Editorial for the Special Issue on Theoretical Foundations of Evolutionary Computation

EVOLUTIONARY computation methods, such as evolutionary algorithms or swarm intelligence algorithms, have been successfully applied to a wide range of difficult problems. These include classical NP-hard combinatorial optimization problems and a variety of hard real-world optimization problems. Real-world problems, in particular, are difficult to solve using traditional search methods because often they are nonlinear, highly constrained, multiobjective, and can include a number of uncertainties.

Many different evolutionary computation methods for dealing with complex problems have been proposed over the years. The theoretical analysis of evolutionary computation has made immense progress during the last 10 years [1]–[3]. Such analysis provides useful insights into the working principles of evolutionary computation techniques. This insight not only leads to a better understanding of the type of problems suitable for a given type of algorithm, but it also provides design guidelines for developing new more powerful methods in practice.

Previous theoretical studies have shown the runtime behavior of bio-inspired computation methods including evolutionary algorithms, ant colony optimization, and particle swarm optimization. These studies explain, in a strict mathematical way, how these algorithms behave on different problem classes. Fitness landscape analysis has provided new insights that enable construction of better mutation and recombination search operators for important problems such as satisfiabilty (SAT) [4] and the travelling salesman problem (TSP) [5]. In the continuous domain, powerful algorithms such as covariance matrix adaptation evolution strategy (CMA-ES) [6] have been designed based on earlier theoretical investigations. Investigations into hypervolume indicators have lead to new high performing algorithms for multiobjective problems [7]. Although this is just a small example of the theoretical results obtained during the last 10 years, it clearly shows the importance of theoretical work in the area of evolutionary computation and the impact it can have on the design of high performance algorithms.

This special issue highlights recent advances in the theory of evolutionary computation. We selected four papers (out of 22 submissions) to illustrate different aspects of theoretical work being conducted in the evolutionary computation field. Each paper describes both strict mathematical investigations and experimental studies.

The first paper by Mills *et al.* "Transforming Evolutionary Search into Higher-Level Evolutionary Search by Capturing Problem Structure" addresses a central idea of algorithmics: solving larger problems by suitably assembling solutions to smaller sub-problems. In classic algorithmics, this concept is found in dynamic programming and divide-and-conquer approaches. In evolutionary computation it is found in the use of crossover, the building block hypothesis and all methods that alter the components of the evolutionary algorithm, based on previously learned information on the problem structure. In this paper, an algorithm of the latter type is analyzed. The paper identifies structural correlations in the problem (termed building blocks in some problem classes) and uses such insight to suitably redefine the variation operators. The analysis conducted both via mathematical means and experiments provides great insight into the working principles of this computational approach, termed multiscale search. A particularly remarkable result is that the multiscale approach provably solves a known test problem in polynomial time for which all previous analyses of other evolutionary approaches showed a super-polynomial time.

Hyper-volume based evolutionary algorithms have received increasing attention in multiobjective optimization and are the focus of the second paper by Bringmann and Friedrich, "Convergence of Hypervolume-Based Archiving Algorithms." A central component of such algorithms, which ultimately determines their potential and limitations, is the archiving mechanism. The archiving mechanism is responsible for deciding which individuals, among parents and offspring, will survive until the next generation. The paper studies the performance of archiving algorithms in terms of their effectiveness, their ability to reach an optimal population assuming an ideal sequence of offspring, and their ability to maintain the best seen individuals when the sequence of offspring is the least favorable. Large classes of archiving mechanisms are studied by rigorous means, including those that never decrease the hypervolume as well as those that always increase the hypervolume whenever possible. The authors found there are no efficient implementations of the latter class of algorithms, unless P = NP, while there exists efficient implementations of the former class. The study is a fundamental contribution to the theory of hypervolume-based multiobjective evolutionary algorithms.

A basic question about any evolutionary algorithm is whether it will discover an optimal solution within finite time. This and other questions related to convergence have long since been resolved for large classes of algorithms. As such, much research focus has shifted toward analysing their runtime. However, the question of convergence still remains open for certain classes of algorithms, including many cross entropy methods. Such a class of algorithms is addressed in the third paper, "Asymptotic Properties of a Generalized Cross-Entropy Optimization Algorithm" by Wu and Kolonko.

Date of publication September 11, 2014; date of current version September 29, 2014.
Digital Object Identifier 10.1109/TEVC.2014.2350673

These methods repeatedly sample solutions from a probability distribution and use the information gained from these samples to adapt the probability distribution. The adaptation of the probability distribution is controlled by a smoothing parameter and it is essential for successful application of the method to set this parameter correctly. The paper shows how convergence properties of the cross entropy method depends on the choice of the smoothing parameter. The authors consider the probability of sampling an optimal solution in finite time, as well as convergence of the probability distribution to a fixed solution. These results are significant because they not only advance the understanding of cross entropy methods, but also contribute to the understanding of related methods such as estimation of distribution algorithms and ant colony optimization.

In immune-inspired optimization, the use of hypermutations is well established. However, all theoretical work so far has shown the optimum is found quicker by avoiding hypermutations. The fourth paper by Jansen and Zarges, entitled "Reevaluating Immune-Inspired Hypermutations using the Fixed Budget Perspective," provides a striking explanation. It shows how hypermutations can greatly reduce the time needed to find a near-optimal solution. Moreover, the authors argue that previously observed inferior performance occurs only when hypermutations are aiming for the perfect optimum. Besides clarifying the role of hypermutations, this work also demonstrates how to apply this insight in practice. The solution involves applying the immune-inspired algorithm in the traditional way, with hypermutations, but only up to a certain point after which hypermutations should be suppressed.

The four papers in this special issue provide only a sampling of the active theoretical research ongoing in the evolutionary computation field today. It is hoped these papers will inspire more readers to enter this dynamic and exciting area of research.

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REFERENCES

[1] A. Auger and B. Doerr, *Theory of Randomized Search Heuristics: Foundations and Recent Developments*. Singapore: World Scientific, 2011.
[2] T. Jansen, *Analyzing Evolutionary Algorithms—The Computer Science Perspective* (Natural Computing Series). Berlin, Germany: Springer, 2013.
[3] F. Neumann and C. Witt, *Bioinspired Computation in Combinatorial Optimization: Algorithms and Their Computational Complexity*. Berlin, Germany: Springer, 2010.
[4] D. Hains, D. Whitley, A. E. Howe, and W. Chen, "Hyperplane initialized local search for MAXSAT," in *Proc. 15th Annu. Conf. Genet. Evol. Comput. (GECCO)*, Amsterdam, The Netherlands, 2013, pp. 805–812.
[5] D. Whitley, D. Hains, and A. E. Howe, "Tunneling between optima: Partition crossover for the traveling salesman problem," in *Proc. 11th Annu. Conf. Genet. Evol. Comput. (GECCO)*, 2009, pp. 915–922.
[6] N. Hansen, "The CMA evolution strategy: A comparing review," in *Towards a New Evolutionary Computation. Advances on Estimation of Distribution Algorithms*, J. Lozano, P. Larranaga, I. Inza, and E. Bengoetxea, Eds. Berlin, Germany: Springer, 2006, pp. 75–102.
[7] K. Bringmann and T. Friedrich, "Approximating the least hypervolume contributor: NP-hard in general, but fast in practice," *Theor. Comput. Sci.*, vol. 425, pp. 104–116, Mar. 2012.

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