References

Abraham, R., & Marsden, J. E. (1978). *Foundations of mechanics*. San Francisco: Benjamin Cummings.

Abraham, R., & Shaw, C. D. (1985). *Dynamics-the geometry of behavior*. Santa Cruz, CA: Aerial Press.

Aihara, K., Matsumoto, G., & Ichikawa, M. (1985). An alternating periodic-chaotic sequence observed in neural oscillators. *Physics Letters A*, *111*(5), 251–255.

Allesina, S., & Pascual, M. (2009). Googling food webs: Can an eigenvector measure species' importance for coextinctions? *PLoS Computational Biology*, *5*(9), e1000494.

Anderson, R. M., May, R. M., & Anderson, B. (1992). *Infectious diseases of humans: Dynamics and control*. Oxford, UK: Oxford University Press.

Beuter, A., Titcombe, M., Richer, F., Gross, C., & Guehl, D. (2001). Effect of deep brain stimulation on amplitude and frequency characteristics of rest tremor in Parkinson's disease. *Thalamus and Related Systems*, *1*(3), 203–211.

Bodine, E. N., Lenhart, S., & Gross, L. J. (2014). *Mathematics for the life sciences*. Princeton, NJ: Princeton University Press.

Boiteux, A., Goldbeter, A., & Hess, B. (1975). Control of oscillating glycolysis of yeast by stochastic, periodic, and steady source of substrate: a model and experimental study. *Proceedings of the National Academy of Sciences*, *72*(10), 3829–3833.

Brin, S., & Page, L. (1998). The anatomy of a large-scale hypertextual web search engine. *Computer Networks and ISDN systems*, *30*(1), 107–117.

Chou, H., Berman, N., & Ipp, E. (1992). Oscillations of lactate released from islets of Langerhans: evidence for oscillatory glycolysis in beta-cells. *American Journal of Physiology-Endocrinology and Metabolism*, *262*(6), E800–E805.

Crouse, D. T., Crowder, L. B., & Caswell, H. (1987). A stage-based population model for loggerhead sea turtles and implications for conservation. *Ecology*, *68*(5), 1412–1423.

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Crutchfield, J., Farmer, J. D., Packard, N., & Shaw, R. (1986). Chaos. *Scientific American*, *254*(12), 46–57.

Farkas, I., Helbing, D., & Vicsek, T. (2002). Social behaviour: Mexican waves in an excitable medium. *Nature*, *419*(6903), 131–132.

Fath, B. D., & Patten, B. C. (1999). Review of the foundations of network environ analysis. *Ecosystems*, *2*(2), 167–179.

Gardner, T. S., Cantor, C. R., & Collins, J. J. (2000). Construction of a genetic toggle switch in Escherichia coli. *Nature*, *403*(6767), 339–342.

Garfinkel, A. (1981). *Forms of explanation: Rethinking the questions in social theory*. New Haven, CT: Yale University Press.

Garfinkel, A. (1983). A mathematics for physiology. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *245*(4), R455–R466.

Garfinkel, A., Spano, M., Ditto, W., & Weiss, J. N. (1992). Controlling cardiac chaos. *Science*, *257*, 1230–1235.

Ghosh, A., & Chance, B. (1964). Oscillations of glycolytic intermediates in yeast cells. *Biochemical and biophysical research communications*, *16*(2), 174–181.

Gragnani, A., Rinaldi, S., & Feichtinger, G. (1997). Cyclic dynamics in romantic relationships. *International Journal of Bifurcation and Chaos*, *7*(11), 2611–2619.

Grier, D. A. (2013). *When computers were human*. Princeton, NJ: Princeton University Press.

Hannon, B. (1973). The structure of ecosystems. *Journal of Theoretical Biology*, *41*(3), 535–546.

Hastings, A., Hom, C. L., Ellner, S., Turchin, P., & Godfray, H. C. J. (1993). Chaos in ecology: Is mother nature a strange attractor? *Annual Review of Ecology and Systematics*, *24*(1), 1–33.

Hastings, A., & Powell, T. (1991). Chaos in a three-species food chain. *Ecology*, *72*(3), 896–903.

Hayashi, H., Ishizuka, S., Ohta, M., & Hirakawa, K. (1982). Chaotic behavior in the onchidium giant neuron under sinusoidal stimulation. *Physics Letters A*, *88*(8), 435–438.

Hilborn, R. C. (2000). *Chaos and nonlinear dynamics: An introduction for scientists and engineers*. Oxford, UK: Oxford University Press.

Hirata, H., Yoshiura, S., Ohtsuka, T., Bessho, Y., Harada, T., Yoshikawa, K., et al. (2002). Oscillatory expression of the bHLH factor Hes1 regulated by a negative feedback loop. *Science*, *298*(5594), 840–843.

Hirsch, M. W., Smale, S., & Devaney, R. L. (2012). *Differential equations, dynamical systems, and an introduction to chaos*. Cambridge, MA: Academic Press.

Hodgkin, A. L., & Huxley, A. F. (1939). Action potentials recorded from inside a nerve fibre. *Nature*, *144*(3651), 710–711.

Hodgkin, A. L., & Huxley, A. F. (1952). A quantitative description of membrane current and its application to conduction and excitation in nerve. *The Journal of Physiology*, *117*(4), 500.

Holdaway, R. N., & Jacomb, C. (2000). Rapid extinction of the moas (aves: Dinornithiformes): model, test, and implications. *Science*, *287*(5461), 2250–2254.

Ingalls, B. (2013). *Mathematical modeling in systems biology: An introduction*. Cambridge, MA: MIT Press.

Izhikevich, E. M. (2007). *Dynamical systems in neuroscience*. Cambridge, MA: MIT Press.

Keener, J. P., & Sneyd, J. (2009). *Mathematical physiology*. New York: Springer.

Lahav, G., Rosenfeld, N., Sigal, A., Geva-Zatorsky, N., Levine, A. J., Elowitz, M. B., et al. (2004). Dynamics of the p53-Mdm2 feedback loop in individual cells. *Nature Genetics*, *36*(2), 147–150.

Laugesen, J., & Mosekilde, E. (2006). Border-collision bifurcations in a dynamic management game. *Computers and Operations Research*, *33*(2), 464–478.

Licinio, J., Negrão, A. B., Mantzoros, C., Kaklamani, V., Wong, M.-L., Bongiorno, P. B., et al. (1998). Synchronicity of frequently sampled, 24-h concentrations of circulating leptin, luteinizing hormone, and estradiol in healthy women. *Proceedings of the National Academy of Sciences*, *95*(5), 2541–2546.

Luciani, D. S., Misler, S., & Polonsky, K. S. (2006). Ca2+ controls slow nad (p) h oscillations in glucose-stimulated mouse pancreatic islets. *The Journal of physiology*, *572*(2), 379–392.

Luo, C.-H., & Rudy, Y. (1991). A model of the ventricular cardiac action potential. depolarization, repolarization, and their interaction. *Circulation Research*, *68*(6), 1501–1526.

Lux, T. (1995). Herd behaviour, bubbles and crashes. *The Economic Journal*, *105*(431), 881–896.

Mackey, M. C., & Glass, L. (1977). Oscillation and chaos in physiological control systems. *Science*, *197*(4300), 287–289.

Martien, P., Pope, S., Scott, P., & Shaw, R. (1985). The chaotic behavior of the leaky faucet. *Physics Letters A*, *110*(7), 399–404.

Martin, C. H., & Wainwright, P. C. (2013). Multiple fitness peaks on the adaptive landscape drive adaptive radiation in the wild. *Science*, *339*(6116), 208–211.

May, R. M. (1976). Simple mathematical models with very complicated dynamics. *Nature*, *261*(5560), 459–467.

McLean, A. R., Emery, V. C., Webster, A., & Griffiths, P. D. (1991). Population dynamics of HIV within an individual after treatment with zidovudine. *AIDS*, *5*(5), 485–490.

Meltzer, M. I., Atkins, C. Y., Santibanez, S., Knust, B., Petersen, B. W., Ervin, E. D., et al. (2014). Estimating the future number of cases in the Ebola epidemic–Liberia and Sierra Leone, 2014–2015. *MMWR Surveill Summ*, *63*(Suppl 3), 1–14.

Miller, R. E., & Blair, P. D. (2009). *Input-output analysis: Foundations and extensions*. Cambridge, UK: Cambridge University Press.

Monod, J., & Jacob, F. (1961). General conclusions: Teleonomic mechanisms in cellular metabolism, growth, and differentiation. In *Cold Spring Harbor Symposia on Quantitative Biology* (vol. 26, pp. 389–401). Cold Spring Harbor Laboratory Press.

Mosekilde, E., & Laugesen, J. L. (2007). Nonlinear dynamic phenomena in the beer model. *System Dynamics Review*, *23*(2–3), 229–252.

Patten, B. (1985). Energy cycling, length of food chains, and direct versus indirect effects in ecosystems. *Canadian Bulletin of Fisheries and Aquatic Science*, *213*, 119–138.

Phillips, A. N. (1996). Reduction of HIV concentration during acute infection: Independence from a specific immune response. *Science*, *271*(5248), 497.

Putnam, H. (1975). Philosophy and our mental life. In Language Mind (Ed.), *Mind, language, and reality*. Cambridge, UK: Cambridge University Press.

Riemann, B. (1873). On the hypotheses which lie at the bases of geometry (translated by William Kingdom Clifford). *Nature*, *8*(183, 184), 14–17, 36, 37.

Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., & Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, *413*(6856), 591–596.

Shetterly, M. L. (2016). *Hidden figures: The untold story of the African-American women who helped win the space race*. New York: HarperCollins.

Smith, W. R. (1983). Qualitative mathematical models of endocrine systems. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *245*(4), R473–R477.

Sprott, J. (2004). Dynamical models of love. *Nonlinear Dynamics, Psychology, and Life Sciences*, *8*(3), 303–314.

Sterman, J. D. (1989). Modeling managerial behavior: Misperceptions of feedback in a dynamic decision making experiment. *Management Science*, *35*(3), 321–339.

Stewart, I. (1997). *Does God play dice?: The new mathematics of chaos*. Malden, MA: Blackwell Publishers.

Strogatz, S. H. (1988). Love affairs and differential equations. *Mathematics Magazine*, *61*(1), 35.

Strogatz, S. H. (2014). *Nonlinear dynamics and chaos: With applications to physics, biology, chemistry, and engineering*. Boulder, CO: Westview Press.

Sturis, J., Polonsky, K. S., Blackman, J. D., Knudsen, C., Mosekilde, E., & Van Cauter E. (1991a). Aspects of oscillatory insulin secretion. In E. Mosekilde & L. Mosekilde (Eds.), *Complexity, Chaos, and Biological Evolution* (vol. 270, pp. 75–93). New York: Plenum Press.

Sturis, J., Polonsky, K. S., Mosekilde, E., & Van Cauter, E. (1991b). Computer model for mechanisms underlying ultradian oscillations of insulin and glucose. *American Journal of Physiology-Endocrinology and Metabolism*, *260*(5), E801–E809.

Tanner, J. T. (1975). The stability and the intrinsic growth rates of prey and predator populations. *Ecology*, *56*(4), 855–867.

Watt, J., & Young, A. (1962). An attempt to simulate the liver on a computer. *The Computer Journal*, *5*(3), 221–227.

Weinstein, M. S. (1977). Hares, lynx, and trappers. *The American Naturalist*, *111*(980), 806–808.

Wright, S (1932). The roles of mutation, inbreeding, crossbreeding, and selection in evolution. In *Proceedings of the Sixth International Congress on Genetics* (pp. 356–366).

Yodzis, P. (1998). Local trophodynamics and the interaction of marine mammals and fisheries in the benguela ecosystem. *Journal of Animal Ecology*, *67*(4), 635–658.

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