

## **Automata learning: from probabilistic to quantum** Chu, W.

## Citation

Chu, W. (2024, December 4). *Automata learning: from probabilistic to quantum*. Retrieved from https://hdl.handle.net/1887/4170915

Version:	Publisher's Version
License:	Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden
Downloaded from:	https://hdl.handle.net/1887/4170915

Note: To cite this publication please use the final published version (if applicable).

## References

- [1] D.V. Alekseev, G.A. Kazunina, and A.V. Cherednichenko. Rock failure forecasting with 3d modeling using probabilistic cellular automata. *Journal of Mining Science*, 51:917–923, 2015.
- [2] Dana Angluin. Learning regular sets from queries and counterexamples. *Information and computation*, 75(2):87–106, 1987.
- [3] Dana Angluin. *Identifying languages from stochastic examples*. Yale University. Department of Computer Science, 1988.
- [4] Dana Angluin. Queries and concept learning. *Machine learning*, 2:319–342, 1988.
- [5] Srinivasan Arunachalam and Ronald de Wolf. Guest column: A survey of quantum learning theory. *ACM Sigact News*, 48(2):41–67, 2017.
- [6] Srinivasan Arunachalam and Ronald De Wolf. Optimal quantum sample complexity of learning algorithms. *The Journal of Machine Learning Research*, 19(1):2879–2878, 2018.
- [7] Lalit R. Bahl, Peter F. Brown, Peter V. de Souza, and Robert L. Mercer. Estimating hidden Markov model parameters so as to maximize speech recognition accuracy. *IEEE Transactions on Speech and Audio Processing*, 1(1):77–83, 1993.
- [8] Pierre Baldi and Søren Brunak. *Bioinformatics: the machine learning approach*. MIT press, 2001.
- [9] Borja Balle and Mehryar Mohri. Learning weighted automata. In Algebraic Informatics: 6th International Conference, CAI 2015, Stuttgart, Germany, September 1-4, 2015. Proceedings 6, pages 1–21. Springer, 2015.
- [10] Leonard E. Baum, Ted Petrie, George Soules, and Norman Weiss. A maximization technique occurring in the statistical analysis of probabilistic functions of Markov chains. *The annals of mathematical statistics*, 41(1):164–171, 1970.
- [11] Amos Beimel, Francesco Bergadano, Nader H. Bshouty, Eyal Kushilevitz, and Stefano Varricchio. On the applications of multiplicity automata in learning. In *Proceedings of 37th Conference on Foundations of Computer Science*, pages 349–358. IEEE, 1996.
- [12] Amos Beimel, Francesco Bergadano, Nader H. Bshouty, Eyal Kushilevitz, and Stefano Varricchio. Learning functions represented as multiplicity automata. *Journal of the ACM (JACM)*, 47(3):506–530, 2000.

- [13] Charles H. Bennett, Péter Gács, Ming Li, Paul M.B. Vitányi, and Wojciech H Zurek. Thermodynamics of computation and information distance. In *Proceedings of the twenty-fifth annual ACM symposium on Theory of computing*, pages 21–30, 1993.
- [14] Francesco Bergadano and Stefano Varricchio. Learning behaviors of automata from multiplicity and equivalence queries. *SIAM Journal on Computing*, 25(6):1268–1280, 1996.
- [15] Daniel Berrar. Bayes' theorem and naive bayes classifier. *Encyclopedia of bioinformatics and computational biology: ABC of bioinformatics*, 403:412, 2018.
- [16] Alberto Bertoni and Marco Carpentieri. Analogies and differences between quantum and stochastic automata. *Theoretical Computer Science*, 262(1-2):69–81, 2001.
- [17] Paul Bogdan and Massoud Pedram. Toward enabling automated cognition and decision-making in complex cyber-physical systems. In 2018 IEEE International Symposium on Circuits and Systems (ISCAS), pages 1–4. IEEE, 2018.
- [18] Benedikt Bollig, Peter Habermehl, Carsten Kern, and Martin Leucker. Angluin-style learning of nfa. In *IJCAI*, volume 9, pages 1004–1009, 2009.
- [19] Joseph-Frédéric Bonnans, Jean Charles Gilbert, Claude Lemaréchal, and Claudia A Sagastizábal. *Numerical optimization: theoretical and practical aspects*. Springer Science & Business Media, 2006.
- [20] Cynthia Brame. Active learning. Vanderbilt University Center for Teaching, 2016.
- [21] Paula Branco, Luís Torgo, and Rita P. Ribeiro. A survey of predictive modeling on imbalanced domains. *ACM computing surveys (CSUR)*, 49(2):1–50, 2016.
- [22] Alex Brodsky and Nicholas Pippenger. Characterizations of 1-way quantum finite automata. *SIAM Journal on Computing*, 31(5):1456–1478, 2002.
- [23] Nader H. Bshouty and Jeffrey C. Jackson. Learning dnf over the uniform distribution using a quantum example oracle. In *Proceedings of the 8th annual conference on Computational Learning Theory*, pages 118–127, 1995.
- [24] Rafael C. Carrasco and Jose Oncina. Learning stochastic regular grammars by means of a state merging method. In *International Colloquium on Grammatical Inference*, pages 139–152. Springer, 1994.
- [25] Rafael C. Carrasco and Jose Oncina. Learning deterministic regular grammars from stochastic samples in polynomial time. *RAIRO-Theoretical Informatics and Applications*, 33(1):1–19, 1999.
- [26] Wenjing Chu and Marcello Bonsangue. Learning probabilistic languages by k-testable machines. In 2020 International Symposium on Theoretical Aspects of Software Engineering (TASE), pages 129–136. IEEE, 2020.
- [27] Wenjing Chu, Shuo Chen, and Marcello Bonsangue. Learning probabilistic automata using residuals. In *Theoretical Aspects of Computing–ICTAC 2021: 18th International Colloquium, Virtual Event, Nur-Sultan, Kazakhstan, September 8–10, 2021, Proceedings 18*, pages 295–313. Springer, 2021.

- [28] Wenjing Chu, Shuo Chen, and Marcello Bonsangue. Non-linear optimization methods for learning regular distributions. In *Formal Methods and Software Engineering: 23rd International Conference on Formal Engineering Methods, ICFEM 2022, Madrid, Spain, October 24–27, 2022, Proceedings*, pages 54–70. Springer, 2022.
- [29] Wenjing Chu, Shuo Chen, Marcello Bonsangue, and Zenglin Shi. Approximately learning quantum automata. In *International Symposium on Theoretical Aspects of Software Engineering*, pages 268–285. Springer, 2023.
- [30] Corinna Cortes, Mehryar Mohri, and Ashish Rastogi. Lp distance and equivalence of probabilistic automata. *International Journal of Foundations of Computer Science*, 18(04):761–779, 2007.
- [31] Corinna Cortes, Mehryar Mohri, Ashish Rastogi, and Michael Riley. On the computation of the relative entropy of probabilistic automata. *International Journal of Foundations of Computer Science*, 19(01):219–242, 2008.
- [32] François Coste. Learning the language of biological sequences. In *Topics in grammatical inference*, pages 215–247. Springer, 2016.
- [33] Colin De La Higuera. Characteristic sets for polynomial grammatical inference. *Machine Learning*, 27(2):125–138, 1997.
- [34] Colin De la Higuera. *Grammatical inference: learning automata and grammars*. Cambridge University Press, 2010.
- [35] Colin de la Higuera, Franck Thollard, Enrique Vidal, Francisco Casacuberta, and Rafael C. Carrasco. Probabilistic finite state automata–part ii. *Rapport technique RR-0403, EURISE*, 2004.
- [36] Jacob de Nobel, Diederick Vermetten, Hao Wang, Carola Doerr, and Thomas Bäck. Tuning as a means of assessing the benefits of new ideas in interplay with existing algorithmic modules. In *Proceedings of the Genetic and Evolutionary Computation Conference Companion*, pages 1375–1384, 2021.
- [37] François Denis, Aurélien Lemay, and Alain Terlutte. Learning regular languages using rfsa. In *International Conference on Algorithmic Learning Theory*, pages 348–363. Springer, 2001.
- [38] François Denis, Aurélien Lemay, and Alain Terlutte. Some classes of regular languages identifiable in the limit from positive data. In *International Colloquium on Grammatical Inference*, pages 63–76. Springer, 2002.
- [39] Pierre Dupont, François Denis, and Yann Esposito. Links between probabilistic automata and hidden Markov models: probability distributions, learning models and induction algorithms. *Pattern recognition*, 38(9):1349–1371, 2005.
- [40] Pierre Dupont, Laurent Miclet, and Enrique Vidal. What is the search space of the regular inference? In *Grammatical Inference and Applications: Second International Colloquium, ICGI-94 Alicante, Spain, September 21–23, 1994 Proceedings 2*, pages 25–37. Springer, 1994.

- [41] Richard Durbin, Sean R. Eddy, Anders Krogh, and Graeme Mitchison. *Biological sequence analysis: probabilistic models of proteins and nucleic acids*. Cambridge University Press, 1998.
- [42] C. Fernando, N. Pereira, and M. Riley. Speech recognition by composition of weighted finite automata. *Finite-State Language Processing*. *MIT Press, Cambridge, Massachusetts*, 1997.
- [43] Michel Fliess. Matrices de hankel. J. Math. Pures Appl, 53(9):197-222, 1974.
- [44] Pedro García and Enrique Vidal. Inference of k-testable languages in the strict sense and application to syntactic pattern recognition. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 12(9):920–925, 1990.
- [45] Pedro Garcia, Enrique Vidal, and José Oncina. Learning locally testable languages in the strict sense. In *ALT*, pages 325–338, 1990.
- [46] E. Mark Gold. Language identification in the limit. *Information and control*, 10(5):447–474, 1967.
- [47] E Mark Gold. Complexity of automaton identification from given data. *Information and control*, 37(3):302–320, 1978.
- [48] Mykhailo Granik and Volodymyr Mesyura. Fake news detection using naive bayes classifier. In 2017 IEEE first Ukraine conference on Electrical and Computer Engineering (UKRCON), pages 900–903. IEEE, 2017.
- [49] John J. Grefenstette. Genetic algorithms and machine learning. In *Proceedings of the* 6th annual conference on Computational Learning Theory, pages 3–4, 1993.
- [50] Lov K. Grover. A fast quantum mechanical algorithm for database search. In *Proceedings of the twenty-eighth annual ACM symposium on Theory of computing*, pages 212–219, 1996.
- [51] Jozef Gruska et al. *Quantum computing*, volume 2005. McGraw-Hill London, 1999.
- [52] Jozef Gruska, Daowen Qiu, and Shenggen Zheng. Potential of quantum finite automata with exact acceptance. *International Journal of Foundations of Computer Science*, 26(03):381–398, 2015.
- [53] Mohamed Hamada and Sayota Sato. Simulator and robot-based game for learning automata theory. In *Entertainment for Education. Digital Techniques and Systems: 5th International Conference on E-learning and Games, Edutainment 2010, Changchun, China, August 16-18, 2010. Proceedings 5*, pages 429–437. Springer, 2010.
- [54] Christian Hammerschmidt, Benjamin Loos, Thomas Engel, et al. Flexible statemerging for learning dfas in python. In *International Conference on Grammatical Inference*, pages 154–159. PMLR, 2017.
- [55] Nikolaus Hansen. The cma evolution strategy: A tutorial. *arXiv preprint arXiv:1604.00772*, 2016.

- [56] John H. Holland. Genetic algorithms. Scientific american, 267(1):66–73, 1992.
- [57] John E. Hopcroft, Rajeev Motwani, and Jeffrey D. Ullman. Introduction to automata theory, languages, and computation. *Acm Sigact News*, 32(1):60–65, 2001.
- [58] James Jay Horning. A study of grammatical inference. Stanford University, 1969.
- [59] Henrik Jacobsson, Geert-Jan Kruijff, and Maria Staudte. From rule extraction to active learning symbol grounding. In *Proceedings of ICRA 2007 Workshop on Concept Learning for Embodied Agents*, 2007.
- [60] Frederick Jelinek. Statistical methods for speech recognition. MIT press, 1998.
- [61] Ronald M. Kaplan and Martin Kay. Regular models of phonological rule systems. *Computational linguistics*, 20(3):331–378, 1994.
- [62] Kevin Knight and Jonathan Graehl. An overview of probabilistic tree transducers for natural language processing. In *International Conference on Intelligent Text Processing and Computational Linguistics*, pages 1–24. Springer, 2005.
- [63] Attila Kondacs and John Watrous. On the power of quantum finite state automata. In *Proceedings 38th annual symposium on foundations of computer science*, pages 66–75. IEEE, 1997.
- [64] Takeshi Koshiba. Polynomial-time algorithms for the equivalence for one-way quantum finite automata. In *International Symposium on Algorithms and Computation*, pages 268–278. Springer, 2001.
- [65] Werner Kuich and Arto Salomaa. *Semirings, automata, languages*, volume 5. Springer Science & Business Media, 2012.
- [66] John Lafferty, Andrew McCallum, and Fernando C.N. Pereira. Conditional random fields: Probabilistic models for segmenting and labeling sequence data. 2001.
- [67] Kevin J. Lang. Random dfa's can be approximately learned from sparse uniform examples. In *Proceedings of the fifth annual workshop on Computational learning theory*, pages 45–52, 1992.
- [68] Kai-Fu Lee. On large-vocabulary speaker-independent continuous speech recognition. *Speech communication*, 7(4):375–379, 1988.
- [69] Tianrong Lin. Another approach to the equivalence of measure-many one-way quantum finite automata and its application. *Journal of Computer and System Sciences*, 78(3):807–821, 2012.
- [70] Stephen Paul Linder, Brian Edward Nestrick, Symen Mulders, and Catherine Leah Lavelle. Facilitating active learning with inexpensive mobile robots. *Journal of Computing Sciences in Colleges*, 16(4):21–33, 2001.
- [71] Rune B. Lyngsø and Christian N.S. Pedersen. The consensus string problem and the complexity of comparing hidden Markov models. *Journal of Computer and System Sciences*, 65(3):545–569, 2002.

- [72] Hiren M. Mandalia and Mandalia Dario D. Salvucci. Using support vector machines for lane-change detection. In *Proceedings of the human factors and ergonomics society annual meeting*, volume 49, pages 1965–1969. SAGE Publications Sage CA: Los Angeles, CA, 2005.
- [73] Hua Mao, Yingke Chen, Manfred Jaeger, Thomas D. Nielsen, Kim G. Larsen, and Brian Nielsen. Learning deterministic probabilistic automata from a model checking perspective. *Machine Learning*, 105:255–299, 2016.
- [74] Andrey Andreyevich Markov. An example of statistical investigation in the text of 'eugene onyegin'illustrating coupling of 'tests' in chains. *Proceedings of the Academy of Sciences of St. Petersburg*, 7:153–162, 1913.
- [75] Carlo Mereghetti, Beatrice Palano, Simone Cialdi, Valeria Vento, Matteo G.A. Paris, and Stefano Olivares. Photonic realization of a quantum finite automaton. *Physical Review Research*, 2(1):013089, 2020.
- [76] Aaron Meurer et al. Sympy: symbolic computing in python. *PeerJ Computer Science*, 3:e103, January 2017.
- [77] Marian Mindek. Finite state automata and image recognition. In *Dateso*, pages 141–151, 2004.
- [78] Melanie Mitchell. An introduction to genetic algorithms. MIT press, 1998.
- [79] Mehryar Mohri. Finite-state transducers in language and speech processing. *Computational linguistics*, 23(2):269–311, 1997.
- [80] Mehryar Mohri et al. Semiring frameworks and algorithms for shortest-distance problems. *Journal of Automata, Languages and Combinatorics*, 7(3):321–350, 2002.
- [81] Mehryar Mohri, Fernando Pereira, and Michael Riley. Weighted automata in text and speech processing. *arXiv preprint cs/0503077*, 2005.
- [82] Mehryar Mohri, Fernando Pereira, and Michael Riley. Speech recognition with weighted finite-state transducers. *Springer Handbook of Speech Processing*, pages 559–584, 2008.
- [83] Cristopher Moore and James P. Crutchfield. Quantum automata and quantum grammars. *Theoretical Computer Science*, 237(1-2):275–306, 2000.
- [84] Kevin P. Murphy et al. Passively learning finite automata. Citeseer, 1995.
- [85] Edi Muškardin, Bernhard K Aichernig, Ingo Pill, Andrea Pferscher, and Martin Tappler. Aalpy: an active automata learning library. *Innovations in Systems and Software Engineering*, 18(3):417–426, 2022.
- [86] Azqa Nadeem, Sicco Verwer, and Shanchieh Jay Yang. Sage: Intrusion alert-driven attack graph extractor. In 2021 IEEE symposium on visualization for cyber security (*VizSec*), pages 36–41. IEEE, 2021.
- [87] Kaddour Najim and Alexander S. Poznyak. *Learning automata: theory and applications*. Elsevier, 2014.

- [88] Vladimir Nasteski. An overview of the supervised machine learning methods. *Horizons. b*, 4:51–62, 2017.
- [89] José Oncina and Pedro Garcia. Inferring regular languages in polynomial updated time. In *Pattern recognition and image analysis: selected papers from the IVth Spanish Symposium*, pages 49–61. World Scientific, 1992.
- [90] Rajesh Parekh, Codrin Nichitiu, and Vasant Honavar. A polynomial time incremental algorithm for learning dfa. In *Grammatical Inference: 4th International Colloquium*, *ICGI-98 Ames, Iowa, USA, July 12–14, 1998 Proceedings 4*, pages 37–49. Springer, 1998.
- [91] Corina S Păsăreanu and Mihaela Bobaru. Learning techniques for software verification and validation. In *International Symposium On Leveraging Applications of Formal Methods, Verification and Validation*, pages 505–507. Springer, 2012.
- [92] Shreyasi Shubhendu Paul. Active and passive learning: A comparison. *GRD Journal* for Engineering, 2(9):27–29, 2017.
- [93] Azaria Paz. Introduction to probabilistic automata. Academic Press, 2014.
- [94] Daowen Qiu. Learning quantum finite automata with queries. *arXiv preprint arXiv:2111.14041*, 2021.
- [95] Michael O. Rabin. Probabilistic automata. *Information and control*, 6(3):230–245, 1963.
- [96] Michael O Rabin and Dana Scott. Finite automata and their decision problems. *IBM journal of research and development*, 3(2):114–125, 1959.
- [97] Lawrence Rabiner and Biing-Hwang Juang. *Fundamentals of speech recognition*. Prentice-Hall, Inc., 1993.
- [98] Raghu Raghavan. Cellular automata in pattern recognition. *Information Sciences*, 70(1-2):145–177, 1993.
- [99] Romesh Ranawana and Vasile Palade. Optimized precision-a new measure for classifier performance evaluation. In 2006 IEEE International Conference on Evolutionary Computation, pages 2254–2261. IEEE, 2006.
- [100] James Rogers and Geoffrey K. Pullum. Aural pattern recognition experiments and the subregular hierarchy. *Journal of Logic, Language and Information*, 20(3):329–342, 2011.
- [101] Dana Ron, Yoram Singer, and Naftali Tishby. On the learnability and usage of acyclic probabilistic finite automata. *Journal of Computer and System Sciences*, 56(2):133– 152, 1998.
- [102] Arto Salomaa and Matti Soittola. *Automata-theoretic aspects of formal power series*. Springer Science & Business Media, 2012.
- [103] Claude Sammut and Geoffrey I. Webb. *Encyclopedia of machine learning*. Springer Science & Business Media, 2011.

- [104] A.C. Cem Say and Abuzer Yakaryılmaz. Quantum finite automata: A modern introduction. In *Computing with New Resources: Essays Dedicated to Jozef Gruska on the Occasion of His 80th Birthday*, pages 208–222. Springer, 2014.
- [105] Erhard Schmidt. Zur theorie der linearen und nichtlinearen integralgleichungen. *Mathematische Annalen*, 63(4):433–476, 1907.
- [106] Burr Settles. Active learning literature survey. 2009.
- [107] Kristie Seymore, Andrew McCallum, Roni Rosenfeld, et al. Learning hidden Markov model structure for information extraction. In *AAAI-99 workshop on machine learning for information extraction*, pages 37–42, 1999.
- [108] Peter W. Shor. Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer. *SIAM review*, 41(2):303–332, 1999.
- [109] Marina Sokolova and Guy Lapalme. A systematic analysis of performance measures for classification tasks. *Information processing & management*, 45(4):427–437, 2009.
- [110] Ray J. Solomonoff. A formal theory of inductive inference. part i. *Information and control*, 7(1):1–22, 1964.
- [111] Bernhard Steffen, Falk Howar, and Malte Isberner. Active automata learning: from dfas to interface programs and beyond. In *International Conference on Grammatical Inference*, pages 195–209. PMLR, 2012.
- [112] Bernhard Steffen, Falk Howar, and Maik Merten. Introduction to active automata learning from a practical perspective. Formal Methods for Eternal Networked Software Systems: 11th International School on Formal Methods for the Design of Computer, Communication and Software Systems, SFM 2011, Bertinoro, Italy, June 13-18, 2011. Advanced Lectures 11, pages 256–296, 2011.
- [113] Frédéric Tantini, Alain Terlutte, and Fabien Torre. Sequences classification by least general generalisations. In *International Colloquium on Grammatical Inference*, pages 189–202. Springer, 2010.
- [114] Martin Tappler, Bernhard K. Aichernig, Giovanni Bacci, Maria Eichlseder, and Kim G. Larsen. L\*-based learning of Markov decision processes. In *International Symposium on Formal Methods*, pages 651–669. Springer, 2019.
- [115] Franck Thollard, Pierre Dupont, and Colin De La Higuera. Probabilistic dfa inference using kullback-leibler divergence and minimality. 2000.
- [116] Yuling Tian, Tianfeng Feng, Maolin Luo, Shenggen Zheng, and Xiaoqi Zhou. Experimental demonstration of quantum finite automaton. *npj Quantum Information*, 5(1):56, 2019.
- [117] Flemming Topsoe. Some inequalities for information divergence and related measures of discrimination. *IEEE Transactions on information theory*, 46(4):1602–1609, 2000.
- [118] Leslie G. Valiant. A theory of the learnable. *Communications of the ACM*, 27(11):1134–1142, 1984.

- [119] Gerco van Heerdt, Matteo Sammartino, and Alexandra Silva. Calf: categorical automata learning framework. *arXiv preprint arXiv:1704.05676*, 2017.
- [120] Sicco Verwer and Christian A. Hammerschmidt. Flexfringe: a passive automaton learning package. In 2017 IEEE International Conference on Software Maintenance and Evolution (ICSME), pages 638–642. IEEE, 2017.
- [121] E. Vidal, F. Thollard, C. de la Higuera, F. Casacuberta, and R.C. Carrasco. Probabilistic finite state automata-part i. *Pattern Analysis and Machine Intelligence*, 27(7):1013– 1025, 2005.
- [122] R. Michael Wharton. Approximate language identification. *Information and control*, 26(3):236–255, 1974.