

This is a section of [doi:10.7551/mitpress/14723.001.0001](https://doi.org/10.7551/mitpress/14723.001.0001)

Gradient Expectations

Structure, Origins, and Synthesis of Predictive Neural Networks

By: Keith L. Downing

Citation:

Gradient Expectations: Structure, Origins, and Synthesis of Predictive Neural Networks

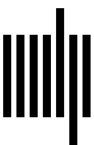
By: Keith L. Downing

DOI: 10.7551/mitpress/14723.001.0001

ISBN (electronic): 9780262374675

Publisher: The MIT Press

Published: 2023



The MIT Press

References

- Abbott, Larry, Kurt Thoroughman, Astrid Prinz, Vatsala Thirumalai, and Eve Marder. 2003. "Activity-Dependent Modification of Intrinsic and Synaptic Conductances in Neurons and Rhythmic Networks." In *Modeling Neural Development*, edited by Arjen van Ooyen, 151–166. Cambridge, MA: MIT Press.
- Ackley, David, Geoffrey Hinton, and Terrence Sejnowski. 1985. "A Learning Algorithm for Boltzmann Machines." *Cognitive Science* 9:147–169.
- Ahmadi, Ahmadreza, and Jun Tani. 2019. "A Novel Predictive-Coding-Inspired Variational RNN Model for Online Prediction and Recognition." *Neural Computation* 31:2025–2074.
- Albus, James. 1971. "A Theory of Cerebellar Function." *Mathematical Biosciences* 10:25–61.
- Allman, John. 1999. *Evolving Brains*. New York: W.H. Freeman / Company.
- Amit, Daniel. 2003. "Cortical Hebbian Modules." In *The Handbook of Brain Theory and Neural Networks*, edited by Michael Arbib, 285–290. Cambridge, MA: MIT Press.
- Andersen, Per, Richard Morris, David Amaral, Tim Bliss, and John O'Keefe. 2007. *The Hippocampus Book*. New York: Oxford University Press.
- Artola, Alain, Susanne Brocher, and Wolf Singer. 1990. "Different Voltage-Dependent Thresholds for Inducing Long-Term Depression and Long-Term Potentiation in Slices of Rat Visual Cortex." *Nature* 347:69–72.
- Attneave, Fred. 1954. "Some Informational Aspects of Visual Perception." *Psychological Review* 61 (3): 183–193.
- Baldominos, Alejandro, Yago Saez, and Pedro Isasi. 2020. "On the Automated, Evolutionary Design of Neural Networks: Past, Present and Future." *Neural Computing and Applications* 32:519–545.
- Ballard, Dana. 2015. *Brain Computation as Hierarchical Abstraction*. Cambridge, MA: MIT Press.
- Banzhaf, Wolfgang, Peter Nordin, Robert E. Keller, and Frank D. Francone. 1998. *Genetic Programming—An Introduction; On the Automatic Evolution of Computer Programs and Its Applications*. Burlington, MA: Morgan Kaufmann.
- Barto, Andrew. 1995. "Adaptive Critics and the Basal Ganglia." In *Models of Information Processing in the Basal Ganglia*, edited by James Houk, Joel Davis, and David Beiser, 215–232. Cambridge, MA: MIT Press.
- Bastos, Andre, Martin Usrey, Rick Adams, George Mangun, Pascal Fries, and Karl Friston. 2012. "Canonical Microcircuits for Predictive Coding." *Neuron* 76:695–711.
- Bear, Mark, Barry Connors, and Michael Paradiso. 2001. *Neuroscience: Exploring the Brain*. 2nd ed. Baltimore, MD: Lippincott Williams / Wilkins.
- Beer, Randall. 2003. "The Dynamics of Active Categorical Perception in an Evolved Model Agent." *Adaptive Behavior* 11 (4): 209–243.
- Beer, Randall, and John Gallagher. 1982. "Evolving Dynamical Neural Networks for Adaptive Behavior." *Adaptive Behavior* 1 (1): 91–122.
- Beer, Randall, and Paul Williams. 2015. "Information Processing and Dynamics in Minimally Cognitive Agents." *Cognitive Science* 39 (2): 1–38.
- Bell, Curtis, David Bodznick, John Montgomery, and J. Bastian. 1997. "The Generation and Subtraction of Sensory Expectations within Cerebellum-Like Structures." *Brain, Behavior and Evolution* 50:17–31.

- Bellmund, Jacob, Peter Gardenfors, Edvard Moser, and Christian Doeller. 2018. "Navigating Cognition: Spatial Codes for Human Thinking." *Science* 362 (July): eaat7666.
- Bergquist, Harry, and Bengt Kallen. 1953. "On the Development of Neuromeres to Migration Areas in the Vertebrate Cerebral Tube." *Acta Anat (Basel)* 18:65–63.
- Bogacz, Rafal. 2017. "A Tutorial on the Free-Energy Framework for Modelling Perception and Learning." *Journal of Mathematical Psychology* 76:198–211.
- Bongard, Josh, and Rolf Pfeifer. 2001. "Repeated Structure and Dissociation of Genotypic and Phenotypic Complexity in Artificial Ontogeny." *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO-2001)* 33:829–836.
- Brockman, Greg, Vicki Cheung, Ludweige Pettersson, Jonas Schneider, John Schulman, Jie Tang, and Wojciech Zaremba. 2016. *Open AI Gym*. arXiv preprint:1606.01540.
- Brooks, Rodney. 1999. *Cambrian Intelligence: The Early History of the New AI*. Cambridge, MA: MIT Press.
- Burgess, Neil, and John O'Keefe. 2003. "Hippocampus: Spatial Models." In *The Handbook of Brain Theory and Neural Networks*, edited by Michael Arbib, 539–543. Cambridge, MA: MIT Press.
- Buzsaki, Gyorgy. 2006. *Rhythms of the Brain*. New York: Oxford University Press.
- Buzsaki, Gyorgy. 2019. *The Brain from Inside Out*. New York: Oxford University Press.
- Carpenter, Gail, and Stephen Grossberg. 2003. "Adaptive Resonance Theory." In *The Handbook of Brain Theory and Neural Networks*, edited by Michael Arbib, 87–90. Cambridge, MA: MIT Press.
- Clark, Andy. 2003. *Natural-Born Cyborgs*. New York: Oxford University Press.
- Clark, Andy. 2016. *Surfing Uncertainty: Prediction, Action and the Embodied Mind*. Oxford: Oxford University Press.
- Dayan, Peter, Geoffrey Hinton, Brendan Frey, and Radford Neal. 1995. "The Helmholtz Machine." *Neural Computation* 7 (5): 889–904.
- Deacon, Terrence. 1998. *The Symbolic Species: The Co-evolution of Language and the Brain*. New York: W.W. Norton.
- Dehaene, Stanislas. 1997. *The Number Sense*. New York: Oxford University Press.
- Dickens, Charles. 1861. *Great Expectations*. London: Chapman / Hall.
- Downing, Keith. 2007a. "Neuroscientific Implications for Situated and Embodied Artificial Intelligence." *Connection Science* 19 (1): 75–104.
- Downing, Keith. 2007b. "Supplementing Evolutionary Developmental Systems with Abstract Models of Neurogenesis." In *GECCO '07: Proceedings of the 2007 Conference on Genetic and Evolutionary Computation*, 990–996. London.
- Downing, Keith. 2009. "Predictive Models in the Brain." *Connection Science* 21 (1): 39–74.
- Downing, Keith. 2015. *Intelligence Emerging: Adaptivity and Search in Evolving Neural Systems*. Cambridge, MA: MIT Press.
- Doya, Kenji. 1999. "What Are the Computations of the Cerebellum, the Basal Ganglia, and the Cerebral Cortex?" *Neural Networks* 12:961–974.
- Dunn, Felice, Martin Lankheet, and Fred Rieke. 2007. "Light Adaptation in Cone Vision Involves Switching between Receptor and Post-Receptor Sites." *Nature* 449:603–606.
- Dusenbery, David. 1992. *Sensory Ecology: How Organisms Acquire and Respond to Information*. New York: W.H. Freeman.
- Edelman, Gerald. 1987. *Neural Darwinism: The Theory of Neuronal Group Selection*. New York: Basic Books.
- Edelman, Gerald. 1992. *Bright Air, Brilliant Fire: On the Matter of the Mind*. New York: Basic Books.
- Edelman, Gerald, and Giulio Tononi. 2000. *A Universe of Consciousness*. New York: Basic Books.
- Fahlan, Scott, and Christian Lebiere. 1997. "The Cascade-Correlation Learning Architecture." *Advances in Neural Information Processing Systems* 2 (October).
- Finlay, Barbara, and Richard Darlington. 1995. "Linked Regularities in the Development and Evolution of Mammalian Brains." *Science* 268:1578–1584.
- Fregnac, Yves. 2003. "Hebbian Synaptic Plasticity." In *The Handbook of Brain Theory and Neural Networks*, edited by Michael Arbib, 515–522. Cambridge, MA: MIT Press.
- Friston, Karl. 2005. "A Theory of Cortical Responses." *Philosophical Transactions of the Royal Society B* 360: 815–836.

- Friston, Karl. 2010. "A Free Energy Principle: A Unified Brain Theory?" *Nature Reviews Neuroscience* 11: 127–138.
- Friston, Karl, James Kilner, and Lee Harrison. 2006. "A Free Energy Principle for the Brain." *Journal of Physiology—Paris* 100:70–87.
- Fujita, M. 1982. "Adaptive Filter Model of the Cerebellum." *Biological Cybernetics* 45:195–206.
- Fukushima, Kunihiko, and Sei Miyake. 1982. "Neocognitron: A New Algorithm for Pattern Recognition Tolerant of Deformations and Shifts in Position." *Pattern Recognition* 15:455–469.
- Fuster, Joaquin. 2003. *Cortex and Mind: Unifying Cognition*. Oxford: Oxford University Press.
- Gärdenfors, Peter. 2000. *Conceptual Spaces: The Geometry of Thought*. Cambridge, MA: MIT Press.
- Glorot, Xavier, Antoine Bordes, and Yoshua Bengio. 2011. "Deep Sparse Rectifier Neural Networks." In *Proceedings 14th International Conference on Artificial Intelligence and Statistics*, 315–323. <https://proceedings.mlr.press/v15/glorot11a/glorot11a.pdf>.
- Goodfellow, Ian, Yoshua Bengio, and Aaron Courville. 2016. *Deep Learning*. Cambridge, MA: MIT Press.
- Gould, Stephen Jay. 1970. *Ontogeny and Phylogeny*. Cambridge, MA: Belknap Press of Harvard University Press.
- Graybiel, Ann M., and Esen Saka. 2004. "The Basal Ganglia and the Control of Action." In *The Cognitive Neurosciences III*, edited by Michael S. Gazzaniga, 495–510. Cambridge, MA: MIT Press.
- Grossberg, Stephen. 1969. "On Learning and Energy-Entropy Dependence in Recurrent and Nonrecurrent Signed Networks." *Journal of Statistical Physics* 1 (July): 319–350.
- Hafting, Torkel, Marianne Fyhn, Sturla Molden, May-Britt Moser, and Edvard Moser. 2005. "Microstructure of a Spatial Map in the Entorhinal Cortex." *Nature* 436:801–806.
- Harding, Simon, Julian Miller, and Wolfgang Banzhaf. 2009. "Evolution, Development and Learning Using Self-Modifying Cartesian Genetic Programming." In *Proceedings of the 11th Genetic and Evolutionary Computation Conference*, edited by Dirk Thierens et al., 699–706. Montreal, ACM.
- Hasselmo, Michael, Bradley Wyble, and Erik Fransen. 2003. "Neuromodulation in Mammalian Nervous Systems." In *The Handbook of Brain Theory and Neural Networks*, edited by Michael Arbib, 761–765. Cambridge, MA: MIT Press.
- Hawkins, Jeff. 2004. *On Intelligence*. New York: Henry Holt.
- Hawkins, Jeff. 2021. *A Thousand Brains: A New Theory of Intelligence*. New York: Basic Books.
- Hawkins, Jeff, and Subal Ahmad. 2016. "Why Neurons Have Thousands of Synapses, a Theory of Sequence Memory in Neocortex." *Frontiers in Neural Circuits* 10 (March): 1–18.
- Hawkins, Jeff, Subal Ahmad, and Yuwei Cui. 2017. "A Theory of How Columns in the Neocortex Enable Learning the Structure of the World." *Frontiers in Neural Circuits* 11 (October): 1–13.
- Hayes, Patrick. 1979. "The Naive Physics Manifesto." In *Expert Systems in the Micro-Electronic Age*, edited by Donald Michie, 761–765. Edinburgh: Edinburgh University Press.
- Hebb, Donald. 1949. *The Organization of Behavior*. New York: John Wiley / Sons.
- Hiesinger, Peter. 2021. *The Self-Assembling Brain: How Neural Networks Grow Smarter*. Princeton, NJ: Princeton University Press.
- Hinton, Geoffrey. 2002. "Training Products of Experts by Minimizing Contrastive Divergence." *Neural Computation* 15 (8): 1771–1800.
- Hinton, Geoffrey, Peter Dayan, Brendan Frey, and Radford Neal. 1995. "The Wake-Sleep Algorithm for Unsupervised Neural Networks." *Science* 268 (5214): 1158–1161.
- Hinton, Geoffrey, and R. Salakhutdinov. 2006. "Reducing the Dimensionality of Data with Neural Networks." *Science* 313 (5214): 504–507.
- Hochreiter, Sepp, and Jurgen Schmidhuber. 1997. "Long Short-Term Memory." *Neural Computation* 9 (8): 1735–1780.
- Holland, John H. 1992. *Adaptation in Natural and Artificial Systems*. 2nd ed. Cambridge, MA: MIT Press.
- Hopfield, John. 1982. "Neural Networks and Physical Systems with Emergent Collective Computational Abilities." *Proceedings of the National Academy of Sciences* 79:2554–2558.
- Hopfield, John. 1984. "Neurons with Graded Response Properties Have Collective Computational Properties Like Those of Two-State Neurons." *Proceedings of the National Academy of Sciences* 81:3088–3092.
- Hosoya, Toshihiko, Stephen Baccus, and Markus Meister. 2005. "Dynamic Predictive Coding by the Retina." *Nature* 436:71–77.

- Houk, James, James Adams, and Andrew Barto. 1995. "A Model of How the Basal Ganglia Generate and Use Neural Signals That Predict Reinforcement." In *Models of Information Processing in the Basal Ganglia*, edited by James Houk, Joel Davis, and David Beiser, 249–270. Cambridge, MA: MIT Press.
- Houk, James, Joel Davis, and David Beiser. 1995. *Models of Information Processing in the Basal Ganglia*. Cambridge, MA: MIT Press.
- Izquierdo, Eduardo, and Randall Beer. 2013. "Connecting a Connectome to Behavior: An Ensemble of Neuroanatomical Models of *C. elegans* Klinotaxis." *PLoS Computational Biology* 9 (2): e1002890.
- Kabadayi, Can, and Mathias Osvath. 2017. "Ravens Parallel Great Apes in Flexible Planning for Tool-Use and Bartering." *Science* 357 (July): 202–204.
- Kandel, Eric, James Schwartz, and Thomas Jessell. 2000. *Principles of Neural Science*. New York: McGraw-Hill.
- Kirschner, Marc W., and John C. Gerhart. 2005. *The Plausibility of Life: Resolving Darwin's Dilemma*. New Haven, CT: Yale University Press.
- Kok, Peter, and Floris de Lange. 2015. "Predictive Coding in Sensory Cortex." In *An Introduction to Model-Based Cognitive Neuroscience*, edited by Birte Forstmann and Eric-Jan Wagenmakers, 221–244. New York: Springer.
- Koza, John R. 1992. *Genetic Programming: On the Programming of Computers by Natural Selection*. Cambridge, MA: MIT Press.
- Koza, John R., David Andre, Forrest H. Bennett III, and Martin Keane. 1999. *Genetic Programming 3: Darwinian Invention and Problem Solving*. Burlington, MA: Morgan Kaufman.
- Krizhevsky, Alex. 2009. "Learning Multiple Layers of Features from Tiny Images." *Google Labs Tech Report*. www.cs.toronto.edu/~kriz/learning-features-2009-TR.pdf.
- Kropff, Emilio, James Carmichael, May-Britt Moser, and Edvard Moser. 2015. "Speed Cells in the Medial Entorhinal Cortex." *Nature* 523 (July): 419–442.
- Kuhn, Thomas. 1970. *The Structure of Scientific Revolutions*. Chicago, IL: University of Chicago Press.
- Kurzweil, Ray. 2005. *The Singularity Is Near*. New York: Viking Press.
- Kurzweil, Ray. 2012. *How to Create a Mind: The Secret of Human Thought Revealed*. New York: Viking Press.
- Lake, Brenden, Ruslan Salakhutdinov, and Joshua Tenenbaum. 2015. "Human-Level Concept Learning through Probabilistic Program Induction." *Science* 350 (6266): 1332–1338.
- Lakoff, George, and Mark Johnson. 1980. *Metaphors We Live By*. Chicago, IL: University of Chicago Press.
- Lakoff, George, and Rafael Nunez. 2000. *Where Mathematics Comes From*. New York: Basic Books.
- Langton, Christopher. 1989. "Artificial Life." In *Artificial Life: Proceedings of an Interdisciplinary Workshop on the Synthesis and Simulation of Living Systems*, edited by C. Langton, 1–49. Reading, MA: Addison-Wesley.
- Larsch, Johannes, Steven Flavell, Qiang Liu, Andrew Gordus, Dirk Albrecht, and Cornelia Bargmann. 2015. "A Circuit for Gradient Climbing in *C. elegans* Chemotaxis." *Cell Reports* 12 (11): 1748–1760.
- Larson, Erik. 2021. *The Myth of Artificial Intelligence: Why Computers Can't Think the Way We Do*. Cambridge, MA: Belknap Press of Harvard University Press.
- LeCun, Yann, Yoshua Bengio, and Geoffrey Hinton. 2015. "Deep Learning." *Nature* 521:436–444.
- LeCun, Yann, Bernhard Boser, John Denker, Donnie Henderson, R. Howard, Wayne Hubbard, and Lawrence Jackel. 1990. "Handwritten Digit Recognition with a Back-Propagation Network." In *Advances in Neural Information Processing Systems*, 396–404. Burlington, MA: Morgan Kaufmann.
- LeDoux, Joseph. 2002. *Synaptic Self: How Our Brains Become Who We Are*. Middlesex, UK: Penguin Books.
- Levine, Steve. 2017. "Artificial Intelligence Pioneer Says We Need to Start Over." *Axios* (September).
- Levit, Mikhail, and Jeffrey Stock. 2002. "Receptor Methylation Controls the Magnitude of Stimulus-Response Coupling in Bacterial Chemotaxis." *Journal of Biological Chemistry* 277 (29): 36760–36765.
- Lillicrap, Timothy, Adam Santoro, Luke Marris, Colin Akermann, and Geoffrey Hinton. 2020. "Backpropagation and the Brain." *Nature Reviews Neuroscience* 21 (June): 335–346.
- Lisman, John, and Anthony Grace. 2005. "The Hippocampal-VTA Loop: Controlling the Entry of Information into Long-Term Memory." *Neuron* 46:703–713.
- Linas, Rudolfo. 2001. *i of the Vortex*. Cambridge, MA: MIT Press.
- Mackay, David. 2003. *Information Theory, Inference, and Learning Algorithms*. New York: Cambridge University Press.
- Mackie, George. 1970. "Neuroid Conduction and the Evolution of Conducting Tissues." *Quarterly Review of Biology* 45:319–332.

- Marcus, Mitchell, Mary Ann Marcinkiewicz, and Beatrice Santorini. 1993. "Building a Large Annotated Corpus of English: The Penn Treebank." *Computational Linguistics* 19 (2): 313–330.
- Marr, David. 1969. "A Theory of Cerebellar Cortex." *Journal of Physiology* 202:437–470.
- Marr, David. 1982. *Vision: A Computational Investigation into the Human Representation and Processing of Visual Information*. New York: Henry Holt.
- Matsumoto, Takazumi, and Jun Tani. 2020. "Goal-Directed Planning for Habituated Agents by Active Inference Using a Variational Recurrent Neural Network." *Entropy* 22 (564): e22050564.
- McNaughton, Bruce, Francesco Battaglia, Ole Jensen, Edvard Moser, and May-Britt Moser. 2006. "Path Integration and the Neural Basis of the 'Cognitive Map.'" *Nature Reviews Neuroscience* 7 (8): 663–678.
- Mehta, Mayank. 2001. "Neuronal Dynamics of Predictive Coding." *Neuroscientist* 7 (6): 490–495.
- Miikkulainen, Risto, Jason Zhi Liang, Elliot Meyerson, Aditya Rawal, Daniel Fink, Olivier Francon, Bala Raju, et al. 2017. "Evolving Deep Neural Networks." *CoRR* abs/1703.00548. arXiv: 1703.00548.
- Miller, Julian. 2021. "DEMANDED: Designing Multiple ANNs via Evolved Developmental Neurons." *Artificial Life* 1 (1): 1–41.
- Miller, Julian, and Wolfgang Banzhaf. 2003. "Evolving the Program for a Cell: From French Flags to Boolean Circuits." In *On Growth, Form and Computers*, edited by Sanjay Kumar and Peter Bentley, 278–301. Amsterdam: Elsevier Press.
- Mitchell, Melanie. 2019. *Artificial Intelligence: A Guide for Thinking Humans*. London: Penguin Books.
- Mitchell, Melanie, and Richard Belew. 1996. "Preface to Chapter 25." In *Adaptive Individuals in Evolving Populations: Models and Algorithms*, edited by Richard Belew and Melanie Mitchell, 443–445. Reading, MA: Addison-Wesley.
- Mnih, Volodymyr, Koray Kavukcuoglu, David Silver, Andrei Rosu, Joel Veness, Marc Bellemare, Alex Graves, Martin Riedmiller, Andreas Fiedjeland, and Georg Ostrovski. 2015. "Human-Level Control through Deep Reinforcement Learning." *Nature* 518 (7540): 529–533.
- Moriarty, David, and Risto Miikkulainen. 1997. "Forming Neural Networks through Efficient and Adaptive Coevolution." *Evolutionary Computation* 5 (4): 373–399.
- Moser, Edvard, Yasser Roudi, Menno Witter, Clifford Kentros, Tobias Bonhoeffer, and May-Britt Moser. 2014. "Grid Cells and Cortical Representation." *Nature Reviews Neuroscience* 15 (July): 466–481.
- Mountcastle, Vernon. 1998. *Perceptual Neuroscience: The Cerebral Cortex*. Cambridge, MA: Harvard University Press.
- Mumford, David. 1992. "On the Computational Architecture of the Neocortex." *Biological Cybernetics* 66:241–251.
- Nakajima, K., Marc Maier, Peter Kirkwood, and Roger Lemon. 2000. "Striking Differences in Transmission of Coricospinal Excitation to Upper Limb Motoneurons in Two Primate Species." *Journal of Neurophysiology* 84:698–709.
- Newell, Allen, and Herbert Simon. 1972. *Human Problem Solving*. Englewood Cliffs, NJ: Prentice Hall.
- Nilsson, Nils. 1980. *Principles of Artificial Intelligence*. Palo Alto, CA: Tioga Publishers.
- Nolfi, Stefano, and Dario Floreano. 2000. *Evolutionary Robotics: The Biology, Intelligence, and Technology of Self-Organizing Machines*. Cambridge, MA: MIT Press.
- O'Keefe, John, and Jonathan Dostrovsky. 1971. "The Hippocampus as a Spatial Map: Preliminary Evidence from Unit Activity in the Freely-Moving Rat." *Journal of Brain Research* 34:171–175.
- Oliver, Bernard. 1952. "Efficient Coding." *Bell Systems Technical Journal* 31:724–750.
- Ooyen, Arjen van, Jaap van Pelt, Michael Corner, and Stanley Kater. 2003. "Activity-Dependent Neurite Outgrowth: Implications for Network Development and Neuronal Morphology." In *Modeling Neural Development*, edited by Arjen van Ooyen, 111–132. Cambridge, MA: MIT Press.
- O'Reilly, Randall, and Yuko Munakata. 2000. *Computational Explorations in Cognitive Neuroscience*. Cambridge, MA: MIT Press.
- Ouden, Hanneke den, Peter Kok, and Floris de Lange. 2012. "How Prediction Errors Shape Perception, Attention, and Motivation." *Frontiers in Psychology* 3 (548): 1–12.
- Patton, Lydia. 2018. "Hermann von Helmholtz." In *The Stanford Encyclopedia of Philosophy*, Winter 2018, edited by Edward N. Zalta. Stanford, CA: Metaphysics Research Lab, Stanford University.
- Petanjek, Zdravko, Milos Judas, Goran Simic, Mladen Rasin, Harry Uylings, Pasko Rakic, and Ivica Kostovic. 2011. "Extraordinary Neoteny of Synaptic Spines in the Human Prefrontal Cortex." *Proceedings of the National Academy of Sciences (PNAS)* 108 (32): 13181–13286.

- Phattanasri, Phattanard, Hillel Chiel, and Randall Beer. 2007. "The Dynamics of Associative Learning in Evolved Model Circuits." *Adaptive Behavior* 15 (4): 377–396.
- Porri, John, and Paul Dean. 2016. "Cerebellar Adaptation and Supervised Learning in Motor Control." In *From Neuron to Cognition via Computational Neuroscience*, edited by Michael Arbib and James Bonaiuto, 617–647. Cambridge, MA: MIT Press.
- Prescott, Tony, Kevin Gurney, and Peter Redgrave. 2003. "Basal Ganglia." In *The Handbook of Brain Theory and Neural Networks*, edited by Michael Arbib, 147–151. Cambridge, MA: MIT Press.
- Puelles, Luis, and John Rubenstein. 1993. "Expression Patterns of Homeobox and Other Putative Regulatory Genes in the Embryonic Mouse Forebrain Suggest a Neuromeric Organization." *Trends in Neuroscience* 16: 472–479.
- Quartz, Steven, and Terrence Sejnowski. 1997. "The Neural Basis of Cognitive Development: A Constructivist Manifesto." *Behavioral and Brain Sciences* (20): 537–596.
- Queisser, Jeffrey, Minju Jung, Takazumi Matsumoto, and Jun Tani. 2021. "Emergence of Content-Agnostic Information Processing by a Robot Using Active Inference, Visual Attention, Working Memory and Planning." *Neural Computation* 33:2353–2407.
- Rakic, Pasko. 2008. "Confusing Cortical Columns." *Proceedings of the National Academy of Sciences (PNAS)* 105 (34): 12099–12100.
- Rao, Rajesh, and Dana Ballard. 1999. "Predictive Coding in the Visual Cortex: A Functional Interpretation of Some Extra-Classical Receptive-Field Effects." *Nature* 2 (1): 79–87.
- Raut, Ryan, Abraham Snyder, and Marcus Raichle. 2020. "Hierarchical Dynamics as a Macroscopic Organizing Principle of the Human Brain." *Proceedings of the National Academy of Sciences (PNAS)* 117:20890–20897.
- Real, Esteban, Chen Liang, David So, and Quoc Le. 2020. "AutoML-Zero: Evolving Machine Learning Algorithms from Scratch." *Proceedings of the 37th International Conference on Machine Learning (ICML)*. Vienna, Austria: PMLR.
- Rodriguez, A., James Whitson, and Richard Granger. 2004. "Derivation and Analysis of Basic Computational Operations of Thalamic Cortical Circuits." *Journal of Cognitive Neuroscience* 16 (5): 856–877.
- Rolls, Edmund, and Alessandro Treves. 1998. *Neural Networks and Brain Function*. New York: Oxford University Press.
- Rumelhart, David, Geoffrey Hinton, and Ronald Williams. 1986. "Learning Internal Representations by Error Propagation." In *Parallel Distributed Processing: Explorations in the Microstructure of Cognition*, edited by David Rumelhart and James McClelland, 318–362. Cambridge, MA: MIT Press.
- Salimans, Tim, Jonathan Ho, Xi Chen, Szymon Sidor, and Ilya Sutskever. 2017. "Evolution Strategies as a Scalable Alternative to Reinforcement Learning." *Open AI Lab Tech Report* (March). <https://arxiv.org/pdf/1703.03864.pdf>.
- Sanes, Dan, Thomas Reh, and William Harris. 2006. *Development of the Nervous System*. Burlington, MA: Elsevier Academic Press.
- Schneider, Gerald. 2014. *Brain Structure and Its Origins*. Cambridge, MA: MIT Press.
- Schultz, Wolfram, Paul Apicella, Eugenio Scarnati, and Tomas Ljungberg. 1992. "Neural Activity in Monkey Ventral Striatum Related to the Expectation of Reward." *Journal of Neuroscience* 12 (12): 4595–4610.
- Shatner, William. 2013. *Star Trek Convention—Saturday Night Live*. <https://www.youtube.com/watch?v=Rqb4V9GxaBo>.
- Shipp, Steward, Rick Adams, and Karl Friston. 2013. "Reflections on Agranular Architecture: Predictive Coding in the Motor Cortex." *Trends in Neuroscience*: 1–11. doi:10.1016/j.tins.2013.09.004.
- Silver, David, Aja Huang, Chris Maddison, Arthur Guez, Laurent Sifre, George van den Driessche, Julian Schrittwieser, et al. 2016. "Mastering the Game of Go with Deep Neural Networks and Tree Search." *Nature* 529 (January): 484–503.
- Silver, David, Thomas Hubert, Julian Schrittwieser, Ioannis Antonoglou, Matthew Lai, Arthur Guez, Marc Lanctot, et al. 2018. "A General Reinforcement Learning Algorithm That Masters Chess, Shogi and Go through Self-Play." *Science* 362 (6419): 1140–1144.
- Silver, David, Julian Schrittwieser, Karen Simonyan, Ioannis Antonoglou, Aja Huang, Arthur Guez, Thomas Hubert, et al. 2017. "Mastering the Game of Go without Human Knowledge." *Nature* 550 (October): 354–371.
- Sims, Karl. 1994. "Evolving 3D Morphology and Behavior by Competition." In *Artificial Life IV*, edited by R. Brooks and P. Maes, 28–39. Cambridge, MA: MIT Press.
- Slocum, Andrew, Douglas Downey, and Randall Beer. 2000. "Further Experiments in the Evolution of Minimally-Cognitive Behavior: From Perceiving Affordances to Selective Attention." In *From Animals to Animats 6*:

- Proceedings of the Sixth International Conference on Simulation of Adaptive Behavior*, edited by J. Meyer, A. Berthoz, D. Floreano, H. Roitblat, and S. Wilson, 430–439. Cambridge, MA: MIT Press.
- Smolensky, Paul. 1986. “Information Processing in Dynamical Systems: Foundations of Harmony Theory.” In *Parallel Distributed Processing: Explorations in the Microstructure of Cognition*, edited by David Rumelhart and James McClelland, 194–263. Cambridge, MA: MIT Press.
- Soltoggio, Andrea, John Bullinaria, Claudio Mattiussi, Peter Durr, and Dario Floreano. 2008. “Evolutionary Advantages of Neuromodulated Plasticity in Dynamic, Reward-based Scenarios.” In *Artificial Life XI*, edited by S. Bollock, J. Noble, R. Watson, and M. Bedau, 569–576. Cambridge, MA: MIT Press.
- Soltoggio, Andrea, Kenneth Stanley, and Sebastian Risi. 2018. “Born to Learn: The Inspiration, Progress, and Future of Evolved Plastic Artificial Neural Networks.” *Neural Networks* 1:48–67.
- Song, Sen, Kenneth Miller, and Larry Abbott. 2000. “Competitive Hebbian Learning through Spike-Timing-Dependent Synaptic Plasticity.” *Nature Neuroscience* 3 (9): 919–926.
- Song, Yuhang, Thomas Lukasiewicz, Zhenghua Xu, and Rafal Bogacz. 2020. “Can the Brain Do Backpropagation? Exact Implementation of Backpropagation in Predictive Coding Networks.” *Advances in Neural Information Processing Systems* 33:22566–22579.
- Spratling, Michael. 2008. “Reconciling Predictive Coding and Biased Competition Models of Cortical Function.” *Frontiers in Computational Neuroscience* 2 (4): 1–8.
- Spratling, Michael. 2017. “A Review of Predictive Coding Algorithms.” *Brain and Cognition* 112 (March): 92–97.
- Spratling, Michael. 2019. “Fitting Predictive Coding to the Neurophysiological Data.” *Brain Research* (October): 1–12.
- Squire, Larry, and Stuart Zola. 1996. “Structure and Function of Declarative and Nondeclarative Memory Systems.” *Genetic Programming and Evolvable Machines* 93:13515–13522.
- Srinivasan, Mandyam, Simon Laughlin, and A. Dubs. 1982. “Predictive Coding: A Fresh View of Inhibition in the Retina.” *Proceedings of the Royal Society of London B* 216:427–459.
- Stanley, Kenneth. 2007. “Compositional Pattern Producing Networks: A Novel Abstraction of Development.” *Genetic Programming and Evolvable Machines: Special Issue on Developmental Systems* 8 (2): 131–162.
- Stanley, Kenneth, Jeff Clune, Jeff Lehman, and Risto Miikkulainen. 2019. “Designing Neural Networks through Neuroevolution.” *Nature Machine Intelligence* 1:24–35.
- Stanley, Kenneth, and Risto Miikkulainen. 2002. “Evolving Neural Networks through Augmenting Topologies.” *Evolutionary Computation* 10 (2): 99–127.
- Stanley, Kenneth, and Risto Miikkulainen. 2003. “A Taxonomy for Artificial Embryogeny.” *Artificial Life* 9 (2): 93–130.
- Steels, Luc. 2003. “Intelligence with Representation.” *Philosophical Transactions: Mathematical, Physical and Engineering Sciences* 361 (1811): 2381–2395.
- Sterling, Peter, and Simon Laughlin. 2015. *Principles of Neural Design*. Cambridge, MA: MIT Press.
- Stone, James. 2018. *Principles of Neural Information Theory*. Sheffield, UK: Sebtel Press.
- Stone, James. 2020. *Artificial Intelligence Engines*. Sheffield, UK: Sebtel Press.
- Striedter, Georg. 2005. *Principles of Brain Evolution*. Sunderland, MA: Sinauer Associates.
- Sutton, Richard S., and Andrew G. Barto. 1998. *Reinforcement Learning: An Introduction*. Cambridge, MA: MIT Press.
- Sutton, Richard S., and Andrew G. Barto. 2018. *Reinforcement Learning: An Introduction*. Cambridge, MA: MIT Press.
- Tani, Jun. 2014. “Self-Organization and Compositionality in Cognitive Brains: A Neurorobotics Study.” *Proceedings of the IEEE* 102 (4): 586–605.
- Tani, Jun. 2017. *Exploring Robotic Minds*. New York: Oxford University Press.
- Thomson, Alex, and Peter Bannister. 2003. “Interlaminar Connections in the Neocortex.” *Cerebral Cortex* 13 (1): 5–14.
- Thompson, D’Arcy. 1992. *On Growth and Form*. Mineola, NY: Cambridge University Press.
- Tripp, Bryan, and Chris Eliasmith. 2010. “Population Models of Temporal Differentiation.” *Neural Computation* 22 (3): 621–659.
- Wallenstein, Gene, Howard Eichenbaum, and Michael Hasselmo. 1998. “The Hippocampus as an Associator of Discontiguous Events.” *Trends in Neuroscience* 21 (8): 317–323.

- Werbos, Paul. 1990. "Backpropagation through Time: What It Does and How to Do It." *Proceedings of the IEEE* 78 (10): 1550–1560.
- Whittington, James, and Rafal Bogacz. 2017. "An Approximation of the Error Backpropagation Algorithm in a Predictive Coding Network with Local Hebbian Synaptic Plasticity." *Neural Computation* 29:1229–1262.
- Whittington, James, and Rafal Bogacz. 2019. "Theories of Error Back-Propagation in the Brain." *Trends in Cognitive Sciences* 23 (3): 235–250.
- Wierstra, Daan, Tom Schaul, Tobias Glasmachers, Yi Sun, Jan Peters, and Jürgen Schmidhuber. 2014. "Natural Evolution Strategies." *Journal of Machine Learning Research* 15:949–980.
- Wolpert, Daniel, R. Miall, and Mitsuo Kawato. 1998. "Internal Models in the Cerebellum." *Trends in Cognitive Sciences* 2 (9): 338–347.
- Yamashita, Yuichi, and Jun Tani. 1996. "Emergence of a Functional Hierarchy in a Multiple Timescale Neural Network Model: A Humanoid Robot Experiment." *PLoS Computational Biology* 4 (11): e37843.
- Yao, Xin. 1999. "Evolving Artificial Neural Networks." *Proceedings of the IEEE* 87 (9): 1423–1447.
- Yuille, Alan, and Daniel Kersten. 2006. "Vision as Bayesian Inference: Analysis by Synthesis?" *Trends in Cognitive Science* 10 (7): 301–308.

© 2023 Keith L. Downing

This work is subject to a Creative Commons CC-BY-NC-ND license. Subject to such license, all rights are reserved.



The MIT Press would like to thank the anonymous peer reviewers who provided comments on drafts of this book. The generous work of academic experts is essential for establishing the authority and quality of our publications. We acknowledge with gratitude the contributions of these otherwise uncredited readers.

This book was set in Times New Roman by Westchester Publishing Services.

Library of Congress Cataloging-in-Publication Data

Names: Downing, Keith L., author.

Title: Gradient expectations : structure, origins, and synthesis of predictive neural networks / Keith L. Downing.

Description: [Cambridge, Massachusetts] : The MIT Press, [2023] | Includes bibliographical references and index.

Identifiers: LCCN 2022037237 (print) | LCCN 2022037238 (ebook) |

ISBN 9780262545617 (paperback) | ISBN 9780262374682 (epub) |

ISBN 9780262374675 (pdf)

Subjects: LCSH: Deep learning (Machine learning) | Neural networks (Computer science) | Conjugate gradient methods.

Classification: LCC Q325.73 .D88 2023 (print) | LCC Q325.73 (ebook) |

DDC 006.3/2—dc23/eng20230302

LC record available at <https://lcn.loc.gov/2022037237>

LC ebook record available at <https://lcn.loc.gov/2022037238>