Guest Editorial
Learning Automata: Theory, Paradigms, and Applications

Mohammad S. Obaidat, *Senior Member, IEEE*, Georgios I. Papadimitriou, *Senior Member, IEEE*, and Andreas S. Pomportsis

LEARNING automata [1] have attracted a considerable interest in the last three decades. They are adaptive decision making devices that operate in unknown stochastic environments and progressively improve their performance via a learning process. They have been initially used by psychologists and biologists to describe the human behavior from both psychological and biological viewpoints. Learning automata have made a significant impact on all areas of engineering. They can be applied to a broad range of modeling and control problems, which are characterized by nonlinearity and a high degree of uncertainty. Learning automata have some key features, which make them applicable to a broad range of applications: they combine rapid and accurate convergence with a low computational complexity.

Learning is defined as any permanent change in behavior as a result of past experience, and a learning system should therefore have the ability to improve its behavior with time, toward a final goal. In a purely mathematical context, the goal of a learning system is the optimization of a function not known explicitly [2].

Thirty years ago, Tsypkin [3] introduced a method to reduce the problem to the determination of an optimal set of parameters and then applied stochastic hill-climbing techniques. Tsetlin [4] started the work on learning automata during the same period. An alternative approach to applying stochastic hill-climbing techniques, introduced by Narendra and Viswanathan [5], is to regard the problem as one of finding an optimal action out of a set of allowable actions and to achieve this using stochastic automata. The difference between the two approaches is that the former updates the parameter space at each iteration while the latter updates the probability space.

The stochastic automaton attempts a solution of the problem without any information on the optimal action. One action is selected at random, the response from the environment is observed, action probabilities are updated based on that response, and the procedure is repeated. A stochastic automaton acting as described to improve its performance is called a learning automaton.

The learning automata were developed in the area of mathematical psychology. Early research in this area is surveyed by Bush and Mosteller [6] and Atkinson *et al.* [7]. Tsetlin [4] introduced deterministic automaton operating in random environments as a model of learning. Most of the efforts done on learning automata theory have followed the trend set by Tsetlin, Varshavski, and Vorontsova [8] and described the use of stochastic automata with updating of action probabilities which results in reduction in the number of states in comparison with deterministic automata.

Fu [9] introduced stochastic automata into the control scientific area. Linear updating schemes are presented by McLaren [10]. Chandrasekaran and Shen [11], [12] studied nonlinear updating schemes, nonstationary environments and games of automata.

Thathachar and Sastry [13], [14] introduced the class of estimator learning automata. Estimator learning automata are characterized by the use of running estimates of the reward probabilities of actions. The change in the probability of choosing an action is based on the running estimates of the probability of reward rather than on the feedback from the environment. This means that even when an action is rewarded it is possible that the probability of choosing another action is increased. These algorithms, at every time instant, increase the probability of choosing the action with the maximum current estimate of reward probability. Simulation results have demonstrated the superiority of the estimator algorithms over the traditional learning algorithms.

Oommen and Christensen [15] introduced the discretized learning automata. Automata of this category are characterized by the fact that action probabilities can take values from a finite set only. Discretized learning automata converge faster than the continuous ones and consequently, they achieve a higher performance. Oommen and Lanctot [16] presented a discretized estimator-based learning automaton that achieves a high performance in every stationary stochastic environment.

Apart from papers that address theoretical aspects of learning automata [2]–[23], a broad range of applications of learning automata to practical problems have also been presented.

Manuscript received November 15, 2001; revised March 1, 2002.

M. S. Obaidat is with the Department of Computer Science, Monmouth University, West Long Branch, NJ 07764 USA (e-mail: obaidat@monmouth.edu).

G. I. Papadimitriou and A. S. Pomportsis are with the Department of Informatics, Aristotle University, 54006 Thessaloniki, Greece (e-mail: gp@csd.auth.gr; apombo@csd.auth.gr).

Publisher Item Identifier S 1083-4419(02)06470-1.

In [24], Najim and Poznyak introduced a multimodal searching technique which is based on learning automata with changing number of actions.

An application of learning automata in the medium access control of optical networks is presented in [25]. Each station of the network is provided with a learning automaton that decides which of the packets waiting for transmission will be transmitted during the next time slot. The learning algorithm is designed in such a way, that the probability of choosing each packet asymptotically tends to be proportional to the probability that no receiver conflict will appear to the destination node of this packet. In this way, the number of receiver conflicts is reduced and the network performance is significantly improved.

Oommen and De St. Croix [26] proposed the use of learning automata in the graph partitioning problem. It is the first reported learning-automata-based solution to the above NP-complete problem which involves partitioning the nodes of a graph into sets of equal size in order to minimize the sum of the costs of the edges having end-points in different sets.

The same authors [27] proposed an application of learning automata in a pattern recognition problem that involves comparing a noisy string with every element of a dictionary. A learning-automaton-based solution to string taxonomy is proposed.

In [28], Ikonen and Najim proposed a learning-automata-based algorithm for training the rule base of a fuzzy logic processor.

Unsal *et al.* [29] introduced an intelligent controller for an automated vehicle, planning its own trajectory based on sensor and communication data. The intelligent controller is designed using learning automata theory. Using the data received from on-board sensors, two automata (one for lateral actions, one for longitudinal actions) can learn the best possible action to avoid collisions. The system has the advantage of being able to work in unmodeled stochastic environments, unlike adaptive control methods or expert systems.

In [30], Oommen and Roberts proposed a learning-automata-based solution to the capacity assignment problem of communication networks. This problem focuses on finding the lowest cost link capacity assignments that satisfy certain delay constraints for several distinct classes of packets that traverse the network.

The objective of this special issue is to present high-quality papers on theoretical aspects and real-world applications of learning automata. In this issue, we have accepted eight regular papers and three technical correspondences out of 24 submissions from all over the world. Each paper was refereed by at least three qualified reviewers according to the practice of the IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS—PART B: CYBERNETICS. The accepted papers cover a broad area of theory and applications of learning automata. We hope this special issue will give a boost to the research in the learning automata area.

Thathachar and Sastry provide an overview of the learning automata area. The focus is on the latest developments in the area, such as parametrized learning automata, generalized learning automata, and continuous action-set learning automata. Groups of learning automata forming teams and feedforward networks are also considered. The authors attempt to bring together latest developments in the learning automata area in a unified framework.

Economides and Kehagias introduce a fixed-structure, multi-action, reward-penalty learning automaton. The proposed STAR automaton is characterized by the star-shaped structure of its state transition diagram. The proposed scheme is ϵ-optimal and has a faster convergence rate than variable structure automata.

Agache and Oommen present two estimator-based generalized pursuit learning algorithms. These algorithms differ from the well-known pursuit algorithms in that they pursue all the actions with higher reward estimates than the chosen action, rather than pursuing only the current estimated optimal action. In this way, the speed of convergence and accuracy are significantly improved. The proposed algorithms are among the fastest learning automata reported in the literature and are proved to be ϵ-optimal.

Baba and Mogami propose and extension of the relative reward strength algorithm [17] in such a way, that it can be applied to learning automata with hierarchical structure. It is proved that the proposed scheme converges with probability one under certain type of nonstationary stochastic environment.

Poznyak and Najim introduce a new learning algorithm for an N-person averaged stochastic game with constraints, and unknown payoffs and constraints. A reinforcement learning algorithm for obtaining stationary Nash equilibrium strategies is presented. Under the assumption that the game has a unique Nash equilibrium, it is proved that the algorithm asymptotically achieves Nash equilibrium.

Verbeeck and Nowe compare the field of ant colony optimization with an interconnected learning automata model. They find that these two models match perfectly and the theory of learning automata can serve as a good theoretical tool for analyzing ant colony optimization algorithms and multiagent systems in general.

Papadimitriou *et al.* present a new adaptive medium access control protocol for broadcast networks with bursty traffic, which is based on the use learning automata. According to the proposed protocol, the station which is granted permission to transmit at each time slot is selected by means of learning automata. The choice probability of the selected station is updated by taking into account the network feedback information. The system which consists of the learning automata and the network is analyzed and it is proven that the choice probability of each station asymptotically tends to be proportional to the probability that this station is not idle. In this way, the number of idle slots is minimized and a high network performance is achieved.

El-Osery *et al.* present an application of learning automata in the area of multiagent robotics. They use a virtual laboratory architecture to demonstrate the use of stochastic-learning-automata-based control of two cooperative robots.

Howell *et al.* combine learning automata and genetic algorithms to achieve an increase in the rate of convergence for learning automata and also improve the escape from local minima.

Obaidat *et al.* present an adaptive learning-automata-based shared-medium ATM switch. The proposed switch achieves a high performance and is scalable for large number of ports, because the time complexity of the proposed learning algorithm is independent of the number of ports.

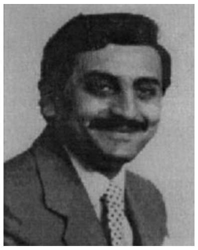
Oommen and Roberts present a solution to the capacity assignment problem for prioritized networks, that is based on the use of discretized learning automata. The proposed solution finds the best possible set of capacities for the links that satisfy the traffic requirements of the network while minimizing the cost.

Acknowledgment

The guest editors wish to thank all those who submitted papers for this special issue. Special thanks to Krishna Pattipati, former editor of IEEE Transactions on Systems, Man, and Cybernetics—Part B: Cybernetics, and Larry Hall, current editor, for hosting this special issue. Finally, thanks are expressed to the editorial staff of IEEE Transactions on Systems, Man, and Cybernetics for their cooperation and fine support.

References

[1] K. S. Narendra and M. L. Thathachar, *Learning Automata: An Introduction*. Englewood Cliffs, NJ: Prentice-Hall, 1989.
[2] K. S. Narendra and M. A. L. Thathachar, "Learning automata: A survey," *IEEE Trans. Syst., Man, Cybern.*, vol. SMC-4, pp. 323–334, July 1974.
[3] Yn. Z. Tsypkin, *Adaptation and Learning in Automatic Systems*. New York: Academic, 1971.
[4] M. L. Tsetlin, *Automaton Theory and Modeling of Biological Systems, vol. 102 in Mathematics in Science and Engineering*. New York: Academic, 1973.
[5] K. S. Narendra and R. Viswanathan, "Learning models using stochastic automata," presented at the Proc. Int. Conf. Cybernetics and Society, Washington, DC, Oct. 9–12, 1972.
[6] R. R. Bush and F. Mosteller, *Stochastic Models for Learning*. New York: Wiley, 1958.
[7] R. C. Atkinson, G. H. Bower, and E. J. Crothers, *An Introduction to Mathematical Learning Theory*. New York: Wiley, 1965.
[8] V. I. Varshavski and I. P. Vorontsova, "On the behavior of stochastic automata with variable structure," *Automat. Telemekh.*, vol. 24, pp. 253–360, 1963.
[9] K. S. Fu, "Stochastic automata as models of learning systems," in *Computer and Information Sciences II*, J. T. Lou, Ed. New York: Academic, 1967.
[10] R. W. McLaren, "A stochastic automaton model for synthesis of learning systems," *IEEE Trans. Syst. Sci. Cybern.*, vol. SSC-2, pp. 109–114, 1966.
[11] B. Chandrasekharan and D. W. C. Shen, "On expediency and convergence in variable structure stochastic automata," *IEEE Trans. Syst. Sci. Cybern.*, vol. SSC-5, pp. 145–149, 1968.
[12] ——, "Stochastic automata games," *IEEE Trans. Syst. Sci. Cybern.*, vol. SSC-5, pp. 145–149, 1969.
[13] M. A. L. Thathachar and P. S. Sastry, "A new approach to the design of reinforcement schemes for learning automata," *IEEE Trans. Syst., Man, Cybern.*, vol. SMC-15, pp. 168–175, Jan./Feb. 1985.
[14] ——, "Estimator algorithms for learning automata," presented at the Proc. Platinum Jubilee Conf. System Signal Processing, Bangalore, Karnataka, India, Dec. 1986.
[15] B. J. Oommen and J. P. R. Christensen, "Epsilon optimal discretized linear reward-penalty learning automata," *IEEE Trans. Syst., Man, Cybern.*, vol. 18, no. 3, pp. 451–458, May/June 1988.
[16] B. J. Oommen and J. K. Lanctot, "Discretized pursuit learning automata," *IEEE Trans. Syst., Man, Cybern.*, vol. 20, pp. 931–938, July/Aug. 1990.
[17] R. Simha and J. F. Kurose, "Relative reward strength algorithms for learning automata," *IEEE Trans. Syst., Man, Cybern.*, vol. 19, pp. 388–398, Apr. 1989.
[18] K. Najim and A. S. Poznyak, Eds., *Learning Automata: Theory and Applications*. Amsterdam, The Netherlands: Elsevier, 1994.
[19] P. S. Sastry, K. Rajaraman, and S. R. Ranjan, "Learning optimal conjunctive concepts through a team of stochastic automata," *IEEE Trans. Syst., Man, Cybern.*, vol. 23, pp. 1175–1184, July–Aug. 1993.
[20] G. I. Papadimitriou, "A new approach to the design of reinforcement schemes for learning automata: Stochastic estimator learning algorithms," *IEEE Trans. Knowledge Data Eng.*, vol. 6, pp. 649–654, Aug. 1994.
[21] A. A. Economides, "Multiple response learning automata," *IEEE Trans. Syst., Man, Cybern. B*, vol. 26, pp. 153–156, Feb. 1996.
[22] A. Poznyak, K. Najim, and E. Ikonen, "Adaptive selection of the optimal model order of linear regression models using learning automata," *Int. J. Syst. Sci.*, vol. 27, no. 2, pp. 151–159, 1996.
[23] B. J. Oommen and M. Agache, "Continuous and discretized pursuit learning schemes: Various algorithms and their comparison," *IEEE Trans. Syst., Man, Cybern. B*, vol. 31, pp. 277–287, June 2001.
[24] K. Najim and A. S. Poznyak, "Multimodal searching technique based on learning automata with continuous input and changing number of actions," *IEEE Trans. Syst., Man, Cybern. B*, vol. 26, pp. 666–673, Aug. 1996.
[25] G. I. Papadimitriou and D. G. Maritsas, "Learning automata-based receiver conflict avoidance algorithms for WDM broadcast-and-select star networks," *IEEE/ACM Trans. Networking*, vol. 4, pp. 407–412, June 1996.
[26] B. J. Oommen and E. V. De St. Croix, "Graph partitioning using learning automata," *IEEE Trans. Comput.*, vol. 45, pp. 195–208, Feb. 1996.
[27] ——, "String taxonomy using learning automata," *IEEE Trans. Syst., Man, Cybern. B*, vol. 27, pp. 354–365, Apr. 1997.
[28] E. Ikonen and K. Najim, "Use of learning automata in distributed fuzzy logic processor training," in *Proc. Inst. Elect. Eng., Control Theory Applicat.*, vol. 144, May 1997, pp. 255–262.
[29] C. Unsal, P. Kachroo, and J. S. Bay, "Multiple stochastic learning automata for vehicle path control in an automated highway system," *IEEE Trans. Syst., Man, Cybern. A*, vol. 29, pp. 120–128, Jan. 1999.
[30] B. J. Oommen and T. D. Roberts, "Continuous learning automata solutions to the capacity assignment problem," *IEEE Trans. Comput.*, vol. 49, pp. 608–620, June 2000.



Mohammad S. Obaidat (S'85–M'86–SM'91) was born in Irbid, Jordan. He received the B.S. degree in electrical engineering from Aleppo University, Aleppo, Syria, and the M.S. and Ph.D. degrees in computer engineering with a minor in computer science from The Ohio State University, Columbus.

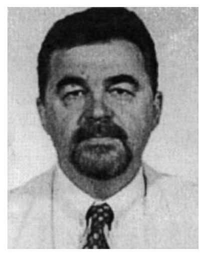
He is an internationally well-known Academic/Researcher/ Scientist. He is currently a tenured Full Professor of Computer Science at Monmouth University, West Long Branch, NJ. Among his previous positions are Chair of the Department of Computer Science and Director of the Graduate Program at Monmouth University and a Faculty Member at the City University of New York. He has received extensive research funding and has published over 240 refereed technical articles in refereed scholarly journals and proceedings of refereed international conferences. He is the author of the book *Performance Evaluation of Computer and Telecommunications Systems* (Wiley), to appear in 2003. He is the coauthor of the books *Wireless Networks*, Wiley, 2003 and *Multiwavelength Optical LANs*, Wiley, 2003. He is also the co-editor of the book *Applied System Simulation: Methodologies and Applications* (Norwell, MA: Kluwer), to appear in March 2003. His research interests include performance evaluation of computer systems, algorithms and networks, telecommunications and networking systems, wireless communications and networks, high-performance and parallel computing/computers, applied neural networks and pattern recognition, computer security, and speech processing. He has served as a Consultant for several corporations worldwide.

Dr. Obaidat is the Chief Editor of the *International Journal of Communication Systems* published by Wiley. He is also a Technical Editor of *Simulation: Transactions of the Society for Modeling and Simulations (SCS) International*. He is an Associate Editor/Editorial Board Member of seven other refereed scholarly journals, including three IEEE Transactions. He has guest edited four special issues of the journal *Simulation* journal. He also guest edited a special issue on Neural Network Applications of the IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS. He also guest edited special issues for the *Computer Communications Journal* and the *Journal of Computers Electrical Engineering*. Currently, he is guest editing special issues for the *Transactions of the Society for Computer Simulation*, *Elsevier Computer Communications Journal*, and the the IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS PART B. He has served as the Steering Committee Chair and the Program Chair of the 1995 IEEE International Conference on Electronics, Circuits, and Systems (ICECS'95), and as the Program Chair of the 1996 IEEE International Phoenix Conference on Computers and Communications (IPCCC"96). He served as the Vice General Chair of the 1997 IEEE International Performance, Computing, and Communications Conference and the General and Program Chair of the 1997 Summer Computer Simulation (SCSC) Conference. He also served as the General Chair of SCSC'98 and SCSC'99. He also served as Vice Program Chair for the 1997 IEEE International Conference on Computer Communications and Networks (IC^3N'97). He served as the General Co-Chair of the 1998 IEEE International Performance, Computing, and Communications Conference. He is the founder of the SCS International Symposium on Performance Evaluation of Computer and Telecommunication Systems (SPECTS) and has served as the General Chair of SPECTS'98, SPECTS'99, SPECTS'01, and SPECTS'02. He will be the General Chair of SPECTS'2003 and steering committee chair of SCSC2003. He has served as the Steering Committee Chair of SCSC2002, SCSC2001, and SCSC2002. He served as the Vice Program Chair of the 2001 International Conference on Parallel Processing (ICPP'01). He has served on the program, advisory, organizing, and steering committees of numerous international conferences. He is the Chair of the International Advisory Committee of ICECS2003 Conference. He has received a recognition certificate from the IEEE. Between 1994 and 1997, he has served as Distinguished Speaker/Visitor of the IEEE Computer Society. Since 1995, he has been serving as an ACM Distinguished Lecturer. Between 1996 and 1999, he served as an IEEE/ACM Program Evaluator of the Computing Sciences Accreditation Board/Commission, CSAB/CSAC. He is the founder and first Chairman of SCS Technical Chapter (Committee) on PECTS (Performance Evaluation of Computer and Telecommunication Systems). He has been a member of the Board of Directors of the Society for Modeling and Simulation International, SCS, since 1994. He is now the Vice President of Conferences of the Society for Modeling and Simulation International. He has been invited to lecture and give keynote speeches worldwide. Prof. Obaidat has been elected to be a Fellow of the Society for Modeling and Simulation International. He is the Scientific Advisor of the 2002 UNDP/World Bank Workshop on Fostering Digital Inclusion-The Role of ICT in Development that is part of the MDF-4. Recently, he has been awarded a Nokia Research Fellowship.

Georgios I. Papadimitriou (M'89–SM'02) received the Diploma and Ph.D. degrees in computer engineering from the University of Patras, Patras, Greece, in 1989 and 1994, respectively.

From 1989 to 1994, he was a Teaching Assistant at the Department of Computer Engineering of the University of Patras and a Research Scientist at the Computer Technology Institute, Patras. From 1994 to 1996, he was a Postdoctorate Research Associate at the Computer Technology Institute. From 1997 to 2001, he was a Lecturer at the Department of Informatics, Aristotle University of Thessaloniki, Thessaloniki, Greece. Since 2001, he has been an Assistant Professor at the Department of Informatics, Aristotle University of Thessaloniki. His research interests include design and analysis of broadband networks and learning automata.

Prof. Papadimitriou is a Member of the Editorial Board of the *International Journal of Communication Systems*. He is also an Associate Editor of the journal *Simulation: Transactions of the Society for Modeling and Simulation International*. He is the coauthor of the books *Wireless Networks*, Wiley, 2003 and *Multiwavelength Optical LANs*, Wiley, 2003. He is also co-editor of the book *Applied System Simulation: Methodologies and Applications* (Norwell, MA: Kluwer) to appear in March 2003. He is the author of more than 70 refereed journal and conference papers.



Andreas S. Pomportsis received the B.S. degree in physics in 1978 and the M.S. degree in electronics and communications in 1981, both from the University of Thessaloniki, Thessaloniki, Greece, the Dipl. degree in electrical engineering from the Technical University of Thessaloniki in 1985, and the Ph.D. degree in computer science from the University of Thessaloniki In 1987.

Currently, he is a Professor at the Department of Informatics, Aristotle University of Thessaloniki. His research interests include computer networks, learning automata, computer architecture, parallel and distributed computer systems, and multimedia systems.