
Feedback Systems

An Introduction for Scientists and Engineers
SECOND EDITION

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Bibliography

- [Abk69] M. A. Abkowitz. *Stability and Motion Control of Ocean Vehicles*. MIT Press, Cambridge, MA, 1969.
- [Ack72] J. Ackermann. Der Entwurf linearer Regelungssysteme im Zustandsraum. *Regelungstechnik und Prozessdatenverarbeitung*, 7:297–300, 1972.
- [Ack85] J. Ackermann. *Sampled-Data Control Systems*. Springer, Berlin, 1985.
- [Agn76] C. E. Agnew. Dynamic modeling and control of congestion-prone systems. *Operations Research*, 24(3):400–419, 1976.
- [ÅH05] K. J. Åström and T. Hägglund. *Advanced PID Control*. ISA—The Instrumentation, Systems, and Automation Society, Research Triangle Park, NC, 2005.
- [Ahl66] L. V. Ahlfors. *Complex Analysis*. McGraw-Hill, New York, 1966.
- [ÅKL05] K. J. Åström, R. E. Klein, and A. Lennartsson. Bicycle dynamics and control. *IEEE Control Systems Magazine*, 25(4):26–47, 2005.
- [AM90] B. D. O. Anderson and J. B. Moore. *Optimal Control Linear Quadratic Methods*. Prentice Hall, Englewood Cliffs, NJ, 1990. Republished by Dover Publications, 2007.
- [Apo67] T. M. Apostol. *Calculus*, Vol. II: *Multi-Variable Calculus and Linear Algebra with Applications*. Wiley, New York, 1967.
- [Apo69] T. M. Apostol. *Calculus*, Vol. I: *One-Variable Calculus with an Introduction to Linear Algebra*. Wiley, New York, 1969.
- [Ari94] R. Aris. *Mathematical Modeling Techniques*. Dover, New York, 1994. Originally published by Pitman, 1978.
- [Arn78] V. I. Arnold. *Mathematical Methods in Classical Mechanics*. Springer, New York, 1978.
- [Arn87] V. I. Arnold. *Ordinary Differential Equations*. MIT Press, Cambridge, MA, 1987. 10th printing 1998.
- [AS82] R. H. Abraham and C. D. Shaw. *Dynamics—The Geometry of Behavior*, Part 1: *Periodic Behavior*. Aerial Press, Santa Cruz, CA, 1982.
- [ASMN03] M. Atkinson, M. Savageau, J. Myers, and A. Ninfa. Development of genetic circuitry exhibiting toggle switch or oscillatory behavior in *Escherichia coli*. *Cell*, 113(5):597–607, 2003.
- [Åst00] K. J. Åström. Limitations on control system performance. *European Journal on Control*, 6(1):2–20, 2000.
- [Åst06] K. J. Åström. *Introduction to Stochastic Control Theory*. Dover, New York, 2006. Originally published by Academic Press, New York, 1970.
- [Ath75] D. P. Atherton. *Nonlinear Control Engineering*. Van Nostrand, New York, 1975.
- [AVK87] A. A. Andronov, A. A. Vitt, and S. E. Khaikin. *Theory of Oscillators*. Dover, New York, 1987.

- [ÅW97] K. J. Åström and B. Wittenmark. *Computer-Control Systems: Theory and Design*. Prentice Hall, Englewood Cliffs, NJ, 3rd edition, 1997.
- [ÅW08] K. J. Åström and B. Wittenmark. *Adaptive Control*. Dover, New York, 2nd edition, 2008. Originally published by Addison Wesley, 1995.
- [BÅ70] R. Bellman and K. J. Åström. On structural identifiability. *Mathematical Biosciences*, 7:329–339, 1970.
- [Bas01] T. Basar, editor. *Control Theory: Twenty-five Seminal Papers (1932–1981)*. IEEE Press, New York, 2001.
- [BB91] T. Basar and P. Bernhard. *H^∞ -Optimal Control and Related Minimax Design Problems: A Dynamic Game Approach*. Birkhauser, Boston, 1991.
- [BC48] G. S. Brown and D. P. Campbell. *Principles of Servomechanisms*. Wiley, New York, 1948.
- [BD04] W. E. Boyce and R. C. DiPrima. *Elementary Differential Equations*. Wiley, New York, 2004.
- [Bec05] J. Bechhoefer. Feedback for physicists: A tutorial essay on control. *Reviews of Modern Physics*, 77:783–836, 2005.
- [Ben79] S. Bennett. *A History of Control Engineering: 1800–1930*. Peter Peregrinus, Stevenage, 1979.
- [Ben93] S. Bennett. *A History of Control Engineering: 1930–1955*. Peter Peregrinus, Stevenage, 1993.
- [Ber54] L. L. Beranek. *Acoustics*. McGraw-Hill, New York, 1954.
- [Ber89] R. N. Bergman. Toward physiological understanding of glucose tolerance: Minimal model approach. *Diabetes*, 38:1512–1527, 1989.
- [BG68] B. Brawn and F. Gustavson. Program behavior in a paging environment. *Proceedings of the AFIPS Fall Joint Computer Conference*, pages 1019–1032, 1968.
- [BG87] D. Bertsekas and R. Gallager. *Data Networks*. Prentice Hall, Englewood Cliffs, 1987.
- [BH75] A. E. Bryson, Jr. and Y.-C. Ho. *Applied Optimal Control: Optimization, Estimation, and Control*. Wiley, New York, 1975.
- [Bia95] B. Bialkowski. Process control sample problems. In N. J. Sell, editor, *Process Control Fundamentals for the Pulp & Paper Industry*. Tappi Press, Norcross, GA, 1995.
- [BK64] R. E. Bellman and R. Kalaba. *Selected Papers on Mathematical Trends in Control Theory*. Dover, New York, 1964.
- [Bla34] H. S. Black. Stabilized feedback amplifiers. *Bell System Technical Journal*, 13:1–2, 1934.
- [Bla77] H. S. Black. Inventing the negative feedback amplifier. *IEEE Spectrum*, pages 55–60, 1977.
- [Bla91] J. H. Blakelock. *Automatic Control of Aircraft and Missiles*. Addison-Wesley, Cambridge, MA, 2nd edition, 1991.
- [Bli90] G. Blickley. Modern control started with Ziegler-Nichols tuning. *Control Engineering*, 37:72–75, 1990.
- [Bod45] H. W. Bode. *Network Analysis and Feedback Amplifier Design*. Van Nostrand, New York, 1945.
- [Bod60] H. W. Bode. Feedback—The history of an idea. In *Symposium on Active Networks and Feedback Systems*. Polytechnic Institute of Brooklyn, New York, 1960. Reprinted in [BK64].

- [BP96] M. B. Barron and W. F. Powers. The role of electronic controls for future automotive mechatronic systems. *IEEE Transactions on Mechatronics*, 1(1):80–89, 1996.
- [Bro70] R. W. Brockett. *Finite Dimensional Linear Systems*. Wiley, New York, 1970.
- [Bro00] R. W. Brockett. New issues in the mathematics of control. In B. Engquist and W. Schmid, editors, *Mathematics Unlimited—2001 and Beyond*, pages 189–220. Springer-Verlag, Berlin, 2000.
- [BRS60] J. F. Blackburn, G. Reethof, and J. L. Shearer. *Fluid Power Control*. MIT Press, Cambridge, MA, 1960.
- [Can03] R. H. Cannon. *Dynamics of Physical Systems*. Dover, New York, 2003. Originally published by McGraw-Hill, 1967.
- [CD75] R. F. Coughlin and F. F. Driscoll. *Operational Amplifiers and Linear Integrated Circuits*. Prentice Hall, Englewood Cliffs, NJ, 6th edition, 1975.
- [CD91] F. M. Callier and C. A. Desoer. *Linear System Theory*. Springer-Verlag, London, 1991.
- [CJ59] H. S. Carslaw and J. C. Jaeger. *Conduction of Heat in Solids*. Clarendon Press, Oxford, UK, 2nd edition, 1959.
- [CM51] H. Chestnut and R. W. Mayer. *Servomechanisms and Regulating System Design*, Vol. 1. Wiley, New York, 1951.
- [Cro75] Crocus. *Systemes d'Exploitation des Ordinateurs*. Dunod, Paris, 1975.
- [CT84] C. Cobelli and G. Toffolo. Model of glucose kinetics and their control by insulin, compartmental and non-compartmental approaches. *Mathematical Biosciences*, 72(2):291–316, 1984.
- [DB04] R. C. Dorf and R. H. Bishop. *Modern Control Systems*. Prentice Hall, Upper Saddle River, NJ, 10th edition, 2004.
- [DFT92] J. C. Doyle, B. A. Francis, and A. R. Tannenbaum. *Feedback Control Theory*. Macmillan, New York, 1992.
- [DGH⁺02] Y. Diao, N. Gandhi, J. L. Hellerstein, S. Parekh, and D. M. Tilbury. Using MIMO feedback control to enforce policies for interrelated metrics with application to the Apache web server. In *Proceedings of the IEEE/IFIP Network Operations and Management Symposium*, pages 219–234, 2002.
- [DGKF89] J. C. Doyle, K. Glover, P. P. Khargonekar, and B. A. Francis. State-space solutions to standard H_2 and H_∞ control problems. *IEEE Transactions on Automatic Control*, 34(8):831–847, 1989.
- [DH85] J. P. Den Hartog. *Mechanical Vibrations*. Dover, New York, 1985. Reprint of 4th ed. from 1956; 1st ed. published in 1934.
- [dJ02] H. de Jong. Modeling and simulation of genetic regulatory systems: A literature review. *Journal of Computational Biology*, 9:67–103, 2002.
- [DM02] L. Desborough and R. Miller. Increasing customer value of industrial control performance monitoring—Honeywell’s experience. In *Sixth International Conference on Chemical Process Control*. AIChE Symposium Series Number 326 (Vol. 98), 2002.
- [Dos68] F. H. Dost. *Grundlagen der Pharmakokinetik*. Thieme Verlag, Stuttgart, 1968.
- [Doy78] J. C. Doyle. Guaranteed margins for LQG regulators. *IEEE Transactions on Automatic Control*, 23(4):756–757, 1978.
- [Dub57] L. E. Dubins. On curves of minimal length with a constraint on average curvature, and with prescribed initial and terminal positions and tangents. *American Journal of Mathematics*, 79:497–516, 1957.

- [Dys04] F. Dyson. A meeting with Enrico Fermi. *Nature*, 247(6972):297, 2004.
- [EG05] S. P. Ellner and J. Guckenheimer. *Dynamic Models in Biology*. Princeton University Press, Princeton, NJ, 2005.
- [EKR03] E. N. Elnozahy, M. Kistler, and R. Rajamony. Energy-efficient server clusters. In *Power-Aware Computer Systems*, pages 179–197. Springer, 2003.
- [EL00] M. B. Elowitz and S. Leibler. A synthetic oscillatory network of transcriptional regulators. *Nature*, 403(6767):335–338, 2000.
- [Eli94] J. R. Ellis. *Vehicle Handling Dynamics*. Mechanical Engineering Publications, London, 1994.
- [ESGK02] H. El-Samad, J. P. Goff, and M. Khammash. Calcium homeostasis and parturient hypocalcemia: An integral feedback perspective. *Journal of Theoretical Biology*, 214:17–29, 2002.
- [FCF⁺06] P. G. Fabietti, V. Canonico, M. O. Federici, M. Benedetti, and E. Sarti. Control oriented model of insulin and glucose dynamics in type 1 diabetes. *Medical and Biological Engineering and Computing*, 44:66–78, 2006.
- [FLMR92] M. Fliess, J. Levine, P. Martin, and P. Rouchon. On differentially flat nonlinear systems. *Comptes Rendus des Séances de l’Académie des Sciences, Serie I*, 315:619–624, 1992.
- [FLMR95] M. Fliess, J. Levine, P. Martin, and P. Rouchon. Flatness and defect of non-linear systems: Introductory theory and examples. *International Journal of Control*, 61(6):1327–1361, 1995.
- [Fou07] J. B. J. Fourier. On the propagation of heat in solid bodies. Memoir, read before the Class of the Institut de France, 1807.
- [FPEN05] G. F. Franklin, J. D. Powell, and A. Emami-Naeini. *Feedback Control of Dynamic Systems*. Prentice Hall, Upper Saddle River, NJ, 5th edition, 2005.
- [Fra87] B. A. Francis. *A Course in $\mathcal{H}_\infty$ Control*. Springer-Verlag, Berlin, 1987.
- [Fra07] A. Fradkov. *Cybernetical Physics: From Control of Chaos to Quantum Control*. Springer, Berlin, 2007.
- [Fri04] B. Friedland. *Control System Design: An Introduction to State Space Methods*. Dover, New York, 2004.
- [Gan60] F. R. Gantmacher. *The Theory of Matrices*. Chelsea Publishing Company, 1960.
- [GB42] M. A. Gardner and J. L. Barnes. *Transients in Linear Systems*. Wiley, New York, 1942.
- [GF71] L. Gunkel and G. F. Franklin. A general solution for linear sampled data systems. *IEEE Transactions on Automatic Control*, AC-16:767–775, 1971.
- [GGS01] G. C. Goodwin, S. F. Graebe, and M. E. Salgado. *Control System Design*. Prentice Hall, Upper Saddle River, NJ, 2001.
- [GH83] J. Guckenheimer and P. Holmes. *Nonlinear Oscillations, Dynamical Systems, and Bifurcations of Vector Fields*. Springer-Verlag, Berlin, 1983.
- [Gil63] E. Gilbert. Controllability and observability in multivariable control systems. *SIAM Journal of Control*, 1(1):128–151, 1963.
- [GL95] M. Green and D. J. N. Limebeer. *Linear Robust Control*. Prentice Hall, Englewood Cliffs, NJ, 1995.
- [GM61] D. Graham and D. McRuer. *Analysis of Nonlinear Control Systems*. Wiley, New York, 1961.
- [God83] K. Godfrey. *Compartment Models and Their Application*. Academic Press, New York, 1983.

- [Gol53] H. Goldstein. *Classical Mechanics*. Addison-Wesley, Cambridge, MA, 1953.
- [Gol70] S. W. Golomb. Mathematical models—Uses and limitations. *Simulation*, 4(14):197–198, 1970.
- [GP82] M. Giobaldi and D. Perrier. *Pharmacokinetics*. Marcel Dekker, New York, 2nd edition, 1982.
- [GPD59] J. C. Gille, M. J. Pelegrin, and P. Decaulne. *Feedback Control Systems; Analysis, Synthesis, and Design*. McGraw-Hill, New York, 1959.
- [Gui63] E. A. Guillemin. *Theory of Linear Physical Systems*. MIT Press, Cambridge, MA, 1963.
- [Hah67] W. Hahn. *Stability of Motion*. Springer, Berlin, 1967.
- [HB90] J. K. Hedrick and T. Batsuen. Invariant properties of automobile suspensions. In *Proceedings of the Institution of Mechanical Engineers*, volume 204, pages 21–27, London, 1990.
- [HD95] M. B. Hoagland and B. Dodson. *The Way Life Works*. Times Books, New York, 1995.
- [HDPT04] J. L. Hellerstein, Y. Diao, S. Parekh, and D. M. Tilbury. *Feedback Control of Computing Systems*. Wiley, New York, 2004.
- [Her04] D. V. Herlihy. *Bicycle—The History*. Yale University Press, New Haven, CT, 2004.
- [HH52] A. L. Hodgkin and A. F. Huxley. A quantitative description of membrane current and its application to conduction and excitation in nerve. *Journal of Physiology*, 117(500–544), 1952.
- [HMTG00] C. V. Hollot, V. Misra, D. Towsley, and W-B. Gong. A control theoretic analysis of RED. In *Proceedings of IEEE Infocom*, pages 1510–1519, 2000.
- [Hor63] I. M. Horowitz. *Synthesis of Feedback Systems*. Academic Press, New York, 1963.
- [Hor75] I. M. Horowitz. Superiority of transfer function over state-variable methods in linear, time-invariant feedback system design. *IEEE Transactions on Automatic Control*, AC-20(1):84–97, 1975.
- [Hor91] I. M. Horowitz. Survey of quantitative feedback theory. *International Journal of Control*, 53:255–291, 1991.
- [Hug93] T. P. Hughes. *Elmer Sperry: Inventor and Engineer*. John Hopkins University Press, Baltimore, MD, 1993.
- [Isi95] A. Isidori. *Nonlinear Control Systems*. Springer-Verlag, Berlin, 3rd edition, 1995.
- [Ito70] M. Ito. Neurophysiological aspects of the cerebellar motor system. *International Journal of Neurology*, 7:162–178, 1970.
- [Jac72] J. A. Jacquez. *Compartment Analysis in Biology and Medicine*. Elsevier, Amsterdam, 1972.
- [Jac95] V. Jacobson. Congestion avoidance and control. *ACM SIGCOMM Computer Communication Review*, 25:157–173, 1995.
- [JNP47] H. James, N. Nichols, and R. Phillips. *Theory of Servomechanisms*. McGraw-Hill, New York, 1947.
- [JT61] P. D. Joseph and J. T. Tou. On linear control theory. *Transactions of the AIEE*, 80(18), 1961.
- [Jun02] W. G. Jung, editor. *Op Amp Applications*. Analog Devices, Norwood, MA, 2002.
- [Kal60] R. E. Kalman. Contributions to the theory of optimal control. *Boletín de la Sociedad Matemática Mexicana*, 5:102–119, 1960.

- [Kal61a] R. E. Kalman. New methods and results in linear prediction and filtering theory. Technical Report 61-1, Research Institute for Advanced Studies (RIAS), Baltimore, MD, February 1961.
- [Kal61b] R. E. Kalman. On the general theory of control systems. In *Proceedings of the First IFAC Congress on Automatic Control, Moscow, 1960*, volume 1, pages 481–492. Butterworths, London, 1961.
- [KB61] R. E. Kalman and R. S. Bucy. New results in linear filtering and prediction theory. *Transactions of the ASME (Journal of Basic Engineering)*, 83 D:95–108, 1961.
- [Kel85] F. P. Kelly. Stochastic models of computer communication. *Journal of the Royal Statistical Society*, B47(3):379–395, 1985.
- [Kel94] K. Kelly. *Out of Control*. Addison-Wesley, Reading, MA, 1994. Available at <http://www.kk.org/outofcontrol>.
- [KFA69] R. E. Kalman, P. L. Falb, and M. A. Arbib. *Topics in Mathematical System Theory*. McGraw-Hill, New York, 1969.
- [KG02] B. C. Kuo and F. Golnaraghi. *Automatic Control Systems*. Wiley, New York, 8th edition, 2002.
- [Kha01] H. K. Khalil. *Nonlinear Systems*. Macmillan, New York, 3rd edition, 2001.
- [KHN63] R. E. Kalman, Y. Ho, and K. S. Narendra. *Controllability of Linear Dynamical Systems*, volume 1 of *Contributions to Differential Equations*. Wiley, New York, 1963.
- [Kit95] C. Kittel. *Introduction to Solid State Physics*. Wiley, New York, 1995.
- [KKK95] M. Krstić, I. Kanellakopoulos, and P. Kokotović. *Nonlinear and Adaptive Control Design*. Wiley, 1995.
- [Kle75] L. Kleinrock. *Queuing Systems*, Vols. I and II. Wiley-Interscience, New York, 2nd edition, 1975.
- [KN00] U. Kiencke and L. Nielsen. *Automotive Control Systems: For Engine, Driveline, and Vehicle*. Springer, Berlin, 2000.
- [Kra63] N. N. Krasovski. *Stability of Motion*. Stanford University Press, Stanford, CA, 1963.
- [KS01] J. Keener and J. Sneyd. *Mathematical Physiology*. Springer, New York, 2001.
- [Kum01] P. R. Kumar. New technological vistas for systems and control: The example of wireless networks. *Control Systems Magazine*, 21(1):24–37, 2001.
- [Kun93] P. Kundur. *Power System Stability and Control*. McGraw-Hill, New York, 1993.
- [KV86] P. R. Kumar and P. Varaiya. *Stochastic Systems: Estimation, Identification, and Adaptive Control*. Prentice Hall, Englewood Cliffs, NJ, 1986.
- [LaS60] J. P. LaSalle. Some extensions of Lyapunov’s second method. *IRE Transactions on Circuit Theory*, CT-7(4):520–527, 1960.
- [Lew03] A. D. Lewis. A mathematical approach to classical control. Technical report, Queens University, Kingston, Ontario, 2003.
- [LPD02] S. H. Low, F. Paganini, and J. C. Doyle. Internet congestion control. *IEEE Control Systems Magazine*, pages 28–43, February 2002.
- [LPW⁺02] S. H. Low, F. Paganini, J. Wang, S. Adlakha, and J. C. Doyle. Dynamics of TCP/RED and a scalable control. In *Proceedings of IEEE Infocom*, pages 239–248, 2002.
- [Lun05] K. H. Lundberg. History of analog computing. *IEEE Control Systems Magazine*, pages 22–28, March 2005.
- [Mac37] D. A. MacLulich. *Fluctuations in the Numbers of the Varying Hare (Lepus americanus)*. University of Toronto Press, 1937.

- [Mac45] L.A. MacColl. *Fundamental Theory of Servomechanisms*. Van Nostrand, Princeton, NJ, 1945. Dover reprint 1968.
- [Mac89] J. M. Maciejowski. *Multivariable Feedback Design*. Addison Wesley, Reading, MA, 1989.
- [Mal59] J. G. Malkin. *Theorie der Stabilität einer Bewegung*. Oldenbourg, München, 1959.
- [Man02] R. Mancini. *Op Amps for Everyone*. Texas Instruments, Houston. TX, 2002.
- [May70] O. Mayr. *The Origins of Feedback Control*. MIT Press, Cambridge, MA, 1970.
- [McF53] M. W. McFarland, editor. *The Papers of Wilbur and Orville Wright*. McGraw-Hill, New York, 1953.
- [MG90] D. C. McFarlane and K. Glover. *Robust Controller Design Using Normalized Coprime Factor Plant Descriptions*. Springer, New York, 1990.
- [MH98] J. E. Marsden and M. J. Hoffmann. *Basic Complex Analysis*. W. H. Freeman, New York, 1998.
- [Mil66] H. T. Milhorn. *The Application of Control Theory to Physiological Systems*. Saunders, Philadelphia, 1966.
- [Min02] D. A. Mindel. *Between Human and Machine: Feedback, Control, and Computing Before Cybernetics*. Johns Hopkins University Press, Baltimore, MD, 2002.
- [Min08] D. A. Mindel. *Digital Apollo: Human and Machine in Spaceflight*. The MIT Press, Cambridge, MA, 2008.
- [MLK06] A. Makroglou, J. Li, and Y. Kuang. Mathematical models and software tools for the glucose-insulin regulatory system and diabetes: An overview. *Applied Numerical Mathematics*, 56:559–573, 2006.
- [MLS94] R. M. Murray, Z. Li, and S. S. Sastry. *A Mathematical Introduction to Robotic Manipulation*. CRC Press, 1994.
- [MR94] J. E. Marsden and T. S. Ratiu. *Introduction to Mechanics and Symmetry*. Springer-Verlag, New York, 1994.
- [Mur03] R. M. Murray, editor. *Control in an Information Rich World: Report of the Panel on Future Directions in Control, Dynamics and Systems*. SIAM, Philadelphia, 2003.
- [Mur04] J. D. Murray. *Mathematical Biology*, Vols. I and II. Springer-Verlag, New York, 3rd edition, 2004.
- [Nah88] P. J. Nahin. *Oliver Heaviside: Sage in Solitude: The Life, Work and Times of an Electrical Genius of the Victorian Age*. IEEE Press, New York, 1988.
- [NS99] H. Nijmeijer and J. M. Schumacher. Four decades of mathematical system theory. In J. W. Polderman and H. L. Trentelman, editors, *The Mathematics of Systems and Control: From Intelligent Control to Behavioral Systems*, pages 73–83. University of Groningen, 1999.
- [Nyq32] H. Nyquist. Regeneration theory. *Bell System Technical Journal*, 11:126–147, 1932.
- [Nyq56] H. Nyquist. The regeneration theory. In R. Oldenburger, editor, *Frequency Response*, page 3. MacMillan, New York, 1956.
- [Oga01] K. Ogata. *Modern Control Engineering*. Prentice Hall, Upper Saddle River, NJ, 4th edition, 2001.
- [Old56] R. Oldenburger, editor. *Frequency Response*. MacMillan, New York, 1956.
- [OSFM07] R. Olfati-Saber, J. A. Fax, and R. M. Murray. Consensus and cooperation in networked multi-agent systems. *Proceedings of the IEEE*, 95(1):215–233, 2007.

- [PB86] G. Pacini and R. N. Bergman. A computer program to calculate insulin sensitivity and pancreatic responsivity from the frequently sampled intravenous glucose tolerance test. *Computer Methods and Programs in Biomedicine*, 23:113–122, 1986.
- [Phi48] G. A. Philbrick. Designing industrial controllers by analog. *Electronics*, 21(6):108–111, 1948.
- [PN00] W. F. Powers and P. R. Nicastrì. Automotive vehicle control challenges in the 21st century. *Control Engineering Practice*, 8:605–618, 2000.
- [PPP02] S. Prajna, A. Papachristodoulou, and P. A. Parrilo. SOSTOOLS: Sum of squares optimization toolbox for MATLAB, 2002. Available from <http://www.cds.caltech.edu/sostools>.
- [Rig63] D. S. Riggs. *The Mathematical Approach to Physiological Problems*. MIT Press, Cambridge, MA, 1963.
- [RM71] H. H. Rosenbrock and P. D. Moran. Good, bad or optimal? *IEEE Transactions on Automatic Control*, AC-16(6):552–554, 1971.
- [RST12] G. Rafal, R. G. Sanfelice, and A. Teel. *Hybrid Dynamical Systems: Modeling, Stability, and Robustness*. Princeton University Press, 2012.
- [Rug95] W. J. Rugh. *Linear System Theory*. Prentice Hall, Englewood Cliffs, NJ, 2nd edition, 1995.
- [SÅD⁺07] G. Schitter, K. J. Åström, B. DeMartini, P. J. Thurner, K. L. Turner, and P. K. Hansma. Design and modeling of a high-speed AFM-scanner. *IEEE Transactions on Control System Technology*, 15(5):906–915, 2007.
- [Sar91] D. Sarid. *Atomic Force Microscopy*. Oxford University Press, Oxford, UK, 1991.
- [Sas99] S. Sastry. *Nonlinear Systems*. Springer, New York, 1999.
- [Sch87] M. Schwartz. *Telecommunication Networks*. Addison Wesley, Reading, MA, 1987.
- [Sch01] G. Schitter. High performance feedback for fast scanning atomic force microscopes. *Review of Scientific Instruments*, 72(8):3320–3327, 2001.
- [SEM04] D. E. Seborg, T. F. Edgar, and D. A. Mellichamp. *Process Dynamics and Control*. Wiley, Hoboken, NJ, 2nd edition, 2004.
- [Sen01] S. D. Senturia. *Microsystem Design*. Kluwer, Boston, MA, 2001.
- [Shi96] F. G. Shinskey. *Process-Control Systems. Application, Design, and Tuning*. McGraw-Hill, New York, 4th edition, 1996.
- [Son98] E. P. Sontag. *Mathematical Control Theory: Deterministic Finite Dimensional Systems*. Springer, New York, 2nd edition, 1998.
- [SP05] S. Skogestad and I. Postlethwaite. *Multivariable Feedback Control*. Wiley, Hoboken, NJ, 2nd edition, 2005.
- [SS02] E. B. Saff and A. D. Snider. *Fundamentals of Complex Analysis with Applications to Engineering, Science and Mathematics*. Prentice Hall, Englewood Cliffs, NJ, 2002.
- [Sta68] L. Stark. *Neurological Control Systems—Studies in Bioengineering*. Plenum Press, New York, 1968.
- [Ste02] J. Stewart. *Calculus: Early Transcendentals*. Brooks Cole, Pacific Grove, CA, 2002.
- [Ste03] G. Stein. Respect the unstable. *Control Systems Magazine*, 23(4):12–25, 2003.
- [Str88] G. Strang. *Linear Algebra and Its Applications*. Harcourt Brace Jovanovich, San Diego, 3rd edition, 1988.
- [Str94] S. H. Strogatz. *Nonlinear Dynamics and Chaos, with Applications to Physics, Biology, Chemistry, and Engineering*. Addison-Wesley, Reading, MA, 1994.

- [SV89] M. W. Spong and M. Vidyasagar. *Dynamics and Control of Robot Manipulators*. John Wiley, 1989.
- [Tan96] A. S. Tannenbaum. *Computer Networks*. Prentice Hall, Upper Saddle River, NJ, 3rd edition, 1996.
- [Teo37] T. Teorell. Kinetics of distribution of substances administered to the body, I and II. *Archives Internationales de Pharmacodynamie et de Therapie*, 57:205–240, 1937.
- [Tha89] G. T. Thaler. *Automatic Control Systems*. West Publishing, St. Paul, MN, 1989.
- [Til01] M. Tiller. *Introduction to Physical Modeling with Modelica*. Springer, Berlin, 2001.
- [Tru55] J. G. Truxal. *Automatic Feedback Control System Synthesis*. McGraw-Hill, New York, 1955.
- [TS90] D. Tipper and M. K. Sundareshan. Numerical methods for modeling computer networks under nonstationary conditions. *IEEE Journal of Selected Areas in Communications*, 8(9):1682–1695, 1990.
- [Tus52] A. Tustin. Feedback. *Scientific American*, 48–54, 1952.
- [Vin01] G. Vinnicombe. *Uncertainty and Feedback: $\mathcal{H}_\infty$ Loop-Shaping and the v -Gap Metric*. Imperial College Press, London, 2001.
- [Whi99] F. J. W. Whipple. The stability of the motion of a bicycle. *Quarterly Journal of Pure and Applied Mathematics*, 30:312–348, 1899.
- [Wid41] D. V. Widder. *Laplace Transforms*. Princeton University Press, Princeton, NJ, 1941.
- [Wig90] S. Wiggins. *Introduction to Applied Nonlinear Dynamical Systems and Chaos*. Springer-Verlag, Berlin, 1990.
- [Wil99] H. R. Wilson. *Spikes, Decisions, and Actions: The Dynamical Foundations of Neuroscience*. Oxford University Press, Oxford, UK, 1999.
- [Wil04] D. G. Wilson. *Bicycling Science*. MIT Press, Cambridge, MA, 3rd edition, 2004. With contributions by Jim Papadopoulos.
- [Wis07] K. A. Wise. Guidance and control for military systems: Future challenges. In *AIAA Conference on Guidance, Navigation, and Control*, 2007. AIAA Paper 2007-6867.
- [WT24] E. P. M. Widmark and J. Tandberg. Über die Bedingungen für die Akkumulation indifferenten Narkotika. *Biochemische Zeitung*, 148:358–389, 1924.
- [YH91] S. Yamamoto and I. Hashimoto. Present status and future needs: The view from Japanese industry. In Y. Arkun and W. H. Ray, editors, *Chemical Process Control—CPC IV*, 1991.
- [YHSD00] T.-M. Yi, Y. Huang, M. I. Simon, and J. Doyle. Robust perfect adaptation in bacterial chemotaxis through integral feedback control. *PNAS*, 97:4649–4653, 2000.
- [Zam81] G. Zames. Feedback and optimal sensitivity: Model reference transformations, multiplicative seminorms, and approximative inverse. *IEEE Transactions on Automatic Control*, AC-26(2):301–320, 1981.
- [ZD63] L. A. Zadeh and C. A. Desoer. *Linear System Theory: the State Space Approach*. McGraw-Hill, New York, 1963.
- [ZDG96] J. C. Zhou, J. C. Doyle, and K. Glover. *Robust and Optimal Control*. Prentice Hall, Englewood Cliffs, NJ, 1996.
- [ZN42] J. G. Ziegler and N. B. Nichols. Optimum settings for automatic controllers. *Transactions of the ASME*, 64:759–768, 1942.

Index

- +, A-13, A-18, A-25, A-29
- access control, *see* admission control
- acknowledgment (ack) packet, A-13–A-15
- activator, 2-35, 4-35
- active filter, *see also* operational amplifier, 5-24
- actuators, 1-4, 2-5, 2-26, 6-12, 7-24, 8-38, 9-17, 10-21, 11-10, 11-22–11-24, 11-26, A-1, A-17
- effect on zeros, 9-18, 11-23
- in computing systems, A-11
- saturation, 2-25, 7-25, 10-8, 10-14–10-15, 10-21, 11-10
- A/D converters, *see* analog-to-digital converters
- adaptation, 10-5
- adaptive control, 12-27, 12-28
- additive uncertainty, 12-3, 12-7, 12-10, 12-30
- adjacency matrix, 2-32
- admission control, 2-29, 2-39, 9-8, A-14, A-15
- aerospace systems, *see also* vectored thrust aircraft; X-29 aircraft, 1-7, 11-28
- AFM, *see* atomic force microscope
- air-fuel ratio control, 1-14
- aircraft, *see* flight control
- alcohol, metabolism of, A-30
- algebraic loops, 7-11, 8-21–8-22
- aliasing, 7-25
- all-pass transfer function, 11-20
- alternating current (AC), 5-25
- amplifier, *see* operational amplifier
- amplitude ratio, *see* gain
- analog computing, 2-26, 8-22, 10-20, A-7
- analog implementation, controllers, 8-35, 10-20–10-21, A-10
- analog-to-digital converters, 1-4, 7-24, 7-25, 10-21, A-18
- analytic function, 8-8
- angle, 3-4
- anti-windup compensation, 1-12
- anticipation, in controllers, *see also* derivative action, 1-12, 10-4
- antiresonance, 5-26
- anti-windup compensation, 10-15, 10-21, 10-23, 10-25
- Apache web server, *see also* web server control, A-12
- apparent volume of distribution, A-22, A-30
- Arbib, M. A., 6-1
- argument, of a complex number, 8-22
- arrival rate (queuing systems), 2-30
- asymptotes, in Bode plot, 8-25, 8-26
- asymptotic stability, 2-17, 4-8–4-10, 4-12, 4-18, 4-20, 4-24, 4-26, 5-10
- discrete-time systems, 5-35
- atmospheric dynamics, *see* environmental science
- atomic force microscopes, 1-3, 2-26, A-17–A-20
- contact mode, 5-26, 6-33, A-17
- horizontal positioning, 9-15, 12-20
- system identification, 8-29
- tapping mode, 9-24, 10-7, 10-12, 11-14, A-17
- with preloading, A-29
- attractor (equilibrium point), 4-10
- automatic reset, in PID control, 10-4
- automatic tuning, 10-14, 12-27
- automotive control systems, *see also* cruise control; vehicle steering, 1-9, 2-26, A-5
- autonomous differential equation, *see also* time-invariant systems, 2-3
- autopilot, 1-7, 1-8
- balance systems, *see also* cart-pendulum system; inverted pendulum, 2-9–2-11, 2-24, 6-4, 6-22, 8-12, 11-23
- band-pass filter, 5-24, 5-25, 8-27, 8-28
- bandwidth, 5-25, 6-20, 11-8, 11-22
- Bell Labs, 1-6, 9-24
- Bennett, S., 1-16, 9-24, 10-23
- bicycle dynamics, 4-29, 7-26, A-5–A-7, A-27
- Whipple model, A-7
- bicycle model, for vehicle steering, 2-26–2-28
- bicycledynamics
- Whipple model, 6-33
- bifurcations, *see also* root locus plots, 4-27–4-29, 4-36

- biological circuits, 2-20,
 - 2-34–2-36, 4-35, 5-36, 8-28
 - genetic switch, 2-39, 4-21
 - repressilator, 2-35–2-36
- biological systems, *see also*
 - biological circuits; drug administration; neural systems; population dynamics, 1-1–1-3, 1-10, 1-16, 2-34–2-37, 4-32, 10-1, 10-5
- bistability, 1-10, 4-23
- Black, H. S., 1-6, 1-8, 5-1, 9-1, 9-24, 12-1, A-7, A-9
- block diagonal systems, 4-12, 4-35, 5-9, 5-15, 5-19, 7-12
- block diagram algebra, 8-14, 8-17, 12-10
- block diagrams, 1-1, 2-19–2-22, 8-10, 8-14–8-19, 8-21
- control system, 1-4, 8-1, 8-16, 11-1
- Kalman decomposition, 7-23
- observable canonical form, 7-5
- observer, 7-2, 7-10
- observer-based control system, 7-13
- PID controllers, 10-1, 10-4, 10-21
- reachable canonical form, 6-6
- two degree-of-freedom controller, 7-19, 11-2, 12-12
- Youla parameterization, 12-11
- Bode, H., 8-1, 9-24, 11-33, 12-28
- Bode plots, 8-22–8-29, 9-16
 - asymptotic approximation, 8-25, 8-26, 8-36
 - low-, band-, high-pass filters, 8-28
 - nonminimum phase systems, 9-18
 - of rational function, 8-23
 - sketching, 8-26
- Bode's ideal loop transfer function, 12-10, 12-29
- Bode's integral formula, 11-24–11-26, 11-28–11-29
- Bode's relations, 9-16, 9-17, 11-13
- Brahe, T., 2-2
- breakpoint, 8-25, 9-6
- Brockett, R. W., xii, 1-1, 5-33
- Bryson, A. E., 6-34
- bumpless transfer, 12-27
- Bush, V., 10-23
- calibration, versus feedback, 6-14, 6-29, 6-31
- Cannon, R. H., 2-37, 5-1
- capacitor, transfer function for, 8-8
- car, *see* automotive control systems; cruise control; vehicle steering
- carrying capacity, in population models, A-26
- cart-pendulum system, *see also* balance systems, 2-10, 3-18, 6-6
- causal reasoning, 1-1, A-6
- Cayley-Hamilton theorem, 6-4, 6-33, 7-3
- center (equilibrium point), 4-10
- centrifugal governor, 1-2, 1-3, 1-6
- chain of integrators (normal form), 2-37, 6-7
- characteristic equation, 3-2, 3-5
- characteristic polynomial, 3-1, 4-11, 6-33, 8-7, 8-12
 - for closed loop transfer function, 9-2
- observable canonical form, 7-5
- output feedback controller, 7-12, 7-13
- reachable canonical form, 6-7, 6-9, 6-13, 6-32
- chemical systems, *see also* process control; compartment models, 10-1
- chordal distance, 12-5
- circuits, *see* biological circuits; electrical circuits
- classical control, xi, 12-28
- closed loop, 1-1, 1-2, 1-4, 5-32, 6-10, 6-17, 9-1, 9-2, 9-21, 11-1
 - versus open loop, 1-2, 9-3, 9-22, 11-1
- Command signal following, 3-11
- command signals, *see also* reference signal; setpoint, 1-4, 1-10, 7-20, 10-1
- compartment models, 4-13, 5-21, 6-20, 7-3, 7-8, 7-27, A-21–A-25
 - exercises, 5-34
- compensator, *see* control law
- complementary sensitivity function, 11-3, 11-11, 11-26, 12-4, 12-8, 12-10, 12-14, 12-19, 12-23, 12-29
- complexity, of control systems, 1-9, 10-6
- computed torque, 5-33
- computer implementation, controllers, 7-24–7-26, 10-21–10-23
- computer science, relationship to control, 1-5
- computer systems, control of, *see also* queuing systems, 1-16, 2-13, 2-31, 2-32, 5-27, A-11–A-17
- conditional integration, 10-25
- conditional stability, 9-9
- congestion control, *see also* queuing systems, 4-10, 9-7, 9-26, 10-24, A-13–A-16
 - router dynamics, A-29
- consensus, 2-32
- control
 - definition of, 1-3–1-5
 - early examples, 1-2, 1-6, 1-9, 1-16, 10-4
 - fundamental limitations, 9-17, 11-20–11-29, 11-33, 12-17, 12-20, 12-27–12-28
 - history of, 1-16, 10-23

- modeling for, 1-5, 2-5–2-6, 2-37, 12-1
- successes of, 1-16
- system, 1-3, 6-9, 7-13, 7-19, 7-24, 8-1, 11-2, 11-4, 12-12
- using estimated state, 7-11–7-14, 12-24
- Control architecture with two degrees of freedom, 3-13
- control error, 1-11, 8-16, 10-2
- control law, 1-4, 1-11, 5-32, 6-10, 6-13, 8-16
- control Lyapunov function, 4-30
- control matrix, 2-8, 2-12
- control signal, 2-5, 5-27, 10-1
- controllability, *see also* reachability, 6-31
- controlled differential equation, 2-3, 2-8, 8-7
- convolution equation, 5-15–5-17, 5-19, 5-20, 6-4, 8-33
- discrete-time, 5-35
- coordinate transformations, 4-12, 5-17–5-19, 6-7, 7-26, 8-6–8-7
- to Jordan form, 5-9
- to observable canonical form, 7-6
- to reachable canonical form, 6-8, 6-9
- Coriolis forces, 2-10, 5-33
- corner frequency, 8-25
- correlation matrix, 7-15, 7-16
- cost function, 6-24
- coupled spring-mass system, 5-12, 5-14, 5-18
- covariance matrix, 7-15
- critical gain, 10-11, 10-13, 10-14
- critical period, 10-11, 10-13
- critical point, 9-5, 9-7, 9-13, 9-23, 9-24, 10-11, 12-6, 12-7, 12-26
- critically damped oscillator, 6-18
- crossover frequency, *see* gain crossover frequency; phase crossover frequency
- crossover frequency inequality, *see* gain crossover frequency inequality
- cruise control, 1-6, 1-15, A-1–A-5
- control design, 6-30, 10-8, 10-19
- feedback linearization, 5-32
- integrator windup, 10-14, 10-15
- linearization, 5-28
- pole/zero cancellation, 8-20
- robustness, 1-6, 12-1, 12-2, 12-8
- Curtiss seaplane, 1-7, 1-8
- cybernetics, *see also* robotics
- D/A converters, *see* digital-to-analog converters
- damped frequency, 6-18
- damping, 2-2, 2-10, 2-16, 4-2, 8-37, 8-38
- damping ratio, 3-10, 6-18, 6-19, 6-22, 10-8
- DC gain, *see also* zero frequency gain, 5-25
- dead zone, 1-11
- delay, *see* time delay
- delay compensation, 9-26, 12-29
- delay margin, 9-15
- delta function, *see* impulse function
- derivative action, 1-12, 1-13, 10-1, 10-4–10-6, 10-20, 11-16
- filtering, 10-5, 10-18–10-19, 10-22, 10-23
- setpoint weighting, 10-19, 10-23
- time constant, 10-2
- versus lead compensator, 11-16
- describing functions, 9-22–9-24
- design of dynamics, 1-7–1-8, 4-15, 4-30–4-32, 5-1, 6-1, 6-11, 6-16
- diabetes, *see* insulin-glucose dynamics
- diagonal systems, 4-11, 5-8
- Kalman decomposition for, 7-22
- transforming to, 4-12, 4-35, 5-8
- difference equations, 2-8, 2-12–2-14, 2-16, 2-37, 5-27, 7-24, 10-22
- differential algebraic equations, *see also* algebraic loops, 2-7
- differential equations, 2-2, 2-8–2-11, 4-1–4-4
- controlled, 2-3, 5-3, 8-7
- equilibrium points, 4-6–4-7
- existence and uniqueness of solutions, 4-2–4-4
- first-order, 2-6, 10-6
- isolated solution, 4-7
- periodic solutions, 4-7–4-8, 4-15
- qualitative analysis, 4-4–4-8
- second-order, 4-5, 6-17, 10-6
- solutions, 4-1, 4-2, 5-3, 5-6, 5-15, 8-35
- stability, *see* stability
- transfer functions for, 8-8
- differential flatness, 7-21
- digital control systems, *see* computer implementation, controllers
- digital-to-analog converters, 1-4, 7-24, 7-25, 10-21, A-18
- dimension-free variables, 2-23, 2-37
- direct term, 2-8, 2-12, 5-17, 7-11, 8-22
- discrete control, 2-31
- discrete-time systems, 2-12, 2-37, 4-35, 5-27, 5-35, 10-21
- Kalman filter for, 7-15
- linear quadratic regulator for, 6-26
- disk drives, 2-40
- disturbance attenuation, 1-4, 6-10, 11-9–11-10, 12-12–12-13
- design of controllers for, 11-5, 11-6, 11-13, 11-26, 11-34, 12-23

- fundamental limits, 11-25
- in biological systems, 8-29, 10-5
- integral gain as a measure of, 10-4, 11-10, 12-13
- relationship to sensitivity function, 11-9, 11-24, 11-34, 12-12
- disturbance weighting, 12-26
- disturbances, 1-4, 2-3, 2-6, 8-16, 8-20, 11-1, 11-4, 11-5
- generalized, 12-25
- random, 7-15
- Dodson, B., 1-1
- dominant eigenvalues (poles), 6-21, 10-8, 10-9
- double integrator, 5-7, 6-2, 8-8
- Doyle, J. C., xii, 11-33, 12-28
- drug administration, *see also* compartment models, 5-21, 6-20, A-21–A-25, A-30
- duality, 7-7, 7-11
- Dubins car, 2-28
- dynamic compensator, 6-30, 7-13
- dynamic inversion, 5-33
- dynamical systems, 1-1, 2-1, 4-1, 4-4, 4-32
- linear, 4-11, 5-1
- observer as a, 7-1
- state of, 6-9
- stochastic, 7-15
- uncertainty in, 12-1–12-3
- zz, *see also* differential equations
- dynamics matrix, 2-8, 2-12, 4-11, 5-12
- Dyson, F., 2-1
- e-mail server, control of, 2-13, 5-27
- economic systems, 1-10, 2-38
- ecosystems, *see also* predator-prey system, 6-15, A-25
- eigenvalue assignment, 6-10, 6-12, 6-14–6-16, 6-22, 7-12, 10-8, 10-23
- by output feedback, 7-13
- for observer design, 7-8
- eigenvalues, 4-11, 4-20, 4-29, 5-12, 8-4
- and Jordan form, 5-9–5-11, 5-35
- distinct, 4-34, 4-35, 5-8, 5-14, 7-22
- dominant, 6-21
- effect on dynamic behavior, 6-17, 6-19–6-21, 8-5
- for discrete-time systems, 5-35
- invariance under coordinate transformation, 4-12
- relationship to modes, 5-12, 5-15
- relationship to poles, 8-11
- relationship to stability, 4-24, 5-10, 5-11
- eigenvectors, 4-12, 4-35, 5-12
- relationship to mode shape, 5-13
- electric power, *see* power systems (electric)
- electrical circuits, *see also* operational amplifier, 2-7, 2-20, 5-1, 8-8, A-10
- electrical engineering, 2-3–2-5, 5-25, 9-9
- elephant, modeling of an, 2-1
- Elowitz, M. B., 2-35
- encirclement, *see also* Nyquist criterion, 9-5
- environmental science, 1-3
- equilibrium points, 4-6, 4-11, 5-2, 5-29, 6-2, A-26
- bifurcations of, 4-27
- discrete time, 2-37
- for closed loop system, 6-10, 6-29
- for planar systems, 4-10
- region of attraction, 4-25–4-27, 4-34
- stability, 4-8
- error feedback, 3-12, 10-1, 10-2, 10-19, 11-3
- estimators, *see* observers
- Euler integration, 2-16, 2-17
- exponential signals, 8-2–8-7, 8-11, 8-22
- extended Kalman filter, 7-20
- Falb, P. L., 6-1
- Feedback, 3-1
- feedback, 1-1–1-3
- as technology enabler, 1-3, 1-8
- drawbacks of, 1-3, 1-9, 10-18, 12-6, 12-13
- in biological systems, *see also* biological circuits, 1-1–1-3, 1-16, 10-5
- in engineered systems, *see* control
- in financial systems, 1-3
- in nature, 1-3, A-25
- positive, *see* positive feedback
- properties, 1-3, 1-5–1-10, 11-1, 11-6, 12-1
- robustness through, 1-6
- versus feedforward, 1-10, 10-4, 11-6
- feedback connection, 8-15, 9-21, 9-22
- feedback controller, 8-16, 11-1
- feedback linearization, 5-31–5-33
- feedback loop, 1-4, 9-1, 11-1, 12-12
- feedback uncertainty, 12-3, 12-10
- feedforward, 1-9, 1-10, 3-21, 7-19–7-22, 8-16, 11-1, 11-5, 11-7
- Fermi, E., 2-1
- filters
- active, 5-24
- for disturbance weighting, 12-27
- for measurement signals, 1-9, 7-25, 12-13
- zz, *see also* band-pass filters; high-filters; low-pass filters
- financial systems, *see* economic systems
- finite escape time, 4-3
- finite state machine, 1-15, A-5, A-12
- first-order systems, 5-4, 5-35, 8-8, 8-24, 8-25
- fisheries management, A-30
- flatness, *see* differential flatness

- flight control, 1-7, 2-28, 5-33
 - X-29 aircraft, 11-26
 - zz, *see also* vectored thrust aircraft
- flow, of a vector field, 2-3, 4-5
- flow in a tank, 4-33
- flow model (queuing systems), 2-30, 9-26, 10-24
- flyball governor, *see* centrifugal governor
- forced response, 5-3, 8-3
- Fourier, J. B. J., 2-36, 8-34
- frequency domain, 8-1–8-3, 9-1, 9-19, 11-1
- frequency response, 2-4, 2-18, 2-19, 3-4, 5-22–5-27, 8-2, 9-24, 10-11, 11-8
 - relationship to Bode plot, 8-22
 - relationship to Nyquist plot, 9-4, 9-6
- second-order systems, 6-19, 8-28
- system identification using, 8-29
- fully actuated systems, 8-12
- fundamental limits, *see* control: fundamental limitations
- Furuta pendulum, 4-36
- gain, 1-12, 2-18, 3-4, 5-23, 5-24, 6-20, 8-2, 8-6, 8-11, 8-22, 9-12, 9-19–9-22, 12-1, A-8
 - H_∞ , 9-20, 9-21, 12-25
 - observer, *see* observer gain of a system, 9-19
 - reference, 6-29
 - state feedback, 6-10, 6-11, 6-14, 6-29, 6-31
 - zero frequency, *see* zero frequency gain
 - zz, *see also* integral gain
- gain crossover frequency, 9-13, 9-14, 11-8, 11-12, 11-21, 12-5, 12-19
- gain crossover frequency inequality, 11-21, 11-23
- gain curve (Bode plot), 8-22–8-26, 9-16, 11-12
- gain margin, 9-12–9-15
 - from Bode plot, 9-13
 - reasonable values, 9-15
- gain scheduling, 7-20, 12-27
- gain-bandwidth product, 8-9, 12-15, A-10
- Gang of Four, 11-3, 11-33, 12-12
- Gang of Six, 11-3, 11-8
- gene regulation, 2-34, 2-35, 5-36, 8-28
- general solution to the
 - homogeneous equation, 3-1
- genetic switch, 2-39, 4-21
- global behavior, 4-10, 4-26–4-29
- Glover, K., 11-33, 12-28
- glucose regulation, *see* insulin-glucose dynamics
- Golomb, S., A-1
- governor, *see* centrifugal governor
- H_∞ control, 12-25–12-28, 12-30
- haptics, 3-19
- Harrier AV-8B aircraft, 2-28
- heat propagation, 8-10
- Heaviside, O., 5-33
- Heaviside step function, 5-20, 5-33
- Hellerstein, J. L., 1-16, A-17
- high-frequency roll-off, 11-13, 12-13, 12-20
- high-pass filter, 8-27, 8-28
- Hill function, 2-34
- Hoagland, M. B., 1-1
- Hodgkin-Huxley equations, 2-36
- homeostasis, 1-3, 2-34
- homogeneous equation, 3-2
- homogeneous solution, 5-3, 5-6, 8-11
- Horowitz, I. M., 7-26, 11-32, 12-23, 12-28
- human-machine interface, 1-15, A-1, A-4
- hysteresis, 1-11, 9-23
- identification, *see* system identification
- impedance, 8-8, 10-20
- impedance control, 3-19
- implementation, controllers, *see* analog implementation; computer implementation
- impulse function, 5-16, 5-34, 6-3
- impulse response, 5-5, 5-16, 5-17, 8-33
- inductor, transfer function for, 8-8
- inertia matrix, 2-10, 5-33
- infinity norm, 9-20, 12-26
- information systems, *see also* congestion control; web server control, 2-29–2-34
- initial condition, 4-2, 4-5, 4-8, 5-2, 5-6, 5-7, 5-14, 7-15
- initial condition response, 5-3, 5-6–5-9, 5-12, 5-14, 5-17, 8-3
- initial value problem, 4-2
- inner loop control, 11-30, 11-32
- input sensitivity function, *see* load sensitivity function
- input/output models, *see also* frequency response; steady-state response; step response, 1-5, 2-3–2-5, 5-2, 5-15–5-28, 8-1, 9-20
 - and transfer functions, 8-33
 - and uncertainty, 2-26, 12-3
 - from experiments, 8-29
 - relationship to state space models, 2-6, 4-1, 5-16
 - steady-state response, 5-19
 - transfer function for, 8-7
- inputs, 2-3, 2-6
- insect flight control, 2-21–2-22
- instrumentation, A-7
- insulin-glucose dynamics, 1-2, A-24–A-25
- integral action, 1-12, 1-13, 1-17, 6-29–6-32, 10-1, 10-3–10-4, 10-6, 11-10
 - for bias compensation, 7-27
 - setpoint weighting, 10-19, 10-23
 - time constant, 10-2
- integral gain, 1-12, 10-2, 10-4, 10-7

- integrator windup, 1-12, 7-25, 10-14–10-15, 10-24
- conditional integration, 10-25
- intelligent machines, *see* robotics
- internal model principle, 7-14, 7-21
- Internet, *see also* congestion control, A-11, A-13, A-16, A-29
- Internet Protocol (IP), A-13
- invariant set, 4-24, 4-27
- inverse, 3-21
- inverse model, 5-32, 7-19, 11-6
- inverse response, 3-22, 9-18, 9-26
- inverted pendulum, *see also* balance systems, 2-11, 4-6, 4-14, 4-25, 4-27, 4-34, 4-36, 9-10, 11-26, A-5
- Jacobian linearization, 5-29–5-31
- Jordan block, 5-9
- Jordan form, 5-9–5-12, 5-35, 6-22
- Kalman, R. E., 6-1, 6-31, 7-1, 7-23, 7-26
- Kalman decomposition, 7-22–7-24, 8-7, 8-34, 8-36
- Kalman filter, 7-15–7-18, 7-26, 12-24
 - extended, 7-20
- Kalman-Bucy filter, 7-17
- Kelly, F. P., A-16
- Kepler, J., 2-2
- Keynesian economic model, 2-38, 5-36
- Krasovski-Lasalle principle, 4-24
- LabVIEW, 4-29, 5-34
- lag, *see* phase lag
- lag compensation, 11-13, 11-14
- Laplace transforms, xi, 3-4, 8-31–8-34
- Laplace transforms and transfer functions, 3-4
- Laplacian matrix, 2-33
- Lasalle's invariance principle, *see* Krasovski-Lasalle principle
- lead, *see* phase lead
- lead compensation, 11-14–11-17, 11-30, 11-35
- limit cycle, 4-7, 4-15, 4-17, 4-28, 4-29, 9-22, 9-23, A-27
- linear quadratic control, 6-24–6-28, 7-16, 7-26, 12-23–12-25
- linear systems, 2-4, 2-8, 4-11, 5-1–5-34, 7-22, 8-3, 8-7, 8-34, 9-20, A-10
- linear time-invariant systems, 2-4, 2-8, 5-4, 8-33
- linearity, 5-3, 8-22
- linearization, 4-15, 4-24, 5-2, 5-28–5-33, 7-20, 12-1
- Lipschitz continuity, 4-4
- load disturbances, *see also* disturbances, 11-1, 12-13
- load sensitivity function, 11-3
- local behavior, 4-9, 4-15, 4-24, 4-26, 5-29
- locally asymptotically stable, 4-9
- logistic growth model, A-25, A-26, A-30
- loop analysis, 9-1, 11-1
- loop shaping, 9-4, 11-12–11-17, 11-32, 12-23
 - design rules, 11-13
 - fundamental limitations, 11-20–11-29
 - zz, *see also* Bode's loop transfer function
- loop transfer function, *see also* Bode's loop transfer function, 9-1–9-4, 9-12–9-14, 9-21, 11-1, 11-4, 11-12, 11-13, 11-15, 11-25, 11-33
- Lotus Notes server, *see* e-mail server
- low-order models, 10-6
- low-pass filter, 8-27, 8-28, 10-18
- LQ control, *see* linear quadratic control
- LTI systems, *see* linear time-invariant systems
- Lyapunov equation, 4-20, 4-34
- Lyapunov functions, 4-17–4-20, 4-27, 4-33, 5-34
 - design of controllers using, 4-24, 4-30
 - existence of, 4-19
- Lyapunov stability analysis, 2-18, 4-16–4-26, 4-32
 - discrete time, 4-35
- magnitude, 3-4
- manifold, 4-26
- margins, *see* stability margins
- Mathematica, 2-16, 4-29, 5-34
- MATLAB, 1-17, 2-16, 4-29, 5-34, 6-34
 - acker, 6-15, 7-11
 - dlqe, 7-16
 - dlqr, 6-28
 - hinfsv, 12-26
 - jordan, 5-10
 - linmod, 5-30
 - lqr, 6-25
 - place, 6-15, 6-23, 7-11
 - trim, 5-30
- matrix exponential, 5-6–5-9, 5-13, 5-15, 5-33, 5-34
 - coordinate transformations, 5-18
 - Jordan form, 5-10
 - second-order systems, 5-34
- maximum complementary sensitivity, 12-8, 12-19
- maximum selector, 1-14
- maximum sensitivity, 11-9, 12-6, 12-20
- measured signals, 2-5, 2-6, 2-8, 4-1, 7-1, 7-13, 7-25, 11-2, 11-4, 12-25
- measurement noise, 1-4, 1-9, 7-1, 7-3, 7-15, 7-17, 8-16, 10-18, 11-1–11-3, 11-13, 12-13
 - response to, 11-10–11-12, 12-13

- mechanical systems, 2-6, 2-10, 2-17, 2-26, 2-36, 5-33
- mechanics, 2-2-2-3, 2-5, 4-32, 5-1
- minimal model
 - (insulin-glucose), *see also* insulin-glucose dynamics, A-24, A-25
- minimum phase, 9-17, 9-24, 11-20
- minimum selector, 1-14
- modal form, 4-36, 5-19
- Modelica, 2-7
- modeling, 1-5, 2-1-2-7, 2-36, A-1
 - control perspective, 2-5
 - discrete control, 2-31
 - discrete-time, 2-12, 5-27-5-28
 - frequency domain, 8-1-8-3
 - from experiments, 2-22-2-23
 - model reduction, 1-5
 - normalization and scaling, 2-23
 - of uncertainty, 2-25-2-26
 - simplified models, use of, 2-6, 10-6, 12-2, 12-8, 12-9
 - software for, 2-7, 5-30, 5-33
 - state space, 2-8-2-18
 - uncertainty, *see* uncertainty
- modes, 5-12-5-14, 8-11
 - relationship to poles, 8-12
- motion control systems, 2-26-2-29, 7-26
- motors, electric, 2-40, 6-33, 7-28
- multi-input, multi-output systems, *see also* input/output models, 9-20, 11-4, 11-13
- multiplicative uncertainty, 12-3, 12-10
- nanopositioner (AFM), 9-15, 12-20
- natural frequency, 6-18, 10-8
- negative definite function, 4-17
- negative feedback, 1-6, 1-10, 6-10, 9-1, 10-5, A-9
- Nernst's law, 2-36
- networking, *see also* congestion control, 2-20, A-16
- neural systems, 2-22, 2-36, 10-5
- neutral stability, 4-8-4-10
- Newton, I., 2-2
- Nichols, N. B., 5-33, 10-10, 11-32
- Nichols chart, 12-23, 12-24
- Nobel Prize, 2-36, A-17
- noise, *see* disturbances; measurement noise
- noise attenuation, 8-29, 11-10-11-12
- noise cancellation, 4-30
- noise sensitivity function, 11-3
- nonlinear systems, 2-5, 4-1, 4-4, 4-7, 4-14, 4-16, 4-20, 4-26-4-32, 7-2, 7-20, 9-20-9-22
 - linear approximation, 4-15, 4-23, 5-29, 5-36, 12-1
 - system identification, 2-38
- nonminimum phase, *see also* inverse response, 9-17, 9-18, 9-26, 11-20-11-22
- nonunique solutions (ODEs), 4-3
- normalized coordinates, 2-23-2-25, 2-38, 5-31
- norms, 9-19-9-20
- Nyquist, H., 9-1, 9-24
- Nyquist criterion, 9-5, 9-7, 9-9, 9-12, 9-21, 9-22, 10-11
 - for robust stability, 12-6, 12-30
- Nyquist D contour, 9-4, 9-10
- Nyquist plot, 9-4-9-5, 9-12, 9-13, 10-11, 11-10, 12-24
- observability, 2-6, 7-1-7-2, 7-22, 7-26
 - rank condition, 7-3
 - tests for, 7-2-7-3
 - unobservable systems, 7-4, 7-22-7-23, 8-37
- observability matrix, 7-3, 7-5
- observable canonical form, 7-4, 7-5, 7-26
- observer gain, 7-7, 7-9-7-11, 7-13, 7-15-7-17
- observers, 7-1, 7-6-7-9, 7-17, 7-20
 - block diagram, 7-2, 7-10
 - zz, *see also* Kalman filter
- ODEs, *see* differential equations
- Ohm's law, 2-36, 8-8, A-9
- on-off control, 1-11
- open loop, 1-1, 1-2, 6-2, 8-18, 9-1, 10-14, 11-1, 11-9, 12-3, A-8
- open loop gain, 8-9, 9-12, 11-8
- operational amplifiers, 8-9, 10-20, 12-10, A-7-A-11
 - circuits, 5-24, 9-2, 12-14, A-28
 - dynamic model, 8-9, A-10
 - input/output characteristics, A-8
 - oscillator using, 4-35, A-28
 - static model, 8-9, A-8
- optimal control, 6-24, 7-15, 7-17, 12-24
- order, of a model, 2-8, 2-9, 8-7
- ordinary differential equations, *see* differential equations
- oscillator dynamics, 4-2, 4-3, 5-7, 5-8, 6-18, 8-5, 8-8, A-28
- normal form, 2-38
- zz, *see also* nanopositioner (AFM); spring-mass system
- outer loop control, 11-30-11-32
- output feedback, *see also* control: using estimated state; loop shaping; PID control, 7-11, 7-12, 7-26
- output sensitivity function, *see* noise sensitivity function
- outputs, *see* measured signals
- overdamped oscillator, 6-18
- overshoot, 5-21, 6-10, 6-19, 11-8
- P control, 3-7, 3-8
- Padé approximation, 9-26, 11-22

- paging control (computing), 2-31
- parallel connection, 8-15
- parametric stability diagram, 4-28, 4-29
- parametric uncertainty, 2-25, 12-1
- particular solution, *see also* forced response, 3-1, 5-22
 - non-uniqueness, 3-1
 - transfer function, 3-3
- passive systems, 9-21, 11-25
- passivity theorem, 9-22
- PD control, 3-18, 10-4, 11-14
- peak frequency, 5-26, 11-8
- pendulum dynamics, *see also* inverted pendulum, 4-19
- perfect adaptation, 10-5
- performance, A-12
- performance limitations, 11-20, 11-25, 12-19, 12-27
 - due to right half-plane poles and zeros, 9-17
 - zz, *see also* control:
 - fundamental limitations
- performance specifications, *see also* overshoot; maximum sensitivity; resonant peak; rise time; settling time, 5-21, 6-9, 11-1, 11-8–11-13, 12-12
- periodic solutions, *see* differential equations; limit cycles
- persistence, of a web
 - connection, A-12, A-13
- Petri net, 2-20
- pharmacokinetics, *see also* drug administration, A-21, A-25
- phase, *see also* minimum
 - phase; nonminimum
 - phase, 2-18, 3-4, 5-23, 5-24, 6-20, 8-2, 8-6, 8-22, 9-22
 - minimum vs. nonminimum, 9-17
- phase crossover frequency, 9-13, 9-14
- phase curve (Bode plot), 8-22–8-24, 8-26
 - relationship to gain curve, 9-16, 11-13
- phase lag, 5-23, 5-24, 8-28, 9-17, 11-21, 11-22
- phase lead, 5-23, 8-28, 11-16, 11-35
- phase margin, 9-13, 9-14, 11-13, 11-15, 11-21, 11-35, 12-29
 - from Bode plot, 9-13
 - reasonable values, 9-15
- phase portrait, 2-3, 4-4–4-6, 4-27
- Philbrick, G. A., A-11
- photoreceptors, 10-5
- physics, relationship to
 - control, 1-5
- PI Control, 3-9
- PI control, 1-6, 1-12, 3-8, 10-4, 10-9, 11-14, A-1, A-4
 - first-order system, 10-8, 12-18
- PID control, 1-11–1-12, 8-7, 10-1–10-23, 11-16
 - block diagram, 10-2, 10-4, 10-16
 - computer implementation, 10-21
 - ideal form, 10-1, 10-23
 - implementation, 10-4, 10-18–10-23
 - in biological systems, 10-5
 - op amp implementation, 10-20–10-21
 - tuning, 10-10–10-14
 - zz, *see also* derivative action; integral action
- pitchfork bifurcation, 4-36
- planar dynamical systems, *see also* second-order systems, 4-5, 4-10
- pole excess, 11-18
- pole placement, *see also* eigenvalue assignment, 6-10, 12-15, 12-19–12-20
 - robust, 12-15
- pole zero diagram, 8-12
- pole/zero cancellations, 8-19–8-21, 8-37, 12-19, 12-20
- poles, 3-3, 8-11, 8-12
 - dominant, *see also* dominant eigenvalues (poles), 10-9
 - fast stable, 12-18, 12-20
 - pure imaginary, 9-4, 9-10
 - relationship to eigenvalues, 8-11
 - right half-plane, 8-12, 9-10, 9-17, 11-20, 11-22–11-23, 11-25, 11-35, 12-20
- population dynamics, *see also* predator-prey system, A-25–A-27, A-30
- positive definite function, 4-17, 4-18, 4-20, 4-24
- positive definite matrix, 4-20, 6-25
- positive feedback, 1-9–1-10, 4-35, 10-4
- positive real (transfer function), 11-25
- power of a matrix, 5-6
- power systems (electric), 2-39, 4-7, 4-34
- predator-prey system, 2-12, 4-28, 6-15, A-26–A-27
- prediction, in controllers, *see also* derivative action, 1-12, 7-20, 10-4, 12-29
- prediction time, 10-5
- principle of the argument, *see* variation of the argument, principle of
- process control, 2-20
- proportional (P) control, 3-7
- proportional control, *see also* PID control, 1-11, 1-12, 3-7, 10-1
- proportional, integral, derivative control, *see* PID control
- proportional-derivative (PD) controller, 3-18
- Proportional-Integral Control, 3-9
- protocol, *see* congestion control; consensus
- pulse signal, *see also* impulse function, 5-16, 5-17, 6-21
- pupil response, 8-30, 10-5
- pure exponential response, 8-4
- Q-value, 2-39, 6-20, 8-26

- quantitative feedback theory (QFT), 12-23
- quarter car model, 8-37, 8-38
- queuing systems, 2-29–2-31, 2-39
- random process, 2-30, 7-15, 7-28
- reachability, 2-6, 6-1–6-9, 6-31, 7-22
- rank condition, 6-4
- tests for, 6-3
- unreachable systems, 6-5, 6-33, 7-22–7-23, 8-37
- reachability matrix, 6-3, 6-7
- reachable canonical form, 2-9, 6-6–6-9, 6-12, 6-14, 6-32
- reachable set, 6-1
- real-time systems, 1-5
- reference signal, *see also* command signals; setpoint, 1-11, 6-9, 6-10, 8-1, 8-16, 10-1, 10-19, 11-3, 11-5
 - effect on observer error, 7-12, 7-19, 7-24
 - response to, 11-8, 11-34
 - tracking, 6-9, 7-19, 7-20, 11-13, 12-14
- reference weighting, *see* setpoint weighting
- region of attraction, *see* equilibrium points: regions of attraction
- regulation problem, 3-7
- regulator, *see* control law
- relay feedback, 9-23, 10-13
- Reno (protocol), *see* Internet; congestion control
- repressilator, 2-35–2-36
- repressor, 2-35, 2-39, 4-21, 5-36, 8-29
- reset, in PID control, 10-3, 10-4
- resonant frequency, 6-20, 9-20
- resonant peak, 5-26, 6-20, 11-8, 12-9
- resource usage, in computing systems, 2-30, 2-32, A-11, A-12
- response, *see* input/output models
- retina, *see also* pupil response, 10-5
- Riccati equation, 6-25, 7-17, 12-26, 12-28
- Riemann sphere, 12-5
- right half-plane poles and zeros, *see* poles: right half-plane; zeros: right half-plane
- rise time, 5-21, 6-10, 6-19, 11-8
- robotics, 5-33
- robustness, 1-6–1-7, 11-8, 12-3, 12-28
 - performance, 12-12–12-15, 12-23–12-28
 - stability, 12-6–12-12
 - using gain and phase margin, 9-15, 11-12
 - using maximum sensitivity, 11-9, 11-12, 12-7, 12-29, 12-30
 - using pole placement, 12-15–12-22
 - via gain and phase margin, 9-14
 - zz, *see also* uncertainty
- roll-off, *see* high-frequency roll-off
- root locus, 11-17
 - asymptotes, 11-35
 - real line segment, 11-35
- root locus diagram, 4-29, 4-30
- root locus method, 11-17
- Routh-Hurwitz criterion, 3-5, 4-36
- Routh-Hurwitz stability criterion, 3-5
- rush-hour effect, 2-31, 2-39
- saddle (equilibrium point), 4-10
- sampling, 5-27, 7-24, 7-25, 10-22
- saturation function, *see also* actuators: saturation, 2-20, 10-21, A-8
- scaling, *see* normalized coordinates
- scanning tunneling microscope, A-17
- schematic diagrams, 2-19, 2-20, A-7
- Schitter, G., A-20
- second-order systems, 2-2, 5-34, 6-17–6-21, 6-34, 8-25, 10-9
- Segway Personal Transporter, 2-9, 6-4
- selector, 1-14
- selector control
 - of air-fuel, 1-14
- selector, maximum, 1-14
- selector, minimum, 1-14
- self-activation, 4-35
- self-repression, 5-36, 8-28
- semidefinite function, 4-17
- sensitivity crossover
 - frequency, 11-10
- sensitivity function, 11-3, 11-10–11-12, 11-25, 12-6, 12-14, 12-20
 - and disturbance attenuation, 11-9, 11-25, 11-34
- sensor matrix, 2-8, 2-12
- sensor networks, 2-32
- sensors, 1-3, 1-4, 7-2, 7-24, 9-17, 10-21, 11-1, 11-4, 11-22, 11-23, 12-24
 - effect on zeros, 9-18, 11-23
 - in computing systems, A-11
 - zz, *see also* measured signals
- separation principle, 7-1, 7-13
- series connection, 8-15
- service rate (queuing systems), 2-30
- servo problem, 3-11
- setpoint, 10-1
- setpoint weighting, 10-19, 10-23
- settling time, 5-21, 5-35, 6-10, 6-19, 11-8
- similarity of two systems, 12-3–12-6
- simulation, 2-15–2-17, 2-26
- SIMULINK, 5-30
- single-input, single-output (SISO) systems, 4-1, 5-2, 5-3, 5-29, 7-4, 9-20
- singular values, 9-20, 9-21, 12-30
- sink (equilibrium point), 4-10

- small gain theorem, 9-21–9-22, 12-9
- Smith predictor, 12-29
- software tools for control, x
- solution (ODE), *see*
 - differential equations: solutions
- source (equilibrium point), 4-10
- special particular solution, 5-3
- spectrum analyzer, 8-29
- Sperry autopilot, 1-7
- spring-mass system, 2-2, 2-15, 2-17, 2-18, 4-33, A-18
 - coupled, 5-14, 5-18
 - generalized, 2-10, A-7
 - identification, 2-22
 - normalization, 2-24, 2-38
 - zz, *see also* oscillator dynamics
- Stability, 3-5
- stability, 1-3, 1-5, 1-7, 2-17, 3-5, 4-4, 4-8–4-26
 - asymptotic stability, 4-8, 4-12
 - conditional, 9-9
 - in the sense of Lyapunov, 4-8
 - local versus global, 4-9, 4-16, 4-26, 4-27
- Lyapunov analysis, *see*
 - Lyapunov stability analysis
- neutrally stable, 4-8, 4-10
- of a system, 4-11
- of equilibrium points, 2-17, 4-8, 4-10, 4-17, 4-18, 4-24
- of feedback loop, *see*
 - Nyquist criterion
- of limit cycles, 4-15
- of linear systems, 4-11–4-13, 4-20, 5-10
- of solutions, 4-8, 4-9, 4-16
- of transfer functions, 8-12
- robust, *see* robust stability
- unstable solutions, 4-9
- using eigenvalues, 4-24, 5-10, 5-11
- using linear approximation, 4-14, 4-24, 5-30
- using Routh-Hurwitz criterion, 4-36
- using state feedback, 6-9–6-28
 - zz, *see also* bifurcations; equilibrium points
- stability diagram, *see*
 - parametric stability diagram
- stability margin (quantity), 9-13, 9-15, 11-9, 11-35, 12-7, 12-26
 - reasonable values, 9-15
- stability margins (concept), 9-12–9-16, 9-26, 11-12
- stable, 3-5
- stable pole, 8-12
- stable zero, 8-12
- Stark, L., 8-30
- state, of a dynamical system, 2-2, 2-5, 2-8
- state estimators, *see* observers
- state feedback, *see also*
 - eigenvalue assignment; linear quadratic control, 6-1–6-31, 7-7, 7-12, 7-19–7-21, 7-24–7-26, 12-16, 12-24
- state space, 2-2, 2-8–2-18, 6-9
- state vector, 2-2, 2-8
- static gain, 3-4
- steady-state gain, *see* zero frequency gain
- steady-state response, 1-17, 2-17, 5-19–5-27, 5-35, 6-10, 6-19, 8-2, 8-3, 8-5, 8-29, 8-34
- steam engines, 1-2, 1-6
- steering, *see* vehicle steering
- Stein, G., xii, 1-1, 11-1, 11-26
- step input, 2-4, 5-5, 5-20, 8-11, 10-10
- step response, 2-4, 2-5, 2-22, 2-23, 5-5, 5-17, 5-20, 5-21, 6-10, 6-18, 6-19, 10-10
- stochastic systems, 7-15, 7-17
- summing junction, 2-20
- superposition, 2-4, 5-3, 5-17, 5-34, 8-2
- supervisory control, *see*
 - decision making: higher levels of
- supremum (sup), 9-20
- switching behavior, 1-10, 1-16, 2-40, 4-23, 12-27
- system identification, 2-22, 2-38, 8-29
- system inversion, 3-21
- tapping mode, *see* atomic force microscope
- TCP/IP, *see* Internet;
 - congestion control
- Teorell, T., A-21, A-25
- three-term controllers, *see also*
 - PID control, 10-1
- thrust vectored aircraft, *see*
 - vectored thrust aircraft
- time constant, 3-2
- time constant, first-order system, 5-35
- time delay, 8-7, 8-8, 9-15, 9-17, 10-10, 10-21, 11-21–11-23
 - compensation for, 12-29
 - Padé approximation, 9-26, 11-21
- time plot, 2-3
- time-invariant systems, 2-4, 2-8, 4-33, 5-4–5-5
- TM, 3-20
- tracking, *see* reference signal: tracking
- tracking mode, 10-17
- trail (bicycle dynamics), A-6
- transcription factors, 2-34
- transcriptional regulation, *see*
 - gene regulation
- transfer function, 3-3
- Transfer functions, 3-4
- transfer functions, 8-1–8-34
 - by inspection, 8-7
 - derivation using exponential signals, 8-3
 - derivation using Laplace transforms, 8-33
 - for control systems, 8-16, 8-36
 - for electrical circuits, 8-8
 - for time delay, 8-7
 - frequency response, 8-2, 8-22
 - from experiments, 8-29
 - irrational, 8-8, 8-11

- linear input/output systems, 8-3, 8-7, 8-36
- Transfer functions and Laplace transforms, 3-4
- transient response, 2-17, 5-20, 5-21, 5-23, 6-2, 6-22, 8-3, 8-4
- Transmission Control Protocol (TCP), A-13
- tuning rules, *see* Ziegler-Nichols tuning, 10-24
- Tustin, A., 3-1
- two degree-of-freedom control, 7-19, 10-2, 11-5, 11-7, 11-32, 11-34
- two degrees of freedom, 3-12, 3-13, 3-24
- two degrees of freedom, 2 DOF, 3-24
- uncertainty, 1-4, 1-6–1-7, 2-6, 2-25–2-26, 6-29, 12-1–12-6
 - component or parameter variation, 1-4, 2-25, 12-1
 - disturbances and noise, 1-4, 2-6, 6-9, 8-16, 11-1
 - unmodeled dynamics, 1-4, 2-25, 12-2, 12-7
 - zz*, *see also* additive uncertainty; feedback uncertainty; multiplicative uncertainty
- uncertainty band, 2-25
- uncertainty lemon, 2-25, 2-26, A-4, A-10, A-20
- undamped natural frequency, 3-9
- underdamped oscillator, 4-3, 6-18, 6-19
- unit step, 5-20
- unmodeled dynamics, *see* uncertainty: unmodeled dynamics, 3-10
- unstable pole, *see* poles: right half-plane
- unstable pole/zero cancellation, 8-20
- unstable solution, for a dynamical system, 4-9, 4-10, 4-12, 5-10, 8-12
- unstable zero, *see* zeros: right half-plane
- variation of the argument, principle of, 9-11, 9-24
- vector field, 2-3, 4-5
- vectored thrust aircraft, 2-28–2-29, 5-11, 6-25, 7-17, 8-36, 11-15, 11-29
- vehicle steering, 2-26–2-28, 5-30, 6-11, 7-9, 7-14, 7-21, 8-17, 9-18, 9-25, 11-7, 12-16
 - ship dynamics, 2-26
- vehicle suspension, *see also* coupled spring-mass system, 8-37
- vertical takeoff and landing, *see* vectored thrust aircraft
- vibration absorber, 8-38
- Vinnicombe, G., 11-33, 12-5, 12-28
- Vinnicombe metric, 12-3–12-6, 12-26
- voltage clamp, 2-36
- waterbed effect, 11-25, 11-26
- Watt governor, *see* centrifugal governor
- Watt steam engine, 1-3, 1-6
- web server control, 6-26, A-11–A-13
- web site, companion, x
- Whipple, F. J. W., A-7
- winding number, 9-11
- window size (TCP), 4-10, A-14, A-16
- windup, *see* integrator windup
- Wright, W., 1-7
- Wright Flyer, 1-7
- X-29 aircraft, 11-26
- Youla parameterization, 12-10–12-12
- zero frequency gain, 3-4, 5-25, 6-11, 6-14, 6-20, 8-11
- zero:blocking property, 3-4
- zeros, 3-3, 8-11
 - Bode plot for, 8-36
 - effect of sensors and actuators on, 9-18, 11-23
 - for a state space system, 8-12
 - right half-plane, 8-12, 9-17, 11-20–11-23, 11-26, 11-35, 12-19
 - signal-blocking property, 8-11
 - slow stable, 12-16, 12-17, 12-19
- Ziegler, J. G., 10-10, 10-23
- Ziegler-Nichols tuning, 10-10–10-13, 10-23
 - frequency response, 10-11
 - improved method, 10-11
 - step response, 10-10

