Detailed Information: *www.human-competitive.org*

Techniques of genetic and evolutionary computation are being increasingly applied to difficult real-world problems — often yielding results that are not merely academically interesting, but competitive with the work done by creative and inventive humans. Starting at the *Genetic and Evolutionary Computation Conference* (GECCO) in 2004, cash prizes have been awarded for human competitive results that had been produced by some form of genetic and evolutionary computation in the previous year.

This prize competition is based on *published* results. The publication may be a paper at the GECCO conference (i.e., regular paper, poster paper, or any other full-length paper), a paper published anywhere in the open literature (e.g., another conference, journal, technical report, thesis, book chapter, book), or a paper in final form that has been unconditionally accepted by a publication and is "in press" (that is, the entry must be identical to something that will be published imminently without any further changes). The publication may *not* be an intermediate or draft version that is still subject to change or revision by the authors or editors. The publication must meet the usual standards of a scientific publication in that it must clearly describe a problem, the methods used to address the problem, the results obtained, and sufficient informationabout how the work was done in order to enable the work described to be replicated by an independent person.

Cash prizes of $5,000 (gold), $3,000 (silver), and bronze (either one prize of $2,000 or two prizes of $1,000) will be awarded for the best entries that satisfy the criteria for human-competitiveness. The awards will be divided equally among co-authors unless the authors specify a different division at the time of submission. Prizes are paid by check in U.S. dollars.

The Virtual Creatures Competition

Organizers: Joel Lehman, Dan Lessin

Time and Location: Monday, July 14, 16:10-18:30, Pavilion Ballroom

The contest's purpose is to highlight progress in virtual creatures research and showcase evolutionary computation's ability to craft interesting well-adapted creatures with evolved morphologies and controllers. Video entries demonstrating evolved virtual creatures will be judged by technical achievement, aesthetic appeal, innovation, and perceptual animacy (perceived aliveness).

The Evolutionary Art, Design, and Creativity Competition

Organizers: Alan Dorin, Amy K. Hoover

Time and Location: Monday, July 14, 16:10-18:30, Pavilion Ballroom

The Evolutionary Art, Design, and Creativity Competition showcases the power of evolutionary computation through human-quality artistic works or creativity enhancing experiences generated by or with the assistance of evolution. Entries can be music, images, sculptures, videos, or interactive online experiences, but are not limited to these forms of expression; the goal is that the submissions exhibit some form of independent creativity through genetic and evolutionary computation.

Windfarm Layout Optimization Competition

Organizers: Sylvain Cussat-Blanc, Dennis Wilson, Kalyan Veeramachaneni

Time and Location: Monday, July 14, 16:10-18:30, Pavilion Ballroom

Wind farm design has long been a favored application across artificial life due to its complexity, the wake capture of a field being a difficult value to optimize analytically, and its pertinence to the world of alternative energy. We propose the following competition to create a basis of comparison for the existing algorithms and to encourage both new ways to solve the windfarm optimization problem and a new mindset for the optimization goal.

Permutation-Based Combinatorial Optimization Problems

Organizers: Leticia Hernando, Josu Ceberio, Alexander Mendiburu, Jose A. Lozano

Time and Location: Monday, July 14, 16:10-18:30, Pavilion Ballroom

This competition is designed with the objective of providing a first overview of the current state-of-the-art metaheuristic algorithms for solving permutation-based optimization problems. In this sense, we will accept population-based approaches as well as local search-based proposals. In order to evaluate the submitted algorithms, we propose a wide benchmark of instances from well known problems as well as artificially generated instances.

Industrial Challenge

Organizers: Martina Friese, Andreas Fischbach, Oliver Flasch, Olaf Mersmann, Thomas Bartz-Beielstein, Klaus Walbeck

Time and Location: Monday, July 14, 16:10-18:30, Pavilion Ballroom

Water covers 71% of the Earth's surface and is vital for all known forms of life. The protection of the surface water is a generally recognised political aim. The Aggerverband, a special legal Watercompany based in Gummersbach, is operating 32 sewage treatment plants purifying the wastewater of about 350,000 inhabitants in the area of 'Bergisches Land' near Cologne. For this year's GECCO Industrial Challenge the Aggerverband kindly provides data from these sensors. Goal of the GECCO 2014 Industrial Challenge is to analyze the data to develop accurate forecasting methods that allow the prediction of the emergence of ammonia.

Evolutionary Computation in Practice

Organizers: Thomas Bartz-Beielstein, *Cologne University of Applied Sciences*
Anna I. Esparcia-Alcázar, *S2 Grupo*
Jörn Mehnen, *Cranfield University*

Session 1: Tuesday, July 15, 10:40-12:20
Academic Aspects Port Hardy

Well-known speakers with outstanding reputation in academia and industry present background and insider information on how to establish reliable cooperation with industrial partners. If you are working in academia and are interested in managing industrial projects, you will receive valuable hints for your own research projects.

Session 2: Tuesday, July 15, 14:00-15:40
Optimization in Industry Port Hardy

In this session industry speakers will be presenting. They actually run companies in the field of optimization and applied statistics. If you attend, you will learn multiple ways to extend EC practice beyond the approaches found in textbooks.

Experts in real-world optimization with decades of experience share their approaches to creating successful projects for real-world clients. Some of what they do is based on sound project management principles, and some is specific to our type of optimization projects. In this session a panel of experts describes a range of techniques you can use to identify, design, manage, and successfully complete an EA project for a client.

Session 3: Tuesday, July 15, 16:10-17:50
Getting a Job Port Hardy

This lively session consists of a panel of experts with decades of real-world application experience answering questions posed by attendees of the session. In the past, we have always had two or three discussions on industrial problems that lie on the cutting edge of EA development. This session gives you the opportunity to get free consulting from the experts!

Getting a job with training in evolutionary computation can be much easier if you know the things to do and the things not to do in your last year or two of study. In this session you will hear from a panel of experts who have trained students and who have hired students to carry out real-world optimization. Highly recommended if you will be looking for a job in the next few years — or if you are thinking of changing jobs.

Papers and Posters

ALIFE1: Neuroevolution

Monday, July 14, 10:40-12:20, Junior Ballroom A
Chair: Roderich Gross

Automated Generation of Environments to Test the General Learning Capabilities of AI Agents
Oliver J. Coleman, Alan D. Blair, Jeff Clune 10:40-11:05

Generational Neuro-Evolution: Restart and Retry for Improvement
David Peter Shorten, Geoffrey Stuart Nitschke 11:05-11:30

Directional Communication in Evolved Multiagent Teams
Justin K. Pugh, Skyler Goodell, Kenneth O. Stanley 11:30-11:55

Evolution of Biologically Plausible Neural Networks Performing a Visually Guided Reaching Task
Derrik E. Asher, Jeffrey L. Krichmar, Nicolas Oros 11:55-12:20

AIS: Artificial Immune Systems

Monday, July 14, 10:40-12:20, Junior Ballroom B
Chair: Emma Hart

A Generic Finite Automata Based Approach to Implementing Lymphocyte Repertoire Models
Johannes Textor, Katharina Dannenberg, Macie Liskiewicz 10:40-11:05

An Improved Immune Inspired Hyper-Heuristic for Combinatorial Optimisation Problems
Kevin Sim, Emma Hart 11:05-11:30

A Two-Leveled Hybrid Dendritic Cell Algorithm Under Imprecise Reasoning
Zeineb Chelly, Zied Elouedi 11:30-11:55

Clonal Selection Based Fuzzy C-Means Algorithm for Clustering
Simone A. Ludwig 11:55-12:20

ECOM1: Heuristics and Landscapes

Monday, July 14, 10:40-12:20, Junior Ballroom C
Chair: Alexandru-Adrian Tantar

On the Efficiency of Worst Improvement for Climbing NK-Landscapes
Matthieu Basseur, Adrien Goëffon 10:40-11:05

Socially Inspired Algorithms for the Travelling Thief Problem
Mohammad Reza Bonyadi, Zbigniew Michalewicz, Michał Roman Przybyłek, Adam Wierzbicki 11:05-11:30

Data-Driven Local Optima Network Characterization of QAPLIB Instances
David Iclanzan, Fabio Daolio, Marco Tomassini 11:30-11:55

Asymmetric Quadratic Landscape Approximation Model
Alexandru-Adrian Tantar, Emilia Tantar, Oliver Schütze 11:55-12:20

GA1: About Fitness Landscapes

Monday, July 14, 10:40-12:20, Junior Ballroom D
Chair: Kalyanmoy Deb

From Fitness Landscape to Crossover Operator Choice
Stjepan Picek, Domagoj Jakobovic 10:40-11:05

Unbiased Black-Box Complexities of Jump Functions — How to Cross Large Plateaus
Benjamin Doerr, Carola Doerr, Timo Kötzing 11:05-11:30

Stochastic Tunneling Transformation during Selection in Genetic Algorithm
Benjamin E. Mayer, Kay Hamacher 11:30-11:55

Adaptive-Surrogate Based on a Neuro-Fuzzy Network and Granular Computing
Israel Cruz-Vega, Mauricio Garcia-Limon, Hugo Jair Escalante 11:55-12:20

THEORY1

Monday, July 14, 10:40-12:20, Parksville
Chair: Benjamin Doerr

Refined Upper Bounds on the Expected Runtime of Non-Elitist Populations from Fitness-Levels
Duc-Cuong Dang, Per Kristian Lehre 10:40-11:05

Runtime Analysis to Compare Best-Improvement and First-Improvement in Memetic Algorithms
Kuai Wei, Michael J. Dinneen 11:05-11:30

Model-Optimal Optimization by Solving Bellman Equations
Alan J. Lockett 11:30-11:55

MMAS vs. Population-Based EA on a Family of Dynamic Fitness Functions
Andrei Lissovoi, Carsten Witt 11:55-12:20

PES1: Parallel Evolutionary Systems

Monday, July 14, 10:40-12:20, Port Hardy
Chair: Gabriel Luque

Solving GA-Hard Problems with EMMRS and GPGPUs
J. Ignacio Hidalgo, J. Manuel Colmenar, Jose L. Risco-Martín, Carlos Sánchez-Lacruz, Juan Lanchares, Oscar Garnica, Josefa Díaz 10:40-11:05

An Implicitly Parallel EDA Based on Restricted Boltzmann Machines
Malte Probst, Franz Rothlauf, Jörn Grahl 11:05-11:30

GPU-Accelerated Evolutionary Design of the Complete Exchange Communication on Wormhole Networks
Jiri Jaros, Radek Tyrala 11:30-11:55

Towards Highly Optimized Cartesian Genetic Programming: From Sequential via SIMD and Thread to Massive Parallel Implementation
Radek Hrbacek, Lukas Sekanina 11:55-12:20

RWA1: Process Optimization; Wireless Networks

Monday, July 14, 10:40-12:20, Port Alberni
Chair: Nikola Aulig (Best Paper Nominees are marked with an asterisk)

Multi-Objective Routing Optimisation for Battery-Powered Wireless Sensor Mesh Networks*
Alma As-Aad Mohammad Rahat, Richard M. Everson, Jonathan E. Fieldsend 10:40-11:05

On Homogenization of Coal in Longitudinal Blending Beds*
Pradyumn Kumar Shukla, Michael P. Cipold, Claus Bachmann, Hartmut Schmeck 11:05-11:30

The Tradeoffs between Data Delivery Ratio and Energy Costs in Wireless Sensor Networks: A Multi-Objective Evolutionary Framework for Protocol Analysis
Doina Bucur, Giovanni Iacca, Giovanni Squillero, Alberto Tonda 11:30-11:55

Dynamic Multi-Dimensional PSO with Indirect Encoding for Proportional Fair Constrained Resource Allocation
Jonathan Hudson, Majid Ghaderi, Jörg Denzinger 11:55-12:20

ALIFE2: Best Papers; Evolutionary Robotics

Monday, July 14, 14:00-15:40, Junior Ballroom A
Chair: Roderich Gross (Best Paper Nominees are marked with an asterisk)

Overcoming Deception in Evolution of Cognitive Behaviors*
Joel Lehman, Risto Miikkulainen 14:00-14:25

A Novel Human-Computer Collaboration: Combining Novelty Search with Interactive Evolution*
Brian G. Woolley, Kenneth O. Stanley 14:25-14:50

Encouraging Creative Thinking in Robots Improves Their Ability to Solve Challenging Problems
Jingyu Li, Jed Storie, Jeff Clune 14:50-15:15

Evolving Joint-Level Control with Digital Muscles
Jared M. Moore, Philip K. McKinley 15:15-15:40

SELF-*1

Monday, July 14, 14:00-15:40, Junior Ballroom B
Chair: Dirk Thierens

Evolvability Metrics in Adaptive Operator Selection
Jorge A. Soria Alcaraz, Gabriela Ochoa, Martin Carpio, Hector Puga 14:00-14:25

Analysis of Evolutionary Algorithms Using Multi-Objective Parameter Tuning
Roberto Ugolotti, Stefano Cagnoni 14:25-14:50

On the Pathological Behavior of Adaptive Differential Evolution on Hybrid Objective Functions
Ryoji Tanabe, Alex S. Fukunaga 14:50-15:15

A Grammatical Evolution Based Hyper-Heuristic for the Automatic Design of Split Criteria
Márcio Porto Basgalupp, Rodrigo Coelho Barros, Tiago Barabasz 15:15-15:40

ECOM2: Best Papers; Heuristics

Monday, July 14, 14:00-15:40, Junior Ballroom C
Chair: Manuel López-Ibañez (Best Paper Nominees are marked with an asterisk)

NSGA-II with Iterated Greedy for a Bi-Objective Three-Stage Assembly Flowshop Scheduling Problem
Saulo Cunha Campos, Jose Elias Claudio Arroyo 14:00-14:25

Efficient Identification of Improving Moves in a Ball for Pseudo-Boolean Problems
Francisco Chicano, Darrell Whitley, Andrew M. Sutton 14:25-14:50

A Heuristic Approach to Schedule Reoptimization in the Context of Interactive Optimization*
David Meignan 14:50-15:15

Revised Analysis of the (1+1) EA for the Minimum Spanning Tree Problem*
Carsten Witt 15:15-15:40

GA2: Developing Genetic Algorithms

Monday, July 14, 14:00-15:40, Junior Ballroom D
Chair: Thomas Jansen

Among-Site Rate Variation: Adaptation of Genetic Algorithm Mutation Rates at Each Single Site
Fatemeh Vafaee, Gyorgy Turan, Peter C. Nelson, Tanya Y. Berger-Wolf 14:00-14:25

A Bilevel Optimization Approach to Automated Parameter Tuning
Ankur Sinha, Pekka Malo, Peng Xu, Kalyanmoy Deb 14:25-14:50

Feedback Control for Multi-Modal Optimization Using Genetic Algorithms
Jun Shi, Ole J. Mengshoel, Dipan K. Pal 14:50-15:15

Genetic Algorithm for Sampling from Scale-free Data and Networks
Pavel Krömer, Jan Platoš 15:15-15:40

THEORY2

Monday, July 14, 14:00-15:40, Parksville
Chair: Per Kristian Lehre

Concentration of First Hitting Times under Additive Drift
Timo Kötzing 14:00-14:25

The Impact of Random Initialization on the Runtime of Randomized Search Heuristics
Benjamin Doerr, Carola Doerr 14:25-14:50

A Theoretical Analysis of Volume Based Pareto Front Approximations
Pradyumn Kumar Shukla, Nadja Doll, Hartmut Schmeck 14:50-15:15

The Query Complexity of Finding a Hidden Permutation
Peyman Afshani, Manindra Agrawal, Benjamin Doerr, Carola Doerr, Kasper Green Larsen, Kurt Mehlhorn 15:15-15:40

BIO1: Biological and Biomedical Applications

Monday, July 14, 14:00-15:40, Port Hardy
Chair: Jason H. Moore

Enhancing Genetic Algorithm-Based Genome-scale Metabolic Network Curation Efficiency
Eddy J. Bautista, Ranjan Srivastava 14:00-14:25

Multiple Feature Construction for Effective Biomarker Identification and Classification Using Genetic Programming
Soha Ahmed, Mengjie Zhang, Lifeng Peng 14:25-14:50

GA-Based Selection of Vaginal Microbiome Features Associated with Bacterial Vaginosis
Joi Carter, Daniel Beck, Henry Williams, Gerry Dozier, James A. Foster 14:50-15:15

Multiple Graph Edit Distance — Simultaneous Topological Alignment of Multiple Protein-Protein Interaction Networks with an Evolutionary Algorithm
Rashid Ibragimov, Maximilian Malek, Jan Baumbach, Jiong Guo 15:15-15:40

RWA2: Financial-Social Systems; Network Security

Monday, July 14, 14:00-15:40, Port Alberni
Chair: Robin C. Purshouse

ALIFE3: Investigating and Abstracting from Nature

Tuesday, July 15, 10:40-12:20, Junior Ballroom A
Chair: Kenneth O. Stanley

Wolfpack-Inspired Evolutionary Algorithm and a Reaction-Diffusion-Based Controller are Used for Pattern Formation
Payam Zahadat, Thomas Schmickl 10:40-11:05

The Evolution of Kin Inclusivity Levels
Anya E. Johnson, Heather J. Goldsby, Sherri Goings, Charles Ofria 11:05-11:30

Evolution of Honest Signaling by Social Punishment
David Catteeuw, The Anh Han, Bernard Manderick 11:30-11:55

Evolution of Communication and Cooperation
Jason Fairey, Terence Soule 11:55-12:20

GP1: Platforms and Programming

Tuesday, July 15, 10:40-12:20, Junior Ballroom B
Chairs: William B. Langdon and Malcolm I. Heywood

GPU-Parallel SubTree Interpreter for Genetic Programming
Alberto Cano, Sebastian Ventura 10:40-11:05

Improving 3D Medical Image Registration CUDA Software with Genetic Programming
William B. Langdon, Marc Modat, Justyna Petke, Mark Harman 11:05-11:30

Grammar-Based Genetic Programming with Dependence Learning and Bayesian Network Classifier
Pak-Kan Wong, Leung-Yau Lo, Man-Leung Wong, Kwong-Sak Leung 11:30-11:55

Utilization of Reductions and Abstraction Elimination in Typed Genetic Programming
Tomáš Kren, Roman Neruda 11:55-12:20

ACO-SI1: Best Papers; Ant Colony Optimization

Tuesday, July 15, 10:40-12:20, Junior Ballroom C
Chair: Carlos A. Coello Coello (Best Paper Nominees are marked with an asterisk)

Ant Colony Optimization with Group Learning
Gunnar Völkel, Markus Maucher, Uwe Schöning, Hans A. Kestler 10:40-11:05

Energy Aware Virtual Machine Placement Scheduling in Cloud Computing Based on Ant Colony Optimization Approach
Xiao-Fang Liu, Zhi-Hui Zhan, Ke-Jing Du, Wei-Neng Chen 11:05-11:30

Anticipatory Stigmergic Collision Avoidance under Noise*
Friedrich Burkhard von der Osten, Michael Kirley 11:30-11:55

SPSO2011 — Analysis of Stability, Local Convergence, and Rotation Sensitivity*
Mohammad Reza Bonyadi, Zbigniew Michalewicz 11:55-12:20

GA3: Best Papers; Theory

Tuesday, July 15, 10:40-12:20, Junior Ballroom D
Chair: Thomas Jansen (Best Paper Nominees are marked with an asterisk)

Runtime Analysis for Maximizing Population Diversity in Single-Objective Optimization
Wanru Gao, Frank Neumann 10:40-11:05

Monotonic Functions in EC: Anything but Monotone!
Sylvain Colin, Benjamin Doerr, Gaspard Ferey 11:05-11:30

A Fixed Budget Analysis of Randomized Search Heuristics for the Traveling Salesperson Problem*
Samadhi Nallaperuma, Frank Neumann, Dirk Sudholt 11:30-11:55

Parameter-less Population Pyramid*
Brian W. Goldman, William F. Punch 11:55-12:20

THEORY3

Tuesday, July 15, 10:40-12:20, Parksville
Chair: Carsten Witt

Robustness of Populations in Stochastic Environments
Christian Gießen, Timo Kötzing 10:40-11:05

Superpolynomial Lower Bounds for the (1+1) EA on Some Easy Combinatorial Problems
Andrew M. Sutton 11:05-11:30

Gaussian Mixture Model of Evolutionary Algorithms
Bo Song, Victor O. K. Li 11:30-11:55

Theory Track Business Meeting (open to all)
Brief summary of this year's theory track from the track chairs' perspective; discussion. 11:55-12:20

EMO1: Ranking, Selection, and Preferences

Tuesday, July 15, 10:40-12:20, Port McNeill
Chair: Joshua D. Knowles

Efficiently Identifying Pareto Solutions when Objective Values Change
Jonathan E. Fieldsend, Richard M. Everson 10:40-11:05

Controlling Selection Area of Useful Infeasible Solutions and Their Archive for Directed Mating in Evolutionary Constrained Multiobjective Optimization
Minami Miyakawa, Keiki Takadama, Hiroyuki Sato 11:05-11:30

A Framework for the Study of Preference Incorporation in Multiobjective Evolutionary Algorithms
Raluca Iordache, Serban Iordache, Florica Moldoveanu 11:30-11:55

Two-Dimensional Subset Selection for Hypervolume and Epsilon-Indicator
Karl Bringmann, Tobias Friedrich, Patrick Klitzke 11:55-12:20

RWA3: Image Processing; Computer Science

Tuesday, July 15, 10:40-12:20, Port Alberni
Chair: Matthew Eicholtz

ALIFE4/PES2: Parallel Algorithms; Collective Behaviours

Tuesday, July 15, 14:00-15:40, Junior Ballroom A
Chair: Payam Zahadat

Enhancing Parallel Cooperative Trajectory Based Metaheuristics with Path Relinking
Gabriel Luque, Enrique Alba 14:00-14:25

MapReduce-Based Optimization of Overlay Networks Using Particle Swarm Optimization
Simone A. Ludwig 14:25-14:50

Coevolutionary Learning of Swarm Behaviors without Metrics
Wei Li, Melvin Gauci, Roderich Gross 14:50-15:15

Adapting to a Changing Environment Using Winner and Loser Effects
Jeremy Acre, Brent E. Eskridge, Nicholas Zoller, Ingo Schlupp 15:15-15:40

GP2: Time for Something Different . . .

Tuesday, July 15, 14:00-15:40, Junior Ballroom B
Chair: Lee Spector

Kaizen Programming
Vinícius Veloso de Melo 14:00-14:25

Multiple Regression Genetic Programming
Ignacio Arnaldo, Krzysztof Krawiec, Una-May O'Reilly 14:25-14:50

Asynchronously Evolving Solutions with Excessively Different Evaluation Time by Reference-Based Evaluation
Tomohiro Harada, Keiki Takadama 14:50-15:15

Elevator Pitches
Very short presentations to encourage uptake of tools or resources related to GP; discussion. 15:15-15:40

ACO-SI2: Differential Evolution and Other Swarm Intelligence Approaches

Tuesday, July 15, 14:00-15:40, Junior Ballroom C
Chair: Wei-Neng Chen

A Tribal Ecosystem Inspired Algorithm (TEA) for Global Optimization
Ying Lin, Jing-Jing Li, Jun Zhang, Meng Wan 14:00-14:25

Stepsize Control on the Modified Bacterial Foraging Algorithm for Constrained Numerical Optimization
Betania Hernández-Ocaña, María de Pilar Pozos-Parra, Efrén Mezura-Montes 14:25-14:50

Differential Evolution Using Mutation Strategy with Adaptive Greediness Degree Control
Wei-Jie Yu, Jing-Jing Li, Jun Zhang, Meng Wan 14:50-15:15

Automatic Path Planning for Autonomous Underwater Vehicles Based on an Adaptive Differential Evolution
Chuan-Bin Zhang, Yue-Jiao Gong, Jing-Jing Li, Ying Lin 15:15-15:40

BP1: Best Papers DETA, EML, GDS, SBSE

Tuesday, July 15, 14:00-15:40, Junior Ballroom D
Chair: Christian Igel (Best Paper Nominees are marked with an asterisk)

Evolving Multimodal Behavior with Modular Neural Networks in Ms. Pac-Man*
Jacob Schrum, Risto Miikkulainen 14:00-14:25

Salient Object Detection Using Learning Classifier Systems that Compute Action Mappings*
Muhammad Iqba, Syed S. Naqvi, Will N. Browne, Christopher Hollitt, Mengjie Zhang 14:25-14:50

Some Distance Measures for Morphological Diversification in Generative Evolutionary Robotics*
Eivind Samuelsen, Kyrre Glette 14:50-15:15

On the Performance of Multiple Objective Evolutionary Algorithms for Software Architecture Discovery*
Aurora Ramírez, José Raúl Romero, Sebastián Ventura 15:15-15:40

IGEC1

Tuesday, July 15, 14:00-15:40, Parksville
Chair: Renato Tinos

Use of Explicit Memory in the Dynamic Traveling Salesman Problem
Renato Tinos, Darrell Whitley, Adele Howe 14:00-14:25

Neuro-Evolutionary Topology Optimization of Structures by Utilizing Local State Features
Nikola Aulig, Markus Olhofer 14:25-14:50

A Novel Population-Based Multi-Objective CMA-ES and the Impact of Different Constraint Handling Techniques
Silvio Rodrigues, Pavol Bauer, Peter A. N. Bosman 14:50-15:15

Evolutionary Algorithms and Artificial Immune Systems on a Bi-Stable Dynamic Optimisation Problem
Thomas Jansen, Christine Zarges 15:15-15:40

EMO2: Many-Objective Optimization; Best Papers

Tuesday, July 15, 14:00-15:40, Port McNeill
Chair: Dimo Brockhoff (Best Paper Nominees are marked with an asterisk)

Improving Many-Objective Optimization Performance by Sequencing Evolutionary Algorithms
Martin Dohr, Bernd Eichberger 14:00-14:25

Evolutionary Many-Objective Optimization Using Ensemble Fitness Ranking
Yuan Yuan, Hua Xu, Bo Wang 14:25-14:50

An Improved NSGA-III Procedure for Evolutionary Many-Objective Optimization*
Yuan Yuan, Hua Xu, Bo Wang 14:50-15:15

Inverted PBI in MOEA/D and Its Impact on the Search Performance on Multi and Many-Objective Optimization*
Hiroyuki Sato 15:15-15:40

RWA4: Material, Natural, and Space Sciences

Tuesday, July 15, 14:00-15:40, Port Alberni
Chair: Bernhard Sendhoff

HOP1: Robotics and Medical Applications

Tuesday, July 15, 16:10-17:50, Junior Ballroom A
Chair: Jürgen Branke

Non-Additive Multi-Objective Robot Coalition Formation
Manoj Agarwal, Naveen Kumar, Lovekesh Vig 16:10-16:35

Evolvability Is Inevitable: Increasing Evolvability without the Pressure to Adapt
Joel Lehman, Kenneth O. Stanley 16:35-17:00

Cracking the Egg: Virtual Embryogenesis of Real Robots
Sylvain Cussat-Blanc, Jordan Pollack 17:00-17:25

Role of Genetic Heterogeneity and Epistasis in Bladder Cancer Susceptibility and Outcome: A Learning Classifier System Approach
Ryan John Urbanowicz, Angeline S. Andrew, Margaret Rita Karagas, Jason H. Moore 17:25-17:50

SBSE1: Empirical Studies

Tuesday, July 15, 16:10-17:50, unior Ballroom B
Chair: Marouane Kessentini

Improved Heuristics for Solving OCL Constraints Using Search Algorithms
Shaukat Ali, Muhammad Zohaib Iqbal, Andrea Arcuri 16:10-16:35

Applying Search Algorithms for Optimizing Stakeholders Familiarity and Balancing Workload in Requirements Assignment
Tao Yue, Shaukat Ali 16:35-17:00

Robust Next Release Problem: Handling Uncertainty During Optimization
Lingbo Li, Mark Harman, Emmanuel Letier, Yuanyuan Zhang 17:00-17:25

Surrogate-Assisted Optimisation of Composite Applications in Mobile Ad hoc Networks
Dionysios Efstathiou, Peter McBurney, Steffen Zschaler, Johann Bourcier 17:25-17:50

ACO-SI3: Swarming in Continuous Spaces

Tuesday, July 15, 16:10-17:50, Junior Ballroom C
Chair: Michael Kirley

Identifying and Exploiting the Scale of a Search Space in Particle Swarm Optimization
Yasser Gonzalez-Fernandez, Stephen Chen 16:10-16:35

An Improved Multi-Start Particle Swarm-Based Algorithm for Protein Structure Comparison
Hazem Radwan Ahmed, Janice I. Glasgow 16:35-17:00

Consensus Costs and Conflict in a Collective Movement
Timothy Solum, Brent E. Eskridge, Ingo Schlupp 17:00-17:25

Constrained Multi-Objective Aerodynamic Shape Optimization via Swarm Intelligence
Saul Zapotecas Martinez, Alfredo Arias Montaño, Carlos A. Coello Coello 17:25-17:50

GP3: Best Papers, Theory, and Proposals

Tuesday, July 15, 16:10-17:50, Junior Ballroom D
Chair: Wolfgang Banzhaf (Best Paper Nominees are marked with an asterisk)

On Size, Complexity and Generalisation Error in GP
Jeannie Fitzgerald, Conor Ryan 16:10-16:35

Word Count as a Traditional Programming Benchmark Problem for Genetic Programming
Thomas Helmuth, Lee Spector 16:35-17:00

Evolving "Less-Myopic" Scheduling Rules for Dynamic Job Shop Scheduling with Genetic Programming*
Rachel Hunt, Mark Johnston, Mengjie Zhang 17:00-17:25

Behavioral Programming: A Broader and More Detailed Take on Semantic GP*
Krzysztof Krawiec, Una-May O'Reilly 17:25-17:50

ESEP/IGEC2

Tuesday, July 15, 16:10-17:50, Parksville
Chair: Ilya Loshchilov

Comparison-Based Natural Gradient Optimization in High Dimension
Youhei Akimoto, Anne Auger, Nikolaus Hansen 16:10-16:35

Halfspace Sampling in Evolution Strategies
Chun-Kit Au, Ho-Fung Leung 16:35-17:00

Handling Sharp Ridges with Local Supremum Transformations
Tobias Glasmachers 17:00-17:25

Derivative Free Optimization Using a Population-Based Stochastic Gradient Estimator
Azhar Khayrattee, Georgios C. Anagnostopoulos 17:25-17:50

HOP2: Games and Multi-Objective Optimization

Tuesday, July 15, 16:10-17:50, Port McNeill
Chair: Julian Togelius

Genetic Algorithms for Evolving Computer Chess Programs
Omid E. David, H. Jaap van den Herik, Moshe Koppel, Nathan S. Netanyahu 16:10-16:35

EvoMCTS: A Scalable Approach for General Game Learning
Amit Benbassat, Moshe Sipper 16:35-17:00

Playing Mastermind with Many Colors
Benjamin Doerr, Carola Doerr, Reto Spoehel, Henning Thomas 17:00-17:25

The Rolling Tide Evolutionary Algorithm: A Multi-Objective Optimiser for Noisy Optimisation Problems
Jonathan E. Fieldsend, Richard Everson 17:25-17:50

RWA5: Traffic Management; Civil Engineering

Tuesday, July 15, 16:10-17:50, Port Alberni
Chair: Bernhard Sendhoff

GDS1

Wednesday, July 16, 8:30-10:10, Junior Ballroom A
Chair: Michael E. Palmer

Novelty Search Creates Robots with General Skills for Exploration
Roby Velez, Jeff Clune 8:30-8:55

Evolving Neural Networks that Are Both Modular and Regular: HyperNeat Plus the Connection Cost Technique
Joost Huizinga, Jeff Clune, Jean-Baptiste Mouret 8:55-9:20

Guided Self-Organization in Indirectly Encoded and Evolving Topographic Maps
Sebastian Risi, Kenneth O. Stanley 9:20-9:45

There and Back Again: Gene-Processing Hardware for the Evolution and Robotic Deployment of Robust Navigation Strategies
David M. Bryson, Aaron P. Wagner, Charles Ofria 9:45-10:10

DETA1

Wednesday, July 16, 8:30-10:10, Junior Ballroom B
Chair: Christian Jacob

Semantic Aware Methods for Evolutionary Art
Penousal Machado, João Correia 8:30-8:55

EVOR: An Online Evolutionary Algorithm for Car Racing Games
Samadhi Nallaperuma, Frank Neumann, Mohammad Reza Bonyadi, Zbigniew Michalewicz 8:55-9:20

Automatic Design of Sound Synthesizers as Pure Data Patches Using Coevolutionary Mixed-Typed Cartesian Genetic Programming
Matthieu Macret, Philippe Pasquier 9:20-9:45

Monte Mario: Platforming with MCTS
Emil Juul Jacobsen, Rasmus Greve, Julian Togelius 9:45-10:10

BP2: Best Papers AIS, ESEP, PES, THEORY

Wednesday, July 16, 8:30-10:10, Junior Ballroom D
Chair: Christian Igel (Best Paper Nominees are marked with an asterisk)

On the Runtime Analysis of Stochastic Ageing Mechanisms*
Pietro S. Oliveto, Dirk Sudholt 8:30-8:55

A Computationally Efficient Limited Memory CMA-ES for Large Scale Optimization*
Ilya Loshchilov 8:55-9:20

Design and Analysis of Adaptive Migration Intervals in Parallel Evolutionary Algorithms*
Andrea Mambrini, Dirk Sudholt 9:20-9:45

Evolution under Partial Information*
Duc-Cuong Dang, Per Kristian Lehre 9:45-10:10

EML1/RWA6: Applied Machine Learning; Time Series

Wednesday, July 16, 8:30-10:10, Parksville
Chair: Jan Koutnik

Genetic Algorithms and Deep Learning for Automatic Painter Classification
Erez Levy, Omid E. David, Nathan S. Netanyahu 8:30-8:55

SAX-EFG: An Evolutionary Feature Generation Framework for Time Series Classification
Uday Kamath, Jessica Lin, Kenneth De Jong 8:55-9:20

A Modified XCS Classifier System for Sequence Labeling
Masaya Nakata, Tim Kovacs, Keiki Takadama 9:20-9:45

Evolving Deep Unsupervised Convolutional Networks for Vision-Based Reinforcement Learning
Jan Koutník, Jürgen Schmidhuber, Faustino Gomez 9:45-10:10

EMO3: Surrogates and Applications

Wednesday, July 16, 8:30-10:10, Port McNeill
Chair: Tobias Friedrich

Steady State IBEA Assisted by MLP Neural Networks for Expensive Multi-Objective Optimization Problems
Nessrine Azzouz, Slim Bechikh, Lamjed Ben Said 8:30-8:55

Hypervolume-Based Local Search in Multi-Objective Evolutionary Optimization
Martin Pilat, Roman Neruda 8:55-9:20

Hybridization of Electromagnetism with Multi-Objective Evolutionary Algorithms for RCPSP
Jing Xiao, Zhou Wu, Jian-Chao Tang 9:20-9:45

The Parameter Optimization of Kalman Filter Based on Multi-Objective Memetic Algorithm
Yu Dan Huo, Zhi Hua Cai, Wen Yin Gong, Qin Liu 9:45-10:10

EDA1

Wednesday, July 16, 8:30-10:10, Port Hardy
Chair: John A. W. McCall

Estimation of Distribution Algorithm Using Factor Graph and Markov Blanket Canonical Factorization
Bentolhoda Helmi, Adel Torkaman Rahmani 8:30-8:55

Multimodality and the Linkage-Learning Difficulty of Additively Separable Functions
Jean P. Martins, Alexandre C. B. Delbem 8:55-9:20

Solving Building Block Problems Using Generative Grammar
Chris R. Cox, Richard A. Watson 9:20-9:45

Minimal Walsh Structure and Ordinal Linkage of Monotonicity-Invariant Function Classes on Bit Strings
Lee A. Christie, John A. W. McCall, David P. Lonie 9:45-10:10

ECOM3: Evolutionary Algorithms

Wednesday, July 16, 8:30-10:10, Port Alberni
Chair: Gabriela Ochoa

GDS2/DETA2

Wednesday, July 16, 10:40-12:20, Junior Ballroom A
Chair: Sebastian Risi

Growth in Co-Evolution of Sensory System and Signal Processing for Optimal Wing Control
Olga Smalikho, Markus Olhofer 10:40-11:05

Trading Control Intelligence for Physical Intelligence: Muscle Drives in Evolved Virtual Creatures
Dan Lessin, Don Fussell, Risto Miikkulainen 11:05-11:30

A Continuous Developmental Model for Wind Farm Layout Optimization
Dennis Wilson, Sylvain Cussat-Blanc, Kalyan Veeramachaneni, Una-May O'Reilly, Hervé Luga 11:30-11:55

Virtual Photography Using Multi-Objective Particle Swarm Optimization
William Barry, Brian J. Ross 11:55-12:20

SBSE2: Applications

Wednesday, July 16, 10:40-12:20, Junior Ballroom B
Chair: Guenther Ruhe

A Parallel Evolutionary Algorithm for Prioritized Pairwise Testing of Software Product Lines
Roberto Erick Lopez-Herrejon, Javier Ferrer, Francisco Chicano, Evelyn Nicole Haslinger, Alexander Egyed, Enrique Alba 10:40-11:05

Generating Structured Test Data with Specific Properties Using Nested Monte-Carlo Search
Simon Poulding, Robert Feldt 11:05-11:30

Comparing Search Techniques for Finding Subtle Higher Order Mutants
Elmahdi Omar, Sudipto Ghosh, Darrell Whitley 11:30-11:55

High Dimensional Search-Based Software Engineering: Finding Tradeoffs among 15 Objectives for Automating Software Refactoring Using NSGA-III
Mohamed Wiem Mkaouer, Marouane Kessentini, Slim Bechikh, Kalyanmoy Deb, Mel Ó Cinnéide 11:55-12:20

HOP3: GP and Combinatorial Optimization

Wednesday, July 16, 10:40-12:20, Junior Ballroom C
Chair: Erik D. Goodman

Exploiting *Interestingness* in a Computational Evolution System for the Genome-Wide Genetic Analysis of Alzheimer's Disease
Jason H. Moore, Douglas P. Hill, Andrew Saykin, Li Shen 10:40-11:05

Automatic Synthesis of Regular Expressions from Examples
Alberto Bartoli, Giorgio Davanzo, Andrea De Lorenzo, Eric Medvet, Enrico Sorio 11:05-11:30

A Lifelong Learning Hyper-Heuristic Method for Bin Packing
Emma Hart, Kevin Sim 11:30-11:55

Improving Source Code with Genetic Programming
William B. Langdon, Mark Harman 11:55-12:20

GA4: Applying Genetic Algorithms

Wednesday, July 16, 10:40-12:20, Junior Ballroom D
Chair: Thomas Jansen

Learning the Structure of Large-Scale Bayesian Networks Using Genetic Algorithm
Fatemeh Vafaee 10:40-11:05

Evolving QWOP Gaits
Steven Ray, Vahl Scott Gordon, Laurent Vaucher 11:05-11:30

Efficient Global Optimization for Combinatorial Problems
Martin Zaefferer, Jörg Stork, Martina Friese, Andreas Fischbach, Boris Naujoks, Thomas Bartz-Beielstein 11:30-11:55

Search For Maximal Snake-in-the-Box Using New Genetic Algorithm
Kim-Hang Ruiz 11:55-12:20

EML2: Classification and Preprocessing

Wednesday, July 16, 10:40-12:20, Parksville
Chair: Jaume Bacardit

Three-Cornered Coevolution Learning Classifier Systems for Classification Tasks
Syahaneim Marzukhi, Will N. Browne, Mengjie Zhang 10:40-11:05

Complete Action Map or Best Action Map in Accuracy-Based Reinforcement Learning Classifier Systems
Masaya Nakata, Pier Luca Lanzi, Tim Kovacs, Keiki Takadama 11:05-11:30

Simultaneous Generation of Prototypes and Features through Genetic Programming
Mauricio Garcia-Limon, Hugo Jair Escalante, Eduardo Morales, Alicia Morales-Reyes 11:30-11:55

A Memetic Algorithm to Select Training Data for Support Vector Machines
Jakub Nalepa, Michal Kawulok 11:55-12:20

HOP4: Swarms and Populations

Wednesday, July 16, 10:40-12:20, Port McNeill
Chair: Kenneth A. De Jong

A Generalized Theoretical Deterministic Particle Swarm Model
Christopher W. Cleghorn, Andries P. Engelbrecht 10:40-11:05

Experimental Analysis of Bound Handling Techniques in Particle Swarm Optimization
Sabine Helwig, Jürgen Branke, Sanaz Mostaghim 11:05-11:30

Adaptive Generalized Crowding for Genetic Algorithms
Ole J. Mengshoel, Severino Galan 11:30-11:55

General Subpopulation Framework and Taming the Conflict Inside Populations
Danilo Vasconcellos Vargas, Junichi Murata, Hirotaka Takano, Alexandre Cláudio Botazzo Delbem 11:55-12:20

SELF-*2/EDA2

Wednesday, July 16, 10:40-12:20, Port Hardy
Chair: Georgios C. Anagnostopoulos

Generic Parameter Control with Reinforcement Learning
Giorgos Karafotias, A. E. Eiben, Mark Hoogendoorn 10:40-11:05

Online Model Racing Based on Extreme Performance
Tiantian Zhang, Michael Georgiopoulos, Georgios C. Anagnostopoulos 11:05-11:30

Fair-Share ILS: A Simple State-of-the-Art Iterated Local Search Hyperheuristic
Steven Adriaensen, Tim Brys, Ann Nowé 11:30-11:55

Multi-Objective Gene-Pool Optimal Mixing Evolutionary Algorithms
Ngoc Hoang Luong, Han La Poutré, Peter A. N. Bosman 11:55-12:20

ECOM4/BIO2

Wednesday, July 16, 10:40-12:20, Port Alberni
Chair: Matthieu Basseur

Performance of Metropolis Algorithm for the Minimum Weight Code Word Problem
Ajitha Shenoy K. B., Somenath Biswas, Piyush P. Kurur 10:40-11:05

A Comprehensive Benchmark Set and Heuristics for the Traveling Thief Problem
Sergey Polyakovskiy, Mohammad Reza Bonyadi, Markus Wagner, Zbigniew Michalewicz, Frank Neumann 11:05-11:30

Predicting Patterns of Gene Expression During *Drosophila* Embryogenesis
Rotem Golan, Christian Jacob, Savraj Grewal, Jörg Denzinger 11:30-11:55

Poster Session

Monday, July 14, 16:10-18:30, Pavilion Ballroom

Ant Colony Optimization and Swarm Intelligence

A PSO Approach for Software Project Planning
Ya-Hui Jia, Wei-Neng Chen, Xiao-Min Hu

Introducing Particle Swarm Optimization into a Genetic Algorithm to Evolve Robot Controllers
Malte Langosz, Kai Alexander von Szadkowski, Frank Kirchner

Fitness Proportionate Selection Based Binary Particle Swarm Optimization
Xing Liu, Lin Shang

Under-Informed Momentum in PSO
Christopher K. Monson, Kevin D. Seppi

Multi-Swarm Particle Swarm Optimization with Multiple Learning Strategies
Meng-Qi Peng, Yue-Jiao Gong, Jing-Jing Li, Ying-Biao Lin

An Ant Colony Optimization for Solving a Hybrid Flexible Flowshop
Aymen Sioud, Caroline Gagné, Marc Gravel

An Improved Artificial Bee Colony Algorithm for Clustering
Qiuhang Tan, Hejun Wu, Biao Hu, Xingcheng Liu

Artificial Immune Systems

Artificial Immune Systems in the Context of Autonomic Computing: Integrating Design Paradigms
Nicola Capodieci, Emma Hart, Giacomo Cabri

Adapting to Dynamically Changing Noise During Learning of Heart Sounds: An AIS-Based Approach Using Systemic Computation
Yiqi Deng, Peter J. Bentley

Artificial Life, Robotics, and Evolvable Hardware

Lifetimes of Migration
Faith Agwan, Will van Heerden, Geoff Nitschke

Incremental Evolution of HERCL Programs for Robust Control
Alan Blair

High-Level Behavior Regulation for Multi-Robot Systems
Martin Delecluse, Stéphane Sanchez, Sylvain Cussat-Blanc, Nicolas Schneider, Jean-Baptiste Welcomme

Evolving Prediction Machines: Collective Behaviors Based on Minimal Surprisal
Heiko Hamann

Minimal Variable Quantum Decision Makers for Robotic Control
Walter O. Krawec

General Intelligence through Prolonged Evolution of Densely Connected Neural Networks
Padmini Rajagopalan, Aditya Rawal, Kay E. Holekamp, Risto Miikkulainen

Biological and Biomedical Applications

Prediction of Detectable Peptides in MS Data Using Genetic Programming
Soha Ahmed, Mengjie Zhang, Lifeng Peng

A Semantic Expert System for the Evolutionary Design of Synthetic Gene Networks
Vitoantonio Bevilacqua, Paolo Pannarale

Evolving Small GRNs with a Top-Down Approach
Javier Garcia-Bernardo, Margaret J. Eppstein

iSyn: De Novo Drug Design with Click Chemistry Support
Hongjian Li, Kwong-Sak Leung, Chun Ho Chan, Hei Lun Cheung, Man-Hon Wong

Digital Entertainment Technologies and Arts

A Multi-Population Genetic Algorithm for Procedural Generation of Levels for Platform Games
Lucas Ferreira, Leonardo Pereira, Claudio Toledo

Evolutionary Approaches to Evolve AI Scripts for a RTS
Lucas Ferreira, Leonardo Pereira, Claudio Toledo, Rodrigo Pereira

A Methodology for Designing Emergent Literary Backstories on Non-player Characters Using Genetic Algorithms
Rubén Héctor García-Ortega, Pablo García, Antonio Mora, Juan Julián Merelo

Control of Non Player Characters in a Medical Learning Game with Monte Carlo Tree Search
Sanselone Maxime, Sanchez Stéphane, Sanza Cédric, Panzoli David, Duthen Yves

Estimation of Distribution Algorithms

Estimation of Distribution Algorithms Based on n-gram Statistics for Sequencing and Optimization
Chung-Yao Chuang, Stephen F. Smith

Complexity of Model Learning in EDAs: Multi-Structure Problems
Hadi Sharifi, Amin Nikanjam, Hossein Karshenas, Negar Najimi

A Two-Level Hierarchical EDA Using Conjugate Priori
Bo Wang, Hua Xu, Yuan Yuan

Evolution Strategies and Evolutionary Programming

An Algorithm for Evolving Multiple Quantum Operators for Arbitrary Quantum Computational Problems
Walter O. Krawec

A Mathematically Derived Number of Resamplings for Noisy Optimization
Jialin Liu, David L. St-Pierre, Olivier Teytaud

SEA: An Evolutionary Algorithm Based on Spherical Inversions
Juan Pablo Serrano Rubio, Arturo Hernández Aguirre, Rafael Herrera Guzmán

Evolutionary Combinatorial Optimization and Metaheuristics

Use EMO to Protect Sensitive Knowledge in Association Rule Mining by Adding Items
Peng Cheng, Jeng-Shyang Pan

Inferring Automata-Based Programs from Specification With Mutation-Based Ant Colony Optimization
Daniil Chivilikhin, Vladimir Ulyantsev

Combinatorial Optimization with Differential Evolution: A Set-Based Approach
Andre L. Maravilha, Jaime A. Ramirez, Felipe Campelo

Hyper-Heuristics, Grammatical Evolution and the Capacitated Vehicle Routing Problem
Richard J. Marshall, Mark Johnston, Mengjie Zhang

On the Effectiveness of Genetic Algorithms for the Multidimensional Knapsack Problem
Jean P. Martins, Humberto Longo, Alexandre C. B. Delbem

Evolutionary Machine Learning

Uncovering Communities in Multidimensional Networks with Multiobjective Genetic Algorithms
Alessia Amelio, Clara Pizzuti

A Variable Kernel Function for Hybrid Unsupervised Kernel Regression
Daniel Lückehe, Oliver Kramer

Time-Series Forecasting with Evolvable Partially Connected Artificial Neural Network
Mina Moradi Kordmahalleh, Mohammad Gorji Sefidmazg, Abdollah Homaifar, Dukka B. K. C., Anthony Guiseppi-Elie

Novelty-Organizing Classifiers Applied to Classification and Reinforcement Learning: Towards Flexible Algorithms
Danilo Vasconcellos Vargas, Hirotaka Takano, Junichi Murata

Differential Evolution (DE) for Multi-Objective Feature Selection in Classification
Bing Xue, Wenlong Fu, Mengjie Zhang

Evolutionary Multiobjective Optimization

An Indicator-Based Chemical Reaction Optimization Algorithm for Multi-Objective Search
Abir Chaabani, Slim Bechikh, Lamjed Ben Said

Non-Dominated Sorting Differential Evolution with Improved Directional Convergence and Spread for Multi-objective Optimization
Wentao Guo, Xinjie Yu

Meta-Level Multi-Objective Formulations of Set Optimization for Multi-Objective Optimization Problems: Multi-Reference Point Approach to Hypervolume Maximization
Hisao Ishibuchi, Hiroyuki Masuda, Yusuke Nojima

Evolutionary Many-Objective Optimization Using Preference on Hyperplane
Kaname Narukawa, Yuki Tanigaki, Hisao Ishibuchi

MOEA/D with a Delaunay Triangulation Based Weight Adjustment
Yutao Qi, Xiaoliang Ma, Minglei Yin, Jingxuan We

On the Interrelationships Between Knees and Aggregate Objective Functions
Pradyumn Kumar Shukla, Marlon A. Braun, Hartmut Schmeck

Hybridization of NSGA-II with Greedy Re-Assignment for Variation Tolerant Logic Mapping on Nano-Scale Crossbar Architectures
Fugui Zhong, Bo Yuan, Bin Li

Generative and Developmental Systems

Nu-life: Spontaneous Dynamic Hierarchical Organization in a Non-Uniform "Life-like" Cellular Automata
Ben Cole, Michael Muthukrishna

Toward Organogenesis of Artificial Creatures
Jean Disset, Sylvain Cussat-Blanc, Yves Duthen

Deep Learning through Generative and Developmental Systems
Phillip Verbancsics, Joshua Harguess

Genetic Algorithms

Getting You Faster to Work — A Genetic Algorithm Approach to the Traffic Assignment Problem
Daniel Cagara, Ana L. C. Bazzan, Björn Scheuermann

Novel Virtual Fitness Evaluation Framework for Fitness Landscape Learning Evolutionary Computation
Taku Hasegawa, Kaname Matsumura, Kaiki Tsuchie, Naoki Mori, Keinosuke Matsumoto

The Creation and Facilitation of Speech and Language Therapy Sessions for Individuals with Aphasia
Conor Higgins, Conor Ryan, Aine Kearns, Mikael Fernstrom

A Novel Genetic Algorithm Based on Partitioning for Large-Scale Network Design Problems
Xiao-Ma Huang, Yue-Jiao Gong, Jing-Jing Li, Xiao-Min Hu

A Novel Genetic Algorithm Based on the Life Cycle of Dictyostelium
Kazuyuki Inoue, Naoki Mori, Keinosuke Matsumoto

Ancestral Networks in Evolutionary Algorithms
Karthik Kuber, Stuart W. Card, Kishan G. Mehrotra, Chilukuri K. Mohan

Search for the Most Reliable Network of Fixed Connectivity Using Genetic Algorithm
Ho Tat Lam, Kwok Yip Szeto

Assessing Different Architectures for Evolutionary Algorithms in JavaScript
Juan Julián Merelo, Pedro Castillo, Antonio Mora, Anna I. Esparcia-Alcázar, Víctor M. Rivas Santos

On Dedicated Evolutionary Algorithms for Large Non-Linear Constrained Optimization Problems
Janusz Orkisz, Maciej Głowacki

A Dimensional-Level Adaptive Differential Evolutionary Algorithm for Continuous Optimization
Ming Yang, Jing Guan, Zhihua Cai, Changhe Li

Evolutionary Computation for Lifetime Maximization of Wireless Sensor Networks in Complex 3D Environments
Xin-Yuan Zhang, Yue-Jiao Gong, Jing-Jing Li, Ying Lin

Genetic Programming

Efficient Interleaved Sampling of Training Data in Genetic Programming
R. Muhammad Atif Azad, David Medernach, Conor Ryan

Evolved Nonlinear Predictor Functions for Lossless Image Compression
Kevin M. Barresi

Predict the Success or Failure of an Evolutionary Algorithm Run
Gopinath Chennupati, Conor Ryan, R. Muhammad Atif Azad

CityBreeder: City Design with Evolutionary Computation
Adam T. S. Cohen, Tony White

Comparison of Linear Genetic Programming Variants for Symbolic Regression
Léo Françoso Dal Picco Sotto, Vinícius Veloso de Melo

Universal Information Distance for Genetic Programming
Marco Gaudesi, Giovanni Squillero, Alberto Tonda

On Improving Grammatical Evolution Performance in Symbolic Regression with Attribute Grammar
Muhammad Rezaul Karim, Conor Ryan

Evolving Differential Equations with Developmental Linear Genetic Programming and Epigenetic Hill Climbing
William La Cava, Lee Spector, Kourosh Danai, Matthew Lackner

A Comparison between Geometric Semantic GP and Cartesian GP for Boolean Functions Learning
Andrea Mambrini, Luca Manzoni

Incorporating Expert Knowledge in Object-Oriented Genetic Programming
Michael Richard Medland, Kyle Robert Harrison, Beatrice Ombuki-Berman

Effective Simplification of Evolved Push Programs Using a Simple, Stochastic Hill-Climber
Lee Spector, Thomas Helmuth

Towards a Quantum-Inspired Multi-Gene Linear Genetic Programming Model
Guilherme Cesário Strachan, Adriano Soares Koshiyama, Douglas Mota Dias, Marley Maria Bernardes Rebuzzi Vellasco, Marco Aurélio Cavalcanti Pacheco

GPGPU-Assisted Denoising Filter Generation for Video Coding
Seishi Takamura, Atsushi Shimizu

A Projection-Based Decomposition in EHW Method for Design of Relatively Large Circuits
Yanyun Tao, Yuzhen Zhang, Lijun Zhang, Chao Gu

Integrative Genetic and Evolutionary Computation

An Artificial Ecosystem Algorithm Applied to the Travelling Salesman Problem
Manal T. Adham, Peter J. Bentley

Risk Aversion and Mobility in the Public Goods Game
Michael Kirley, Friedrich Burkhard von der Osten

The Structure of an 8-state Finite Transducer Representation for Prisoner's Dilemma
Jeffrey Tsang

Enhancing the Differential Evolution with Convergence Speed Controller for Continuous Optimization Problems
Shujin Ye, Han Huang, Changjian Xu

Parallel Evolutionary Systems

GPU-Based Massively Parallel Quantum Inspired Genetic Algorithm for Detection of Communities in Complex Networks
Shikha Gupta, Naveen Kumar

Real World Applications

Darwin: A Ground Truth Agnostic CAPTCHA Generator Using Evolutionary Algorithm
Eric Y. Chen, Lin-Shung Huang, Ole J. Mengshoel, Jason D. Lohn

Using EMO to Completely Hide Sensitive Association Rules by Deleting Transactions
Peng Cheng, Jeng-Shyang Pan

Distributed Multi-Robot Search in The Real-World Using Modified Particle Swarm Optimization
Amirali Darvishzadeh, Bir Bhanu

Using Evolutionary Techniques to Analyze the Security of Quantum Key Distribution Protocols
Walter O. Krawec

Detection and Estimation of Unmodeled Narrowband Nonstationary Signals
Soumya D. Mohanty

Semi-Fragile Watermark Design for Detecting Illegal Two-Dimensional Barcodes by Evolutionary Multi-Objective Optimization
Satoshi Ono, Takeru Maehara, Kentaro Nakai, Ryo Ikeda, Koutaro Taniguchi

Multi-Objective Optimization Applied to Systematic Conservation Planning and Spatial Conservation Priorities under Climate Change
Shana Schlottfeldt, Jon Timmis, Maria Emilia M. T. Walter, André C. P. L. F. Carvalho, Jose Alexandre F. Diniz-Filho, Lorena M. Simon, Rafael D. Loyola, Mariana P. C. Telles

Evolution of Digital Modulation Schemes for Radio Systems
Ervin Teng, Derek Kozel, Bob Iannucci, Jason Lohn

Windmill Farm Pattern Optimization Using Evolutionary Algorithms
Charlie Vanaret, Nicolas Durand, Jean-Marc Alliot

Normalization Group Brain Storm Optimization for Power Electronic Circuit Optimization
Guang-Wei Zhang, Zhi-Hui Zhan, Ke-Jing Du, Wei-Neng Chen

Search Based Software Engineering

An Adaptive Memetic Algorithm Based on Multiobjecitve Optimization for Software Next Release Problem
Xin Cheng, Yuanyuan Huang, Xinye Cai, Ou Wei

Software Refactoring Under Uncertainty: A Robust Multi-Objective Approach
Mohamed Wiem Mkaouer, Marouane Kessentini, Slim Bechikh, Mel Ó Cinnéide, Kalyanmoy Deb

Learning from Evolved Next Release Problem Instances
Zhilei Ren, He Jiang, Jifeng Xuan, Shuwei Zhang, Zhongxuan Luo

Self-* Search

Fate Agent Evolutionary Algorithms with Self-Adaptive Mutation
Arthur Ervin Avramiea, Giorgos Karafotias, A. E. Eiben

Reinforcement Learning for Adaptive Operator Selection in Memetic Search Applied to Quadratic Assignment Problem
Stephanus Daniel Handoko, Duc Thien Nguyen, Zhi Yuan, Hoong Chuin Lau

Multi-Sample Evolution of Robust Black-Box Search Algorithms
Matthew A. Martin, Daniel R. Tauritz

Building Algorithm Portfolios for Memetic Algorithms
Mustafa Misir, Daniel Handoko, Hoong Chuin Lau

On the Locality of Neural Meta-Representations
Lus F. Simões, A. E. Eiben

Theory

OneMax Helps Optimizing XdivK: Theoretical Runtime Analysis for RLS and EA+RL
Maxim Buzdalov, Arina Buzdalova

NM Landscapes: Beyond NK
Narine Manukyan, Margaret J. Eppstein, Jeffrey S. Buzas

Best Paper Nominations

Candidates for Best Paper Awards at GECCO are proposeed by the reviewers and nominated by the track chairs and Editor-in-Chief. The winners are chosen in secret ballot votes by the GECCO attendees after the papers have been presented at the conference. The titles and authors of all nominated papers, along with nomination statements by the track chairs, are given below.

Ant Colony Optimization and Swarm Intelligence

SPSO2011 – Analysis of Stability, Local Convergence, and Rotation Sensitivity
Mohammad Reza Bonyadi, Zbigniew Michalewicz

This paper sheds light on parameter selection of an important PSO variant by studying its stability, convergence, and rotational invariance. Unlike other works on similar topics, the dimensionality of the problem is shown to play a significant role in parameter setting. We expect the community to greatly benefit from Bonyadi and Michalewicz's work.

Marco A. Montes de Oca
Konstantinos E. Parsopoulos

Anticipatory Stigmergic Collision Avoidance under Noise
Friedrich Burkhard von der Osten, Michael Kirley, Tim Miller

This paper introduces a novel scheme based on stigmergic principles where pheromones are not related to previous actions but rather on intended future actions. Through this scheme it is possible to reduce conflicts among agents, and therefore, it may be used for increasing the efficiency of a swarm. The scheme is shown to be very robust in agent-based simulations of reactive path planning and obstacle avoidance under noise.

Marco A. Montes de Oca
Konstantinos E. Parsopoulos

Artificial Immune Systems

On the Runtime Analysis of Stochastic Ageing Mechanisms
Pietro S. Oliveto, Dirk Sudholt

The paper considers the use of different ageing operators within artificial immune systems in both static and dynamic settings. It contributes significantly to the understanding of how and why ageing can be useful by presenting an elegant and sound theoretical analysis. The paper which is accessible to both, theoreticians and practitioners, is an excellent contribution that will highly benefit not only the field of artificial immune systems but the wider GECCO community by introducing new concepts to the algorithmic toolbox to tackle practical problems.

Emma Hart
Christine Zarges

Artificial Life, Robotics, and Evolvable Hardware

Overcoming Deception in Evolution of Cognitive Behavior
Joel Lehman, Risto Miikkulainen

The paper was recognized by reviewers for revealing a potentially important insight into the conditions that lead to the evolution of cognitive-level behavior. In short, objective-driven or goal-oriented fitness functions may be less effective than more open-ended evolution for achieving cognitive capabilities. The reviewers' comments stand for themselves: "A truly excellent paper." "Really cool paper." "A very good work on an important topic."

Thomas Schmickl
Kenneth O. Stanley

A Novel Human-Computer Collaboration: Combining Novelty Search with Interactive Evolution
Brian Woolley, Kenneth O. Stanley

This paper describes a novel method named "NA-IEC" which is combining interactive evolution and novelty search. This novel approach is shown to increase the speed of evolution compared to other state-of-the-art methods. The study contains several well-motivated experiments with a self-critical discussion of the gained results. This is leading to interesting conclusions and a strong argumentation of this novel method, bringing it into the context of the work of the scientific community.

Thomas Schmickl

Digital Entertainment and Arts

Evolving Multimodal Behavior With Modular Neural Networks in Ms. Pac-Man
Jacob Schrum, Risto Miikkulainen

This paper convincingly shows not only that Ms. Pac-Man is a multimodal problem, but also that this can be solved with a modular neural network and that the task decomposition can be found automatically through evolution. These results are important both for the study of modular neural networks, and for the development of high-performing game and robot controllers.

Christian Jacob
Julian Togelius

Evolution Strategies and Evolutionary Programming

A Computationally Efficient Limited Memory CMA-ES for Large Scale Optimization
Ilya Loshchilov

The paper pens a new direction for scaling covariance matrix adaptation to search and optimization in extremely high-dimensional search spaces. The algorithm allows for the application of modern evolution strategies to novel application areas and hence addresses a highly relevant problem. The presented linear time low-rank covariance matrix update is elegant, theoretically sound, and effective.

Anne Auger
Tobias Glasmachers

Evolutionary Combinatorial Optimization and Metaheuristics

A Heuristic Approach to Schedule Reoptimization in the Context of Interactive Optimization
David Meignan

This paper proposes a new heuristic approach to the reoptimization of schedules, which is a task that frequently arises in practical situations, where experts assess and adjust solutions before taking final decisions. A detailed experimental study clearly establishes the effectiveness and the adequacy of the proposed approach.

Günther Raidl
Thomas Stützle

Revised Analysis of the (1+1) EA for the Minimum Spanning Tree Problem
Carsten Witt

Making use of recent, advanced proof techniques, the paper provides improved upper bounds for the running time of a (1+1) EA on the minimum spanning tree problem, a paradigmatic combinatorial problem optimization problem that has received significant attention in recent theoretical work in evolutionary combinatorial computation.

Günther Raidl
Thomas Stützle

Evolutionary Machine Learning

Salient Object Detection Using Learning Classifier Systems that Compute Action Mappings
Muhammad Iqbal, Syed Naqvi, Will N. Browne, Christopher Hollitt, Mengjie Zhang

This is a solid paper showing the applicability of evolutionary machine learning methods to real-world problems, particularly in the computer vision task of salient objects detection. The method presented in this paper leverages on existing computer vision methods and provides added-value on top of these in the form of white-box prediction models from which it is straightforward to extract explanations of the method's predictions

Jaume Bacardit
Tom Schaul

Evolutionary Multiobjective Optimization

Inverted PBI in MOEA/D and Its Impact on the Search Performance on Multi and Many-Objective Optimization
Hiroyuki Sato

The paper adds a simple-looking idea (the kind you wish you'd had yourself) to an already excellent algorithm, MOEA/D, to improve diversity preservation. The idea is to angle the contour lines of the utility functions so that solutions are strongly rewarded for staying close to a particular region in objective space, defined by the weight vectors. Results are promising on a range of problems, especially many-objective ones.

Dimo Brockhoff
Joshua D. Knowles

An Improved NSGA-III Procedure for Evolutionary Many-Objective Optimization
Yuan Yuan, Hua Xu, Bo Wang

The paper contributes a new form of dominance relation called theta-dominance which shows significantly improved results within the recent NSGA-III algorithm in the many-objective scenario of optimizing four or more objective functions simultaneously. A sound experimental method compares the approach to other leading techniques and provides evidence of the robustness of the method with respect to a key parameter choice.

Dimo Brockhoff
Joshua D. Knowles

Generative and Developmental Systems

Some Distance Measures for Morphological Diversification in Generative Evolutionary Robotics
Eivind Samuelsen, Kyrre Glette

Papers advocating diversity or novelty search (basing fitness of a solution, partially or entirely, on how different it is from previously visited solutions) have often applied it in low-dimensional spaces using simple metrics of phenotypic distance, but it has not been clear whether the benefits of rewarding diversity can be extended to high-dimensional problems. In contrast, this paper studies a complex problem domain – locomotion in physically simulated robots with both evolved morphology and control systems. The results highlight the care required to define a useful phenotypic distance metric in high-dimensional spaces: three apparently reasonable metrics hurt overall performance; one helps significantly.

Michael Palmer
Sebastian Risi

Genetic Algorithms

Parameter-less Population Pyramid
Brian W. Goldman, William F. Punch

The paper is a new approach on the old problem of designing a genetic algorithm that gets rid of the problem of finding appropriate parameter setting. The new algorithm shows very impressive performance on a range of different test problems and in comparison with a number of competing algorithms. Among the strengths of the paper are presenting the algorithm together with a thorough empirical evaluation and theoretical analysis.

Kalyanmoy Deb
Thomas Jansen

A Fixed Budget Analysis of Randomized Search Heuristics for the Traveling Salesperson Problem
Samadhi Nallaperuma, Frank Neumann, Dirk Sudholt

The paper is the first to apply the perspective of fixed-budget computations to an NP-hard optimization problem. It tackles one of the best known and most studied such problems, the traveling salesperson problem (TSP), and proves a number of meaningful and relevant lower bounds for the performance of a simple evolutionary algorithm and local search for large classes of TSP instances. The paper is an excellent example of theoretical research delivering tangible results by not restricting the analysis to toy problems.

Kalyanmoy Deb
Thomas Jansen

Genetic Programming

Evolving "Less-Myopic" Scheduling Rules for Dynamic Job Shop Scheduling with Genetic Programming
Rachel J. Hunt, Mark Johnston, Mengjie Zhang

Dispatching rules are frequently used in job-shop scheduling (JSS) tasks as a local heuristic for deciding what task to perform next at each machine comprising a (job-shop) manufacturing facility. However, they also lack many properties found in more global scheduling mechanisms. This work addresses the question of evolving programs to provide less myopic (more globally general) dispatching rules that still retain the local operational properties that make dispatching rules popular from an application perspective.

Malcolm I. Heywood
William B. Langdon

Behavioral Programming: A Broader and More Detailed Take on Semantic GP
Krzysztof Krawiec, Una-May O'Reilly

Generic behavioural fitness measures that guide evolution towards the overall objective without leading to local minima are potentially fundamental to scaling GP to larger tasks. An approach is proposed that uses lists of internal program state during execution to bias the identification of code segments for archiving and reuse. Evaluation over 35 benchmarks demonstrates significant improvements while little computational overhead is encountered.

Malcolm I. Heywood
William B. Langdon

Parallel Evolutionary Systems

Design and Analysis of Adaptive Migration Intervals in Parallel Evolutionary Algorithms
Andrea Mambrini, Dirk Sudholt

Theory is often guiltily neglected in most articles and research lines today, but there is still much to discuss and discover about parallel evolutionary systems. The authors of the paper we nominated propose a new migration scheme, a most relevant factor in the distributed parallel model, and theoretically analyze its influence on the behaviour of the parallel algorithm that relies on it. The method and the results described by the authors can definitely contribute to the creation of a more solid body of knowledge about parallel metaheuristics.

Stefano Cagnoni
Gabriel Luque

Real World Applications

Multi-Objective Routing Optimisation for Battery Powered Wireless Sensor Mesh Networks
Jonathan Edward Fieldsend, Richard Everson, Alma As-Aad Mohammad Rahat

The paper describes the adaptation and use of a multi-objective optimization algorithm to a real world application very well. The illustration of the MOO applied to WSNs for the Victoria & Albert Museum London is an excellent example for applying techniques from natural computation to realistic problem scenarios.

Hitoshi Iba
Bernhard Sendhoff

On Homogenization of Coal in Longitudinal Blending Beds
Pradyumn Kumar Shukla, Michael Cipold, Claus Bachmann, Hartmut Schmeck

The paper is an exceptionally well written description of the adaptation of evolutionary computation to the needs of an industrially relevant real-world application. The problem description is comprehensible to the computational intelligence researcher, the algorithmic instantiation of the optimization method is well described and the analysis is scientifically sound.

Hitoshi Iba
Bernhard Sendhoff

Search Based Software Engineering

On the Performance of Multiple Objective Evolutionary Algorithms for Software Architecture Discovery
Aurora Ramirez, José Raúl Romero, Sebastian Ventura

This paper tackles the problem of finding the most suitable software architecture for a system, whose discovery is realized by means of evolutionary algorithms. The authors explore the performance (considered in terms of a number of different practical aspects) of a set of multi- and many-objective algorithms. The methodology is clearly described, and the empirical analysis for comparison between the five different algorithms is applied to the same experimental data using the same the encoding, genetic operators, and evaluation objectives.

Marouane Kessentini
Guenther Ruhe

Theory

Evolution under Partial Information
Duc-Cuong Dang, Per Kristian Lehre

The paper addresses, by mathematical means, a major challenge in evolutionary computation, namely how to efficiently solve problems when the fitness of individuals or populations can only partially be evaluated. Using advanced drift analysis and fitness level methods, the authors succeed in distilling conditions that allow efficient optimization despite such difficulties. Their results in particular indicate that large parent populations are beneficial.

Benjamin Doerr
Carsten Witt

Abstracts by Track

Ant Colony Optimization and Swarm Intelligence

ACO-SI1

Ant Colony Optimization with Group Learning

Gunnar Völkel, *Ulm University*, Markus Maucher, *Ulm University*, Uwe Schöning, *Ulm University*, Hans A. Kestler, *Ulm University*

We introduce Group Learning for Ant Colony Optimization applied to combinatorial optimization problems with group-structured solution encodings. In contrast to the common assignment of one pheromone value per solution component in Group Learning each solution component has one pheromone value per group. Hence, the algorithm has the possibility to learn the optimal group membership of the components. We present different strategies for Group Learning and evaluate these in simulation experiments for the Vehicle Routing Problem with Time Windows using the problem instances of Solomon. We describe a revised Ant Colony System (ACS) algorithm which does not use a local pheromone update while maintaining the general ideas of ACS. We evaluate the revised ACS experimentally comparing it to the original ACS. Our experimental results show that Group Learning is a valuable modification for Ant Colony Optimization. Additionally, the results indicate that the revised ACS performs at least as well as the original algorithms.

Energy Aware Virtual Machine Placement Scheduling in Cloud Computing Based on Ant Colony Optimization Approach

Xiao-Fang Liu, *Sun Yat-sen University*, Zhi-Hui Zhan, *Sun Yat-sen University*, Ke-Jing Du, *City University of Hong Kong*, Wei-Neng Chen, *Sun Yat-sen University*

Cloud computing provides resources as services in pay-as-you-go mode to customers by using virtualization technology. As virtual machine (VM) is hosted on physical server, great energy is consumed by maintaining the servers in data center. More physical servers means more energy consumption and more money cost. Therefore, the VM placement (VMP) problem is significant in cloud computing. This paper proposes an approach based on ant colony optimization (ACO) to solve the VMP problem, named as ACO-VMP, so as to effectively use the physical resources and to reduce the number of running physical servers. The number of physical servers is the same as the number of the VMs at the beginning. Then the ACO approach tries to reduce the physical server one by one. We evaluate the performance of the proposed ACO-VMP approach in solving VMP with the number of VMs being up to 600. Experimental results compared with the ones obtained by the first-fit decreasing (FFD) algorithm show that ACO-VMP can solve VMP more efficiently to reduce the number of physical servers significantly, especially when the number of VMs is large.

Anticipatory Stigmergic Collision Avoidance under Noise

Friedrich Burkhard von der Osten, *University of Melbourne*, Michael Kirley, *University of Melbourne*

Reactive path planning to avoid collisions with moving obstacles enables more robust agent systems. However, many solutions assume that moving objects are passive; that is, they do not consider that the moving objects are themselves re-planning to avoid collisions, and thus may change their trajectory. In this paper we present a model, Anticipatory Stigmergic Collision Avoidance (ASCA) for reciprocal collision avoidance using anticipatory stigmergy. Unlike standard stigmergy, in which agents leave pheromones to indicate a trace of previous actions, anticipatory stigmergy deposits pheromones on intended future paths. By sharing their intended future paths with each other at regular intervals, agents can re-plan to attempt to avoid collisions. We experimentally evaluate ASCA over three scenarios, and compare with a state of art approach, Reciprocal Velocity Obstacles (RVO). Our evaluation showed that ASCA is consistently more robust in noisy environments in which transmitted information can be lost or degraded. Further, using ASCA without noise results in fewer collisions than RVO when agents are in formation, but more collisions when formed randomly.

SPSO2011 — Analysis of Stability, Local Convergence, and Rotation Sensitivity

Mohammad Reza Bonyadi, *University of Adelaide*, Zbigniew Michalewicz, *University of Adelaide*

In a particle swarm optimization algorithm (PSO) it is essential to guarantee convergence of particles to a point in the search space (this property is called stability of particles). It is also important that the PSO algorithm converges to a local optimum (this is called the local convergence property). Further, it is usually expected that the performance of the PSO algorithm is not affected by rotating the search space (this property is called the rotation sensitivity). In this paper, these three properties, i.e., stability of particles, local convergence, and rotation sensitivity are investigated for a variant of PSO called Standard PSO2011 (SPSO2011). We experimentally define boundaries for the parameters of this algorithm in such a way that if the parameters are selected in these boundaries, the particles are stable, i.e., particles converge to a point in the search space. Also, we show that, unlike earlier versions of PSO, these boundaries are dependent on the number of dimensions of the problem. Moreover, we show that the algorithm is not locally convergent in general case. Finally, we provide a proof and experimental evidence that the algorithm is rotation invariant.

ACO-SI2

A Tribal Ecosystem Inspired Algorithm (TEA) for Global Optimization

Ying Lin, *Sun Yat-sen University*, Jing-Jing Li, *South China Normal University*, Jun Zhang, *Sun Yat-sen University*, Meng Wan, *Chinese Ministry of Education*

Evolution mechanisms of different biological and social systems

have inspired a variety of evolutionary computation (EC) algorithms. However, most existing EC algorithms simulate the evolution procedure at the individual-level. This paper proposes a new EC mechanism inspired by the evolution procedure at the tribe-level, namely tribal ecosystem inspired algorithm (TEA). In TEA, the basic evolution unit is not an individual that represents a solution point, but a tribe that covers a subarea in the search space. More specifically, a tribe represents the solution set locating in a particular subarea with a coding structure composed of three elements: tribal chief, attribute diversity, and advancing history. The tribal chief represents the locally best-so-far solution, the attribute diversity measures the range of the subarea, and the advancing history records the local search experience. This way, the new evolution unit provides extra knowledge about neighborhood profiles and search history. Using this knowledge, TEA introduces four evolution operators, reforms, self-advance, synergistic combination, and augmentation, to simulate the evolution mechanisms in a tribal ecosystem, which evolves the tribes from potentially promising subareas to the global optimum. The proposed TEA is validated on benchmark functions. Comparisons with three representative EC algorithms confirm its promising performance.

Stepsize Control on the Modified Bacterial Foraging Algorithm for Constrained Numerical Optimization

Betania Hernández-Ocaña, *Universidad Juárez Autónoma de Tabasco*, María de Pilar Pozos-Parra, *Universidad Juárez Autónoma de Tabasco*, Efrén Mezura-Montes, *Universidad Veracruzana*

The stepsize value is one of the most sensitive parameters in the bacterial foraging optimization algorithm when solving constrained numerical optimization problems. In this paper, four stepsize control mechanisms are proposed and analyzed in the modified bacterial foraging optimization algorithm. The first one is based on a random value which remains fixed during the search, the second one generates a random value per cycle, the third one is based on a nonlinear decreasing function and the last one is an adaptive approach. Seven experiments are proposed to evaluate the abilities of each mechanism to: (1) obtain competitive final results, (2) find feasible solutions, (3) find the feasible global optimum, (4) promote successful swims, and (5) decrease the constraint violation. A comparison against two state-of-the-art algorithms is considered to evaluate the performance of the most competitive control mechanism. A well-known set of constrained numerical optimization problems is used in the experiments as well as six performance measures. The results obtained show that the control mechanism based on the nonlinear decreasing function is the most competitive and provides the ability to generate better solutions late in the search.

Differential Evolution Using Mutation Strategy with Adaptive Greediness Degree Control

Wei-Jie Yu, *Sun Yat-sen University*, Jing-Jing Li, *South China Normal University*, Jun Zhang, *Sun Yat-sen University*, Meng Wan, *Chinese Ministry of Education*

Differential evolution (DE) has been demonstrated to be one of the most promising evolutionary algorithms (EAs) for global numerical optimization. DE mainly differs from other EAs in that it employs difference of the parameter vectors in mutation operator to search the objective function landscape. Therefore, the performance of a DE algorithm largely depends on the design of its mutation strategy. In this paper, we propose a new kind of DE mutation strategies whose greediness degree can be adaptively adjusted. The proposed mutation strategies utilize the information of top t solutions in the current population. Such a greedy strategy is beneficial to fast convergence performance. In order to adapt the degree of greediness to fit for different optimization scenarios, the parameter t is adjusted in each generation of the algorithm by an adaptive control scheme. This way, the convergence performance and the robustness of the algorithm can be enhanced at the same time. To evaluate the effectiveness of the proposed adaptive greedy mutation strategies, the approach is applied to original DE algorithms, as well as DE algorithms with parameter adaptation. Experimental results indicate that the proposed adaptive greedy mutation strategies yield significant performance improvement for most of cases studied.

Automatic Path Planning for Autonomous Underwater Vehicles Based on an Adaptive Differential Evolution

Chuan-Bin Zhang, *Sun Yat-sen Univerisity*, Yue-Jiao Gong, *Sun Yat-sen University*, Jing-Jing Li, *South China Normal University*, Ying Lin, *Sun Yat-sen University*

This paper proposes a path planner for autonomous underwater vehicles (AUVs) in 3-D underwater space. We simulate an underwater space with rugged seabed and suspending obstacles, which is close to real world. In the proposed representation scheme, the problem space is decomposed into parallel subspaces and each subspace is described by a grid method. The paths of AUVs are simplified as a set of successive points in the problem space. By jointing these waypoints, the entire path of the AUV is obtained. A cost function with penalty method takes into account the length, energy consumption, safety and curvature constraints of AUVs. It is applied to evaluate the quality of paths. Differential evolution (DE) algorithm is used as a black-box optimization tool to provide optimal solutions for the path planning. In addition, we adaptively adjust the parameters of DE according to population distribution and the blockage of parallel subspaces so as to improve its performance. Experiments are conducted on 6 different scenarios. The results validate that the proposed algorithm is effective for improving solution quality and avoiding premature convergence.

ACO-SI3

Identifying and Exploiting the Scale of a Search Space in Particle Swarm Optimization

Yasser Gonzalez-Fernandez, *York University*, Stephen Chen, *York University*

Multi-modal optimization involves two distinct tasks: identify-

ing promising attraction basins and finding the local optima in these basins. Unfortunately, the second task can interfere with the first task if they are performed simultaneously. Specifically, the promise of an attraction basin is often estimated by the fitness of a single sample solution, so an attraction basin represented by a random sample solution can appear to be less promising than an attraction basin represented by its local optimum. The goal of thresheld convergence is to prevent these biased comparisons by disallowing local search while global search is still in progress. Ideally, thresheld convergence achieves this goal by using a distance threshold that is correlated to the size of the attraction basins in the search space. In this paper, a clustering-based method is developed to identify the scale of the search space which thresheld convergence can then exploit. The proposed method employed in the context of a multi-start particle swarm optimization algorithm has led to large improvements across a broad range of multi-modal problems.

An Improved Multi-Start Particle Swarm-Based Algorithm for Protein Structure Comparison

Hazem Radwan Ahmed, *Queen's University*, Janice I. Glasgow, *Queen's University*

This paper proposes a novel particle-swarm based approach for protein structure alignment and comparison. Applying heuristic search to discover similar protein substructure patterns can be easily trapped in certain regions of the sparse and challenging problem search space. Diversification, or restarting the heuristic search, is one of the common strategies used to escape local optima. Agile Particle Swarm Optimization (APSO) is a recent multi-start PSO that addresses the question of when to best restart swarm particles. This paper focuses on where and how to restart the swarm. Another challenge of applying a heuristic search to protein structures is that the fitness landscape does not necessarily guide to the optimal region. To address this issue, we propose the Targeted Agile PSO (TA-PSO) that uses a dynamic window-based search for automatic, variable-size pattern discovery in protein structures. The TA-PSO automatically builds a guiding list of potential patterns and uses it during the search process, which helps to find better solutions faster. The proposed TA-PSO showed up to 4 times improved performance that is approximately 3.5 times faster and 6 times more robust/consistent compared with the traditional "non-targeted" search.

Consensus Costs and Conflict in a Collective Movement

Timothy Solum, *Southern Nazarene University*, Brent E. Eskridge, *Southern Nazarene University*, Ingo Schlupp, *University of Oklahoma*

Aggregation, whether it be in natural or artificial systems, provides numerous benefits to both the individual and the group. However, aggregation has costs and frequently involves inter-individual conflict. Although conflicts in natural systems is understood to be at times beneficial, as well as detrimental, conflict in artificial systems, such as a team of robots, is frequently viewed as inhibiting consensus and, therefore, success. This is particularly the case in large-scale aggregations where ensuring consensus is especially challenging. In response, mechanisms are often integrated into the group's control systems to minimize, or even eliminate, conflicts of interest. As a result, the potential benefits of losing consensus, such as increased diversity and reduced consensus costs, are not available. Using a biologically-based collective movement model, we demonstrate that not enforcing consensus and allowing conflict to evolve as agents make decisions results in a system in which agents meet their own needs, thus minimizing consensus costs, while still maintaining group cohesion when possible. Simulations predict that conflict balances consensus costs with individual preferences such that both individual and group goals are met.

Constrained Multi-Objective Aerodynamic Shape Optimization via Swarm Intelligence

Saul Zapotecas Martinez, *Shinshu University*, Alfredo Arias Montaño, *ESIME-IPN*, Carlos A. Coello Coello, *CINVESTAV-IPN*

In this paper, we present a Multi-Objective Particle Swarm Optimizer (MOPSO) based on a decomposition approach, which is proposed to solve Constrained Multi-Objective Aerodynamic Shape Optimization Problems (CMO-ASOPs). The constraint-handling technique adopted in this approach is based on the well-known epsilon-constraint method. Since the ε-constraint method was initially proposed to deal with constrained single-objective optimization Problems, we adapted it so that it could be incorporated into a MOPSO. Our main focus is to solve CMO-ASOPs in an efficient and effective manner. The proposed constrained MOPSO guides the search by updating the position of each particle using a set of solutions considered as the global best according to both the decomposition approach and the epsilon-constraint method. Our preliminary results indicate that our proposed approach is able to outperform a state-of-the-art MOEA in several CMO-ASOPs.

Artificial Immune Systems

AIS

A Generic Finite Automata Based Approach to Implementing Lymphocyte Repertoire Models

Johannes Textor, *Universiteit Utrecht*, Katharina Dannenberg, *Universität zu Lübeck*, Macie Liskiewicz, *Universität zu Lübeck*

Artificial immune systems (AIS) inspired by lymphocyte repertoires include negative and positive selection, clonal selection, and B cell algorithms. Such AISs are used in computer science

for machine learning and optimization, and in biology for modeling of fundamental immunological processes. In both cases, the necessary size of repertoire models can be huge. Here, we show that when lymphocyte repertoire models based on string patterns can be compactly represented as finite automata (FA), this allows to efficiently perform negative selection, positive selection, insertion into, deletion from, uniform sampling from, and counting the repertoire. Specifically, for r-contiguous pattern matching, all these tasks can be performed in polynomial time. But even in NP-hard cases like Hamming distance matching, the FA representation can still lead to practically important efficiency gains. We demonstrate the feasibility and flexibility of this approach by implementing T cell positive selection simulations based on human genomic data using four different pattern rules. Hence, FA-based repertoire models generalize previous efficient negative selection algorithms to perform several related algorithmic tasks, are easy to implement and customize, and are applicable to real-world bioinformatic problems.

An Improved Immune Inspired Hyper-Heuristic for Combinatorial Optimisation Problems

Kevin Sim, *Edinburgh Napier University*, Emma Hart, *Edinburgh Napier University*

The meta-dynamics of an immune-inspired optimisation system NELLI are considered. NELLI has previously shown to exhibit good performance when applied to a large set of optimisation problems by sustaining a network of novel heuristics. We address the mechanisms by which new heuristics are defined and subsequently generated. A new representation is defined, and a mutation-based operator inspired by clonal-selection introduced to control the balance between exploration and exploitation in the generation of new network elements. Experiments show significantly improved performance over the existing system in the bin-packing domain. New experiments in the job-scheduling domain further show the generality of the approach.

A Two-Leveled Hybrid Dendritic Cell Algorithm Under Imprecise Reasoning

Zeineb Chelly, *University of Tunis*, Zied Elouedi, *University of Tunis*

The Dendritic Cell Algorithm (DCA) is a bio-inspired algorithm based on the behavior of Dendritic Cells (DCs). The DCA performance relies on its data pre-processing phase where feature extraction and signal categorization are performed and which are based on the use of the Principal Component Analysis(PCA) technique. However, using PCA presents a limitation as it destroys the underlying semantics of the features after reduction. To overcome this limitation, Rough Set Theory (RST) was applied as a pre-processor; but, still the developed rough approach presents an information loss as data should be discretized beforehand. Indeed, DCA was known to be sensitive to the input class data order. This is due to the crisp separation between the two DCs contexts; semi-mature and mature. Thus, the aim of this paper is to develop a novel DCA version based on a two-leveled hybrid model handling the mentioned DCA shortcomings. In the top-level, our proposed algorithm applies a more adequate feature extraction technique based on Fuzzy Rough Set Theory (FRST) to build a solid data pre-processing phase. At the bottom level, our algorithm applies Fuzzy Set Theory to smooth the crisp separation between the DCs contexts. Results show that our proposed algorithm succeeds in obtaining significantly improved classification accuracy.

Clonal Selection Based Fuzzy C-Means Algorithm for Clustering

Simone A. Ludwig, *North Dakota State University*

In recent years, fuzzy based clustering approaches have shown to outperform state-of-the-art hard clustering algorithms in terms of accuracy. The difference between hard clustering and fuzzy clustering is that in hard clustering each data point of the data set belongs to exactly one cluster, and in fuzzy clustering each data point belongs to several clusters that are associated with a certain membership degree. Fuzzy c-means clustering is a well-known and effective algorithm, however, the random initialization of the centroids directs the iterative process to converge to local optimal solutions easily. In order to address this issue a clonal selection based fuzzy c-means algorithm (CSFCM) is introduced. CSFCM is compared with the basic Fuzzy C-Means (FCM) algorithm, a genetic algorithm based FCM algorithm, and a particle swarm optimization based FCM algorithm.

BP2

On the Runtime Analysis of Stochastic Ageing Mechanisms

Pietro S. Oliveto, *University of Sheffield*, Dirk Sudholt, *University of Sheffield*

Ageing operators are applied in the field of artificial immune systems (AIS) to increase the diversity of the population during the optimization process. Previous theoretical analyses have shown how static ageing operators can successfully escape local optima by implicitly performing a restart of the algorithm. However, showing naturally that ageing in an AIS is more effective than a conceptually simpler restart strategy has proved to be a hard task. We present a rigorous analysis of stochastic ageing mechanisms and show that superior performance compared to just simple restarts can be achieved. Since standard stochastic pure ageing is only effective for small population sizes, we present a hybrid pure ageing operator that achieves the same performance independent of the population size. For a benchmark function used in dynamic optimisation we rigorously prove that hybrid pure ageing allows to escape local optima beyond restarts while static pure ageing is inefficient. The results also apply to the non-dynamic setting. An analytical general framework for the analysis of standard stochastic pure ageing is presented along the way.

Artificial Life, Robotics, and Evolvable Hardware

ALIFE1

Automated Generation of Environments to Test the General Learning Capabilities of AI Agents

Oliver J. Coleman, *University of New South Wales*, Alan D. Blair, *University of New South Wales*, Jeff Clune, *University of Wyoming*

Algorithms for evolving agents that learn during their lifetime have typically been evaluated on only a handful of environments. Designing such environments is labour intensive, potentially biased, and provides only a small sample size that may prevent accurate general conclusions from being drawn. In this paper we introduce a method for automatically generating MDP environments which allows the difficulty to be scaled in several ways. We present a case study in which environments are generated that vary along three key dimensions of difficulty: the number of environment configurations, the number of available actions, and the length of each trial. The study reveals interesting differences between three neural network models – Fixed-Weight, Plastic-Weight, and Modulated Plasticity – that would not have been obvious without sweeping across these different dimensions. Our paper thus introduces a new way of conducting reinforcement learning science: instead of manually designing a few environments, researchers will be able to automatically generate a range of environments across key dimensions of variation. This will allow scientists to more rigorously assess the general learning capabilities of an algorithm, and may ultimately improve the rate at which we discover how to create AI with general purpose learning.

Generational Neuro-Evolution: Restart and Retry for Improvement

David Peter Shorten, *University of Cape Town*, Geoffrey Stuart Nitschke, *University of Cape Town*

This paper proposes a new Neuro-Evolution (NE) method for automated controller design in agent-based systems. The method is Generational Neuro-Evolution (GeNE), and is comparatively evaluated with established NE methods in a multi-agent predator-prey task. This study is part of an ongoing research goal to derive efficient (minimising convergence time to optimal solutions) and scalable (effective for increasing numbers of agents) controller design methods for adapting agents in neuro-evolutionary multi-agent systems. Dissimilar to comparative NE methods, GeNE employs tiered selection and evaluation as its generational fitness evaluation mechanism and, furthermore, re-initializes the population each generation. Results indicate that GeNE is an appropriate controller design method for achieving efficient and scalable behavior in a multi-agent predator-prey task, where the goal was for multiple predator agents to collectively capture a prey agent. GeNE outperforms comparative NE methods in terms of efficiency (minimising the number of genotype evaluations to attain optimal task performance).

Directional Communication in Evolved Multiagent Teams

Justin K. Pugh, *University of Central Florida*, Skyler Goodell, *University of Central Florida*, Kenneth O. Stanley, *University of Central Florida*

The question of how to best design a communication architecture is becoming increasingly important for evolving autonomous multiagent systems. Directional reception of signals, a design feature of communication that appears in most animals, is present in only some existing artificial communication systems. This paper hypothesizes that such directional reception benefits the evolution of communicating autonomous agents because it simplifies the language required to express positional information, which is critical to solving many group coordination tasks. This hypothesis is tested by comparing the evolutionary performance of several alternative communication architectures (both directional and non-directional) in a multiagent foraging domain designed to require a basic "come here" type of signal for the optimal solution. Results confirm that directional reception is a key ingredient in the evolutionary tractability of effective communication. Furthermore, the real world viability of directional reception is demonstrated through the successful transfer of the best evolved controllers to real robots. The conclusion is that directional reception is important to consider when designing communication architectures for more complicated tasks in the future.

Evolution of Biologically Plausible Neural Networks Performing a Visually Guided Reaching Task

Derrik E. Asher, *University of California Irvine*, Jeffrey L. Krichmar, *University of California Irvine*, Nicolas Oros, *University of California Irvine*

An evolutionary strategy (ES) algorithm was utilized to evolve a simulated neural network based on the known anatomy of the posterior parietal cortex (PPC), to perform a visually guided reaching task. In this task, a target remained visible for the duration of a trial, and an agents goal was to move its hand to the target as rapidly as possible and remain for the duration of that trial. The ES was used to tune the strength of 15609 connections between neural areas and 4 parameters governing the neural dynamics. The model had sensory latencies replicating those found in recording studies with monkeys. The ES ran 100 times and generated very diverse networks that could all perform the task well. The evolved networks 1) showed velocity profiles consistent with biological movements, and 2) found solutions that reflect short-range excitation and long-range, contralateral inhibition similar to neurobiological networks. These results provide theoretical evidence for the important parameters and projections governing sensorimotor transformations in neural systems.

ALIFE2

Overcoming Deception in Evolution of Cognitive Behaviors

Joel Lehman, *University of Texas at Austin*, Risto Miikkulainen,

University of Texas at Austin

When scaling neuroevolution to complex behaviors, cognitive capabilities such as learning, communication, and memory become increasingly important. However, successfully evolving such cognitive abilities remains difficult. This paper argues that a main cause for such difficulty is deception, i.e., evolution converges to a behavior unrelated to the desired solution. More specifically, cognitive behaviors often require accumulating neural structure that provides no immediate fitness benefit, and evolution often thus converges to non-cognitive solutions. To investigate this hypothesis, a common evolutionary robotics T-Maze domain is adapted in three separate ways to require agents to communicate, remember, and learn. Indicative of deception, evolution driven by objective-based fitness often converges upon simple non-cognitive behaviors. In contrast, evolution driven to explore novel behaviors, i.e., novelty search, often evolves the desired cognitive behaviors. The conclusion is that open-ended methods of evolution may better recognize and reward the stepping stones that are necessary for cognitive behavior to emerge.

A Novel Human-Computer Collaboration: Combining Novelty Search with Interactive Evolution

Brian G. Woolley, *U.S. Air Force Institute of Technology*, Kenneth O. Stanley, *University of Central Florida*

Recent work on novelty and behavioral diversity in evolutionary computation has highlighted the potential disadvantage of driving search purely through objective means. This paper suggests that leveraging human insight during search can complement such novelty-driven approaches. In particular, a new approach called novelty-assisted interactive evolutionary computation (NA-IEC) combines human intuition with novelty search to facilitate the serendipitous discovery of agent behaviors in a deceptive maze. In this approach, the human user directs evolution by selecting what is interesting from the on-screen population of behaviors. However, unlike in typical IEC, the user can now request that the next generation be filled with novel descendants. The experimental results demonstrate that combining human insight with novelty search not only finds solutions significantly faster and at lower genomic complexities than fully-automated processes guided purely by fitness or novelty, but it also finds solutions faster than the traditional IEC approach. Such results add to the evidence that combining human users and automated processes creates a synergistic effect in the search for solutions.

Encouraging Creative Thinking in Robots Improves Their Ability to Solve Challenging Problems

Jingyu Li, *University of Wyoming*, Jed Storie, *University of Wyoming*, Jeff Clune, *University of Wyoming*

Evolutionary algorithms frequently get stuck on local optima–and fail to find the global optimum–when local gradients do not point the search process toward the direction of the global optimum. A recent breakthrough called Novelty Search ameliorates this problem by enabling the search process to explore in every direction by encouraging the production of novel, or not-yet-seen, phenotypes (e.g., new robot behaviors). However, a problem with Novelty Search is that it can get lost on "novelty plateaus" wherein novel behaviors in offspring are not immediately produced by mutation and crossover (e.g., when a sequence of specific mutations is required to produce new behaviors, but the intermediate mutations are not rewarded because they do not produce novel behaviors). In such cases, Novelty Search and related approaches that reward behavioral diversity can get stuck. Here we introduce a new approach, borrowed from human psychology, that mitigates this problem: encouraging creative thinking. In addition to rewarding novel behavior, we encourage evolving neural networks to "think differently" by rewarding not-yet-seen firing patterns in hidden neurons, which we call the "Creative Thinking Approach." We hypothesize that encouraging novel thinking can reward stepping stones toward new behaviors. On a variety of challenging robotic control problems from previous publications we demonstrate that, as problem difficulty increases, adding the Creative Thinking Approach increasingly improves performance over simply encouraging novel behaviors. Our results suggest that the Creative Thinking Approach could help improve the scale and complexity of problems that can be solved by EAs.

Evolving Joint-Level Control with Digital Muscles

Jared M. Moore, *Michigan State University*, Philip K. McKinley, *Michigan State University*

The neuromuscular systems of animals are governed by extremely complex networks of control signals, sensory feedback loops, and mechanical interactions. Morphology and control are inherently intertwined. In the case of animal joints, groups of muscles work together to provide power and stability to move limbs in a coordinated manner. In contrast, many robot controllers handle both high-level planning and low-level control of individual joints. In this paper, we propose a joint-level control method, called digital muscles, that operates in a manner analogous to biological muscles, yet is abstract enough to apply to conventional robotic joints. An individual joint is controlled by multiple muscle nodes, each of which responds to a control signal according to a node-specific activation function. Evolving the physical orientation of muscle nodes and their respective activation functions enables relatively complex and coordinated gaits to be realized with simple high-level control. Even using a sinusoid as the high-level control signal, we demonstrate the evolution of effective gaits for a simulated quadruped. The proposed model realizes a control strategy for governing the behavior of individual joints, and can be coupled with a high-level controller that focuses on decision making and planning.

ALIFE3

Wolfpack-Inspired Evolutionary Algorithm and a Reaction-Diffusion-Based Controller are Used for Pattern Formation

Payam Zahadat, *Karl-Franzens-Universität Graz*, Thomas Schmickl, *Karl-Franzens-Universität Graz*

The implicit social structure of population groups have been pre-

viously investigated in the literature representing enhancements in the performance of optimization algorithms. Here we introduce an EA inspired by animal hunting groups (i.e., wolves). The algorithm implicitly maintains diversity in the population and performs higher than two state of the art EAs in the investigated case studies in this article. The case studies are to evolve a hormone-inspired system called AHHS (Artificial Homeostatic Hormone Systems) to develop spatial patterns. The complex spatial patterns are developed in the absence of any explicit spatial information. The results achieved by AHHS are presented and compared with a previous work with Artificial Neural Network (ANNs) indicating higher performance of AHHS.

The Evolution of Kin Inclusivity Levels

Anya E. Johnson, *Michigan State University*, Heather J. Goldsby, *University of Washington*, Sherri Goings, *Carleton College*, Charles Ofria, *Michigan State University*

Altruism is a ubiquitous strategy among organisms ranging from microbes to mammals. Inclusive fitness theory indicates that altruistic strategies can be beneficial when an altruist acts to benefit organisms that share its genes. It is common for such altruistic strategies to be negatively affected by cheaters that do not act altruistically. A more subtle form of cheating involves altruists that are more selective. For example, a selective organism may benefit from a distant kin's altruistic actions without reciprocating. We consider an organism's kin inclusivity level to be the maximum number of mutational differences where the other organism will be considered kin. We use evolving computer programs (digital organisms) to explore competitions among organisms with different kin inclusivity levels. Using competition assays that vary environmental parameters, we find that high mutation rates favor more inclusive colonies. When we competed colonies with a wide range of kin inclusivity levels, we found that moderate mutation rates and populations sizes led to intermediate inclusivity levels winning the competitions, indicating that extreme inclusivity levels were not always optimal. However, when organisms could set their own kin inclusivity level, we found that high mutation rates selected for highly inclusive organisms.

Evolution of Honest Signaling by Social Punishment

David Catteeuw, *Vrije Universiteit Brussel*, The Anh Han, *Vrije Universiteit Brussel*, Bernard Manderick, *Vrije Universiteit Brussel*

When facing dishonest behavior of any form, individuals may choose to punish in order to enhance future honesty from others, even if it is costly for the punishers. Such behavior can be found ubiquitously in human and animal communications, suggesting that it may play an important role in the evolution of honest signaling or reliable communication. By applying Evolutionary Game Theory to the Philip Sidney game, we provide a computational model to investigate whether costly punishment can be a viable strategy for the evolution of honest signaling. We identify four different forms of dishonesty, and study how punishing them affects the level of honesty in the final outcome of evolutionary dynamics. Our results show that punishing those that lie can significantly boost honest signaling when conflicts are moderate and signals are cheap or cost-free. It hence provides an important alternative to the well-known Handicap Principle, which states that honest signaling can evolve only if signals are sufficiently costly for their senders. Furthermore, punishing greedy responses promotes honest signaling if conflicts of interest are high and signals are costly. Lastly, punishing timid or worried individuals does not lead to a clear improvement of honesty.

Evolution of Communication and Cooperation

Jason Fairey, *Washington State University*, Terence Soule, *University of Idaho*

In the wild, spotted hyenas have been observed to chase lions away from a recent kill. This is a high risk, high reward behavior that requires significant teamwork and decision making skills. Modeling this behavior and creating algorithms that can improve evolutionarily may lead to more adaptable artificial systems for robotics and other cooperative artificial agents. Previous research has shown that having a lead or "flag bearer" hyena can significantly improve evolution. Thus, the complex social dynamics and coordination abilities required for this problem make it interesting artificial intelligence task. This also suggests that the type and encoding of the sensory inputs has a significant effect on the evolutionary trajectory and overall success at the task. Additionally, in the wild genetic diversity is driven by the migration of young males between packs, which leads to interesting evolutionary questions. To address the role of input encodings we introduce two evolutionary neural network variants, one using absolute headings as inputs/outputs and one using relative headings as inputs/outputs (headings defined relative to environmental elements). Our results show that the networks with relative inputs and outputs evolve significantly faster and result in better performance, suggesting that a critical difference is the existence of easily accessible, problem relevant, references for defining movement vectors. Our results also show that the inclusion of a leader in the team structure can improve the rate at which cooperative behaviors are evolved, but does not lead to better overall behaviors. In addition, we examine the emerging behaviors as the teams go from random behavior to a circling pattern to an aggressive charge towards the goal.

ALIFE4

Coevolutionary Learning of Swarm Behaviors Without Metrics

Wei Li, *University of Sheffield*, Melvin Gauci, *University of Sheffield*, Roderich Gross, *University of Sheffield*

We propose a coevolutionary approach for learning the behavior of animals, or agents, in collective groups. The approach requires a replica that resembles the animal under investigation in terms of appearance and behavioral capabilities. It is able to identify the rules that govern the animals in an autonomous manner. A population of candidate models, to be executed on the

replica, compete against a population of classifiers. The replica is mixed into the group of animals and all individuals are observed. The fitness of the classifiers depends solely on their ability to discriminate between the replica and the animals based on their motion over time. Conversely, the fitness of the models depends solely on their ability to 'trick' the classifiers into categorizing them as an animal. Our approach is metric-free in that it autonomously learns how to judge the resemblance of the models to the animals. It is shown in computer simulation that the system successfully learns the collective behaviors of aggregation and of object clustering. A quantitative analysis reveals that the evolved rules approximate those of the animals with a good precision.

Adapting to a Changing Environment Using Winner and Loser Effects

Jeremy Acre, *Southern Nazarene University*, Brent E. Eskridge, *Southern Nazarene University*, Nicholas Zoller, *Southern Nazarene University*, Ingo Schlupp, *University of Oklahoma*

Many animals form large aggregations that have no apparent consistent leader, yet are capable of highly coordinated movements. At any given time, it seems like an individual can emerge as a leader only to be replaced by another. Although individuals within a group are largely considered equal, even individuals in a homogeneous group are different. Clearly individuals will differ based on traits like sex, age, and experience. Of particular interest is the idea of individuals differing in their correlated traits, or personality. Different personalities can arise via complex interactions between genes and an environment and are often shaped by individual experience. For example, one would generally predict that individuals characterized as "bold" would more frequently be leaders. However, if the environment changes, how do once successful leaders respond to failure and how do newly successful leaders emerge? Using a biologically-based collective movement model, we demonstrate that a self-assessment mechanism using winner and loser effects is capable of producing transitory leaders who change roles in response to changes in the environment. Furthermore, simulations predict that this self-assessment mechanism allows the group to adapt to drastic changes in the environment and remain successful.

Biological and Biomedical Applications

BIO1

Enhancing Genetic Algorithm-Based Genome-scale Metabolic Network Curation Efficiency

Eddy J. Bautista, *University of Connecticut*, Ranjan Srivastava, *University of Connecticut*

Genome-scale metabolic modeling using constraint-based analysis is a powerful modeling paradigm for simulating metabolic networks. Models are generated via inference from genome annotations. However, errors in the annotation or the identity of a genes function could lead to metabolic inconsistency rendering simulations infeasible. Uncovering the source of metabolic inconsistency is non-trivial due to network size and complexity. Recently published work uses genetic algorithms for curation by generating pools of models with randomly relaxed mass balance constraints. Models are evolved that allow feasible simulation while minimizing the number of constraints relaxed. Relaxed constraints represent metabolites likely to be the root of metabolic inconsistency. Although effective, the approach can result in numerous false positives. Here we present a strategy, MassChecker, which evaluates all of the relaxed mass balance constraints in each generation prior to the next round of evolution to determine if they had become consistent due to recombination/mutation. If so, these constraints are enforced. This approach was applied to the development of genome-scale metabolic model of B. anthracis. The model consisted of 1,049 reactions and 1,003 metabolites. The result was a 60% reduction in the number of relaxed mass balance constraints, significantly speeding up the curation process.

Multiple Feature Construction for Effective Biomarker Identification and Classification Using Genetic Programming

Soha Ahmed, *Victoria University of Wellington*, Mengjie Zhang, *Victoria University of Wellington*, Lifeng Peng, *Victoria University of Wellington*

Biomarker identification, i.e., detecting the features that indicate differences between two or more classes, is an important task in omics sciences. Mass spectrometry (MS) provide a high throughput analysis of proteomic and metabolomic data. The number of features of the MS data sets far exceeds the number of samples, making biomarker identification extremely difficult. Feature construction can provide a means for solving this problem by transforming the original features to a smaller number of high-level features. This paper investigates the construction of multiple features using GP for biomarker identification and classification of mass spectrometry data. In this paper, multiple features are constructed using GP by adopting an embedded approach in which Fisher criterion and p-values are used to measure the discriminating information between the classes. This produces nonlinear high-level features from the low-level features for both binary and multi-class mass spectrometry data sets. Meanwhile, seven different classifiers are used to test the effectiveness of the constructed features. The proposed GP method is tested on eight different mass spectrometry data sets. The results show that the high-level features constructed by the GP method are effective in improving the classification performance in most cases over the original set of features and the low-level selected features. In addition, the new method shows superior performance in terms of biomarker detection rate.

GA-Based Selection of Vaginal Microbiome Features Associated with Bacterial Vaginosis

Joi Carter, *North Carolina A&T State University*, Daniel Beck, *University of Idaho*, Henry Williams, *North Carolina A&T State University*, Gerry Dozier, *North Carolina A&T State University*, James A. Foster, *University of Idaho*

In this paper, we successfully apply GEFeS (Genetic & Evolutionary Feature Selection) to identify the key features in the human vaginal microbiome and in patient meta-data that are associated with bacterial vaginosis (BV). The vaginal microbiome is the community of bacteria found in a patient, and meta-data include behavioral practices and demographic information. Bacterial vaginosis is a disease that afflicts nearly one third of all women, but the current diagnostics are crude at best. We describe two types of classifies for BV diagnosis, and show that each is associated with one of two treatments. Our results show that the classifiers associated with the 'Treat Any Symptom' version have better performances that the classifier associated with the 'Treat Based on N-Score Value'. Our long term objective is to develop a more accurate and objective diagnosis and treatment of BV.

Multiple Graph Edit Distance — Simultaneous Topological Alignment of Multiple Protein-Protein Interaction Networks with an Evolutionary Algorithm

Rashid Ibragimov, *Max Planck Institut für Informatik*, Maximilian Malek, *Universität des Saarlandes*, Jan Baumbach, *University of Southern Denmark*, Jiong Guo, *Universität des Saarlandes*

We address the problem of multiple protein-protein interaction (PPI) network alignment. Given a set of such networks for different species we might ask how much the network topology is conserved throughout evolution. Solving this problem will help to derive a subset of interactions that is conserved over multiple species thus forming a 'core interactome'.
We model the problem as Topological Multiple one-to-one Network Alignment (TMNA), where we aim to minimize the total Graph Edit Distance (GED) between pairs of the input networks. Here, the GED between two graphs is the number of deleted and inserted edges that are required to make one graph isomorphic to another. By minimizing the GED we indirectly maximize the number of edges that are aligned in multiple networks simultaneously. However, computing an optimal GED value is computationally intractable. We thus propose an evolutionary algorithm and developed a software tool, GEDEVO-M, which is able to align multiple PPI networks using topological information only. We demonstrate the power of our approach by computing a maximal common subnetwork for a set of bacterial and eukaryotic PPI networks. GEDEVO-M thus provides great potential for computing the 'core interactome' of different species.

BIO2

Predicting Patterns of Gene Expression During *Drosophila* Embryogenesis

Rotem Golan, *University of Calgary*, Christian Jacob, *University of Calgary*, Savraj Grewal, *University of Calgary*, Jörg Denzinger, *University of Calgary*

Understanding how organisms develop from a single cell into a functioning multicellular organism is one of the key questions in developmental biology. Research in this area goes back decades ago, but only recently have improvements in technology allowed biologists to achieve experimental results that are more quantitative and precise. Here, we show how large biological datasets can be used to learn a model for predicting the patterns of gene expression in *Drosophila melanogaster* (fruit fly) throughout embryogenesis. We also explore the possibility of considering spatial information in order to achieve unique patterns of gene expression in different regions along the anterior-posterior (head-tail) axis of the egg. We then demonstrate how the resulting model can be used to (1) classify these regions into the various segments of the fly, and (2) to conduct a virtual gene knockout experiment. Our learning algorithm is based on a model that has biological meaning, which indicates that its structure and parameters have their correspondence in biology.

Digital Entertainment Technologies and Arts

BP1

Evolving Multimodal Behavior With Modular Neural Networks in Ms. Pac-Man

Jacob Schrum, *University of Texas at Austin*, Risto Miikkulainen, *University of Texas at Austin*

Ms. Pac-Man is a challenging video game in which multiple modes of behavior are required to succeed: Ms. Pac-Man must escape ghosts when they are threats, and catch them when they are edible, in addition to eating all pills in each level. Past approaches to learning behavior in Ms. Pac-Man have treated the game as a single task to be learned using monolithic policy representations. In contrast, this paper uses a framework called Modular Multiobjective NEAT to evolve modular neural networks. Each module defines a separate policy; evolution discovers these policies and when to use them. The number of modules can be fixed or learned using a new version of a genetic operator, called Module Mutation, which duplicates an existing module that can then evolve to take on a distinct behavioral identity. Both the fixed modular networks and Module Mutation networks outperform traditional monolithic networks. More interestingly, the best modular networks dedicate modules to critical behav-

iors that do not follow the customary division of the game into chasing edible and escaping threatening ghosts.

DETA1

Semantic Aware Methods for Evolutionary Art

Penousal Machado, *University of Coimbra*, João Correia, *University of Coimbra*

In the past few years the use of semantic aware crossover and mutation has become a hot topic of research within the Genetic Programming community. Unlike traditional genetic operators that perform syntactic manipulations of programs regardless of their behavior, semantic driven operators promote direct search on the underlying behavioral space. Based on previous work on semantic Genetic Programming and Genetic Morphing, we propose and implement semantic driven crossover and mutation operators for evolutionary art. The experimental results focus on assessing how these operators compare with traditional ones.

EVOR : An Online Evolutionary Algorithm for Car Racing Games

Samadhi Nallaperuma, *University of Adelaide*, Frank Neumann, *University of Adelaide*, Mohammad Reza Bonyadi, *University of Adelaide*, Zbigniew Michalewicz, *University of Adelaide*

In this paper, we present evolutionary racer (EVOR) a simulated car dynamically controlled by an online evolutionary algorithm (EA). The key distinction between EVOR and earlier car racing methods is that it considers car racing as a dynamic optimization problem and is addressed by an evolutionary algorithm. Our approach calculates a car trajectory based on a controller decision and adjusts this decision according to the suitability of its resultant trajectory with the current track status. Furthermore, it allows to integrate features such as opponent handling implicitly. Our experimental results show that EVOR outperforms current best AI controllers on a wide range of tracks.

Automatic Design of Sound Synthesizers as Pure Data Patches Using Coevolutionary Mixed-Typed Cartesian Genetic Programming

Matthieu Macret, *Simon Fraser University*, Philippe Pasquier, *Simon Fraser University*

A sound synthesizer can be defined as a program that takes a few input parameters and returns a sound. The general sound synthesis problem could then be formulated as: given a sound (or a set of sounds) what program and set of input parameters can generate that sound (set of sounds)? We propose a novel approach to tackle this problem in which we represent sound synthesizers using Pure Data (Pd), a graphic programming language for digital signal processing. We search the space of possible sound synthesizers using Coevolutionary Mixed-typed Cartesian Genetic Programming (MT-CGP), and the set of input parameters using a standard Genetic Algorithm (GA). The proposed algorithm coevolves a population of MT-CGP graphs, representing the functional forms of synthesizers, and a population of GA chromosomes, representing their inputs parameters. A fitness function based on the Mel-frequency Cepstral Coefficients (MFCC) evaluates the distance between the target and produced sounds. Our approach is capable of suggesting novel functional forms and input parameters, suitable to approximate a given target sound (and we hope in future iterations a set of sounds). Since the resulting synthesizers are presented as Pd patches, the user can experiment, interact with, and reuse them.

Monte Mario: Platforming with MCTS

Emil Juul Jacobsen, *IT University of Copenhagen*, Rasmus Greve, *IT University of Copenhagen*, Julian Togelius, *IT University of Copenhagen*

Monte Carlo Tree Search (MCTS) is applied to control the player character in a clone of the popular platform game Super Mario Bros. Standard MCTS is applied through search in state space with the goal of moving the furthest to the right as quickly as possible. Despite parameter tuning, only moderate success is reached. Several modifications to the algorithm are then introduced specifically to deal with the behavioural pathologies that were observed. Two of the modifications are to our best knowledge novel. A combination of these modifications is found to lead to almost perfect play on linear levels. Furthermore, when adding noise to the benchmark, MCTS outperforms the best known algorithm for these levels. The analysis and algorithmic innovations in this paper are likely to be useful when applying MCTS to other video games.

DETA2

Virtual Photography Using Multi-Objective Particle Swarm Optimization

William Barry, *Sheridan College*, Brian J. Ross, *Brock University*

Particle swarm optimization (PSO) is a stochastic population-based search algorithm that is inspired by the flocking behaviour of birds. Here, a PSO is used to implement swarms of cameras flying through a virtual world in search of an image that satisfies a set of compositional objectives, for example, the rule of thirds and horizon line rules. To effectively process these multiple, and possible conflicting, criteria, a new multi-objective PSO algorithm called the sum of ranks PSO (SR-PSO) is introduced. The SR-PSO is useful for solving high-dimensional search problems, while discouraging degenerate solutions that can arise with other approaches. Less user intervention is required for the SR-PSO, as compared to a conventional PSO. A number of problems using different virtual worlds and user-supplied objectives were studied. In all cases, solution images were obtained that satisfied the majority of given objectives. The SR-PSO is shown to be superior to other algorithms in solving the high-dimensional virtual photography problems studied.

Estimation of Distribution Algorithms

EDA1

Estimation of Distribution Algorithm Using Factor Graph and Markov Blanket Canonical Factorization

Bentolhoda Helmi, *Iran University of Science and Technology*, Adel Torkaman Rahmani, *Iran University of Science and Technology*

Finding a good model and efficiently estimating the distribution is still an open challenge in estimation of distribution algorithms (EDAs). Factorization encoded by models in most of the EDAs are constrained. However for optimization of many real-world problems, finding the model capable of representing complex interactions without much computational complexity overhead is the key challenge. On the other hand factor graph which is the most natural graphical model for representing additively decomposable functions is rarely employed in EDAs. In this paper we introduce Factor Graph based EDA (FGEDA) which learns factor graph as the model and estimate the probability distribution represented by the learned factor graph using Markov blanket canonical factorization. The class of factorization that is employed for approximation of distribution in FGEDA is expanded relative to famous EDAs. We have used matrix factorization for learning the factor graph of the problem based on the pairwise mutual information between pair of variables. Gibbs sampling and BB-wise crossover are used to generate new samples. Empirical evaluation as well as theoretical analysis of the approach show the efficiency and power of FGEDA in the optimization of functions with complex interactions. It is showed experimentally that FGEDA outperform other well-known EDAs.

Multimodality and the Linkage-Learning Difficulty of Additively Separable Functions

Jean P. Martins, *Universidade de São Paulo*, Alexandre C. B. Delbem, *Universidade de São Paulo*

Estimation of Distribution Algorithms (EDAs) have emerged from the synergy between machine-learning techniques and Genetic Algorithms (GAs). EDAs rely on probabilistic modeling for obtaining information about the underlying structure of optimization problems and implementing effective reproduction operators. The effectiveness of EDAs depends on the capacity of the model-building to extract reliable information about the problem. In this study we analyze additively separable functions and argue that the degree of multimodality of such functions defines their linkage-learning difficulty. Besides, by using entropy-based concepts and Jensen's inequality, we show how allelic pairwise independence may appear as a consequence of an increasing multimodality. The results characterize the linkage-learning difficulty of well-known functions, like the deceptive trap, bipolar and concatenated parity.

Solving Building Block Problems Using Generative Grammar

Chris R. Cox, *University of Southampton*, Richard A. Watson, *University of Southampton*

In this work we demonstrate novel applications of generative grammar to evolutionary search. We introduce a class of grammar that can represent hierarchical schema structure in a problem space, and describe an algorithm that can infer an instance of the grammar from a population of sample phenotypes. Unlike conventional sequence-based grammars this grammar represents set-membership relationships, not strings, and is therefore insensitive to gene-ordering and physical linkage. We show that these methods are capable of accurately identifying problem structure from populations of above-average-fitness individuals on simple modular and hierarchically modular test problems. We then show how these grammatical models can be used to aid evolutionary problem solving by enabling facilitated variation; specifically, by producing novel combinations of schemata observed in the sample population whilst respecting the inherent constraint structure of the problem space. This provides a robust method of building-block recombination that is linkage-invariant and not restricted to low-order schemata.

Minimal Walsh Structure and Ordinal Linkage of Monotonicity-Invariant Function Classes on Bit Strings

Lee A. Christie, *Robert Gordon University*, John A. W. McCall, *Robert Gordon University*, David P. Lonie, *Robert Gordon University*

Problem structure, or linkage, refers to the interaction between variables in a black-box fitness function. Discovering structure is a feature of a range of algorithms, including EDAs and perturbation methods (PMs). The complexity of structure has traditionally been used as a broad measure of problem difficulty, as the computational complexity relates directly to the complexity of structure. The EDA literature describes necessary and unnecessary interactions in terms of the relationship between problem structure and the structure of probabilistic graphical models discovered by the EDA. In this paper we introduce a classification of problems based on monotonicity invariance. We observe that the minimal problem structures for these classes often reveal that significant proportions of detected structures are unnecessary. We perform a complete classification of all functions on 3 bits. We consider nonmonotonicity linkage discovery using perturbation methods and derive a concept of directed ordinal linkage associated to optimization schedules. The resulting refined classification factored out by relabeling, shows a hierarchy of nine directed ordinal linkage classes for all 3-bit functions. We show that this classification allows precise analysis of computational complexity and parallelizability and conclude with a number of suggestions for future work.

EDA2

Multi-Objective Gene-Pool Optimal Mixing Evolutionary Algorithms

Ngoc Hoang Luong, *Centrum Wiskunde & Informatica*, Han La

Poutré, *Centrum Wiskunde & Informatica*, Peter A. N. Bosman, *Centrum Wiskunde & Informatica*

The recently introduced Gene-pool Optimal Mixing Evolutionary Algorithm (GOMEA), with a lean, but sufficient, linkage model and an efficient variation operator, has been shown to be a robust and efficient methodology for solving single objective (SO) optimization problems with superior performance compared to classic genetic algorithms (GAs) and estimation-of-distribution algorithms (EDAs). In this paper, we bring the strengths of GOMEAs to the multi-objective (MO) optimization realm. To this end, we modify the linkage learning procedure and the variation operator of GOMEAs to better suit the need of finding the whole Pareto-optimal front rather than a single best solution. Based on state-of-the-art studies on MOEAs, we further pinpoint and incorporate two other essential components for a scalable MO optimizer. First, the use of an elitist archive is beneficial for keeping track of non-dominated solutions when the main population size is limited. Second, clustering can be crucial if different parts of the Pareto-optimal front need to be handled differently. By combining these elements, we construct a multi-objective GOMEA (MO-GOMEA). Experimental results on various MO optimization problems confirm the capability and scalability of our MO-GOMEA that compare favorably with those of the well-known GA NSGA-II and the more recently introduced EDA mohBOA.

Evolution Strategies and Evolutionary Programming

ESEP

Comparison-Based Natural Gradient Optimization in High Dimension

Youhei Akimoto, *Shinshu University*, Anne Auger, *INRIA Saclay*, Nikolaus Hansen, *INRIA Saclay*

We propose a novel natural gradient based stochastic search algorithm, VD-CMA, for the optimization of high dimensional numerical functions. The algorithm is comparison-based and hence invariant to monotonic transformations of the objective function. It adapts a multivariate normal distribution with a restricted covariance matrix with twice the dimension as degrees of freedom, representing an arbitrarily oriented long axis and additional axis-parallel scaling. We derive the different components of the algorithm and show linear internal time and space complexity. We find empirically that the algorithm adapts its covariance matrix to the inverse Hessian on convex-quadratic functions with an Hessian with one short axis and different scaling on the diagonal. We then evaluate VD-CMA on test functions and compare it to different methods. On functions covered by the internal model of VD-CMA and on the Rosenbrock function, VD-CMA outperforms CMA-ES (having quadratic internal time and space complexity) not only in internal complexity but also in number of function calls with increasing dimension.

Halfspace Sampling in Evolution Strategies

Chun-Kit Au, *Chinese University of Hong Kong*, Ho-Fung Leung, *Chinese University of Hong Kong*

This paper presents a novel halfspace sampling method in single parent elitist evolution strategies (ESs) for unimodal functions. In halfspace sampling, the supporting hyperplane going through a parent separates the search space into a positive halfspace and a negative halfspace. If an offspring lies in the negative halfspace, it will be reflected with respect to the parent so that it lies in the positive halfspace. We derive the convergence rates of a scale-invariant step size (1+1)-ES with halfspace sampling on spherical functions in finite and infinite dimensions. We prove that the lower bounds of convergence rates are improved by a factor of 2 when strategies sample their offspring in the optimal positive halfspace. We also implement halfspace sampling into the (1+1) CMA-ES by introducing the concept of evolution halfspaces. Evolution halfspaces accumulate the significant information of the previous successful and unsuccessful steps in order to estimate the optimal positive halfspace. The (1+1)-CMA-ES with halfspace sampling is benchmarked on the BBOB noise-free testbed and experimentally compared with the standard (1+1)-CMA-ES.

Handling Sharp Ridges with Local Supremum Transformations

Tobias Glasmachers, *Ruhr-Universität Bochum*

A particular strength of many evolution strategies is their invariance against strictly monotonic and therefore rank-preserving transformations of the objective function. Their view onto a continuous fitness landscape is therefore completely determined by the shapes of the level sets. Most modern algorithms can cope well with diverse shapes as long as these are sufficiently smooth. In contrast, the sharp angles found in level sets of ridge functions can cause premature convergence to a non-optimal point. We propose a simple and generic family of transformation of the fitness function to avoid this effect. This allows general purpose evolution strategies to solve even extremely sharp ridge problems.

BP2

A Computationally Efficient Limited Memory CMA-ES for Large Scale Optimization

Ilya Loshchilov, *École Polytechnique Fédérale de Lausanne*

We propose a computationally efficient limited memory Covariance Matrix Adaptation Evolution Strategy for large scale optimization, which we call the LM-CMA-ES. The LM-CMA-ES is a stochastic, derivative-free algorithm for numerical optimization of non-linear, non-convex optimization problems in contin-

uous domain. Inspired by the limited memory BFGS method of Liu and Nocedal (1989), the LM-CMA-ES samples candidate solutions according to a covariance matrix reproduced from m direction vectors selected during the optimization process. The decomposition of the covariance matrix into Cholesky factors allows to reduce the time and memory complexity of the sampling to $O(mn)$, where n is the number of decision variables. When n is large (e.g., $n > 1000$), even relatively small values of m (e.g., $m = 20, 30$) are sufficient to efficiently solve fully non-separable problems and to reduce the overall run-time.

Evolutionary Combinatorial Optimization and Metaheuristics

ECOM1

On the Efficiency of Worst Improvement for Climbing NK-Landscapes

Matthieu Basseur, *Université d'Angers*, Adrien Goëffon, *Université d'Angers*

Climbers are often used in metaheuristics in order to intensify the search and identify local optima with respect to a neighborhood structure. Even if they constitute a central component of modern heuristics, their design principally consists in choosing the pivoting rule, which is often reduced to two alternative strategies: first improvement or best improvement. The conception effort of most metaheuristics belongs in proposing techniques to escape from local optima, and not necessarily on how to climb toward better local optima. In this paper, we are interested in attaining good local optima with basic hill-climbing techniques. The NK model will be used to evaluate a set of climbers proposed in this paper. By focusing on the pivoting rule definition, we show that choosing the worst improving neighbor often leads to attain better local optima. Moreover, by slightly modifying the worst improvement strategy, one can design efficient climbers which outperform first and best improvement in terms of tradeoff between quality and computational effort.

Socially Inspired Algorithms for the Travelling Thief Problem

Mohammad Reza Bonyadi, *University of Adelaide*, Zbigniew Michalewicz, *University of Adelaide*, Michał Roman Przybyłek, *Polish-Japanese Institute of Information Technology*, Adam Wierzbicki, *Polish-Japanese Institute of Information Technology*

Many real-world problems are composed of two or more problems that are interdependent on each other. The interaction of such problems usually is quite complex and solving each problem separately cannot guarantee the optimal solution for the overall multi-component problem. In this paper we experiment with one particular 2-component problem, namely the Traveling Thief Problem (TTP). TTP is composed of the Traveling Salesman Problem (TSP) and the Knapsack Problem (KP). We investigate two heuristic methods to deal with TTP. In the first approach we decompose TTP into two sub-problems, solve them by separate modules/algorithms (that communicate with each other), and combine the solutions to obtain an overall approximated solution to TTP (this method is called CoSolver). The second approach is a simple heuristic (called density-based heuristic, DH) method that generates a solution for the TSP component first (a version of Lin-Kernighan algorithm is used) and then, based on the fixed solution for the TSP component found, it generates a solution for the KP component (associated with the given TTP). In fact, this heuristic ignores the interdependency between sub-problems and tries to solve the sub-problems sequentially. These two methods are applied to some generated TTP instances of different sizes. Our comparisons show that CoSolver outperforms DH specially in large instances.

Data-Driven Local Optima Network Characterization of QAPLIB Instances

David Iclanzan, *Université de Lausanne*, Fabio Daolio, *Université de Lausanne*, Marco Tomassini, *Université de Lausanne*

Inherent networks of potential energy surfaces proposed in physical chemistry inspired a compact network characterization of combinatorial fitness landscapes. In these so-called Local Optima Networks (LON), the nodes correspond to the local optima and the edges quantify a measure of adjacency - transition probability between them.

Methods so far used an exhaustive search for extracting LON, limiting their applicability to small problem instances only. To increase scalability, in this paper a new data-driven methodology is proposed that approximates the LON from actual runs of search methods. The method enables the extraction and study of LON corresponding to the various types of instances from the Quadratic Assignment Problem Library (QAPLIB), whose search spaces are characterized in terms of local minima connectivity. Our analysis provides a novel view of the unified testbed of QAP combinatorial landscapes used in the literature, revealing qualitative inherent properties that can be used to classify instances and estimate search difficulty.

Asymmetric Quadratic Landscape Approximation Model

Alexandru-Adrian Tantar, *University of Luxembourg*, Emilia Tantar, *University of Luxembourg*, Oliver Schütze, *CINVESTAV-IPN*

This work presents an asymmetric quadratic approximation model and an ϵ-archiving algorithm. The model allows to construct, under local convexity assumptions, descriptors for local optima points in continuous functions. A descriptor can be used to extract confidence radius information. The ϵ-archiving algorithm is designed to maintain and update a set of such asymmetric descriptors, spaced at some given threshold distance. An in-depth analysis is conducted on the stability and performance

of the asymmetric model, comparing the results with the ones obtained by a quadratic polynomial approximation. A series of different applications are possible in areas such as dynamic and robust optimization.

ECOM2

NSGA-II with Iterated Greedy for a Bi-Objective Three-Stage Assembly Flowshop Scheduling Problem

Saulo Cunha Campos, *Universidade Federal de Vicosa*, Jose Elias Claudio Arroyo, *Universidade Federal de Vicosa*

In this paper we address a three-stage assembly flowshop scheduling problem where there are m machines at the first stage, a transportation machine at the second stage and an assembly machine at the third stage. At the first stage, different parts of a product are manufactured independently on parallel production lines. At the second stage, the manufactured parts are collected and transferred to the next stage. At the third stage, the parts are assembled into final products. The objective is to schedule n jobs on the machines so that total flowtime and the total tardiness of the jobs are minimized simultaneously. This problem has many applications in industry and belongs to the class of NP-Hard combinatorial optimization problems. In order to obtain near Pareto optimal solutions, we propose an Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) coupled with Iterated Greedy (IG) strategy. IG is a simple heuristic that has shown excellent results for different flowshop scheduling problems. A comparative study is presented between the results obtained using the standard NSGA-II, the enhanced NSGA-II with IG approach and a single-objective GRASP heuristic. Experimental results on both medium and large size of instances show the efficiency of the hybrid NSGA-II approach.

Efficient Identification of Improving Moves in a Ball for Pseudo-Boolean Problems

Francisco Chicano, *Universidad de Málaga*, Darrell Whitley, *Colorado State Univerisity*, Andrew M. Sutton, *Friedrich-Schiller-Universität Jena*

Hill climbing algorithms are at the core of many approaches to solve optimization problems. Such algorithms usually require the complete enumeration of a neighborhood of the current solution. In the case of problems defined over binary strings of length n, we define the r-ball neighborhood as the set of solutions at Hamming distance r or less from the current solution. For $r \ll n$ this neighborhood contains $\Theta(n^r)$ solutions. In this paper efficient methods are introduced to locate improving moves in the r-ball neighborhood for problems that can be written as a sum of a linear number of subfunctions depending on a bounded number of variables. NK-landscapes and MAX-kSAT are examples of these problems. If the number of subfunctions depending on any given variable is also bounded, then we prove that the method can explore the neighborhood in constant time, despite the fact that the number of solutions in the neighborhood is polynomial in n. We develop a hill climber based on our exploration method and we analyze its efficiency and efficacy using experiments with NKq-landscapes instances.

A Heuristic Approach to Schedule Reoptimization in the Context of Interactive Optimization

David Meignan, *Universität Osnabrück*

Optimization models used in planning and scheduling systems are not exempt from inaccuracies. These optimization systems often require an expert to assess solutions and to adjust them before taking decisions. However, adjusting a solution computed by an optimization procedure is difficult, especially because of the cascading effect. A small modification in a candidate solution may require to modify a large part of the solution. This obstacle to the adjustment of a solution can be overcome by interactive reoptimization. In this paper we analyze the impact of the cascading effect on a shift-scheduling problem and propose an efficient heuristic approach for reoptimizing solutions. The proposed approach is a local-search metaheuristic that has been adapted to the reoptimization. This approach is evaluated on a set of problem instances on which additional preferences are generated to simulate desired adjustments of a decision maker. Experimental results indicate that, even with a small perturbation, the cascading effect is manifest and cannot be efficiently tackled by applying recovery actions. Moreover, results show that the proposed reoptimization method provides significant cost gains within a short time while keeping a level of simplicity and modularity adequate for an implementation in a decision support system.

Revised Analysis of the (1+1) EA for the Minimum Spanning Tree Problem

Carsten Witt, *Technical University of Denmark*

We revisit the classical analysis of the (1+1) EA for the minimum spanning tree problem in the case that nothing is known about the weights of the underlying graph. Here the original upper bound on the expected running time by Neumann and Wegener [Theor. Comput. Sci. 378(1), 32-40, 2007], which depends on the largest weight of the graph, is of no use. The best upper bound available before in this case is due to Reichel and Skutella [FOGA 2009, 21-28] and is of order $O(m^3 \log n)$, where m is the number of edges and n the number of vertices. Using an adaptive drift analysis, we show the improved bound $O(m^2(\sqrt{c(G)} + \log n))$, where $c(G)$ is the circumference (length of the longest cycle) of the graph. This is only by an asymptotic factor of at most $\sqrt{n}/\log n$ away from the classical lower bound. Furthermore, an alternative fitness function leading to the bound $O(m^2 \log n)$ is proposed, and limitations of the adaptive drift analysis are pointed out.

ECOM3

Static vs. Dynamic Populations in Genetic Algorithms for Coloring a Dynamic Graph

Cara Monical, *Centre College*, Forrest Stonedahl, *Centre College*

We studied the performance of genetic algorithms for coloring

dynamic graphs under a variety of experimental conditions, focusing on the relationship between the dynamics of the graph and that of the algorithm. Graph coloring is a well-studied NP-hard problem, while dynamic graphs are a natural way to model a diverse range of dynamic systems. Dynamic graph coloring can be applied to online scheduling in a changing environment, such as the online scheduling of conflicting tasks. As genetic algorithms (GAs) have been effective for graph coloring and are adaptable to dynamic environments, they are a promising choice for this problem. Thus, we compared the performance of three algorithms: a GA that maintained a single population adapting to the dynamic graph (DGA), a GA that restarted with a fresh population for the static graph of each time-step (SGA), and DSATUR, a well-known heuristic graph coloring algorithm re-applied at each time-step. We examined the relative performance of these algorithms for dynamic graphs of different sizes, edge densities, structures, and change rates, using different amounts of evolution between time-steps. Overall, the DGA consistently outperformed the SGA, being particularly dominant at low change rates, and under certain conditions was able to outperform DSATUR.

Generalized Asymmetric Partition Crossover (GAPX) for the Asymmetric TSP

Renato Tinos, *Universidade de São Paulo*, Darrell Whitley, *Colorado State University*, Gabriela Ochoa, *University of Stirling*

The Generalized Partition Crossover (GPX) constructs new solutions for the Traveling Salesman Problem (TSP) by finding recombining partitions with one entry and one exit in the graph composed by the union of two parent solutions. If there are k recombining partitions in the union graph, $2^k - 2$ solutions are simultaneously exploited by GPX. Generalized Asymmetric Partition Crossover (GAPX) is introduced; it finds more recombining partitions and can also find partitions for the asymmetric TSP. GAPX does this by locating partitions that cut vertices of degree 4 in the union graph and by finding partitions with multiple entry and exit points, both in $O(n)$ time. GAPX can improve the quality of solutions generated by the Lin-Kernighan-Helsgaun heuristic and improve the state of the art for the asymmetric TSP.

A Hybrid Incremental Genetic Algorithm for Subgraph Isomorphism Problem

HyukGeun Choi, *Seoul National University*, Jinhyun Kim, *Seoul National University*, Byung-Ro Moon, *Seoul National University*

Finding an isomorphic subgraph is a key problem in many real world applications modeled on graph. In this paper, we propose a new hybrid genetic algorithm(GA) for subgraph isomorphism problem which uses an incremental approach. We solve the problem with increasing the size of the subproblem step by step. The graph for which we search is gradually expanded from the empty structure to the entire one. We apply a hybrid GA to each subproblem, initialized with the evolved population of previous step. We present design issues for the incremental approach, and the effects of each design decision are analyzed by experiment. The proposed algorithm is tested on widely used dataset. With apposite vertex reordering along with moderate population diversity, incremental approach brought a significant performance improvement. Experimental results showed that our algorithm outperformed representative previous works.

Evolutionary Algorithms for Overlapping Correlation Clustering

Carlos E. Andrade, *Universidade Estadual de Campinas*, Mauricio G. C. Resende, *AT&T Labs Research*, Howard J. Karloff, *Yahoo Labs*, Flávio K. Miyazawa, *Universidade Estadual de Campinas*

In Overlapping Correlation Clustering (OCC), a number of objects are assigned to clusters. Two objects in the same cluster have correlated characteristics. As opposed to traditional clustering where objects are assigned to a single cluster, in OCC objects may be assigned to one or more clusters. In this paper, we present Biased Random-Key Genetic Algorithms for OCC. We present computational experiments such results outperformed the state of art methods for OCC.

ECOM4

Performance of Metropolis Algorithm for the Minimum Weight Code Word Problem

Ajitha Shenoy K. B., *Indian Institute of Technology Kanpur*, Somenath Biswas, *Indian Institute of Technology Kanpur*, Piyush P. Kurur, *Indian Institute of Technology Kanpur*

We study the performance of the Metropolis algorithm for the problem of finding a code word of weight less than or equal to M, given a generator matrix of an $[n, k]$-binary linear code. The algorithm uses the set $\mathcal{S}_k$ of all $k \times k$ invertible matrices as its search space where two elements are considered adjacent if one can be obtained from the other via an elementary row operation (i.e., by adding one row to another or by swapping two rows.) We prove that the Markov chains associated with the Metropolis algorithm mix rapidly for suitable choices of the temperature parameter T. We ran the Metropolis algorithm for a number of codes and found that the algorithm performed very well in comparison to previously known experimental results.

A Comprehensive Benchmark Set and Heuristics for the Traveling Thief Problem

Sergey Polyakovskiy, *University of Adelaide*, Mohammad Reza Bonyadi, *University of Adelaide*, Markus Wagner, *University of Adelaide*, Zbigniew Michalewicz, *University of Adelaide*, Frank Neumann, *University of Adelaide*

Real-world optimization problems often consist of several NP-hard optimization problems that interact with each other. The goal of this paper is to provide a benchmark suite that promotes a research of the interaction between problems and their mutual influence. We establish a comprehensive benchmark suite for the traveling thief problem (TTP) which combines the traveling

salesman problem and the knapsack problem. Our benchmark suite builds on common benchmarks for the two sub-problems which grant a basis to examine the potential hardness imposed by combining the two classical problems. Furthermore, we present some simple heuristics for TTP and their results on our benchmark suite.

Evolutionary Machine Learning

BP1

Salient Object Detection Using Learning Classifier Systems that Compute Action Mappings

Muhammad Iqbal, *Victoria University of Wellington*, Syed S. Naqvi, *Victoria University of Wellington*, Will N. Browne, *Victoria University of Wellington*, Christopher Hollitt, *Victoria University of Wellington*, Mengjie Zhang, *Victoria University of Wellington*

Learning classifier systems (LCSs) are rule-based online evolutionary machine learning techniques that solve a problem by interacting with an environment. LCSs have been successfully used in various applications such as data mining, robot control and computer vision systems. Salient object detection is the task of automatically localizing the objects of interests in a scene by suppressing the background information, which facilitates various machine learning applications such as object segmentation, recognition and tracking. It is a difficult problem as natural scenes can often have objects with cluttered backgrounds (making it difficult to distinguish the object from background based on its features) or other complicating factors such as multiple objects. Existing saliency learning methods learn a single weight vector emphasizing the importance of each feature/attribute for the whole image dataset, hence losing generalization in the test phase when considering unseen images. LCS technique has the ability to learn weight sets for different types of images automatically. Hence, this paper investigates the application of LCS for learning image dependent feature fusion strategies for the task of salient object detection. Our LCS approach evolves generalized rules for a well known benchmark dataset consisting of 1000 images, of various types and difficulty levels, and outperforms a GA based system that was previously state-of-the-art.

EML1

SAX-EFG: An Evolutionary Feature Generation Framework for Time Series Classification

Uday Kamath, *George Mason University*, Jessica Lin, *George Mason University*, Kenneth De Jong, *George Mason University*

A variety of real world applications fit into the broad definition of time series classification. Using traditional machine learning approaches such as treating the time series sequences as high dimensional vectors have faced the well known "curse of dimensionality" problem. Recently, the field of time series classification has seen success by using preprocessing steps that discretize the time series using a Symbolic Aggregate ApproXimation technique (SAX) and using recurring subsequences ("motifs") as features. In this paper we explore a feature construction algorithm based on genetic programming that uses SAX-generated motifs as the building blocks for the construction of more complex features. The research shows that the constructed complex features improve the classification accuracy in a statistically significant manner for many applications.

A Modified XCS Classifier System for Sequence Labeling

Masaya Nakata, *University of Electro-Communications*, Tim Kovacs, *University of Bristol*, Keiki Takadama, *University of Electro-Communications*

This paper introduces XCS-SL, an extension of XCS for sequence labeling, a form of time-series classification where every input has a class label. Specifically, we consider sequence labeling tasks where on each time step we receive an input/class pair. In sequence labeling the correct class of an input may depend on data received on previous time stamps, so a learner may need to refer to data at previous time stamps. That is, some classification rules (called "classifiers" here) must include conditions on previous inputs (a kind of memory). We assume the agent does not know how many conditions on previous inputs are needed to classify the current input, and the number of conditions/memories needed may be different for each input. Hence, using a fixed number of conditions is not a good solution. A novel idea we introduce is classifiers that have a variable-length condition to refer back to data at previous times. The condition can grow and shrink to find a suitable memory size. On a benchmark problem XCS-SL can learn optimal classifiers, and on a real-world sequence labeling task, it derived high classification accuracy and discovered interesting knowledge that shows dependencies between inputs at different times.

Evolving Deep Unsupervised Convolutional Networks for Vision-Based Reinforcement Learning

Jan Koutník, *IDSIA*, Jürgen Schmidhuber, *IDSIA*, Faustino Gomez, *IDSIA*

Dealing with high-dimensional input spaces, like visual input, is a challenging task for reinforcement learning (RL). Neuroevolution (NE), used for continuous RL problems, has to either reduce the problem dimensionality by (1) compressing the representation of the neural network controllers or (2) employing a preprocessor (compressor) that transforms the high-dimensional raw inputs into low-dimensional features. In this paper, we are able to evolve extremely small recurrent neural network (RNN) controllers for a task that previously required networks with over a million weights. The high-dimensional visual input, which

the controller would normally receive, is first transformed into a compact feature vector through a deep, max-pooling convolutional neural network (MPCNN). Both the MPCNN preprocessor and the RNN controller are evolved successfully to control a car in the TORCS racing simulator using only visual input. This is the first use of deep learning in the context evolutionary RL.

___ EML2 ___

Three-Cornered Coevolution Learning Classifier Systems for Classification Tasks

Syahaneim Marzukhi, *National Defence University Malaysia*, Will N. Browne, *Victoria University of Wellington*, Mengjie Zhang, *Victoria University of Wellington*

The Three-Cornered Coevolution concept describes a framework where artificial problems may be generated in concert with classification agents in order to provide insight into their relationships. This is unlike standard studies where humans set a problem's difficulty, which may have bias or lack understanding of the multiple interactions of a problem's characteristics, such as noise in conjunction with class imbalance. Previous studies have shown that it is feasible to generate problems with one agent in relation to a single classification agent's performance, but when to adjust the problem difficulty was manually set.

This paper introduces a second classification agent to trigger the coevolutionary process within the system, where its functionality and effect on the system requires investigation. The classification agents, in this case Learning Classifier Systems, use different styles of learning techniques (e.g., supervised or reinforcement learning techniques) to learn the problems. Experiments show that the realised system is capable of autonomously generating various problems, triggering learning and providing insight into each learning system's ability by determining the problem domains where they perform relatively well — this is in contrast to humans having to determine the problem domains.

Complete Action Map or Best Action Map in Accuracy-Based Reinforcement Learning Classifier Systems

Masaya Nakata, *University of Electro-Communications*, Pier Luca Lanzi, *Politecnico di Milano*, Tim Kovacs, *University of Bristol*, Keiki Takadama, *University of Electro-Communications*

We study two existing Learning Classifier Systems (LCSs): XCS, which has a complete map (which covers all actions in each state), and XCSAMm, which has a best action map (which covers only the highest-return action in each state). This allows XCSAM to learn with a smaller population size limit (but larger population size) and to learn faster than XCS on well-behaved tasks. However, many tasks have dif- ficulties like noise and class imbalances. XCS and XCSAM have not been compared on such problems before. This paper aims to discover which kind of map is more robust to these difficulties. We apply them to a classification problem (the multiplexer problem) with class imbalance, Gaussian noise or alternating noise (where we return the reward for a different action). We also compare them on real-world data from the UCI repository without adding noise. We analyze how XCSAM focuses on the best action map and introduce a novel deletion mechanism that helps to evolve classifiers towards a best action map. Results show the best action map is more robust (has higher accuracy and sometimes learns faster) in all cases except small amounts of alternating noise.

Simultaneous Generation of Prototypes and Features through Genetic Programming

Mauricio Garcia-Limon, *Instituto Nacional de Astrofísica, Óptica Y Electrónica, México*, Hugo Jair Escalante, *Instituto Nacional de Astrofísica, Óptica Y Electrónica, México*, Eduardo Morales, *Instituto Nacional de Astrofísica, Óptica Y Electrónica, México*, Alicia Morales-Reyes, *Instituto Nacional de Astrofísica, Óptica Y Electrónica, México*

Nearest-neighbor (NN) methods are highly effective and widely used pattern classification techniques. There are, however, some issues that hinder their application for large scale and noisy data sets; including, its high storage requirements, its sensitivity to noisy instances, and the fact that test cases must be compared to all of the training instances. Prototype (PG) and feature generation (FG) techniques aim at alleviating these issues to some extent; where, traditionally, both techniques have been implemented separately. This paper introduces a genetic programming approach to tackle the simultaneous generation of prototypes and features to be used for classification with a NN classifier. The proposed method learns to combine instances and attributes to produce a set of prototypes and a new feature space for each class of the classification problem via genetic programming. An heterogeneous representation is proposed together with ad-hoc genetic operators. The proposed approach overcomes some limitations of NN without degradation in its classification performance. Experimental results are reported and compared with several other techniques. The empirical assessment provides evidence of the effectiveness of the proposed approach in terms of classification accuracy and instance/feature reduction.

A Memetic Algorithm to Select Training Data for Support Vector Machines

Jakub Nalepa, *Silesian University of Technology*, Michal Kawulok, *Silesian University of Technology*

In this paper we propose a new memetic algorithm (MASVM) for fast and efficient selection of a valuable training set for support vector machines (SVMs). This is a crucial step especially in case of large and noisy data sets, since the SVM training has high time and memory complexity. The majority of state-of-the-art methods exploit the data geometry analysis, both in the input and kernel space. Although evolutionary algorithms have been proven to be very efficient for this purpose, they have not been extensively studied so far. Here, we propose a new method employing an adaptive genetic algorithm enhanced by some refinement techniques. The refinements are based on utilizing a pool

of the support vectors identified so far at various steps of the algorithm. Extensive experimental study performed on the well-known benchmark, real-world and artificial data sets clearly confirms the efficacy, robustness and convergence capabilities of the proposed approach, and shows that it is competitive compared with other state-of-the-art techniques.

Evolutionary Multiobjective Optimization

EMO1

Efficiently Identifying Pareto Solutions when Objective Values Change

Jonathan E. Fieldsend, *University of Exeter*, Richard M. Everson, *University of Exeter*

In many multi-objective problems the objective values assigned to a particular design can change during the course of an optimisation. This may be due to dynamic changes in the problem itself, or updates to estimated objectives in noisy problems. In these situations, designs which are non-dominated at one time step may become dominated later not just because a new and better solution has been found, but because the existing solution's performance has degraded. Likewise, a dominated solution may later be identified as non-dominated because its objectives have comparatively improved. We propose management algorithms based on recording single "guardian dominators" for each solution which allow rapid discovery and updating of the non-dominated subset of solutions evaluated by an optimiser. We examine the computational complexity of our proposed approach, and compare the performance of different ways of selecting the guardian dominators.

Controlling Selection Area of Useful Infeasible Solutions and Their Archive for Directed Mating in Evolutionary Constrained Multiobjective Optimization

Minami Miyakawa, *University of Electro-Communications*, Keiki Takadama, *University of Electro-Communications*, Hiroyuki Sato, *University of Electro-Communications*

As an evolutionary approach to solve constrained multi-objective optimization problems (CMOPs), recently a MOEA using the two-stage non-dominated sorting and the directed mating (TNSDM) has been proposed. In TNSDM, the directed mating utilizes infeasible solutions dominating feasible solutions to generate offspring. Although the directed mating contributes to improve the search performance of TNSDM in CMOPs, there are two problems. First, since the number of infeasible solutions dominating feasible solutions in the population depends on each CMOP, the effectiveness of the directed mating also depends on each CMOP. Second, infeasible solutions utilized in the directed mating are discarded in the selection process of parents (elites) population and cannot be utilized in the next generation. To overcome these problems and further improve the effectiveness of the directed mating in TNSDM, in this work we propose an improved TNSDM introducing a method to control selection area of infeasible solutions and an archiving strategy of useful infeasible solutions for the directed mating. The experimental results on m objectives k knapsacks problems shows that the improved TNSDM improves the search performance by controlling the directionality of the directed mating and increasing the number of directed mating executions in the solution search.

A Framework for the Study of Preference Incorporation in Multiobjective Evolutionary Algorithms

Raluca Iordache, *University Politehnica of Bucharest*, Serban Iordache, *SCOOP Software GmbH*, Florica Moldoveanu, *University Politehnica of Bucharest*

We present a formal framework for the study of user preference incorporation into multiobjective evolutionary algorithms. This framework can accommodate virtually any preference model, including those that violate the independence of irrelevant alternatives. We also introduce the Preferanto notation, which permits the specification of a large variety of preference models. A number of properties and indicators are proposed for characterizing preference models. We report the results of a case study experiment assessing the impact of incorporating different preference models into an NSGA-II algorithm.

Two-Dimensional Subset Selection for Hypervolume and Epsilon-Indicator

Karl Bringmann, *Max Planck Institut für Informatik*, Tobias Friedrich, *Friedrich-Schiller-Universität Jena*, Patrick Klitzke, *Universität des Saarlandes*

The goal of bi-objective optimization is to find a small set of good compromise solutions. A common problem for bi-objective evolutionary algorithms is the following subset selection problem (SSP): Given n solutions $P \subset \mathbb{R}^2$ in the objective space, select k solutions P^* from P that optimize an indicator function. In the hypervolume SSP we want to select k points P^* that maximize the hypervolume indicator $\mathcal{I}_{\text{hyp}}(P^*, r)$ for some reference point $r \in \mathbb{R}^2$. Similarly, the ϵ-indicator SSP aims at selecting k points P^* that minimize the ϵ-indicator $\mathcal{I}_{\text{eps}}(P^*, R)$ for some reference set $R \subset \mathbb{R}^2$ of size m (which can be $R = P$). We first present a new algorithm for the hypervolume SSP with runtime $O(n(k + \log n))$. Our second main result is a new algorithm for the ϵ-indicator SSP with runtime $O(n \log n + m \log m)$. Both results improve the current state of the art runtimes by a factor of (nearly) n and make the problems tractable for new applications. Preliminary experiments confirm that the theoretical results translate into substantial empirical runtime improvements.

EMO2

Improving Many-Objective Optimization Performance by

Sequencing Evolutionary Algorithms

Martin Dohr, *Graz University of Technology*, Bernd Eichberger, *Graz University of Technology*

Evolutionary multiobjective optimization (EMO) has been successfully applied to various real-world scenarios with usually two or three contradicting optimization goals. However, several studies have pointed out a great deterioration of computational performance when handling more than three objectives. In order to improve the scalability of multiobjective evolutionary algorithms (MOEAs) onto higher-dimensional objective spaces, techniques using e.g., scalarizing functions and preference- or indicator-based guidance have been proposed. Most of those proposals require a-priori information or a decision maker during optimization, which increases the complexity of the algorithms. In this paper, we propose a divide and conquer method for many-objective optimization. First, we partition a problem into lower-dimensional subproblems for which standard algorithms are known to perform very well. Our key improvement is the sequential usage of MOEAs, utilizing the results of one suboptimization as initial population for another MOEA. This technique allows modular optimization phases and can be applied to common evolutionary algorithms. We test our enhanced method on the hard to solve multiobjective Quadratic Assignment Problem (mQAP), using a variety of established MOEAs.

Evolutionary Many-Objective Optimization Using Ensemble Fitness Ranking

Yuan Yuan, *Tsinghua University*, Hua Xu, *Tsinghua University*, Bo Wang, *Tsinghua University*

In this paper, a new framework, called ensemble fitness ranking (EFR), is proposed for evolutionary many-objective optimization that allows to work with different types of fitness functions and ensemble ranking schemes. The framework aims to rank the solutions in the population more appropriately by combing the ranking results from many simple individual rankers. As to the form of EFR, it can be regarded as an extension of average and maximum ranking methods which have been shown promising for many-objective problems. The significant change is that EFR adopts more general fitness functions instead of objective functions, which would make it easier for EFR to balance the convergence and diversity in many-objective optimization. In the experimental studies, the influence of several fitness functions and ensemble ranking schemes on the performance of EFR is fist investigated. Afterwards, EFR is compared with two state-of-the-art methods (MOEA/D and NSGA-III) on well-known test problems. The computational results show that EFR significantly outperforms MOEA/D and NSGA-III on most instances, especially for those having a high number of objectives.

An Improved NSGA-III Procedure for Evolutionary Many-Objective Optimization

Yuan Yuan, *Tsinghua University*, Hua Xu, *Tsinghua University*, Bo Wang, *Tsinghua University*

Many-objective (four or more objectives) optimization problems pose a great challenge to the classical Pareto-dominance based multi-objective evolutionary algorithms (MOEAs), such as NSGA-II and SPEA2. This is mainly due to the fact that the selection pressure based on Pareto-dominance degrades severely with the number of objectives increasing. Very recently, a reference-point based NSGA-II, referred as NSGA-III, is suggested to deal with many-objective problems, where the maintenance of diversity among population members is aided by supplying and adaptively updating a number of well-spread reference points. However, NSGA-III still relies on Pareto-dominance to push the population towards Pareto front (PF), leaving room for the improvement of its convergence ability. In this paper, an improved NSGA-III procedure, called θ-NSGA-III, is proposed, aiming to better tradeoff the convergence and diversity in many-objective optimization. In θ-NSGA-III, the non-dominated sorting scheme based on the proposed θ-dominance is employed to rank solutions in the environmental selection phase, which ensures both convergence and diversity. Computational experiments have shown that θ-NSGA-III is significantly better than the original NSGA-III and MOEA/D on most instances no matter in convergence and overall performance.

Inverted PBI in MOEA/D and its Impact on the Search Performance on Multi and Many-Objective Optimization

Hiroyuki Sato, *University of Electro-Communications*

MOEA/D decomposes a multi-objective optimization problem into a number of single objective optimization problems. Each single objective optimization problem is defined by a scalarizing function using a weight vector. In MOEA/D, there are several scalarizing approaches such as the weighted Tchebycheff, the weighted sum, and the PBI (penalty-based boundary intersection). However, these conventional scalarizing approaches face a difficulty to approximate a widely spread Pareto front in some problems. To enhance the spread of Pareto optimal solutions in the objective space and improve the search performance of MOEA/D especially in many-objective optimization problems, in this work we propose the inverted PBI scalarizing approach which is an extension of the conventional PBI. We use many-objective knapsack problems and WFG4 problems with 2-8 objectives, and compare the search performance of NSGA-III and four MOEA/Ds using the weighted Tchebycheff, the weighted sum, the PBI and the inverted PBI. As results, we show that MOEA/D using the inverted PBI achieves higher search performance than other algorithms in problems with many-objectives and the difficulty to obtain a widely spread Pareto front in the objective space.

EMO3

Steady State IBEA Assisted by MLP Neural Networks for Expensive Multi-Objective Optimization Problems

Nessrine Azzouz, *University of Tunis*, Slim Bechikh, *University of Tunis*, Lamjed Ben Said, *University of Tunis*

Several engineering problems involve simultaneously several objective functions where at least one of them is expensive to

evaluate. This fact has yielded to a new class of Multi-Objective Problems (MOPs) called expensive MOPs. Several attempts have been conducted in the literature with the goal to minimize the number of expensive evaluations by using surrogate models stemming from the machine learning field. Usually, researchers substitute the expensive objective function evaluation by an estimation drawn from the used surrogate. In this paper, we propose a new way to tackle expensive MOPs. The main idea is to use Neural Networks (NNs) within the Indicator-Based Evolutionary Algorithm (IBEA) in order to estimate the contribution of each generated offspring in terms of hypervolume. After that, only fit individuals with respect to the estimations are exactly evaluated. Our proposed algorithm called NN-SS-IBEA (Neural Networks assisted Steady State IBEA) have been demonstrated to provide good performance with a low number of function evaluations when compared against the original IBEA and MOEA/D-RBF on a set of benchmark problems in addition to the airfoil design problem.

Hypervolume-Based Local Search in Multi-Objective Evolutionary Optimization

Martin Pilat, *Charles University in Prague*, Roman Neruda, *Academy of Sciences of the Czech Republic*

This paper describes a surrogate based multi-objective evolutionary algorithm with hyper-volume contribution-based local search. The algorithm switches between an NSGA-II phase and a local search phase. In the local search phase, a model for each of the objectives is trained and CMA-ES is used to optimize the hyper-volume contribution of each individual with respect to its two neighbors on the non-dominated front. The performance of the algorithm is evaluated using the well known ZDT and WFG benchmark suites.

Hybridization of Electromagnetism with Multi-Objective Evolutionary Algorithms for RCPSP

Jing Xiao, *South China Normal University*, Zhou Wu, *South China Normal University*, Jian-Chao Tang, *South China Normal University*

As one of the most challenging combinatorial optimization problems in scheduling, the resource-constrained project scheduling problem (RCPSP) has attracted numerous scholars' interest resulting in considerable research in the past few decades. However, most of these papers focused on the single objective RCPSP; only a few papers concentrated on the multi-objective resource-constrained project scheduling problem (MORCPSP). Inspired by a procedure called electromagnetism (EM), which can help a generic population-based evolutionary search algorithm to obtain good results for single objective RCPSP, in this paper we attempt to extend EM and hybridize it with three reputable state-of-the-art multi-objective evolutionary algorithms (MOEAs) i.e., NSGA-II, SPEA2 and MOEA/D, for MORCPSP. Our two objectives are minimizing makespan and total tardiness. We perform computational experiments on standard benchmark datasets. Empirical comparison and analysis of the results obtained by the hybridization versions of EM with NSGA-II, SPEA2 and MOEA/D are conducted. The results demonstrate that EM can improve the performance of NSGA-II and SPEA2.

The Parameter Optimization of Kalman Filter Based on Multi-Objective Memetic Algorithm

Yu Dan Huo, *China University of Geosciences*, Zhi Hua Cai, *China University of Geosciences*, Wen Yin Gong, *China University of Geosciences*, Qin Liu, *China University of Geosciences*

Generally, there are two objectives in the optimization of the measurement noise covariance matrix R of Kalman filter. However, most of the traditional optimization methods of Kalman filter only focus on one objective. In this paper, we proposed a new method to optimize the parameter R based on Multi-Objective Memetic Algorithm (MOMA). Compared with traditional methods, it can optimize multiple objectives simultaneously. In this method, the decision vector is the diagonal elements of matrix R, the first objective function f_1 is the mean of the residual vectors, and the second objective function f_2 is the degree of mismatching between the actual value of the residual covariance with its theoretical value. In the MOMA, the global search based on NSGA-II is utilized to minimize the two objective functions, and the local search based on Simulated Annealing (SA) is just used to minimize the f_1. The experimental results demonstrate that the Kalman filter optimized by MOMA, namely MOMA-Kalman, can get much smaller filtering error than regular Kalman filter and other adaptive filter algorithms, such as SageHusa-Kalman and Fuzzy-Kalman.

Generative and Developmental Systems

BP1

Some Distance Measures for Morphological Diversification in Generative Evolutionary Robotics

Eivind Samuelsen, *University of Oslo*, Kyrre Glette, *University of Oslo*

Evolutionary robotics often involves optimization in large, complex search spaces, requiring good population diversity. Recently, measures to actively increase diversity or novelty have been employed in order to get sufficient exploration of the search space either as the sole optimization objective or in combination with some performance measurement.

When evolving morphology in addition to the control system, it can be difficult to construct a measure that sufficiently captures the qualitative differences between individuals. In this paper we investigate four diversity measures, applied in a set of evolution-

ary robotics experiments using an indirect encoding for evolving robot morphology. In the experiments we optimize forward locomotion capabilities of symmetrical legged robots in a physics simulation.
Two distance measures in Cartesian phenotype feature spaces are compared with two methods operating in the space of possible morphology graphs. These measures are used for computing a diversity objective in a multi-objective evolutionary algorithm, and compared to a control case with no diversity objective.
For the given task one of the distance measures shows a clear improvement over the control case in improving the main objectives, while others display better ability to diversify, underlining the difficulty of designing good, general measures of morphological diversity.

GDS1

Novelty Search Creates Robots with General Skills for Exploration

Roby Velez, *University of Wyoming*, Jeff Clune, *University of Wyoming*

Novelty Search, a new type of Evolutionary Algorithm, has shown much promise in the last few years. Instead of selecting for phenotypes that are closer to an objective, Novelty Search assigns rewards based on how different the phenotypes are from those already generated. A common criticism of Novelty Search is that it is effectively random or exhaustive search because it tries solutions in an unordered manner until a correct one is found. Its creators respond that over time Novelty Search accumulates information about the environment in the form of skills relevant to reaching uncharted territory, but to date no evidence for that hypothesis has been presented. In this paper we test that hypothesis by transferring robots evolved under Novelty Search to new environments (here, mazes) to see if the skills they've acquired generalize. Three lines of evidence support the claim that Novelty Search agents do indeed learn general exploration skills. First, robot controllers evolved via Novelty Search in one maze and then transferred to a new maze explore significantly more of the new environment than non-evolved (randomly generated) agents. Second, a Novelty Search process to solve the new mazes works significantly faster when seeded with the transferred controllers versus randomly generated ones. Third, no significant difference exists when comparing transferred agents evolved in the original maze under Novelty Search vs. a traditional, objective-based fitness function. The evidence gathered suggests that, like traditional Evolutionary Algorithms with objective-based fitness functions, Novelty Search is not a random or exhaustive search process, but instead is accumulating information about the environment, resulting in phenotypes possessing skills needed to explore their world.

Evolving Neural Networks that Are Both Modular and Regular: HyperNeat Plus the Connection Cost Technique

Joost Huizinga, *University of Wyoming*, Jeff Clune, *University of Wyoming*, Jean-Baptiste Mouret, *Université Pierre et Marie Curie, CNRS*

One of humanity's grand scientific challenges is to create artificially intelligent robots that rival natural animals in intelligence and agility. A key enabler of such animal complexity is the fact that animal brains are structurally organized in that they exhibit modularity and regularity, amongst other attributes. Modularity is the localization of function within an encapsulated unit. Regularity refers to the compressibility of the information describing a structure, and typically involves symmetries and repetition. These properties improve evolvability, but they rarely emerge in evolutionary algorithms without specific techniques to encourage them. It has been shown that (1) modularity can be evolved in neural networks by adding a cost for neural connections and, separately, (2) that the HyperNEAT algorithm produces neural networks with complex, functional regularities. In this paper we show that adding the connection cost technique to HyperNEAT produces neural networks that are significantly more modular, regular, and higher performing than HyperNEAT without a connection cost, even when compared to a variant of HyperNEAT that was specifically designed to encourage modularity.Our results represent a stepping stone towards the goal of producing artificial neural networks that share key organizational properties with the brains of natural animals.

Guided Self-Organization in Indirectly Encoded and Evolving Topographic Maps

Sebastian Risi, *IT University of Copenhagen*, Kenneth O. Stanley, *University of Central Florida*

An important phenomenon seen in many areas of biological brains and recently in deep learning architectures is a process known as self-organization. For example, in the primary visual cortex, color and orientation maps develop based on lateral inhibitory connectivity patterns and Hebbian learning dynamics. These topographic maps, which are found in all sensory systems, are thought to be a key factor in enabling abstract cognitive representations. This paper shows for the first time that the Hypercube-based NeuroEvolution of Augmenting Topologies (HyperNEAT) method can be seeded to begin evolution with such lateral connectivity, enabling genuine self-organizing dynamics. The proposed approach draws on HyperNEAT's ability to generate a pattern of weights across the connectivity of an artificial neural network (ANN) based on a function of its geometry. Validating this approach, the afferent weights of an ANN self-organize in this paper to form a genuine topographic map of the input space for a simple line orientation task. Most interestingly, this seed can then be evolved further, providing a method to guide the self-organization of weights in a specific way, much as evolution likely guided the self-organizing trajectories of biological brains.

There and Back Again: Gene-Processing Hardware for the Evolution and Robotic Deployment of Robust Navigation Strategies

David M. Bryson, *Michigan State University*, Aaron P. Wagner,

Michigan State University, Charles Ofria, *Michigan State University*

Navigation strategies represent some of the most intriguing examples of complex and intelligent behaviors in nature. Accordingly, they have been the focus of extensive research in animal behavior and in evolutionary robotics. However, engineering successes in harnessing the evolutionary dynamics that shape sophisticated navigation strategies remain limited. Here we describe a novel gene-processing architecture for digital organisms that enables the evolution of central-place-foraging strategies, such as those seen in honeybees and striped hyena. While previous studies have evolved navigation de novo, the resulting algorithms have been relatively fragile and difficult to translate into physical systems. In contrast, the strategies evolved in this study are highly congruous with those seen in nature: a single evolved foraging strategy incorporates periods of directed travel, fixed pattern search, cue response, and reorientation when outcomes do not match expected results. Additionally, the genetic architecture enabled rapid extraction of the underlying behavioral algorithm and transference to a robotic system, proving to be robust to issues of noise and scale that commonly plague such attempts. Accordingly, we demonstrate that the flexibility and interpretability of the new gene-processing hardware readily facilitate the creation, study, and utilization of naturalistic and deployable algorithms for functionally complex behaviors.

GDS2

Growth in Co-Evolution of Sensory System and Signal Processing for Optimal Wing Control

Olga Smalikho, *Technische Universität Darmstadt*, Markus Olhofer, *Honda Research Institute Europe*

The development of adaptive systems, which react autonomously to changes in their environment, require the coordinated generation of sensors, providing information about the environment and signal processing structures, which generate suitable reactions to changed conditions. In this work we demonstrate the applicability of a concurrent evolutionary design of the optimal sensory and controller parts of a system for the example of an adaptive wing design. The focus of the work is twofold. First on the realization of developmental stages of the sensory and controlling systems design, defined as a growth process, and second on the comparison of the differences in structures of the systems developed through the presented evolutionary growth method and of evolved systems, having fixed set of sensory elements. We ascertained that the success of the realized growth process depends among others on the relation between the triggering methods and timing of the system enlargement and on parameter settings of the optimization strategy after a growth phase.

Trading Control Intelligence for Physical Intelligence: Muscle Drives in Evolved Virtual Creatures

Dan Lessin, *University of Texas at Austin*, Don Fussell, *University of Texas at Austin*, Risto Miikkulainen, *University of Texas at Austin*

Traditional evolved virtual creatures are actuated using unevolved, uniform, invisible drives at joints between rigid segments. In contrast, this paper shows how such conventional actuators can be replaced by evolvable muscle drives that are a part of the creature's physical structure. Such a muscle-drive system replaces control intelligence with meaningful morphological complexity. For instance, the experiments in this paper show that control intelligence sufficient for locomotion or jumping can be moved almost entirely from the brain into the musculature of evolved virtual creatures.

This design is important for two reasons: First, the control intelligence is made visible in the purposeful development of muscle density, orientation, attachment points, and size. Second, the complexity that needs to be evolved for the brain to control the actuators is reduced, and in some cases can be essentially eliminated, thus freeing brain power for higher-level functions. Such designs may thus make it possible to create more complex behavior than would otherwise be achievable.

A Continuous Developmental Model for Wind Farm Layout Optimization

Dennis Wilson, *Massachusetts Institute of Technology*, Sylvain Cussat-Blanc, *University of Toulouse*, Kalyan Veeramachaneni, *Massachusetts Institute of Technology*, Una-May O'Reilly, *Massachusetts Institute of Technology*, Hervé Luga, *University of Toulouse*

We present DEVOII, an improved cell-based developmental model for wind farm layout optimization. To address the shortcomings of discretization, DEVOII's gene regulatory networks control cells that act in a continuous rather than discretized grid space. We find that DEVOII is competitive, and in some cases, superior with respect to state-of-the-art global, stochastic search approaches when a suite of algorithms is evaluated on different wind scenarios. The modularity of the genetic regulatory network computational paradigm in terms of isolating its search algorithm, the regulatory network simulation and the cell simulation, allowed this improvement to largely focus upon cell simulation. This indicates robustness of the paradigm's design. As well, wind farm layout optimization highlights how developmental models can be considered more efficient than other optimization methods because of their "optimize once, use-many" adaptability.

Genetic Algorithms

GA1

From Fitness Landscape to Crossover Operator Choice

Stjepan Picek, *Radboud University Nijmegen*, Domagoj Jakobovic, *University of Zagreb*

Genetic algorithms are applied to numerous problems that demonstrate different properties. To efficiently solve these problems, during the years a significant number of variation operators have been and still are created. It is a problem by itself how to correctly choose between those operators, i.e., how to find the most suitable operator (or a set) for a given problem. In this paper we investigate the choice of the suitable crossover operator on the basis of fitness landscape. The fitness landscape can be described with a number of properties, so a thorough analysis needs to be done to find the most useful ones. To achieve that, we experiment with 24 noise-free problems and floating point encoding. The results indicate it is possible to either select a suitable operator or at least to reduce the number of adequate operators with fitness landscape properties.

Unbiased Black-Box Complexities of Jump Functions — How to Cross Large Plateaus

Benjamin Doerr, *École Polytechnique de Paris*, Carola Doerr, *Université Pierre et Marie Curie, CNRS*, Timo Kötzing, *Friedrich-Schiller-Universität Jena*

We analyze the unbiased black-box complexity of jump functions with large jump sizes. Among other results, we show that when the jump size is $(1/2 - \epsilon)n$, that is, only a small constant fraction of the fitness values is visible, then the unbiased black-box complexities for arities 3 and higher are of the same order as those for the simple OneMax function. Even for the extreme jump function, in which all but the two fitness values $n/2$ and n are blanked out, polynomial-time mutation-based (i.e., unary unbiased) black-box optimization algorithms exist. This is quite surprising given that for the extreme jump function almost the whole search space (all but a $\Theta(n^{-1/2})$ fraction) is a plateau of constant fitness.

To prove these results, we introduce new tools for the analysis of unbiased black-box complexities, for example, selecting the new parent individual not by comparing the fitnesses of the competing search points, but also by taking into account the (empirical) expected fitnesses of their offspring.

Stochastic Tunneling Transformation during Selection in Genetic Algorithm

Benjamin E. Mayer, *Technische Universität Darmstadt*, Kay Hamacher, *Technische Universität Darmstadt*

Genetic Algorithms (GA) combine mutational and recombination operators to then select between individuals. Thereby, competition becomes the driving force to improve solutions. Now, this naive approach to biological evolution often assumes a static fitness function, e.g., co-evolutionary effects cannot easily be leveraged.

Here, we introduce a fitness landscape transformation inspired by Monte-Carlo-based optimization schemes. In the Stochastic-Tunneling (STUN) framework fitness values are non-linearly transformed under preservation of the relative ranking of optima. The "base line" of the STUN-transformation can be set based on different memory mechanisms — from current to full history.

This STUN-based GA-variant allows to include co-evolution and history into the GA. Based on analytic arguments we can show that the non-linearity of the transformation generates high population densities in areas of interest.

We numerically simulated small, controllable, and well understood test instance: replicas of Ising-spin glasses. For these systems the STUN-GAs have shown significant improvements in terms of relative error for given computational effort. In addition, we introduce an empirical measure of selection to discuss the improved convergence behavior.

Adaptive-Surrogate Based on a Neuro-Fuzzy Network and Granular Computing

Israel Cruz-Vega, *Instituto Nacional de Astrofísica, Óptica Y Electrónica, México*, Mauricio Garcia-Limon, *Instituto Nacional de Astrofísica, Óptica Y Electrónica, México*, Hugo Jair Escalante, *Instituto Nacional de Astrofísica, Óptica Y Electrónica, México*

Surrogate-based methods aim at reducing the evaluation of expensive fitness functions in optimization processes. Several surrogate-based methods for evolutionary optimization have been proposed so far, including those based on granular computing/clustering. Granular computing provides granules as an assemblage of entities arranged together by their similarity, functional or physical adjacency, indistinguishability, coherency, or the like. Techniques like this avoid multiple and unnecessary evaluations of individuals repeatedly. In this paper, with the aim of granular computing as a method of grouping data, such information is exploited to obtain knowledge of the structure and parameters of individuals and then, design a Neuro-Fuzzy network that adapts granules' parameters, providing convergence to acceptable solutions with a reduced number of evaluations of the fitness function. We implement this adaptive surrogate in a genetic algorithm and show its performance using benchmark functions.

GA2

Among-Site Rate Variation: Adaptation of Genetic Algorithm Mutation Rates at Each Single Site

Fatemeh Vafaee, *University of Sydney*, Gyorgy Turan, *University of Illinois at Chicago*, Peter C. Nelson, *University of Illinois at Chicago*, Tanya Y. Berger-Wolf, *University of Illinois at Chicago*

This paper is concerned with proposing an elitist genetic al-

gorithm which makes use of a new mutation scheme aimed to tackle both explorative and exploitative responsibilities of genetic operators. The proposed mutation scheme follows an approach similar to motif representation in biology, to derive the underlying pattern of highly-fit solutions discovered so far. This pattern is then used to derive mutation rates specified for every site along the encoded solutions. The site-specific rates are amended for every individual to balance the required explorative and exploitative power. The Markov chain model of the proposed method is also derived and used to analyze its convergence properties.

A Bilevel Optimization Approach to Automated Parameter Tuning

Ankur Sinha, *Aalto University*, Pekka Malo, *Aalto University*, Peng Xu, *Aalto University*, Kalyanmoy Deb, *Michigan State University*

Many of the modern optimization algorithms contain a number of parameters that require tuning before the algorithm can be applied to a particular class of optimization problems. A proper choice of parameters may have a substantial effect on the accuracy and efficiency of the algorithm. Until recently, parameter tuning has mostly been performed using brute force strategies, such as grid search and random search. Guesses and insights about the algorithm are also used to find suitable parameters or suggest strategies to adjust them. More recent trends include the use of meta-optimization techniques. Most of these approaches are computationally expensive and do not scale when the number of parameters increases. In this paper, we propose that the parameter tuning problem is inherently a bilevel programming problem. Based on this insight, we introduce an evolutionary bilevel algorithm for parameter tuning. A few commonly used optimization algorithms (Differential Evolution and Nelder-Mead) have been chosen as test cases, whose parameters are tuned on a number of standard test problems. The bilevel approach is found to quickly converge towards the region of efficient parameters. The code for the proposed algorithm can be accessed from the website http://bilevel.org.

Feedback Control for Multi-Modal Optimization Using Genetic Algorithms

Jun Shi, *Carnegie Mellon University*, Ole J. Mengshoel, *Carnegie Mellon University*, Dipan K. Pal, *Carnegie Mellon University*

Many optimization problems are multi-modal. In certain cases, we are interested in finding multiple locally optimal solutions rather than just a single optimum as is computed by traditional genetic algorithms (GAs). Several niching techniques have been developed that seek to find multiple such local optima. These techniques, which include sharing and crowding, are clearly powerful and useful. But they do not explicitly let the user control the number of local optima being computed, which we believe to be an important capability.

In this paper, we develop a method that provides, as an input parameter to niching, the desired number of local optima. Our method integrates techniques from feedback control, includes a sensor based on clustering, and utilizes a scaling parameter in Generalized Crowding to control the number of niches being explored. The resulting Feedback Control GA (FCGA) is tested in several experiments and found to perform well compared to previous approaches. Overall, the integration of feedback control and Generalized Crowding is shown to effectively guide the search for multiple local optima in a more controlled fashion. We believe this novel capability has the potential to impact future applications as well as other evolutionary algorithms.

Genetic Algorithm for Sampling from Scale-free Data and Networks

Pavel Krömer, *University of Alberta*, Jan Platoš, *VŠB-Technical University of Ostrava*

A variety of real-world data and networks can be described by a heavy-tailed probability distribution of its values, vertex degrees, or other significant properties, that follows the power law. Such a scale-free data and networks can be found in both natural phenomena such as protein interaction networks and gene regulation networks and man-made structures like the Internet, language, and various social networks. An efficient analysis of large scale data and networks is often impractical and various heuristic and metaheuristc sampling techniques are deployed to select smaller subsets of the data for analysis and visualisation. A key goal of data and network sampling is to select such a subset of the original data that would accurately represent the original data with respect to selected attributes. In this work we propose a novel genetic algorithm for scale-free data and network sampling and evaluate the algorithm in a series of computational experiments.

GA3

Runtime Analysis for Maximizing Population Diversity in Single-Objective Optimization

Wanru Gao, *University of Adelaide*, Frank Neumann, *University of Adelaide*

Recently Ulrich and Thiele have introduced evolutionary algorithms for the mixed multi-objective problem of maximizing fitness as well as diversity in the decision space. Such an approach allows to generate a diverse set of solutions which are all of good quality. With this paper, we contribute to the theoretical understanding of evolutionary algorithms for maximizing the diversity in a population that contains several solutions of high quality. We study how evolutionary algorithms maximize the diversity of a population where each individual has to have fitness beyond a given threshold value. We present a first runtime analysis in this area and study the classical problems called *OneMax* and *LeadingOnes*. Our results give first rigorous insights on how evolutionary algorithms can be used to produce a maximal diverse set of solutions in which all solutions have quality above a certain threshold value.

Monotonic Functions in EC: Anything but Monotone!

Sylvain Colin, *Ecole Polytechnique de Paris*, Benjamin Doerr, *École Polytechnique de Paris*, Gaspard Ferey, *École Polytechnique de Paris*

To understand how evolutionary algorithms optimize the simple class of monotonic functions, Jansen (FOGA 2007) introduced the partially-ordered evolutionary algorithm (PO-EA) model and analyzed its runtime. The PO-EA is a pessimistic model of the true optimization process, hence performance guarantees for it immediately take over to the true optimization process.

Based on the observation that Jansen's model leads to a process more pessimistic than what any monotonic function would, we extend his model by parametrizing the degree of pessimism. For all degrees of pessimism, and all mutation rates c/n, we give a precise runtime analysis of this process. For all degrees of pessimism lower than that of Jansen, we observe a $\Theta(n \log n)$ runtime for the standard mutation probability of $1/n$. However, we also observe a strange double-jump behavior in terms of the mutation probability. For all non-zero degrees of pessimism, there is a threshold $c \in \mathbb{R}$ such that (i) for mutation rates c'/n with $c' < c$ we have a $\Theta(n \log n)$ runtime, (ii) for the mutation rate c/n we have a runtime of $\Theta(n^{3/2})$, and (iii) for mutation rates c''/n with $c'' > c$ we have an exponential runtime.

To overcome the complicated interplay of mutation and selection in the PO-EA, by define artificial algorithms which provably (via a coupling argument) have the same asymptotic runtime, but allow a much easier computation of the drift towards the optimum.

A Fixed Budget Analysis of Randomized Search Heuristics for the Traveling Salesperson Problem

Samadhi Nallaperuma, *University of Adelaide*, Frank Neumann, *University of Adelaide*, Dirk Sudholt, *University of Sheffield*

Randomized Search heuristics are frequently applied to NP-hard combinatorial optimization problems. The runtime analysis of randomized search heuristics has contributed tremendously to their theoretical understanding. Recently, randomized search heuristics have been examined regarding their achievable progress within a fixed time budget. We follow this approach and present a first fixed budget runtime analysis for a NP-hard combinatorial optimization problem. We consider the well-known Traveling Salesperson problem (TSP) and analyze the fitness increase that randomized search heuristics are able to achieve within a given fixed budget.

Parameter-less Population Pyramid

Brian W. Goldman, *Michigan State University*, William F. Punch, *Michigan State University*

Real world applications of evolutionary techniques are often hindered by the need to determine problem specific parameter settings. While some previous methods have reduced or removed the need for parameter tuning, many do so by trading efficiency for general applicability. The Parameter-less Population Pyramid (P3) is an evolutionary technique that requires no parameters and is still broadly effective. P3 strikes a balance between continuous integration of diversity and exploitative elitist operators, allowing it to solve easy problems quickly and hard problems eventually. When compared with three optimally tuned, state of the art optimization techniques, P3 always finds the optimum at least a constant factor faster across four benchmarks (Deceptive Trap, Deceptive Step Trap, HIFF, Rastrigin). More importantly, on three randomized benchmarks (NK Landscapes, Ising Spin Glasses, MAX-SAT), P3 has a lower order of computational complexity as measured by evaluations. We also provide outlines for expected runtime analysis of P3, setting the stage for future theory based conclusions. Based on over 1 trillion evaluations, our results suggest P3 has wide applicability to a broad class of problems.

GA4

Learning the Structure of Large-Scale Bayesian Networks Using Genetic Algorithm

Fatemeh Vafaee, *University of Sydney*

Bayesian networks are probabilistic graphical models representing conditional dependencies among a set of random variables. Due to their concise representation of the joint probability distribution, Bayesian Networks are becoming incrementally popular models for knowledge representation and reasoning in various problem domains. However, learning the structure of the Bayesian networks is an NP-hard problem since the number of structures grows super-exponentially as the number of variables increases. This work therefore is aimed to propose a new hybrid structure learning algorithm that uses mutual dependencies to reduce the search space complexity and recruits the genetic algorithm to effectively search over the reduced space of possible structures. The proposed method is best suited for problems with medium to large number of variables and a limited dataset. It is shown that the proposed method achieves higher model's accuracy as compared to a series of popular structure learning algorithms particularly when the data size gets smaller.

Evolving QWOP Gaits

Steven Ray, *California State University, Sacramento*, Vahl Scott Gordon, *California State University, Sacramento*, Laurent Vaucher, *Google, Inc.*

QWOP is a popular Flash game in which a human player controls a sprinter in a simulated 100-meter dash. The game is notoriously difficult owing to its ragdoll physics engine, and the simultaneous movements that must be carefully coordinated to achieve forward progress. While previous researchers have evolved gaits using simulations similar to QWOP, we describe a software interface that connects directly to QWOP itself, incorporating a genetic algorithm to evolve actual QWOP gaits. Since QWOP has no API, ours detects graphical screen elements and uses them to build a fitness function. Two variable-length encoding schemes, that codify sequences of QWOP control commands that loop to form gaits, are tested. We then compare the

performance of SGA, Genitor, and a Cellular Genetic Algorithm on this task. Using only the end score as the basis for fitness, the cellular algorithm is consistently able to evolve a successful scooting strategy similar to one most humans employ. The results confirm that steady-state GAs are preferred when the task is sensitive to small input variations. Although the limited feedback does not yet produce performance competitive with QWOP champions, it is the first autonomous software evolution of successful QWOP gaits.

Efficient Global Optimization for Combinatorial Problems

Martin Zaefferer, *Cologne University of Applied Sciences*, Jörg Stork, *Cologne University of Applied Sciences*, Martina Friese, *Cologne University of Applied Sciences*, Andreas Fischbach, *Cologne University of Applied Sciences*, Boris Naujoks, *Cologne University of Applied Sciences*, Thomas Bartz-Beielstein, *Cologne University of Applied Sciences*

Real-world optimization problems may require time consuming and expensive measurements or simulations. Recently, the application of surrogate model-based approaches was extended from continuous to combinatorial spaces. This extension is based on the utilization of suitable distance measures such as Hamming or Swap Distance. In this work, such an extension is implemented for Kriging (Gaussian Process) models. Kriging provides a measure of uncertainty when determining predictions. This can be harnessed to calculate the Expected Improvement (EI) of a candidate solution. In continuous optimization, EI is used in the Efficient Global Optimization (EGO) approach to balance exploitation and exploration for expensive optimization problems. Employing the extended Kriging model, we show for the first time that EGO can successfully be applied to combinatorial optimization problems. We describe necessary adaptations and arising issues as well as experimental results on several test problems. All surrogate models are optimized with a Genetic Algorithm (GA). To yield a comprehensive comparison, EGO and Kriging are compared to an earlier suggested Radial Basis Function Network, a linear modeling approach, as well as model-free optimization with random search and GA. EGO clearly outperforms the competing approaches on most of the tested problem instances.

Search For Maximal Snake-in-the-Box Using New Genetic Algorithm

Kim-Hang Ruiz, *International MIS*

The "Snake-in-the-Box" (SIB) problem is a challenging combinatorial search problem to find the longest constrained open path (k-spread snake) in n-dimensional hypercube (Q_n). In addition to constructive techniques, many search algorithms such as Depth First Search (DFS), Genetic Algorithm (GA), hybrid Evolutionary Computation algorithm (EC), and Nested Monte-Carlo Search (NMCS) have been used to tackle this problem. To get better results and to speed up the process, these techniques often used a long snake as the starting point for the search (priming/seeding).
This paper reviews the hypercube fundamentals, then presents a new search technique, Mitosis Genetic Algorithm (MGA), which was applied in search for the four different spread snakes (spread 2 to 5) in seven different dimensional hypercubes (Q_6 to Q_{13}). The MGA found three new record-breaking 3-spread snakes in Q_{10}, Q_{11} and Q_{13}, all the previously known optimal snakes from spread 2 to spread 5, and the best previous known maximal 3-S_9 snake of length 63. It is remarkable that it found those within minutes to hours without priming, significantly shorter than days to weeks needed in the other techniques.

Genetic Programming

GP1

GPU-Parallel SubTree Interpreter for Genetic Programming

Alberto Cano, *Universidad de Córdoba*, Sebastian Ventura, *Universidad de Córdoba*

Genetic Programming (GP) is a computationally intensive technique but its nature is embarrassingly parallel. Graphic Processing Units (GPUs) are many-core architectures which have been widely employed to speed up the evaluation of GP. In recent years, many works have shown the high performance and efficiency of GPUs on evaluating both the individuals and the fitness cases in parallel. These approaches are known as population parallel and data parallel. This paper presents a parallel GP interpreter which extends these approaches and adds a new parallelization level based on the concurrent evaluation of the individual's subtrees. A GP individual defined by a tree structure with nodes and branches comprises different depth levels in which there are independent subtrees which can be evaluated concurrently. Threads can cooperate to evaluate different subtrees and share the results via GPU's shared memory. The experimental results show the better performance of the proposal in terms of the GP operations per second (GPops/s) that the GP interpreter is able to process, achieving up to 21 billion GPops/s using a NVIDIA 480 GPU. However, some issues raised due to limitations of currently available hardware are to be overcome by the dynamic parallelization capabilities of the next generation of GPUs.

Improving 3D Medical Image Registration CUDA Software with Genetic Programming

William B. Langdon, *University College London*, Marc Modat, *University College London*, Justyna Petke, *University College London*, Mark Harman, *University College London*

Genetic Improvement (GI) is shown to optimise, in some cases by more than 35 percent, a critical component of healthcare

industry software across a diverse range of six nVidia graphics processing units (GPUs). GP and other search based software engineering techniques can automatically optimise the current rate limiting CUDA parallel function in the NiftyReg open source C++ project used to align or register high resolution NMRI and other diagnostic NIfTI images. Future Neurosurgery techniques will require hardware acceleration, such as GPGPU, to enable real time comparison of three dimensional in theatre images with earlier patient images and reference data. With millimetre resolution brain scan measurements comprising more than ten million voxels the modified kernel can process in excess of 3 billion active voxels per second.

Grammar-Based Genetic Programming with Dependence Learning and Bayesian Network Classifier

Pak-Kan Wong, *Chinese University of Hong Kong*, Leung-Yau Lo, *Chinese University of Hong Kong*, Man-Leung Wong, *Lingnan University*, Kwong-Sak Leung, *Chinese University of Hong Kong*

Grammar-Based Genetic Programming formalizes constraints on the solution structure based on domain knowledge to reduce the search space and generate grammatically correct individuals. Nevertheless, building blocks in a program can often be dependent, so the effective search space can be further reduced. Approaches have been proposed to learn the dependence using probabilistic models and shown to be useful in finding the optimal solutions with complex structure. It raises questions on how to use the individuals in the population to uncover the underlying dependence. Usually, only the good individuals are selected. To model the dependence better, we introduce Grammar-Based Genetic Programming with Bayesian Network Classifier (GBGPBC) which also uses poorer individuals. With the introduction of class labels, we further propose a refinement technique on probability distribution based on class label. Our results show that GBGPBC performs well on two benchmark problems. These techniques boost the performance of our system.

Utilization of Reductions and Abstraction Elimination in Typed Genetic Programming

Tomáš Kren, *Charles University in Prague*, Roman Neruda, *Academy of Sciences of the Czech Republic*

Lambda calculus representation of programs offers a more expressive alternative to traditional S-expressions. In this paper we discuss advantages of this representation coming from the use of reductions (beta and eta) and a way to overcome disadvantages caused by variables occurring in the programs by use of the abstraction elimination algorithm. We discuss the role of those reductions in the process of generating initial population and propose two novel crossover operations based on abstraction elimination capable of handling general form of typed lambda term while being a straight generalization of the standard crossover operation. We compare their performances using the even parity benchmark problem.

GP2

Kaizen Programming

Vinícius Veloso de Melo, *Universidade Federal de São Paulo*

This paper presents Kaizen Programming, an evolutionary tool based on the concepts of Continuous Improvement from Kaizen Japanese methodology. One may see Kaizen Programming as a new paradigm since, as opposed to classical evolutionary algorithms where individuals are complete solutions, in Kaizen Programming each expert proposes an idea to solve part of the problem, thus a solution is composed of all ideas together. Consequently, evolution becomes a collaborative approach instead of an egocentric one. An idea's quality (analog to an individual's fitness) is not how good it fits the data, but a measurement of its contribution to the solution, which improves the knowledge about the problem. Differently from evolutionary algorithms that simply perform trial-and-error search, one can determine, exactly, parts of the solution that should be removed or improved. That property results in the reduction in bloat, number of function evaluations, and computing time. Even more important, the Kaizen Programming tool, proposed to solve symbolic regression problems, builds the solutions as linear regression models — not linear in the variables, but linear in the parameters, thus all properties and characteristics of such statistical tool are valid. Experiments on benchmark functions proposed in the literature show that Kaizen Programming easily outperforms Genetic Programming and other methods, providing high quality solutions for both training and testing sets while requiring a small number of function evaluations.

Multiple Regression Genetic Programming

Ignacio Arnaldo, *Massachusetts Institute of Technology*, Krzysztof Krawiec, *Poznan University of Technology*, Una-May O'Reilly, *Massachusetts Institute of Technology*

We propose a new means of executing a genetic program which improves its output quality. Our approach, called Multiple Regression Genetic Programming (MRGP) decouples and linearly combines a program's subexpressions via multiple regression on the target variable. The regression yields an alternate output: the prediction of the resulting multiple regression model. It is this output, over many fitness cases, that we assess for fitness, rather than the program's execution output. MRGP can be used to improve the fitness of a final evolved solution. On our experimental suite, MRGP consistently generated solutions fitter than the result of competent GP or multiple regression. When integrated into GP, inline MRGP, on the basis of equivalent computational budget, outperforms competent GP while also besting post-run MRGP. Thus MRGP's output method is shown to be superior to the output of program execution and it represents a practical, cost neutral, improvement to GP.

Asynchronously Evolving Solutions with Excessively Different Evaluation Time by Reference-based Evaluation

Tomohiro Harada, *University of Electro-Communications*,

Keiki Takadama, *University of Electro-Communications*

The asynchronous evolution has an advantage when evolving solutions with excessively different evaluation time since the asynchronous evolution evolves each solution independently without waiting for other evaluations, unlike the synchronous evolution requires evaluations of all solutions at the same time. As a novel asynchronous evolution approach, this paper proposes Asynchronous Reference-based Evaluation (ARE) that asynchronously selects good parents by the tournament selection using reference solution in order to evolve solutions through a crossover of the good parents. To investigate the effectiveness of ARE in the case of evolving solutions with excessively different evaluation time, this paper applies ARE to Genetic Programming (GP), and compares GP using ARE (ARE-GP) with GP using $(\mu+\lambda)$ selection ($(\mu+\lambda)$-GP) as the synchronous approach in particular situation where the evaluation time of individuals differs from each other. The intensive experiments have revealed the following implications: (1) ARE-GP greatly outperforms $(\mu+\lambda)$-GP from the viewpoint of the elapsed unit time in the parallel computation environment, (2) ARE-GP can evolve individuals without decreasing the searching ability in the situation where the computing speed of each individual differs from each other and some individuals fail in their execution.

GP3

On Size, Complexity and Generalisation Error in GP

Jeannie Fitzgerald, *University of Limerick*, Conor Ryan, *University of Limerick*

For some time, GP research has lagged behind the wider Machine Learning community in the study of generalisation, where the decomposition of generalisation error into *bias* and *variance* components is well understood. However, recent Genetic Programming contributions focusing on complexity, size and bloat as they relate to over-fitting have opened up some interesting avenues of research. In this paper, we carry out a simple empirical study on five binary classification problems. The study is designed to discover what effects may be observed when program size and complexity are varied *in combination*, with the objective of gaining a better understanding of relationships which may exist between solution size, operator complexity and variance error. The results of the study indicate that the simplest configuration, in terms of *operator complexity*, consistently results in the best average performance, and in many cases, the result is significantly better. We further demonstrate that the best results are achieved when this minimum complexity set-up is combined with a less than parsimonious permissible size.

Word Count as a Traditional Programming Benchmark Problem for Genetic Programming

Thomas Helmuth, *University of Massachusetts*, Lee Spector, *Hampshire College*

The Unix utility program wc, which stands for "word count," takes any number of files and prints the number of newlines, words, and characters in each of the files. We show that genetic programming can find programs that replicate the core functionality of the wc utility, and propose this problem as a "traditional programming" benchmark for genetic programming systems. This "wc problem" features key elements of programming tasks that often confront human programmers, including requirements for multiple data types, a large instruction set, control flow, and multiple outputs. Furthermore, it mimics the behavior of a real-world utility program, showing that genetic programming can automatically synthesize programs with general utility. We suggest statistical procedures that should be used to compare performances of different systems on traditional programming problems such as the wc problem, and present the results of a short experiment using the problem. Finally, we give a short analysis of evolved solution programs, showing how they make use of traditional programming concepts.

Evolving "Less-Myopic" Scheduling Rules for Dynamic Job Shop Scheduling with Genetic Programming

Rachel Hunt, *Victoria University of Wellington*, Mark Johnston, *Victoria University of Wellington*, Mengjie Zhang, *Victoria University of Wellington*

Job Shop Scheduling (JSS) is a complex real-world problem aiming to optimise a measure of delivery speed or customer satisfaction by determining a schedule for processing jobs on machines. A major disadvantage of using a dispatching rule (DR) approach to solving JSS problems is their lack of a global perspective of the current and potential future state of the shop. We investigate a genetic programming based hyper-heuristic (GPHH) approach to develop "less-myopic" DRs for dynamic JSS. Results show that in the dynamic ten machine job shop, incorporating features of the state of the wider shop, and the stage of a job's journey through the shop, improves the mean performance, and decreases the standard deviation of performance of the best evolved rules.

Behavioral Programming: A Broader and More Detailed Take on Semantic GP

Krzysztof Krawiec, *Poznan University of Technology*, Una-May O'Reilly, *Massachusetts Institute of Technology*

In evolutionary computation, the fitness of a candidate solution conveys sparse feedback. Yet in many cases, candidate solutions can potentially yield more information. In genetic programming (GP), one can easily examine program behavior on particular fitness cases or at intermediate execution states. However, how to exploit it to effectively guide the search remains unclear. In this study we apply machine learning algorithms to features describing the intermediate behavior of the executed program. We then drive the standard evolutionary search with additional objectives reflecting this intermediate behavior. The machine learning functions independent of task-specific knowledge and discovers potentially useful components of solutions (subprograms), which we preserve in an archive and use as building blocks when composing new candidate solutions. In an experimental assessment on a suite of benchmarks, the proposed approach proves more capable of finding optimal and/or well-performing solutions than control methods.

Hot Off the Press

THEORY2

The Query Complexity of Finding a Hidden Permutation

Peyman Afshani, *Aarhus University*, Manindra Agrawal, *Indian Institute of Technology Kanpur*, Benjamin Doerr, *École Polytechnique de Paris*, Carola Doerr, *Université Pierre et Marie Curie, CNRS*, Kasper Green Larsen, *Aarhus University*, Kurt Mehlhorn, *Max Planck Institut für Informatik*

A useful complement of the well-established runtime analysis in the theory of evolutionary computation is the notion of black-box complexity, which, in short, is an attempt to formulate a meaningful complexity theory for EAs and other randomized search heuristics (RSH). The unrestricted black-box complexity model [Droste, Jansen, Wegener: ToCS 2006] is the broadest complexity notion in our field. It covers all typical RSH. Despite its simple definition, analyzing the unrestricted black-box complexity turns out to be quite tricky already for many standard test functions.

In our work [Space-Efficient Data Structures, Streams, and Algorithms, LNCS 8066, Springer 2013] we study the unrestricted black-box complexity of LeadingOnes, one of the most famous test function in the theory of evolutionary computation. We show that the unrestricted black-box complexity of LeadingOnes is $n \log \log(n)$. This implies that there exists a black-box algorithm which optimizes LeadingOnes in $Cn \log \log(n)$ fitness evaluations, for some constant C. This is much better than what state-of-the-art evolutionary algorithms offer: they typically need n^2 fitness evaluations. Whether this is indeed best possible with evolutionary methods is a challenging open question arising from our work. As has been recently shown [Doerr, Doerr, Ebel: GECCO 2013], such discrepancies between black-box complexity results and the runtime of typical evolutionary algorithms can inspire the design of new bio-inspired heuristics that outperform our currently available RSH.

Also the lower bound is noteworthy. It is the first one of its kind that uses methods beyond the classic fitness level method or the information-theoretic lower bound of [DJW06].

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HOP1

Non-Additive Multi-Objective Robot Coalition Formation

Manoj Agarwal, *University of Delhi*, Naveen Kumar, *University of Delhi*, Lovekesh Vig, *Jawaharlal Nehru Univ.*

Complexity of modern multi-robot systems require coalitions of robots to perform a task. It becomes necessary to accommodate non-additive constraints on the sensory capabilities of the robots. Researchers have devised heuristic based techniques to devise algorithms that yield approximate solutions of this NP hard problem. However, a multiple robot system is required to balance several conflicting objectives such as robot battery life, distance travelled, sensor utilization and task completion. In this paper, the robot coalition formation problem is modelled as a bi-objective optimization problem. The robot resources are assumed to be non-additive, i.e., it is not sufficient for a team of robots to have enough resources in totality, locational constraints imposed on the sensors of individual robots also need to be taken into account.

This paper presents a novel application of the Pareto Archived Evolution Strategy (PAES) algorithm for the multi-robot coalition formation problem. Experiments were carried out by varying the robot to task ratio including the scenarios where enough robots may not be available to complete all the given tasks. In all experiments, we observed that the spread of the Pareto optimal solution set is significantly larger than the sets generated by NSGA-II and SPEA2. Further, three popular methods namely compromise programming, marginal rate of return and weighted average have been implemented to help the decision maker to identify a single solution of interest from the Pareto optimal set of solutions. Realization of the proposed algorithm has been demonstrated using Player/Stage simulations.

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Evolvability Is Inevitable: Increasing Evolvability without the Pressure to Adapt

Joel Lehman, *University of Texas at Austin*, Kenneth O. Stanley, *University of Central Florida*

Why evolvability appears to have increased over evolutionary time is an important unresolved biological question. Unlike most candidate explanations, this paper proposes that increasing evolvability can result without any pressure to adapt. The insight is that if evolvability is heritable, then an unbiased drifting process across genotypes can still create a distribution of phenotypes biased towards evolvability, because evolvable organisms diffuse more quickly through the space of possible phenotypes. Furthermore, because phenotypic divergence often correlates with founding niches, niche founders may on average be more evolvable, which through population growth provides a genotypic bias towards evolvability. Interestingly, the combination of these two mechanisms can lead to increasing evolvability without any pressure to out-compete other organisms, as demonstrated through experiments with a series of simulated models. Thus rather than from pressure to adapt, evolvability may inevitably result from any drift through genotypic space combined with evolution's passive tendency to accumulate niches.

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Cracking the Egg: Virtual Embryogenesis of Real Robots

Sylvain Cussat-Blanc, *Brandeis University*, Jordan Pollack, *Brandeis University*

All multicellular living beings are created from a single cell.

A developmental process, called embryogenesis, takes this first fertilized cell down a complex path of reproduction, migration and specialization into a complex organism adapted to its environment. In most cases, the first steps of the embryogenesis are taking place into a protected environment such as in an egg or in-utero.

Starting from this observation, we propose a new approach to the generation of real robots, strongly inspired by living systems. Our robots are composed of tens of specialized cells, grown from a single cell using a bio-inspired virtual developmental process. Virtual cells, controlled by gene regulatory networks, divide, migrate and specialize to produce the robot's body plan (morphology), and then the robot is manually built from this plan. Because the robot is as easy to assemble as LEGO, the building process could be easily automated.

This paper shows examples of robot produced with this developmental approach. The robots are first evolved with an interactive genetic algorithm (blind watchmaker) to evaluate the capacity of the approach to inherently produce morphologies with crucial properties such as regularities and symmetries. Then, a standard genetic algorithm optimizes the cell's gene regulatory network to generate robots capable of locomotion. The robot blocks have been 3D-printed so that the best individuals can be assembled and tested in reality. The paper also shows some of these.

[to appear in: *Artificial Life*.]

Role of Genetic Heterogeneity and Epistasis in Bladder Cancer Susceptibility and Outcome: A Learning Classifier System Approach

Ryan John Urbanowicz, *Dartmouth College*, Angeline S. Andrew, *Dartmouth College*, Margaret Rita Karagas, *Dartmouth College*, Jason H. Moore, *Dartmouth College*

Detecting complex patterns of association between risk factors and disease risk has become an important target for epidemiological research. In particular, strategies that detect multifactor interactions or heterogeneous patterns of association can offer new insights into common complex disease studies. To concurrently examine these phenomena, previous work has successfully considered the application of learning classifier systems (LCSs), a flexible class of evolutionary algorithms that distributes learned associations over a population of rules. Subsequent work dealt with the inherent problems of knowledge discovery and interpretation within these algorithms, allowing for the characterization of heterogeneous patterns of association. Here we have applied and evaluated this proposed approach in the context of a 'real-world' genetic epidemiology study of bladder cancer susceptibility. We replicated the identification of previously characterized factors that modify bladder cancer risk—namely, single nucleotide polymorphisms from a DNA repair gene, and smoking. Furthermore, we identified potentially heterogeneous groups of subjects characterized by distinct patterns of association. Cox proportional hazard models comparing clinical outcome variables between the cases of the two largest groups yielded a significant, meaningful difference in survival time in years (survivorship). A marginally significant difference in recurrence time was also noted. These results support the hypothesis that an LCS approach can offer greater insight into complex patterns of association. This methodology appears to be well suited to the dissection of disease heterogeneity, a key component in the advancement of personalized medicine.

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HOP2

Genetic Algorithms for Evolving Computer Chess Programs

Omid E. David, *Bar-Ilan University*, H. Jaap van den Herik, *Tilburg University*, Moshe Koppel, *Bar-Ilan University*, Nathan S. Netanyahu, *Bar-Ilan University*

This paper demonstrates the use of genetic algorithms for evolving (1) a grandmaster-level evaluation function and (2) a search mechanism for a chess program, the parameter values of which are initialized randomly. The evaluation function of the program is evolved by learning from databases of (human) grandmaster games. At first the organisms are evolved to mimic the behavior of human grandmasters, and then these organisms are further improved upon by means of coevolution. The search mechanism is evolved by learning from tactical test suites. Our results show that the evolved program outperforms a two-time World Computer Chess Champion, and is on a par with other leading computer chess programs.

[to appear in: *IEEE Transactions on Evolutionary Computation*.]

EvoMCTS: A Scalable Approach for General Game Learning

Amit Benbassat, *Ben-Gurion University of the Negev*, Moshe Sipper, *Ben-Gurion University of the Negev*

We present the application of genetic programming as a generic game learning approach to zero-sum, deterministic, full-knowledge board games by evolving board-state evaluation functions to be used in conjunction with Monte Carlo Tree Search (MCTS). This result has recently been accepted for publication in the journal IEEE Transactions on Computational Intelligence and AI in Games. Our method involves evolving board-evaluation functions that are then used to guide the MCTS playout strategy. We examine several variants of Reversi, Dodgem, and Hex using Genetic Programming (GP). In EvoMCTS we evolve board evaluation functions for a variety of games. These functions are intended to improve on the generic MCTS players that use the UCT variant of the MCTS algorithm. EvoMCTS players use Evolved evaluation functions in the simulation stage of MCTS instead of the default random playout strategy. Our approach is also easily applicable to any game without any need for expert game knowledge (though it can be incorporated into the evolutionary process and may improve final results). The evolutionary tool that we used to improve MCTS board game players can also be used pretty much as is with any other game domain where MCTS is applicable. Our

results show a proficiency that surpasses that of baseline handcrafted players using equal and in some cases a greater amount of search, with little domain knowledge and no expert domain knowledge. Moreover, our results exhibit scalability in both search depth and board size.

[to appear in: *IEEE Transactions on Computational Intelligence and AI in Games*.]

Playing Mastermind with Many Colors

Benjamin Doerr, *École Polytechnique de Paris*, Carola Doerr, *Université Pierre et Marie Curie, CNRS*, Reto Spöhel, *Bern University of Applied Sciences*, Henning Thomas, *ETH Zürich*

Developing a complexity theory for evolutionary algorithms is a recent hot topic on GECCO. In the currently most accepted approach, Droste, Jansen, and Wegener (2006) define the black-box complexity of an optimization problem to be the minimal number of fitness evaluations that suffice to solve it. As one of the first problems regarded, the black-box complexity of the ONEMAX problem was found to be of a surprisingly low order of $n/\log(n)$. Doerr and Winzen (2012) observe that the black-box complexity of ONEMAX is equivalent to the classic Mastermind game with two colors and n positions. Thus the result of Erdős and Rényi (1963) gives an alternative analysis of the black-box complexity of ONEMAX. This observation also allows to translate Mastermind results for more than two colors into black-box complexity results for higher-arity versions of ONEMAX. Unfortunately, the Mastermind game for larger numbers of colors is less understood. For the natural case of n colors, the best known upper bound is $n\log(n)$, see Chvátal (1983). In our work [Proceedings of the ACM-SIAM Symposium on Discrete Algorithms (SODA 2013), pages 695-704, 2013. Extended version: http://arxiv.org/abs/1207.0773], an almost tight upper bound of order $n\log(\log(n))$ is proven. We also show that any non-adaptive strategy needs at least order $n\log(n)$ rounds. This implies a noteworthy complexity difference of the classic binary and the n-ary ONEMAX function: The first can be optimized non-adaptively with the best possible performance, for the latter adaptivity is necessary to gain optimal performance.

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The Rolling Tide Evolutionary Algorithm: A Multi-Objective Optimiser for Noisy Optimisation Problems

Jonathan E. Fieldsend, *University of Exeter*, Richard Everson, *University of Exeter*

Here we address the problem of uncertain evaluation in multi-objective optimisation problems. We develop a novel algorithm, the rolling tide evolutionary algorithm (RTEA), which simultaneously improves the accuracy of its estimated Pareto set as well as its quality. RTEA incorporates an unconstrained accumulative sampling technique to refine the estimated objective values for the non-dominated solutions it maintains every generation. It uses all previously evaluated solutions to underpin its non-dominated estimate. These act as a pool of solutions from which members may (re)enter the elite archive at a later point (if the reevaluation of an elite member means it is reassessed as dominated, or moved to a location which means previously dominated solutions are no longer covered). The algorithm can cope with noise whose characteristics change as a function of both design and objective location, or which alter during the course of an optimisation. State-of-the-art noise-tolerant optimisers (NMOEA-AS, MOP-EA, BES, MOEA-RF), as well as widely used standard optimisers (NSGA-II, SPEA2, PAES, IBEA) are compared to RTEA on 70 instances of ten continuous space test problems from the CEC'09 multi-objective optimisation test suite. These problems are modifying to exhibit different types and intensities of noise, including noise whose characteristics change during the course of the optimisation and across different regions of parameter space. RTEA is found to provide competitive performance across both the range of test problems used, and noise types, compared to the eight comparison algorithms.

[to appear in: *IEEE Transactions on Evolutionary Computation*.]

HOP3

Exploiting *Interestingness* in a Computational Evolution System for the Genome-Wide Genetic Analysis of Alzheimer's Disease

Jason H. Moore, *Dartmouth College*, Douglas P. Hill, *Dartmouth College*, Andrew Saykin, *Dartmouth College*, Li Shen, *Dartmouth College*

Susceptibility to Alzheimer's disease is likely due to complex interaction among many genetic and environmental factors. Identifying complex genetic effects in large data sets will require computational methods that extend beyond parametric statistical methods. We have previously introduced a computational evolution system (CES) that uses genetic programming (GP) to represent genetic models of disease. The CES approach differs from other GP approaches in that it is able to learn how to solve the problem by generating its own operators. A key feature is the ability for the operators to use expert knowledge to guide the search. We have previously shown that CES is able to discover nonlinear genetic models of disease susceptibility in both simulated and real data. The goal of the present study was to introduce a measure of interestingness into the modeling process. Here, we define interestingness as a measure of non-additivity. That is, we are more interested in those CES models that include attributes that exhibit synergistic effects. Here, we first pre-processed the data to measure all pairwise gene-gene interaction effects using entropy-based methods. We then provided these measures to CES as expert knowledge and as one of three fitness criteria in three-dimensional Pareto optimization. We applied this new CES algorithm to an Alzheimer's disease data set with approximately 520,000 attributes. We show that this approach discovers more interesting models with the added benefit of improving classification accuracy. This study demonstrates the applicability of CES to genome-wide genetic analysis using

expert knowledge derived from measures of interestingness.

[published in: R. L. Riolo, J. H. Moore, M. E. Kotanchek (eds.), *Genetic Programming Theory and Practice XI*, pp. 31–45, Springer Verlag, 2014.]

Automatic Synthesis of Regular Expressions from Examples

Alberto Bartoli, *University of Trieste*, Giorgio Davanzo, *University of Trieste*, Andrea De Lorenzo, *University of Trieste*, Eric Medvet, *University of Trieste*, Enrico Sorio, *University of Trieste*

We propose a system for the automatic generation of regular expressions for text-extraction tasks. The user describes the desired task only by means of a set of labeled examples. The system is internally based on Genetic Programming (GP) and generates regexes that may be used with common engines such as those that are part of Java, PHP, Perl and so on. Usage of the system does not require any familiarity with regular expressions syntax nor with GP. The problem of synthesizing either regular expressions or deterministic finite automata (DFAs) from examples is long-established. Most of the research in this area has focussed on binary classifying short input strings drawn from a binary alphabet, while text extraction requires the ability of identifying within a stream of symbols drawn from a large alphabet the portions matching the pattern of interest. We performed an extensive experimental evaluation on 12 different extraction tasks applied to real-world datasets. We obtained very good results in terms of precision and recall, even in comparison to earlier state-of-the-art proposals. Our results are highly promising toward the achievement of a practical surrogate for the specific skills required for generating regular expressions, and significant as a demonstration of what can be achieved with GP-based approaches on modern IT technology.
A prototype of the system is publicly available as a webapp: http://regex.inginf.units.it

[to appear in: *IEEE Computer.*]

A Lifelong Learning Hyper-Heuristic Method for Bin Packing

Emma Hart, *Edinburgh Napier University*, Kevin Sim, *Edinburgh Napier University*

We describe a novel hyper-heuristic system that continuously learns over time to solve a combinatorial optimisation problem. The system continuously generates new heuristics and samples problems from its environment; representative problems and heuristics are incorporated into a self-sustaining network of interacting entities inspired by methods in Artificial Immune Systems.The network is plastic in both its structure and content leading to the following properties: it exploits existing knowledge captured in the network to rapidly produce solutions; it can adapt to new problems with widely differing characteristics; it is capable of generalising over the problem space. The system is tested on a large corpus of 3968 new instances of 1D-bin packing problems as well as on 1370 existing problems from the literature; it shows excellent performance in terms of the quality of solutions obtained across the datasets and in adapting to dynamically changing sets of problem instances compared to previous approaches. As the network self-adapts to sustain a minimal repertoire of both problems and heuristics that form a representative map of the problem space, the system is further shown to be computationally efficient and therefore scalable.

[to appear in: *Evolutionary Computation*, 2014.]

Improving Source Code with Genetic Programming

William B. Langdon, *University College London*, Mark Harman, *University College London*

Bowtie2 is a state-of-the-art Bioinformatics program. It was manipulated by GP to give a variant automatically tuned to a particular task. It consists of 50000 lines of C++. Evolution found a change which speeds it up on the chosen task by a factor of 70, yet still give good answers, indeed they are slightly better.
GISMOE uses a BNF grammar specific to Bowtie2 when mutating genetically improved programs (GIP). Patches delete, move or insert existing lines of code. No new code is created. Mutants' fitness is measured by running them using DNA from The Thousand Genomes Project.
The GP uses variable length linear chromosomes, each gene specifies one change to one line of code. Crossover creates a child by appending two patch lists. Mutation appends another one line change. Random mutations are heavily weighted towards code which are either used many times or which scale badly.
On random DNA sequences from people not used in training the evolved version took 3.9 hours. The released code took 12.2 days. In 89% of sequences the GP and released Bowtie2 produced identical results. In 9% the GP version had a mean Smith-Waterman score better than that of the released code. In one case it was identical and in 1.5% it was very slightly worse.

[to appear in: *IEEE Transactions on Evolutionary Computation*, 2014.]

HOP4

A Generalized Theoretical Deterministic Particle Swarm Model

Christopher W. Cleghorn, *University of Pretoria*, Andries P. Engelbrecht, *University of Pretoria*

A number of theoretical studies of particle swarm optimization (PSO) have been done to gain a better understanding of the dynamics of the algorithm and the behaviour of the particles under different conditions. These theoretical analyses have been performed for both the deterministic PSO model, and more recently for the stochastic model. However, all current theoretical analyses of the PSO algorithm were based on the stagnation assumption, in some form or another. The analysis done under the stagnation assumption is one where the personal best and neighborhood best positions are assumed to be non-changing. While analysis under the stagnation assumption is very informa-

tive, it could never provide a complete description of a PSO's behaviour. Furthermore, the assumption implicitly removes the notion of a social network structure from the analysis. This paper presents a generalisation to the theoretical deterministic PSO model. Under the generalised model, conditions for particle convergence to a point are derived. The model used in this paper greatly weakens the stagnation assumption, by instead assuming that each particle's personal best and neighborhood best can occupy an arbitrarily large number of unique positions. It was found that the conditions derived in previous theoretical deterministic PSO research could be obtained as a specialisation of the new generalised model proposed. Empirical results are presented to support the theoretical findings.

[to appear in: *Swarm Intelligence Journal.*]

Experimental Analysis of Bound Handling Techniques in Particle Swarm Optimization

Sabine Helwig, *University of Erlangen-Nuremberg*, Jürgen Branke, *University of Warwick*, Sanaz Mostaghim, *University of Magdeburg*

Many practical optimization problems are constrained, and have a bounded search space. In this paper, we propose and compare a wide variety of bound handling techniques for particle swarm optimization. By examining their performance on flat landscapes, we show that many bound handling techniques introduce a significant search bias. Furthermore, we compare the performance of many bound handling techniques on a variety of test problems, demonstrating that the bound handling technique can have a major impact on the algorithm performance, and that the method recently proposed as standard does generally not perform well.

[published in: *IEEE Transactions on Evolutionary Computation*, 17(2):259–271, 2013.]

Adaptive Generalized Crowding for Genetic Algorithms

Ole J. Mengshoel, *Carnegie Mellon University*, Severino Galan, *Escuela Técnica Superior de Ingeniería Informática, Spain*

The genetic algorithm technique known as crowding preserves population diversity by pairing each offspring with a similar individual in the current population and deciding which of the two will survive The recently developed generalized crowding approach introduces a scaling factor in the replacement phase, thus generalizing and potentially overcoming the limitations of both deterministic and probabilistic crowding. A key problem not previously addressed, however, is how the scaling factor should be adapted during the search process in order to effectively obtain optimal or near-optimal solutions. The present work investigates this problem by developing and evaluating two methods for adapting, during search, the scaling factor. We call these two methods diversity-adaptive and self-adaptive generalized crowding respectively. Whereas the former method adapts the scaling factor according to the population's diversity, the latter method includes the scaling factor in the chromosome for self-adaptation. Our experiments with real function optimization, Bayesian network inference, and the Traveling Salesman Problem show that both diversity-adaptive and self-adaptive generalized crowding are consistent techniques that produce strong results, often outperforming traditional generalized crowding. We believe that developers of existing and new applications could benefit from improved knowledge of the recent introduction of adaptive techniques into crowding. This talk will present recent developments in crowding, in particular adaptive generalized crowding, and attempt to help bridge the gap between theory and practice.

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General Subpopulation Framework and Taming the Conflict Inside Populations

Danilo Vasconcellos Vargas, *Kyushu University*, Junichi Murata, *Kyushu University*, Hirotaka Takano, *Kyushu University*, Alexandre Cláudio Botazzo Delbem, *Universidade de São Paulo*

In the context of structured evolutionary algorithms, the article presents three major insights/solutions: 1) General Subpopulation Framework (GSF) — GSF is a general formulation which allows the integration of any optimization algorithms, aids the design of algorithms and generalizes all structured algorithms (single or multi objective) under its formulation; 2) Subpopulation Algorithm based on Novelty (SAN) — SAN is multi-objective and many-objective algorithm based on the GSF with state of art solutions in both many-objective and bi-objective problems, surpassing the GDE3 in most of the tests; 3) Definition and comparison of forces between algorithms — if the strategies inside an optimization algorithm are seen as a collection of forces capable of changing the position of solutions, algorithms can be analyzed structurally by measuring the changes in forces with the modification of strategies. An empirical example shows how algorithms can be analyzed in this manner. Moreover, it is presented a justification of why structured EAs, and in special the GSF, achieve better results in general. This derives from the fact that well-designed structured EAs separate better the conflicting strategies, avoiding the deleterious consequences of the competition between themselves.

[to appear in: *Evolutionary Computation.*]

Integrative Genetic and Evolutionary Computation

IGEC1

Use of Explicit Memory in the Dynamic Traveling Salesman Problem

Renato Tinos, *Universidade de São Paulo*, Darrell Whitley, *Colorado State University*, Adele Howe, *Colorado State University*

In the dynamic traveling salesman problem (DTSP), the weights and vertices of the graph representing the TSP are allowed to change during the optimization. This work first discusses some issues related to the use of evolutionary algorithms in the DTSP. When efficient algorithms used for the static TSP are applied with restart in the DTSP, we observe that only some edges are generally inserted in and removed from the best solutions after the changes. This result indicates a possible beneficial use of memory approaches, usually employed in cyclic dynamic environments. We propose a memory approach and a hybrid approach that combines our memory approach with the elitism-based immigrants genetic algorithm (EIGA). We compare these two algorithms to four existing ones and show that memory approaches can be beneficial for the DTSP with random changes.

Neuro-Evolutionary Topology Optimization of Structures by Utilizing Local State Features

Nikola Aulig, *Honda Research Institute Europe*, Markus Olhofer, *Honda Research Institute Europe*

In this paper we propose a novel method for the topology optimization of mechanical structures, based on a hybrid combination of a neuro-evolution with a gradient-based optimizer. Conventional gradient-based topology optimization requires problem-specific sensitivity information, however this is not available in the general case. The proposed method substitutes the analytical gradient by an artificial neural network approximation model, whose parameters are learned by an EA. Advantageous is that the number of parameters in the evolutionary search is not directly coupled to the mesh of the discretized design, potentially enabling the optimization of fine discretizations. Concretely, the network maps features, obtained for each element of the discretized design, to an update signal, that is used to determine a new design. A new network is learned for every iteration of the topology optimization. The proposed method is evaluated on the minimum compliance design problem, with two different sets of features. Feasible designs are obtained, showing that the neural network is able to successfully replace analytical sensitivity information. We also discuss the significant improvement that is achieved when including the strain energy as feature.

A Novel Population-Based Multi-Objective CMA-ES and the Impact of Different Constraint Handling Techniques

Silvio Rodrigues, *Delft University of Technology*, Pavol Bauer, *Delft University of Technology*, Peter A. N. Bosman, *Centrum Wiskunde & Informatica*

The Covariance Matrix Adaptation Evolutionary Strategy (CMA-ES) is a well-known, state-of-the-art optimization algorithm for single-objective real-valued problems, especially in black-box settings. Although several extensions of CMA-ES to multi-objective (MO) optimization exist, no extension incorporates a key component of the most robust and general CMA-ES variant: the association of a population with each Gaussian distribution that drives optimization. To achieve this, we use a recently introduced framework for extending population-based algorithms from single- to multi-objective optimization. We compare, using six well-known benchmark problems, the performance of the newly constructed MO-CMA-ES with existing variants and with the estimation of distribution algorithm (EDA) known as iMAMaLGaM, that is also an instance of the framework, extending the single-objective EDA iAMaLGaM to MO. Results underline the advantages of being able to use populations. Because many real-world problems have constraints, we also study the use of four constraint-handling techniques. We find that CMA-ES is typically less robust to these techniques than iAMaLGaM. Moreover, whereas we could verify that a penalty method that was previously used in literature leads to fast convergence, we also find that it has a high risk of finding only nearly, but not entirely, feasible solutions. We therefore propose that other constraint-handling techniques should be preferred in general.

Evolutionary Algorithms and Artificial Immune Systems on a Bi-Stable Dynamic Optimisation Problem

Thomas Jansen, A*berystwyth University*, Christine Zarges, *University of Birmingham*

Dynamic optimisation is an important area of application for evolutionary algorithms and other randomised search heuristics. Theoretical investigations are currently far behind practical successes. Addressing this deficiency a bi-stable dynamic optimisation problem is introduced and the performance of standard evolutionary algorithms and artificial immune systems is assessed. Deviating from the common theoretical perspective that concentrates on the expected time to find a global optimum (again) here the 'any time performance' of the algorithms is analysed, i.e., the expected function value at each step. Basis for the analysis is the recently introduced perspective of fixed budget computations. Different dynamic scenarios are considered which are characterised by the length of the stable phases. For each scenario different population sizes are examined. It is shown that the evolutionary algorithms tend to have superior performance in almost all cases.

IGEC2

Derivative Free Optimization Using a Population-based Stochastic Gradient Estimator

Azhar Khayrattee, *Intersil Corporation*, Georgios C. Anagnostopoulos, *Florida Institute of Technology*

In this paper we introduce a derivative-free optimization method

that is derived from a population based stochastic gradient estimator. We first demonstrate some properties of this estimator and show how it is expected to always yield a descent direction. We analytically show that the difference between the expected function value and the optimum decreases exponentially for strongly convex functions and the expected distance between the current point and the optimum has an upper bound. Then we experimentally tune the parameters of our algorithm to get the best performance. Finally, we use the Black-Box-Optimization-Benchmarking test function suite to evaluate the performance of the algorithm. The experiments indicate that the method offers notable performance advantages especially, when applied to objective functions that are ill-conditioned and potentially multimodal. This result, coupled with the low computational cost when compared to Quasi-Newton methods, makes it quite attractive.

Parallel Evolutionary Systems

PES1

Solving GA-Hard Problems with EMMRS and GPGPUs

J. Ignacio Hidalgo, *Universidad Complutense de Madrid*, J. Manuel Colmenar, *Universidad Complutense de Madrid*, Jose L. Risco-Martín, *Universidad Complutense de Madrid*, Carlos Sánchez-Lacruz, *Universidad Complutense de Madrid*, Juan Lanchares, *Universidad Complutense de Madrid*, Oscar Garnica, *Universidad Complutense de Madrid*, Josefa Díaz, *Universidad de Extremadura*

Different techniques have been proposed to tackle GA-Hard problems. Some techniques work with different encodings and representations, other use reordering operators and several, such as the Evolutionary Mapping Method (EMM), apply genotype-phenotype mappings. EMM uses multiple chromosomes in a single cell for mating with another cell within a single population. Although EMM gave good results, it fails on solving some deceptive problems. In this line, EMMRS (EMM with Replacement and Shift) adds a new operator, consisting on doing a replacement and a shift of some of the bits within the chromosome. Results showed the efficiency of the proposal on deceptive problems. However, EMMRS was not tested with other kind of hard problems. In this paper we have adapted EMMRS for solving the Traveling Salesman Problem (TSP). The encodings and genetic operators for solving the TSP are quite different to those applied on deceptive problems. In addition, execution times recommended the parallelization of the GA. We implemented a GPU parallel version. We present here some preliminary results proving that Evolutionary Mapping Method with Replacement and Shift gives good results not only in terms of quality but also in terms of speedup on its GPU parallel version for some instances of the TSP problem.

An Implicitly Parallel EDA Based on Restricted Boltzmann Machines

Malte Probst, *Universität Mainz*, Franz Rothlauf, *Universität Mainz*, Jörn Grahl, *Universität Mainz*

We present a parallel version of RBM-EDA. RBM-EDA is an Estimation of Distribution Algorithm (EDA) that models dependencies between decision variables using a Restricted Boltzmann Machine (RBM). In contrast to other EDAs, RBM-EDA mainly uses matrix-matrix multiplications for model estimation and sampling. Hence, for implementation, standard libraries for linear algebra can be used. This allows an easy parallelization and leads to a high utilization of parallel architectures. The probabilistic model of the parallel version and the version on a single core are identical. We explore the speedups gained from running RBM-EDA on a Graphics Processing Unit. For problems of bounded difficulty like deceptive traps, parallel RBM-EDA is faster by several orders of magnitude (up to 750 times) in comparison to a single-threaded implementation on a CPU. As the speedup grows linearly with problem size, parallel RBM-EDA may be particularly useful for large problems.

GPU-Accelerated Evolutionary Design of the Complete Exchange Communication on Wormhole Networks

Jiri Jaros, *Brno University of Technology*, Radek Tyrala, *AT&T Mobility*

The communication overhead is one of the main challenges in the exascale era, where millions of compute cores are expected to collaborate on solving complex jobs. However, many algorithms will not scale since they require complex global communication and synchronisation. In order to perform the communication as fast as possible, contentions, blocking and deadlock must be avoided. Recently, we have developed an evolutionary tool producing fast and safe communication schedules reaching the lower bound of the theoretical time complexity. Unfortunately, the execution time associated with the evolution process raises up to tens of hours, even when being run on a multi-core processor. In this paper, we propose a revised implementation accelerated by a single Graphic Processing Unit (GPU) delivering speed-up of 5 compared to a quad-core CPU. Subsequently, we introduce an extended version employing up to 8 GPUs in a shared memory environment offering a speed-up of almost 30. This significantly extends the range of interconnection topologies we can cover.

Towards Highly Optimized Cartesian Genetic Programming: From Sequential via SIMD and Thread to Massive Parallel Implementation

Radek Hrbacek, *Brno University of Technology*, Lukas Sekanina, *Brno University of Technology*

Most implementations of Cartesian genetic programming (CGP) which can be found in the literature are sequential. However,

solving complex design problems by means of genetic programming requires parallel implementations of search methods and fitness functions. This paper deals with the design of highly optimized implementations of CGP and their detailed evaluation in the task of evolutionary circuit design. Several sequential implementations of CGP have been analyzed and the effect of various additional optimizations has been investigated. Furthermore, the parallelism at the instruction, data, thread and process level has been applied in order to take advantage of modern processor architectures and computer clusters. Combinational adders and multipliers have been chosen to give a performance comparison with state of the art methods.

PES2

Enhancing Parallel Cooperative Trajectory Based Metaheuristics with Path Relinking

Gabriel Luque, *Universidad de Málaga*, Enrique Alba, *Universidad de Málaga*

This paper proposes a novel algorithm combining path relinking with a set of cooperating trajectory based parallel algorithms to yield a new metaheuristic of enhanced search features. Algorithms based on the exploration of the neighborhood of a single solution, like simulated annealing (SA), have offered accurate results for a large number of real-world problems in the past. Because of their trajectory based nature, some advanced models such as the cooperative one are competitive in academic problems, but still show many limitations in addressing large scale instances. In addition, the field of parallel models for trajectory methods has not deeply been studied yet (at least in comparison with parallel population based models). In this work, we propose a new hybrid algorithm which improves cooperative single solution techniques by using path relinking, allowing both to reduce the global execution time and to improve the efficacy of the method. We test here this new model using a large benchmark of instances of two well-known NP-hard problems: MAXSAT and QAP, with competitive results.

MapReduce-Based Optimization of Overlay Networks Using Particle Swarm Optimization

Simone A. Ludwig, *North Dakota State University*

An overlay network is a virtual network that is built on top of the real network such as the Internet. Cloud computing, peer-to-peer networks, and client-server applications are examples of overlay networks since their nodes run on top of the Internet. The major needs of overlay networks are content distribution and caching, file sharing, improved routing, multicast and streaming, ordered message delivery, and enhanced security and privacy. The focus of this paper is the optimization of overlay networks using a Particle Swarm Optimization (PSO) approach. However, since the ever growing need for more infrastructure causes the number of network nodes to grow significantly, the parallelization of the PSO approach becomes a necessity. In this paper, the MapReduce concept, proposed by Google, is adopted for the PSO approach in order to be able to optimize large-scale networks. MapReduce is easy to implement since it is based on the divide and conquer method, and implementation frameworks such has Hadoop allow for scalability and fault tolerance. Experiments of the MapReduce based PSO algorithm are performed to investigate the solution quality and scalability of the approach.

BP2

Design and Analysis of Adaptive Migration Intervals in Parallel Evolutionary Algorithms

Andrea Mambrini, *University of Birmingham*, Dirk Sudholt, *University of Sheffield*

The migration interval is one of the fundamental parameters governing the dynamic behaviour of island models. Yet, there is little understanding on how this parameter affects performance, and how to optimally set it given a problem in hand. We propose schemes for adapting the migration interval according to whether fitness improvements have been found. As long as no improvement is found, the migration interval is increased to minimise communication. Once the best fitness has improved, the migration interval is decreased to spread new best solutions more quickly. We provide a method for analysing the expected running time and the communication effort, defined as the expected number of migrants sent. Example applications of this method to common example functions show that our adaptive schemes are able to compete with, or even outperform, the optimal fixed choice of the migration interval, with regard to running time and communication effort.

Real World Applications

RWA1

Multi-Objective Routing Optimisation for Battery-Powered Wireless Sensor Mesh Networks

Alma As-Aad Mohammad Rahat, *University of Exeter*, Richard M. Everson, *University of Exeter*, Jonathan E. Fieldsend, *University of Exeter*

Mesh network topologies are becoming increasingly popular in battery powered wireless sensor networks, primarily due to the extension of network range and resilience against routing failures. However, multi-hop mesh networks suffer from higher energy costs, and the routing strategy directly affects the lifetime of nodes with limited energy sources. Hence while planning routes there are trade-offs to be considered between individual and system-wide battery lifetimes. We present a novel multi-objective routing optimisation approach using evolution-

ary algorithms to approximate the optimal trade-off between minimum lifetime and the average lifetime of nodes in the network. In order to accomplish this combinatorial optimisation rapidly and thus permit dynamic optimisation for self-healing networks, our approach uses novel k-shortest paths based search space pruning in conjunction with a new edge metric, which associates the energy cost at a pair of nodes with the link between them. We demonstrate our solution on a real network, deployed in the Victoria & Albert Museum, London. We show that this approach provides better trade-off solutions in comparison to the minimum energy option, and how a combination of solutions over the lifetime of the network can enhance the overall minimum lifetime.

On Homogenization of Coal in Longitudinal Blending Beds

Pradyumn Kumar Shukla, *Karlsruhe Institute of Technology*, Michael P. Cipold, *J&C Bachmann GmbH*, Claus Bachmann, *J&C Bachmann GmbH*, Hartmut Schmeck, *Karlsruhe Institute of Technology*

Coal blending processes mainly use static and non-reactive blending methods like the well-known Chevron stacking. Although real-time quality measurement techniques such as online X-ray fluorescence measurements are available, the possibility to explore a dynamic adaptation of the blending process to the current quality data obtained using these techniques has not been explored. A dynamic adaptation helps to mix the coal from different mines in an optimal way and deliver a homogeneous product. The paper formulates homogenization of coal in longitudinal blending beds as a bi-objective problem of minimizing the variance of the cross-sectional quality and minimizing the height variance of the coal heap in the blending bed. We propose a cone based evolutionary algorithm to explore different trade-off regions of the Pareto front. A pronounced knee region on the Pareto front is found and is investigated in detail using a knee search algorithm. There are many interesting problem insights that are gained by examining the solutions found in different regions. In addition, all the knee solutions outperform the traditional Chevron stacking method.

The Tradeoffs between Data Delivery Ratio and Energy Costs in Wireless Sensor Networks: A Multi-Objective Evolutionary Framework for Protocol Analysis

Doina Bucur, *University of Groningen*, Giovanni Iacca, *INCAS*^{3}, Giovanni Squillero, *Politecnico di Torino*, Alberto Tonda, *Institut National de la Recherche Agronomique, France*

Wireless sensor network (WSN) routing protocols, e.g., the Collection Tree Protocol (CTP), are designed to adapt in an ad-hoc fashion to the quality of the environment. WSNs thus have high internal dynamics and complex global behavior. Classical techniques for performance evaluation (such as testing or verification) fail to uncover the cases of extreme behavior which are most interesting to designers. We contribute a practical framework for performance evaluation of WSN protocols. The framework is based on multi-objective optimization, coupled with protocol simulation and evaluation of performance factors. For evaluation, we consider the two crucial functional and non-functional performance factors of a WSN, respectively: the ratio of data delivery from the network (DDR), and the total energy expenditure of the network (COST). We are able to discover network topological configurations over which CTP has unexpectedly low DDR and/or high COST performance, and expose full Pareto fronts which show what the possible performance tradeoffs for CTP are in terms of these two performance factors. Eventually, Pareto fronts allow us to bound the state space of the WSN, a fact which provides essential knowledge to WSN protocol designers.

Dynamic Multi-Dimensional PSO with Indirect Encoding for Proportional Fair Constrained Resource Allocation

Jonathan Hudson, *University of Calgary*, Majid Ghaderi, *University of Calgary*, Jörg Denzinger, *University of Calgary*

Dynamic particle swarm optimization (PSO) problems are generally characterized by the exhaustively examined issues of the changing location of optima, the changing fitness of optima, and measurement noise/errors. However, the challenging issue of continuously changing problem dimensionality has not been similarly examined. Given that in anytime dynamic resource allocation it is necessary to maintain a high quality solution, we argue that, rather than restarting the PSO algorithm, a more appropriate approach is to design an algorithm that robustly handles changing problem dimensionality. Specifically, we propose an indirect particle encoding scheme specifically designed for a dynamic multi-dimensional PSO algorithm for proportional fair constrained resource allocation. This PSO algorithm is implemented for the proportional fair allocation of power and users to channels within a simulation of an Orthogonal Frequency-Division Multiple Access (OFDMA) wireless network with mobile users switching cells as they traverse the simulation environment. The proposed PSO algorithm is evaluated using simulations, which demonstrate the ability of the proposed indirect encoding scheme to maximize the overall proportional fair optimization goal, without unfairly penalizing the individual components of the solution related to newly introduced problem dimensions.

RWA2

Applying GA with Local Search by Taking Hamming Distances into Consideration to Credit Erasure Processing Problems

Yuji Sato, *Hosei University*, Yusuke Oku, *Hosei University*, Masanori Fukuda, *Hitachi Management Partner Corp.*

Credit erasure processing refers to the process of canceling corresponding items from a list of accounts receivable by checking against a detailed statement when receiving accounts receivable and other payments. In credit erasure processing, it is sometimes necessary to perform the laborious task of searching for credited items based solely on billing data and payments received. In

this paper, we define credit erasure processing as a large-scale subset sum problem, and propose a solution based on a genetic algorithm (GA). In particular, we propose improving the search precision by incorporating a local search method that takes Hamming distances into consideration. To this end, we compare the standard GA with the result of adding a simple local search to the standard GA. This is done using a set of data where the numbers of digits in the billed quantities are roughly the same, another set of data where the numbers of digits are more varied, and a set of real data. As a result, we show that the proposed method works effectively when the numbers of digits in the billed quantities are roughly the same or when the fitness score is has a somewhat higher value.

Evolutionary Algorithms for Classification of Malware Families through Different Network Behaviors

M. Zubair Rafique, *KU Leuven*, Ping Chen, *KU Leuven*, Christophe Huygens, *KU Leuven*, Wouter Joosen, *KU Leuven*

The staggering increase of malware families and their diversity poses a significant threat and creates a compelling need for automatic classification techniques. In this paper, we first analyze the role of network behavior as a powerful technique to automatically classify malware families and their polymorphic variants. Afterwards, we present a framework to efficiently classify malware families by modeling their different network behaviors (such as HTTP, SMTP, UDP, and TCP). We propose protocol-aware and state-space modeling schemes to extract features from malware network behaviors. We analyze the applicability of various evolutionary and non-evolutionary algorithms for our malware family classification framework. To evaluate our framework, we collected a real-world dataset of 6,000 unique and active malware samples belonging to 20 different malware families. We provide a detailed analysis of network behaviors exhibited by these prevalent malware families. The results of our experiments shows that evolutionary algorithms, like sUpervised Classifier System (UCS), can effectively classify malware families through different network behaviors in real-time. To the best of our knowledge, the current work is the first malware classification framework based on evolutionary classifier that uses different network behaviors.

Evolutionary Parameter Estimation for a Theory of Planned Behaviour Microsimulation of Alcohol Consumption Dynamics in an English Birth Cohort 2003 to 2010

Robin C. Purshouse, *University of Sheffield*, Abdallah K. Ally, *University of Sheffield*, Alan Brennan, *University of Sheffield*, Daniel Moyo, *University of Sheffield*, Paul Norman, *University of Sheffield*

This paper presents a new real-world application of evolutionary computation: identifying parameterisations of a theory-driven model that can reproduce alcohol consumption dynamics observed in a population over time. Population alcohol consumption is a complex system, with multiple interactions between economic and social factors and drinking behaviours, the nature and importance of which are not well-understood. Prediction of time trends in consumption is therefore difficult, but essential for robust estimation of future changes in health-related consequences of drinking and for appraising the impact of interventions aimed at changing alcohol use in society. The paper describes a microsimulation approach in which an attitude-behaviour model, Theory of Planned Behaviour, is used to describe the frequency of drinking by individuals. Consumption dynamics in the simulation are driven by changes in the social roles of individuals over time (parenthood, partnership, and paid labour). An evolutionary optimizer is used to identify parameterisations of the Theory that can describe the observed changes in drinking frequency. Niching is incorporated to enable multiple possible parameterisations to be identified, each of which can accurately recreate history but potentially encode quite different future trends. The approach is demonstrated using evidence from the 1979-1985 birth cohort in England between 2003 and 2010.

Quantum Inspired Genetic Algorithm for Community Structure Detection in Social Networks

Shikha Gupta, *University of Delhi*, Sheetal Taneja, *University of Delhi*, Naveen Kumar, *University of Delhi*

Community detection is a key problem in social network analysis. We propose a two-phase algorithm for detecting community structure in social networks. First phase employs a local-search method to group together nodes that have a high chance of falling in a single community. The second phase is bi-partitioning strategy that optimizes network modularity and deploys a variant of quantum-inspired genetic algorithm. The proposed algorithm does not require any knowledge of the number of communities beforehand and works well for both directed and undirected networks. Experiments on synthetic and real-life networks show that the method is able to successfully reveal community structure with high modularity.

RWA3

Using an Adaptive Invasion-Based Model for Fast Range Image Registration

Ivanoe De Falco, *Institute of High Performance Computing and Networking, Italy*, Antonio Della Cioppa, *University of Salerno, Domenico Maisto, Institute of High Performance Computing and Networking, Italy*, Ernesto Tarantino, *Institute of High Performance Computing and Networking, Italy*, Umberto Scafuri, *Institute of High Performance Computing and Networking, Italy*

This paper presents an adaptive model for automatically pairwise registering range images. Given two images and set one as the model, the aim is to find the best possible spatial transformation of the second image causing 3D reconstruction of the original object. Registration is effected here by using a distributed Differential Evolution algorithm characterized by a migration model inspired by the phenomenon known as biological invasion, and by applying a parallel Grid Closest Point algo-

rithm. The distributed algorithm is endowed with two adaptive updating schemes to set the mutation and the crossover parameters, whereas the subpopulation size is assumed to be set in advance and kept fixed throughout the evolution process. The adaptive procedure is tied to the migration and is guided by a performance measure between two consecutive migrations. Experimental results achieved by our approach show the capability of this adaptive method of picking up efficient transformations of images and are compared with those of a recently proposed evolutionary algorithm. This efficiency is evaluated in terms of both quality and robustness of the reconstructed 3D image, and of computational cost.

Recognizing Planar Kinematic Mechanisms from a Single Image Using Evolutionary Computation

Matthew Eicholtz, *Carnegie Mellon University*, Levent Burak Kara, *Carnegie Mellon University*, Jason Lohn, *Carnegie Mellon Silicon Valley*

In this paper, a method is presented that automatically recognizes kinematic mechanisms from textbook images using an evolutionary algorithm to complement computer vision techniques for object detection. Specifically, a nondominated sorting genetic algorithm (NSGA-II) is used to optimize the number and position of mechanical joints in an image and corresponding joint connections (i.e., rigid bodies) such that Pareto front solutions maximize image consistency and mechanical feasibility. A well-known object detector is used as an example method for locating joints, and local image features between pairwise detected joints are used to predict likely connections. The performance of the algorithm using these specific vision techniques is compared to a parameterized detection scheme in order to decouple the efficacy of the object detector from the evolutionary algorithm. Experiments were performed to validate this approach on selected images from a custom dataset, and the results demonstrate reasonable success in both accuracy and speed.

Playing Regex Golf with Genetic Programming

Alberto Bartoli, *University of Trieste*, Andrea De Lorenzo, *University of Trieste*, Eric Medvet, *University of Trieste*, Fabiano Tarlao, *University of Trieste*

Regex golf has recently emerged as a specific kind of code golf, i.e., unstructured and informal programming competitions aimed at writing the shortest code solving a particular problem. A problem in regex golf consists in writing the shortest regular expression which matches all the strings in a given list and does not match any of the strings in another given list. The regular expression is expected to follow the syntax of a specified programming language, e.g., Javascript or PHP.

In this paper, we propose a regex golf player internally based on Genetic Programming. We generate a population of candidate regular expressions represented as trees and evolve such population based on a multi-objective fitness which minimizes the errors and the length of the regular expression.

We assess experimentally our player on a popular regex golf challenge consisting of 16 problems and compare our results against those of a recently proposed algorithm—the only one we are aware of.Our player obtains scores which improve over the baseline and are highly competitive also with respect to human players. The time for generating a solution is usually in the order of tens minutes, which is arguably comparable to the time required by human players.

Genetic Algorithm-Based Solver for Very Large Multiple Jigsaw Puzzles of Unknown Dimensions and Piece Orientation

Dror Sholomon, *Bar-Ilan University*, Omid E. David, *Bar-Ilan University*, Nathan S. Netanyahu, *Bar-Ilan University*

In this paper we propose the first genetic algorithm (GA)-based solver for jigsaw puzzles of unknown puzzle dimensions and unknown piece location and orientation. Our solver uses a novel crossover technique, and sets a new state-of-the-art in terms of the puzzle sizes solved and the accuracy obtained. The results are significantly improved, even when compared to previous solvers assuming known puzzle dimensions. Moreover, the solver successfully contends with a mixed bag of multiple puzzle pieces, assembling simultaneously all puzzles.

RWA4

Evolved Spacecraft Trajectories for Low Earth Orbit

David W. Hinckley Jr., *University of Vermont*, Karol Zieba, *University of Vermont*, Darren L. Hitt, *University of Vermont*, Margaret J. Eppstein, *University of Vermont*

In this paper we use Differential Evolution (DE), with best evolved results refined using a Nelder-Mead optimization, to solve complex problems in orbital mechanics relevant to low Earth orbits (LEO). A class of so-called 'Lambert Problems' is examined. We evolve impulsive initial velocity vectors giving rise to intercept trajectories that take a spacecraft from given initial positions to specified target positions. We seek to minimize final positional error subject to time-of-flight and/or energy (fuel) constraints. We first validate that the method can recover known analytical solutions obtainable with the assumption of Keplerian motion. We then apply the method to more complex and realistic non-Keplerian problems incorporating trajectory perturbations arising in LEO due to the Earth's oblateness and rarefied atmospheric drag. The viable trajectories obtained for these difficult problems suggest the robustness of our computational approach for real-world orbital trajectory design in LEO situations where no analytical solution exists.

Tuning Multi-Objective Optimization Algorithms for Cyclone Dust Separators

Martin Zaefferer, *Cologne University of Applied Sciences*, Beate Breiderhoff, *Cologne University of Applied Sciences*, Boris Naujoks, *Cologne University of Applied Sciences*, Martina Friese, *Cologne University of Applied Sciences*, Jörg Stork, *Cologne University of Applied Sciences, Andreas Fischbach,*

Cologne University of Applied Sciences, Oliver Flasch, *Cologne University of Applied Sciences*, Thomas Bartz-Beielstein, *Cologne University of Applied Sciences*

Cyclone separators are filtration devices frequently used in industry, e.g., to filter particles from flue gas. Optimizing the cyclone geometry is a demanding task. Accurate simulations of cyclone separators are based on time consuming computational fluid dynamics simulations. Thus, the need for exploiting cheap information from analytical, approximative models is evident. Here, we employ two multi-objective optimization algorithms on such cheap, approximative models to analyze their optimization performance on this problem. Under various limitations, we tune both algorithms with Sequential Parameter Optimization (SPO) to achieve best possible results in shortest time. The resulting optimal settings are validated with different seeds, as well as with a different approximative model for collection efficiency. Their optimal performance is compared against a model based approach, where multi-objective SPO is directly employed to optimize the Cyclone model, rather than tuning the optimization algorithms. It is shown that SPO finds improved parameter settings of the concerned algorithms and performs excellently when directly used as an optimizer.

Lithology Discrimination Using Seismic Elastic Attributes: A Genetic Fuzzy Classifier Approach

Eric da Silva Praxedes, *Pontifical Catholic University of Rio de Janeiro*, Adriano Soares Koshiyama, *Pontifical Catholic University of Rio de Janeiro*, Elita Selmara Abreu, *University of Houston*, Douglas Mota Dias, *Pontifical Catholic University of Rio de Janeiro*, Marley Maria Bernardes Rebuzzi Vellasco, *Pontifical Catholic University of Rio de Janeiro*, Marco Aurélio Cavalcanti Pacheco, *Pontifical Catholic University of Rio de Janeiro*

One of the most important issues in oil & gas industry is the lithological identification. Lithology is the macroscopic description of the physical characteristics of a rock. This work proposes a new methodology for lithological discrimination, using GPF-CLASS model (Genetic Programming for Fuzzy Classification) a Genetic Fuzzy System based on Multi-Gene Genetic Programming. The main advantage of our approach is the possibility to identify, through seismic patterns, the rock types in new regions without requiring opening wells. Thus, we seek for a reliable model that provides two flexibilities for the experts: evaluate the membership degree of a seismic pattern to the several rock types and the chance to analyze at linguistic level the model output. Therefore, the final tool must afford knowledge discovery and support to the decision maker. Also, we evaluate other 7 classification models (from statistics and computational intelligence), using a database from a well located in Brazilian coast. The results demonstrate the potentialities of GPF-CLASS model when comparing to other classifiers.

Automated Vibrational Design and Natural Frequency Tuning of Multi-Material Structures

Nicholas Cheney, *Cornell University*, Ethan Ritz, *Cornell University*, Hod Lipson, *Cornell University*

Natural frequency tuning is a vital engineering problem. Every structure has natural frequencies, where vibrational loading at nearby frequencies excite the structure. This causes the structure to resonate, oscillating until energy is dissipated through friction or structural failure. Examples of fragility and distress from vibrational loading include civil structures during earthquakes or aircraft rotor blades. Tuning the structure's natural frequencies away from these vibrations increases the structure's robustness. Conversely, tuning towards the frequencies caused by vibrations can channel power into energy harvesting systems. Despite its importance, natural frequency tuning is often performed ad-hoc, by attaching external vibrational absorbers to a structure. This is usually adequate only for the lowest ("fundamental") resonant frequencies, yet remains standard practice due to the unintuitive and difficult nature of the problem. Given Evolutionary Algorithms' (EAs') ability to solve these types of problems, we propose to approach this problem with the EA CPPN-NEAT to evolve multi-material structures which resonate at multiple desired natural frequencies without external damping. The EA assigns the material type of each voxel within the discretized space of the object's existing topology, preserving the object's shape and using only its material composition to shape its frequency response.

RWA5

Passive Solar Building Design Using Genetic Programming

Mohammad M. O. Gholami, *Brock University*, Brian J. Ross, *Brock University*

Passive solar building design considers the effect that sunlight has on energy usage. The goal is to reduce the need for artificial cooling and heating devices, thereby saving energy costs. A number of competing design objectives can arise. Window heat gain during winter requires large windows. These same windows, however, reduce energy efficiency during nights and summers. Other model requirements add further complications, which creates a challenging optimization problem. We use genetic programming for passive solar building design. The EnergyPlus system is used to evaluate energy consumption. It considers factors ranging from model construction (shape, windows, materials) to location particulars (latitude/longitude, weather, time of day/year). We use a strongly typed design language to build 3D models, and multi-objective fitness to evaluate the multiple design objectives. Experimental results showed that balancing window heat gain and total energy use is challenging, although our multi-objective strategy could find interesting compromises. Many factors (roof shape, material selection) were consistently optimized by evolution. We also found that geographic aspects of the location play a critical role in the final building design.

Eco-Friendly Reduction of Travel Times in European Smart Cities

Daniel H. Stolfi, *Universidad de Málaga*, Enrique Alba, *Univer-*

sidad de Málaga

This article proposes an innovative solution for reducing polluting gas emissions from road traffic in modern cities. It is based on our new Red Swarm architecture which is composed of a series of intelligent spots with WiFi connections that can suggest a customized route to drivers. We have tested our proposal in four different case studies corresponding to actual European smart cities. To this end, we first import the city information from OpenStreetMap into the SUMO road traffic microsimulator, propose a Red Swarm architecture based on intelligent spots located at traffic lights, and then optimize the resulting system in terms of travel times and gas emissions by using an evolutionary algorithm. Our results show that an important quantitative reduction in gas emissions as well as in travel times can be achieved when vehicles are rerouted according to our Red Swarm indications. This represents a promising result for the low cost implementation of an idea that could engage the interest of both citizens and municipal authorities.

Hierarchical Simulation for Complex Domains: Air Traffic Flow Management

William Curran, *Oregon State University*, Adrian K. Agogino, *University of California Santa Cruz, NASA Ames*, Kagan Tumer, *Oregon State University*

A key element in the continuing growth of air traffic is the increased use of automation. The Next Generation (Next-Gen) Air Traffic System will include automated decision support systems and satellite navigation that will let pilots know the precise locations of other aircraft around them. This Next-Gen suggestion system can assist pilots in making good decisions when they have to direct the aircraft themselves. However, effective automation is critical in achieving the capacity and safety goals of the Next-Gen Air Traffic System. In this paper we show that evolutionary algorithms can be used to achieve this effective automation.

However, it is not feasible to use a standard evolutionary algorithm learning approach in such a detailed simulation. Therefore, we apply a hierarchical simulation approach to an air traffic congestion problem where agents must reach a destination while avoiding separation violations. Due to the dynamic nature of this problem, agents need to learn fast. Therefore, we apply low fidelity simulation for agents learning their destination, and a high fidelity simulation employing the Next-Gen technology for learning separation assurance. The hierarchical simulation approach increases convergence rate, leads to a better performing solution, and lowers computational complexity by up to 50 times.

Evolutionary Agent-Based Simulation of the Introduction of New Technologies in Air Traffic Management

Logan Yliniemi, *Oregon State University*, Adrian K. Agogino, *University of California Santa Cruz, NASA Ames*, Kagan Tumer, *Oregon State University*

Accurate simulation of the effects of integrating new technologies into a complex system is critical to the modernization of our antiquated air traffic system, where there exist many layers of interacting procedures, controls, and automation all designed to cooperate with human operators. Additions of even simple new technologies may result in unexpected emergent behavior due to complex human/machine interactions. One approach is to create high-fidelity human models coming from the field of human factors that can simulate a rich set of behaviors. However, such models are difficult to produce, especially to show unexpected emergent behavior coming from many human operators interacting simultaneously within a complex system. Instead of engineering complex human models, we directly model the emergent behavior by evolving goal directed agents, representing human users. Using evolution we can predict how the agent representing the human user reacts given his/her goals. In this paradigm, each autonomous agent in a system pursues individual goals, and the behavior of the system emerges from the interactions, foreseen or unforeseen, between the agents/actors. We show that this method reflects the integration of new technologies in a historical case, and apply the same methodology for a possible future technology.

RWA6

Genetic Algorithms and Deep Learning for Automatic Painter Classification

Erez Levy, *Bar-Ilan University*, Omid E. David, *Bar-Ilan University*, Nathan S. Netanyahu, *Bar-Ilan University*

In this paper we describe the problem of painter classification, and propose a novel hybrid approach incorporating genetic algorithms (GA) and deep restricted Boltzmann machines (RBM). Given a painting, we extract features using both generic image processing (IP) functions (e.g., fractal dimension, Fourier spectra coefficients, texture coefficients, etc.) and unsupervised deep learning (using deep RBMs). We subsequently compare several supervised learning techniques for classification using the extracted features as input. The results show that the weighted nearest neighbor (WNN) method, for which the weights are evolved using GA, outperforms both a support vector machine (SVM) classifier and a standard nearest neighbor classifier, achieving over 90% classification accuracy for the 3-painter problem (an improvement of over 10% relatively to previous results due to standard feature extraction only).

Search Based Software Engineering

BP1

On the Performance of Multiple Objective Evolutionary Algorithms for Software Architecture Discovery

Aurora Ramírez, *Universidad de Córdoba*, José Raúl Romero, *Universidad de Córdoba*, Sebastián Ventura, *Universidad de Córdoba*

During the design of complex systems, software architects have to deal with a tangle of abstract artefacts, measures and ideas to discover the most fitting underlying architecture. A common way to structure these systems is in terms of their interacting software components, whose composition and connections need to be properly adjusted. Its abstract and highly combinatorial nature increases the complexity of the problem. In this scenario, Search-based Software Engineering (SBSE) may serve to support this decision making process from initial analysis models, since the discovery of component-based architectures can be formulated as a challenging multiple optimisation problem, where different metrics and configurations can be applied depending on the design requirements and its specific domain. Many-objective optimisation evolutionary algorithms can provide an interesting alternative to classical multi-objective approaches. This paper presents a comparative study of five different algorithms, including an empirical analysis of their behaviour in terms of quality and variety of the returned solutions. Results are also discussed considering those aspects of concern to the expert in the decision making process, like the number and type of architectures found. The analysis of many-objectives algorithms constitutes an important challenge, since some of them have never been explored before in SBSE.

SBSE1

Improved Heuristics for Solving OCL Constraints Using Search Algorithms

Shaukat Ali, *Simula Research Laboratory*, Muhammad Zohaib Iqbal, *University of Luxembourg*, Andrea Arcuri, *Simula Research Laboratory*

The Object Constraint Language (OCL) is a standard language for specifying constraints on Unified Modeling Language (UML) models. The specified constraints can be used for various purposes including verification, and model-based testing (e.g., test data generation). Efficiently solving OCL constraints is one of the key requirements for the practical use of OCL. In this paper, we propose an improvement in existing heuristics to solve OCL constraints using search algorithms. We evaluate our improved heuristics using two empirical studies with three search algorithms: Alternating Variable Method (AVM), (1+1) Evolutionary Algorithm (EA), and a Genetic Algorithm (GA). We also used Random Search (RS) as a comparison baseline. The first empirical study was conducted using carefully designed artificial problems (constraints) to assess each individual heuristics. The second empirical study is based on an industrial case study provided by Cisco about model-based testing of Video Conferencing Systems. The results of both empirical evaluations reveal that the effectiveness of the search algorithms, measured in terms of time to solve the OCL constraints to generate data, is significantly improved when using the novel heuristics presented in this paper. In particular, our experiments show that (1+1) EA with the novel heuristics has the highest success rate among all the analyzed algorithms, as it requires the least number of iterations to solve constraints.

Applying Search Algorithms for Optimizing Stakeholders Familiarity and Balancing Workload in Requirements Assignment

Tao Yue, *Simula Research Laboratory*, Shaukat Ali, *Simula Research Laboratory*

During the early phase of project development lifecycle of large scale cyber-physical systems, a large number of requirements are needed to be assigned to different stakeholders from different organizations or different departments of the same organization for reviewing, clarifying and checking their conformance to industry standards and government or other regulations. These requirements have different characteristics such as various extents of importance to the organization, complexity, and dependencies between each other, thereby requiring different effort (workload) to review and clarify. While working with our industrial partners in the domain of cyber-physical systems, we discovered an optimization problem, where an optimal solution is required for assigning requirements to different stakeholders by maximizing their familiarities to the assigned requirements while balancing the overall workload of each stakeholder. We propose a fitness function which was investigated with four search algorithms: (1+1) Evolutionary Algorithm, Genetic Algorithm, and Alternating Variable Method, whereas Random Search is used as a comparison base line. We empirically evaluated their performance for finding an optimal solution using a large-scale industrial case study and 120 artificial problems with varying complexity. Results show that (1+1) EA gives the best results together with our proposed fitness function as compared to the other three algorithms.

Robust Next Release Problem: Handling Uncertainty During Optimization

Lingbo Li, *University College London*, Mark Harman, *University College London*, Emmanuel Letier, *University College London*, Yuanyuan Zhang, *University College London*

Uncertainty is inevitable in real world requirement engineering. It has a significant impact on the feasibility of proposed solutions and thus brings risks to the software release plan. This paper proposes a multi-objective optimization technique, augmented with Monte-Carlo Simulation, that optimizes requirement choices for the three objectives of cost, revenue, and uncertainty. The paper reports the results of an empirical study over four data sets de-

rived from a single real world data set. The results show that the robust optimal solutions obtained by our approach are conservative compared to their corresponding optimal solutions produced by traditional Multi-Objective Next Release Problem. We obtain a robustness improvement of at least 18% at a small cost (a maximum 0.0285 shift in the 2D Pareto-front in the unit space). Surprisingly we found that, though a requirement's cost is correlated with inclusion on the Pareto-front, a requirement's expected revenue is not.

Surrogate-Assisted Optimisation of Composite Applications in Mobile Ad hoc Networks

Dionysios Efstathiou, *King's College London*, Peter McBurney, *King's College London*, Steffen Zschaler, *King's College London*, Johann Bourcier, *University of Rennes 1*

Infrastructure-less mobile ad-hoc networks enable the development of collaborative pervasive applications. Within such dynamic networks, collaboration between devices can be realised through service-orientation by abstracting device resources as services. Recently, a framework for QoS-aware service composition has been introduced which takes into account a spectrum of orchestration patterns, and enables compositions of a better QoS than traditional centralised orchestration approaches. In this paper, we focus on the automated exploration of trade-off compositions within the search space defined by this flexible composition model. For the studied problem, the evaluation of the fitness functions guiding the search process is computationally expensive because it either involves a high-fidelity simulation or actually requires calling the composite service. To overcome this limitation, we have developed efficient surrogate models for estimating the QoS metrics of a candidate solution during the search. Our experimental results show that the use of surrogates can produce solutions with good convergence and diversity properties at a much lower computational effort.

SBSE2

A Parallel Evolutionary Algorithm for Prioritized Pairwise Testing of Software Product Lines

Roberto Erick Lopez-Herrejon, *Johannes Kepler Universität Linz*, Javier Ferrer, *Universidad de Málaga*, Francisco Chicano, *Universidad de Málaga*, Evelyn Nicole Haslinger, *Johannes Kepler Universität Linz*, Alexander Egyed, *Johannes Kepler Universität Linz*, Enrique Alba, *Universidad de Málaga*

Software Product Lines (SPLs) are families of related software systems, which provide different feature combinations. Different SPL testing approaches have been proposed. However, despite the extensive and successful use of evolutionary computation techniques for software testing, their application to SPL testing remains largely unexplored. In this paper we present the Parallel Prioritized product line Genetic Solver (PPGS), a parallel genetic algorithm for the generation of prioritized pairwise testing suites for SPLs. We perform an extensive and comprehensive analysis of PPGS with 235 feature models from a wide range of number of features and products, using 3 different priority assignment schemes and 5 product prioritization selection strategies. We also compare PPGS with the greedy algorithm prioritized-ICPL. Our study reveals that overall PPGS obtains smaller covering arrays with an acceptable performance difference with prioritized-ICPL.

Generating Structured Test Data with Specific Properties Using Nested Monte-Carlo Search

Simon Poulding, *University of York*, Robert Feldt, *Blekinge Institute of Technology*

Software acting on complex data structures can be challenging to test: it is difficult to generate diverse test data that satisfies structural constraints while simultaneously exhibiting properties, such as a particular size, that the test engineer believes will be effective in detecting faults. In our previous work we introduced GdelTest, a framework for generating such data structures using non-deterministic programs, and combined it with Differential Evolution to optimize the generation process.

Monte-Carlo Tree Search (MCTS) is a search technique that has shown great success in playing games that can be represented as a sequence of decisions. In this paper we apply Nested Monte-Carlo Search, a single-player variant of MCTS, to the sequence of decisions made by the generating programs used by GdelTest, and show that this combination can efficiently generate random data structures which exhibit the specific properties that the test engineer requires. We compare the results to Boltzmann sampling, an analytical approach to generating random combinatorial data structures.

Comparing Search Techniques for Finding Subtle Higher Order Mutants

Elmahdi Omar, *Colorado State University*, Sudipto Ghosh, *Colorado State University*, Darrell Whitley, *Colorado State University*

Subtle Higher Order Mutants (HOMs) are those HOMs that cannot be killed by existing test suites that kill all First Order Mutants (FOMs) for the program under test. Subtle HOMs simulate complex, real faults, whose behavior cannot be simulated using FOMs. However, due to the coupling effect, subtle HOMs are rare in the exponentially large space of candidate HOMs and they can be costly to find even for small programs.

In this paper we propose new search techniques for finding subtle HOMs and extend our prior work with new heuristics and search strategies. We compare the effectiveness of six search techniques applied to Java and AspectJ programs.

Our study shows that more subtle HOMs were found when the new heuristics and search strategies were used. The programming language (Java or AspectJ) did not affect the effectiveness of any search technique.

High Dimensional Search-Based Software Engineering: Finding Tradeoffs among 15 Objectives for Automating Software Refactoring Using NSGA-III

Mohamed Wiem Mkaouer, *University of Michigan*, Marouane

Kessentini, *University of Michigan*, Slim Bechikh, *University of Michigan*, Kalyanmoy Deb, *Michigan State University*, Mel Ó Cinnéide, *University College Dublin*

There is a growing need for scalable search-based software engineering approaches that address software engineering problems where a large number of objectives are to be optimized. Software refactoring is one of these problems where a refactoring sequence is sought that optimizes several software metrics. Most of the existing refactoring work uses a large set of quality metrics to evaluate the software design after applying refactoring operations, but current search-based software engineering approaches are limited to using a maximum of five metrics. We propose for the first time a scalable search-based software engineering approach based on a newly proposed evolutionary optimization method NSGA-III where there are 15 different objectives to be optimized. In our approach, automated refactoring solutions are evaluated using a set of 15 distinct quality metrics. We evaluated this approach on seven large open source systems and found that, on average, more than 92% of code smells were corrected. Statistical analysis of our experiments over 31 runs shows that NSGA-III performed significantly better than two other many-objective techniques (IBEA and MOEA/D), a multi-objective algorithm (NSGA-II) and two mono-objective approaches, hence demonstrating that our NSGA-III approach represents the new state of the art in fully-automated refactoring.

Self-* Search

SELF-*1

Evolvability Metrics in Adaptive Operator Selection

Jorge A. Soria Alcaraz, *Instituto Tecnológico de León*, Gabriela Ochoa, *University of Stirling*, Martin Carpio, *Instituto Tecnológico de León*, Hector Puga, *Instituto Tecnológico de León*

Evolvability metrics gauge the potential for fitness of an individual rather than fitness itself. They measure the local characteristics of the fitness landscape surrounding a solution. In adaptive operator selection the goal is to dynamically select from a given pool the operator to apply next during the search process. An important component of these adaptive schemes is credit assignment, whereby operators are rewarded according to their observed performance. This article brings the notion of evolvability to adaptive operator selection, by proposing an autonomous search algorithm that rewards operators according to their potential for fitness rather than their immediate fitness improvement. The approach is tested within an evolutionary algorithm framework featuring several mutation operators on binary strings. Three benchmark problems of increasing difficulty, Onemax, Royal Staircase and Multiple Knapsack are considered. Experiments reveal that evolvability metrics significantly improve the performance of adaptive operator selection, when compared against standard fitness improvement metrics.The main contribution is to effectively use fitness landscape metrics to guide a self-configuring algorithm.

Analysis of Evolutionary Algorithms Using Multi-Objective Parameter Tuning

Roberto Ugolotti, *Università degli Studi di Parma*, Stefano Cagnoni, *Università degli Studi di Parma*

Evolutionary Algorithms (EAs) and other metaheuristics are greatly affected by the choice of their parameters, not only as regards the precision of the solutions found, but also for repeatability, robustness, speed of convergence, and other properties. Most of these performance criteria are often conflicting with one another. In our work, we see the problem of EAs' parameter selection and tuning as a multi-objective optimization problem, in which the criteria to be optimized are precision and speed of convergence. We propose EMOPaT (Evolutionary Multi-Objective Parameter Tuning), a method that uses a well-known multi-objective optimization algorithm (NSGA-II) to find a front of non-dominated parameter sets which produce good results according to these two metrics. By doing so, we can provide three kinds of results: (i) a method that is able to adapt parameters to a single function, (ii) a comparison between Differential Evolution (DE) and Particle Swarm Optimization (PSO) that takes into consideration both precision and speed, and (iii) an insight into how parameters of DE and PSO affect the performance of these EAs on different benchmark functions.

On the Pathological Behavior of Adaptive Differential Evolution on Hybrid Objective Functions

Ryoji Tanabe, *University of Tokyo*, Alex S. Fukunaga, *University of Tokyo*

Most state-of-the-art Differential Evolution (DE) algorithms are adaptive DEs with online parameter adaptation. We investigate the behavior of adaptive DE on a class of hybrid functions, where independent groups of variables are associated with different component objective functions. An experimental evaluation of 3 state-of-the-art adaptive DEs (JADE, SHADE, jDE) shows that hybrid functions are "adaptive-DE-hard". That is, adaptive DEs have significant failure rates on these new functions. In-depth analysis of the adaptive behavior of the DEs reveals that their parameter adaptation mechanisms behave in a pathological manner on this class of problems, resulting in over-adaptation for one of the components of the hybrids and poor overall performance. Thus, this class of deceptive benchmarks pose a significant challenge for DE.

A Grammatical Evolution Based Hyper-Heuristic for the Automatic Design of Split Criteria

Márcio Porto Basgalupp, *Universidade Federal de São Paulo*,

Rodrigo Coelho Barros, *Pontifícia Universidade do Rio Grande do Sul*, Tiago Barabasz, *Universidade Federal de São Paulo*

Top-down induction of decision trees (TDIDT) is a powerful method for data classification. A major issue in TDIDT is the decision on which attribute should be selected for dividing the nodes in subsets, creating the tree. For performing such a task, decision trees make use of a split criterion, which is usually an information-theory based measure. Apparently, there is no free-lunch regarding decision-tree split criteria, as is the case of most things in machine learning. Each application may benefit from a distinct split criterion, and the problem we pose here is how to identify the suitable split criterion for each possible application that may emerge. We propose in this paper a grammatical evolution algorithm for automatically generating split criteria through a context-free grammar. We name our new approach ESC-GE (Evolutionary Split Criteria with Grammatical Evolution). It is empirically evaluated on public gene expression datasets, and we compare its performance with state-of-the-art split criteria, namely the information gain and gain ratio. Results show that ESC-GE outperforms the baseline criteria in the domain of gene expression data, indicating its effectiveness for automatically designing tailor-made split criteria.

SELF-*2

Generic Parameter Control with Reinforcement Learning

Giorgos Karafotias, *VU University Amsterdam*, A. E. Eiben, *VU University Amsterdam*, Mark Hoogendoorn, *VU University Amsterdam*

Parameter control in Evolutionary Computing stands for an approach to parameter setting that changes the parameters of an Evolutionary Algorithm (EA) on-the-fly during the run. In this paper we address the issue of a generic and parameter-independent controller that can be readily plugged into an existing EA and offer performance improvements by varying the EA parameters during the problem solution process. Our approach is based on a careful study of Reinforcement Learning (RL) theory and the use of existing RL techniques. We present experiments using various state-of-the-art EAs solving different difficult problems. Results show that our RL control method has very good potential in improving the quality of the solution found without requiring additional resources or time and with minimal effort from the designer of the application.

Online Model Racing Based on Extreme Performance

Tiantian Zhang, *University of Central Florida*, Michael Georgiopoulos, *University of Central Florida*, Georgios C. Anagnostopoulos, *Florida Institute of Technology*

Racing algorithms are often used for offline model selection, where models are compared in terms of their average performance over a collection of problems. In this paper, we present a new racing algorithm variant, Max-Race, which makes decisions based on the maximum performance of models. It is an online algorithm, whose goal is to optimally allocate computational resources in a portfolio of evolutionary algorithms, while solving a particular problem instance. It employs a hypothesis test based on extreme value theory in order to decide, which component algorithms to retire, while avoiding unnecessary computations. Experimental results confirm that Max-Race is able to identify the best individual with high precision and low computational overhead. When used as a scheme to select the best from a portfolio of algorithms, the results compare favorably to the ones of other popular algorithm portfolio approaches.

Fair-Share ILS: A Simple State-of-the-Art Iterated Local Search Hyperheuristic

Steven Adriaensen, *Vrije Universiteit Brussel*, Tim Brys, *Vrije Universiteit Brussel*, Ann Nowé, *Vrije Universiteit Brussel*

In this work we present a simple state-of-the-art selection hyperheuristic called Fair-Share Iterated Local Search (FS-ILS). FS-ILS is an iterated local search method using a conservative restart condition. Each iteration, a perturbation heuristic is selected proportionally to the acceptance rate of its previously proposed candidate solutions (after iterative improvement) by a domain-independent variant of the Metropolis condition. FS-ILS was developed in prior work using a semi-automated design approach. That work focused on how the method was found, rather than the method itself. As a result, it lacked a detailed explanation and analysis of the method, which will be the main contribution of this work. In our experiments we analyze FS-ILS's parameter sensitivity, accidental complexity and compare it to the contestants of the CHeSC (2011) competition.

Theory

THEORY1

Refined Upper Bounds on the Expected Runtime of Non-Elitist Populations from Fitness-Levels

Duc-Cuong Dang, *University of Nottingham*, Per Kristian Lehre, *University of Nottingham*

Recently, an easy-to-use fitness-level technique was introduced to prove upper bounds on the expected runtime of randomised search heuristics with non-elitist populations and unary variation operators. Following this work, we present a new and much more detailed analysis of the population dynamics, leading to a significantly improved fitness-level technique. In addition to improving the technique, the proof has been simplified. From the new fitness-level technique, the upper bound on the runtime in terms of generations can be improved from linear to logarithmic in the population size. Increasing the population size therefore

has a smaller impact on the runtime than previously thought. To illustrate this improvement, we show that the current bounds on the runtime of EAs with non-elitist populations on many example functions can be significantly reduced. Furthermore, the new fitness-level technique makes the relationship between the selective pressure and the runtime of the algorithm explicit. Surprisingly, a very weak selective pressure is sufficient to optimise many functions in expected polynomial time. This observation has important consequences of which some are explored in a companion paper.

Runtime Analysis to Compare Best-Improvement and First-Improvement in Memetic Algorithms

Kuai Wei, *University of Auckland*, Michael J. Dinneen, *University of Auckland*

In recent years, the advantage afforded by using multiple local searches in a Memetic Algorithm (MA) to solve one problem (a single fitness function), has been verified in many successful experiments. These experiments also give the observation that the local search operator that gives the best results in an MA on the same fitness function for solving a NP-hard problem is instance specific. This paper will pro- vide a theoretical evidence for this observation. In this paper, we will formalize the (1+1) Restart Memetic Algorithms applying two different local searches, the first-improvement and the best-improvement, respectively. We will then run them on a single fitness function to solve the Clique Prob- lem. We then show that there are two families of graphs such that, for the first family of graphs, MAs with one local search drastically outperform MAs with the other local search, and vice versa for the second family of graphs. Our study explains why using multiple local searches can outperform using a single local search in Memetic Algorithms.

Model-Optimal Optimization by Solving Bellman Equations

Alan J. Lockett, *IDSIA*

This paper analytically identifies the points chosen by the best black-box optimization methods, measured by assigning values to the history of points examined by stochastic optimization methods applied to randomly chosen but static (single) objective functions. Optimizers that make these "best" choices are called *model-optimal*. Model-optimal optimizers may not exist for a given model of static objectives but can always be approximated. If the search domain and the fitness range are both compact, or if other more abstract conditions are satisfied, it can be proven that model-optimal optimizers exist and at least one of them is deterministic. Model-optimality is studied by treating the average performance as a Bellman equation. The overall performance of an optimizer can be assessed based on the sequence of points selected for evaluation. Each choice introduces an error, and the overall performance is in every case just the sum of these errors. It might be possible to extend these results to certain stochastic or dynamic objectives, but they probably do not apply in adaptive or coevolutionary environments. The properties of model-optimality may make it possible to assess the tightness of existing bounds on average performance, and it may be possible to approximate model-optimal optimization decisions directly.

MMAS vs. Population-Based EA on a Family of Dynamic Fitness Functions

Andrei Lissovoi, *Technical University of Denmark*, Carsten Witt, *Technical University of Denmark*

We study the behavior of a population-based EA and the Max-Min Ant System (MMAS) on a family of deterministically-changing fitness functions, where, in order to find the global optimum, the algorithms have to find specific local optima within each of a series of phases. In particular, we prove that a (2+1) EA with genotype diversity is able to find the global optimum of the Maze function, previously considered by Kötzing and Molter (PPSN 2012, 113–122), in polynomial time. This is then generalized to a hierarchy result stating that for every μ, a $(\mu + 1)$ EA with genotype diversity is able to track a Maze function extended over a finite alphabet of μ symbols, whereas population size $\mu - 1$ is not sufficient. Furthermore, we show that MMAS does not require additional modifications to track the optimum of the finite-alphabet Maze functions, and, using a novel drift statement to simplify the analysis, reduce the required phase length of the Maze function.

THEORY2

Concentration of First Hitting Times under Additive Drift

Timo Kötzing, *Friedrich-Schiller-Universität Jena*

Recent advances in drift analysis have given us better and better tools for understanding random processes, including the run time of randomized search heuristics. In the setting of multiplicative drift we do not only have excellent bounds on the expected run time, but also more general results showing the concentration of the run time.
In this paper we investigate the setting of additive drift under the assumption of strong concentration of the "step size" of the process. Under sufficiently strong drift towards the goal we show a strong concentration of the hitting time. In contrast to this, we show that in the presence of small drift a Gambler's-Ruin-like behavior of the process overrides the influence of the drift. Finally, in the presence of sufficiently strong negative drift the hitting time is superpolynomial with high probability; this corresponds to the so-called negative drift theorem, for which we give new variants.

The Impact of Random Initialization on the Runtime of Randomized Search Heuristics

Benjamin Doerr, *École Polytechnique de Paris*, Carola Doerr, *Université Pierre et Marie Curie, CNRS*

It has often been observed that the expected runtime of an evolutionary algorithm with random initialization does not deviate much from the expected runtime when starting in an initial solution of average fitness. Having this information a priori would greatly simplify the runtime analysis for the algorithm using ran-

dom initialization.

We prove such a result for the optimization of the OneMax test function via the two randomized search heuristics *Randomized Local Search (RLS)* and the *(1+1) Evolutionary Algorithm*. For both algorithms, we show that the expected runtime from a random initial solution deviates at most by a constant number of iterations from the expected runtime when starting with a solution having exactly $n/2$ ones.

For RLS we can precisely compute that this constant is $-1/2 \pm o(1)$. This leads to an extremely precise bound for the expected runtime. The expected number of fitness evaluations until an optimal search point is found, is $nH_{n/2} - 1/2 \pm o(1)$, where $H_{n/2}$ denotes the $(n/2)$th harmonic number when n is even, and $H_{n/2} := (H_{\lfloor n/2 \rfloor} + H_{\lceil n/2 \rceil})/2$ when n is odd.

The main technique to obtain these results is a coupling of the optimization process starting from different fitness levels. We believe this technique to be interesting also much beyond the specific results mentioned above; e.g., for the study of other optimization problems.

A Theoretical Analysis of Volume Based Pareto Front Approximations

Pradyumn Kumar Shukla, *Karlsruhe Institute of Technology*, Nadja Doll, *Karlsruhe Institute of Technology*, Hartmut Schmeck, *Karlsruhe Institute of Technology*

Many multi-objective algorithms use volume based quality indicators to approximate the Pareto front. Amongst these, the hypervolume is the most widely used. The distribution of solution sets of finite size μ that maximize the hypervolume have been investigated theoretically. But nearly all results are limited to the bi-objective case. In this paper, many of these results are extended to higher dimensions and a theoretical analysis and characterization of optimal μ-distributions is done. We investigate monotonic Pareto curves that are embedded in three and higher dimensions that keep the property of the bi-objective case that only few points are determining the hypervolume contribution of a point. For finite μ, we consider the influence of the choice of the reference point and determine sufficient conditions that assure the extreme points of the Pareto curves to be included in an optimal μ- distribution. We state conditions about the slope of the front that makes it impossible to include the extremes. Furthermore, we prove more specific results for three dimensional linear Pareto fronts. It is shown that the equispaced property of an optimal distribution for a line in two dimensions does not hold in higher dimensions. We additionally investigate hypervolume in general dimensions and problems with cone domination structures.

THEORY3

Robustness of Populations in Stochastic Environments

Christian Gießen, *Christian-Albrechts-Universität zu Kiel*, Timo Kötzing, *Friedrich-Schiller-Universität Jena*

We consider stochastic versions of ONEMAX and LEADINGONES and analyze the performance of evolutionary algorithms with and without populations on these problems. It is known that the (1+1) EA on ONEMAX performs well in the presence of very small noise, but poorly for higher noise levels. We extend these results to LEADINGONES and to many different noise models, showing how the application of drift theory can significantly simplify *and generalize* previous analyses. Most surprisingly, even small populations (of size $\Theta(\log n)$) can make evolutionary algorithms perform well for high noise levels, well outside the abilities of the (1+1) EA! Larger population sizes are even more beneficial; we consider both parent and offspring populations. In this sense, populations are *robust* in these stochastic settings.

Superpolynomial Lower Bounds for the (1+1) EA on Some Easy Combinatorial Problems

Andrew M. Sutton, *Friedrich-Schiller-Universität Jena*

The (1+1) EA is a simple evolutionary algorithm that is known to be efficient on linear functions and on some combinatorial optimization problems. In this paper, we rigorously study its behavior on two easy combinatorial problems: finding the 2-coloring of a class of bipartite graphs, and constructing satisfying assignments for a class of satisfiable 2-CNF Boolean formulas. We prove that it is inefficient on both problems in the sense that the number of iterations the algorithm needs to minimize the cost functions is superpolynomial with high probability.

Our motivation is to better understand the influence of problem instance structure on the runtime character of a simple evolutionary algorithm. We are interested in what kind of structural features give rise to so-called metastable states at which, with probability $1 - o(1)$, the (1+1) EA becomes trapped and subsequently has difficulty leaving. Finally, we show how to modify the (1+1) EA slightly in order to obtain a polynomial-time performance guarantee on both problems.

Gaussian Mixture Model of Evolutionary Algorithms

Bo Song, *University of Hong Kong*, Victor O. K. Li, *University of Hong Kong*

This paper proposes a novel finite Gaussian mixture model to study the population dynamics of evolutionary algorithms on continuous optimization problems. While previous research taking on a dynamical system view has established the transition equation between the density functions of consecutive populations, the equation usually does not have closed-form solutions and can only be applied to very few optimization problems. In this paper, we address this issue by approximating both the population density function of each generation and the objective function by finite Gaussian mixtures. We show that by making such approximations the transition equation can be solved exactly and key statistics, such as the expected mean and the variance of fitness values of the population, can be calculated easily. We also prove that by choosing appropriate values of the parameters, the L^1-norm error between our model and the actual population density function can be made arbitrarily small, up un-

til a predefined generation. We present experimental results to show that our model is useful in simulating and examining the dynamics of evolutionary algorithms.

___ BP2 ___

Evolution under Partial Information

Duc-Cuong Dang, *University of Nottingham*, Per Kristian Lehre, *University of Nottingham*

Complete and accurate information about the quality of candidate solutions is not always available in real-world optimisation. It is often prohibitively expensive to evaluate candidate solution on more than a few test cases, or the evaluation mechanism itself is unreliable. While evolutionary algorithms are popular methods in optimisation, the theoretical understanding is lacking for the case of partial information. This paper initiates runtime analysis of evolutionary algorithms where only partial information about fitness is available. Two scenarios are investigated. In *partial evaluation of solutions*, only a small amount of information about the problem is revealed in each fitness evaluation. We formulate a model that makes this scenario concrete for pseudo-Boolean optimisation. In *partial evaluation of populations*, only a few individuals in the population are evaluated, and the fitness values of the other individuals are missing or incorrect. For both scenarios, we prove that given a set of specific conditions, non-elitist evolutionary algorithms can optimise many functions in expected polynomial time even when vanishingly little information available. The conditions imply a small enough mutation rate and a large enough population size. The latter emphasises the importance of populations in evolution.

Instructions for Session Chairs and Presenters

Instructions for Session Chairs

Thank you for agreeing to chair a session. Session chairs are essential to keep sessions on schedule and moderate the question period.

- Arrive a few minutes early to check on room and equipment set-up. Let the conference organizers at the registration desk know if problems arise or adjustments are needed.
- Please follow the scheduled order of talks, as well as presentation times.
- In the unlikely event that a speaker is absent, we ask you to announce a short break until the next presentation is due to start. Breathe normally.
- Do not start early, as participants may be moving between sessions/presentations.
- Introduce each speaker.
- Speakers presenting accepted full papers during the technical sessions are allocated 25 minutes for each presentation; 20 minutes for set up and presentation and 5 minutes for questions.
- Moderate questions.
- If you chair a best paper session, please remind the audience that this is a best paper session, distribute the ballots that you will find in the room at the beginning of the session, and collect the votes at the end of the session. After the session, please bring the ballots to the registration desk.

If a session is without a chair, we ask the last scheduled speaker to perform those duties.

Instructions for Paper Presenters

Projectors and screens will be available for all presentations and larger rooms will have microphones. Presenters are requested to bring their own laptops.

- Please adhere to the scheduled slot of your presentation.
- Please quickly check that the computer you are using for the presentation works with the video projector before the beginning of your session.
- Speakers presenting accepted full papers during the technical sessions are allocated 25 minutes for each presentation, 20 minutes for set-up and presentation and 5 minutes for questions.

Instructions for Poster Presenters

- The poster session will be held on Monday, July 14, 16:10-18:30, Pavilion Ballroom.
- Poster set-up is 30 minutes prior to the start of the session.
- Poster boards and thumbtacks or tape will be available.
- Posters should be no more than 90cm (36”) wide and 120cm (48”) high.