Below is a short reference list describing a few of the many important and readable books relevant to the study of computational and neural systems. The books listed contain material ranging far beyond the scope of this course, but you may find them useful as you progress from the most basic material to more complicated ideas. The list emphasizes mathematics, as this is the area which CNS students generally find most difficult to navigate without a guide.

Neurobiology and Neural Networks

• Shepherd, G. (ed.) (3rd edition, 1990) **The Synaptic Organization of the Brain** , Oxford University Press.

A very good overview of sensory, motor and memory systems in the brain. Each chapter is written by people knowledgeable in the field and contains a wealth of information useful to theorists (basic anatomy, type and number of cells involved, etc.)

• Kandel, E., Schwartz, J., Jessell, T. (3d edition, 1991) **Principles of Neural Science**, Elsevier.

This is a large, medical-textbook style text. By this I mean that it is not big on theoretical thinking about underlying issues. Goes superficially over almost everything in neuroscience, and despite this treatment still runs to about 800 pages– which goes to show that there is a *lot* of still-unstructured information in neuroscience. A very good starting point nevertheless, it is used in Bi150.

• Koch, C., Segev, I., ed., (1989) **Methods in neuronal modeling: from synapses to networks**, MIT Press.

If compartmental models of neurons is your thing, this is the place to go. Describes the cable equation and its solutions.

• Levitan and Kaczmarek (1991), **The Neuron: Cell and Molecular Biology**, Oxford University Press.

This book takes a closer look at neurons, their insides and their membranes. Chapter 17 (Learning and memory) contains a very readable brief account of conditioning and of what was known in 1991 about LTP.

• Hertz, J., A. Krogh, and R. Palmer, (1991) **Introduction to the theory of neural computation**, Santa Fe Institute studies in the sciences of complexity, Addison-Wesley.

An excellent synopsis of formal neural networks, from a physics perspective. Required text.

Mathematics

Calculus

• Tom Apostol (1962) **Calculus.** Blaisdell, Random House, New York.

The material covered in a basic calculus course is the starting point for almost every mathematical investigation of neural computation. Apostol's text is a proven reference for this basic information. As well as the usual copious exercises in one-variable differential and integral calculus, this book lays the groundwork for a more theoretical view, with sections on limits and continuity, induction, Riemann's notion of integration, and more.

• Francis Hildebrand (1976) **Advanced calculus for applications.** Prentice-Hall, Englewood Cliffs.

The tools of differentiation and integration find their widest application in the study of ordinary and partial differential equations. Hildebrand's book bridges the gap between a basic course and more advanced applications. In addition to sections on ODE's and PDE's, some transform theory, boundary value problems, vector analysis, and numerical methods are presented. Hildebrand is not the most readable text, but since it covers a wide range of problems and has both examples and exercises with an appendix of solutions, it is a useful reference.

• Michael Spivak (1965) **Calculus on manifolds.** Benjamin/Cummings, Menlo Park.

The material in this deceptively thin monograph cannot be called essential to the study of neural computation. However, it is important to be aware of this classic book because it is a gateway to an imposing body of work – integration and differentiation on non-Euclidean spaces. Detailed considerations of geometry have proven useful in almost every part of physics and applied math, and they may yet be applicable to the study of sensorimotor transformations, dynamic neural behavior, and pattern formation in biology as well.

Linear Representations

• Gilbert Strang (1976) **Linear Algebra and its Applications.** Academic Press, New York.

Even advanced calculus courses can fail to make clear definitions of important mathematical objects and their representations. The properties of vectors and transformations of vectors are of supreme importance to neural computation, since these objects are associated with everything from the kinematic states of a skeleton to the activity of a neural population. Strang offers one of the most readable introductions to vectors and linear transformations around. All the key ideas of orthogonality, eigenstructure, and linear representation are introduced.

• Eugene Butkov (1968) **Mathematical physics.** Addison-Wesley, Reading.

Many of the methods physicists deem essential center on the definition of interesting objects (vectors, tensors, homogeneous transformations, metrics, to name a few) which correspond to physical observable or processes. Almost any book with the words "mathematics," "methods," and "physics" in the title will develop the special tools and techniques physicists need. Most if not all of these tools have been used in the study of neural computation, and Butkov provides one (of many) readable reference in this area. Topics of such books include function spaces and special functions (Bessel, Hankel, Gamma, etc.), Laplace and Fourier transforms, calculus of variations, perturbation theory, and more.

• Richard Courant and David Hilbert (1953) **Methods of Mathematical Physics**, Volume 1. Interscience, New York.

There are many books with similar titles, but Courant and Hilbert is clearly a classic. Its two volumes contain all the material in books like Arkfen above, but with greater detail and sophistication. Unfortunately, this is sometimes at the expense of readability. As a result, to get a handle on a difficult concept it is often useful to read the relevant section in an introductory text (like Arfken) and the read the same material in Courant and Hilbert. The unusually detailed table of contents is useful for exactly this type of cross referencing.

Dynamical Systems

• Ralph Abraham and Christopher Shaw (1992) **Dynamics: the geometry of behavior.** Addison-Wesley, Redwood City.

The language and metaphors of nonlinear dynamical systems have infiltrated, and in some cases dominated, many aspects of neural network research. The collection of ideas produced by this branch of applied mathematics – attractors, chaos, bifurcation, structural stability, and more – are essential knowledge for the student of neural computation. Abraham and Shaw is an unorthodox book in that it consists of only pictures and text – essentially no equations. However, this visual presentation is more than sufficient to explain surprisingly sophisticated concepts and proofs. The motivated student could read the entire volume in a few sittings, and would come away with an invaluable intuition for proofs and concepts at the frontiers of research.

• Morris Hirsch and Stephen Smale (1974) **Differential equations, dynamical systems, and linear algebra.** Academic Press, New York.

For a solid discussion of what is known about linear differential equations, ranging from existence and uniqueness to full solutions, Hirsch and Smale is one of the best books around. More importantly, linear ODE's are treated with the language of nonlinear dynamical systems, so the key ideas of the phase plane, Lyapunov stability, and qualitative analysis are clearly introduced.

• Stephen Wiggins (1990) **Introduction to applied nonlinear dynamical systems and chaos.** Springer-Verlag, New York.

The title says it all in Wiggins's book, and it provides a useful bridge from linear theory (a la Hirsch and Smale) to the current applied mathematical literature. Poincare maps, center manifold theory, normal forms, and bifurcations are all covered here, and the seemingly endless pages of exercises will leave the student with valuable, if hard-earned, concrete knowledge. The currently popular notion of chaos is introduced in detail, along with the kinds on methods people actually use to prove that a system is chaotic. The treatment here provides a perfect complement to the equation-free discussions of chaos in Abraham and Shaw.

Probability and Random Processes

• Athanasios Papoulis (1991) **Probability, random variables, and stochastic processes.** McGraw-Hill, New York.

Whether at the level of the ion channel, the single neuron, or abstract networks of neurons, non-deterministic analysis plays an important role in computational neuroscience. Papoulis's book is a fairly self-contained introduction to the notions of random variables and random processes. What it may lack in stylistic flair it makes up for in comprehensiveness; with sections on Markov processes, Brownian motion, spectral estimation, Kalman filtering, and more, it is a useful "first stop" in the search for a particular subtopic in this category.

• William Feller (1950) **An introduction to probability theory and its applications**, Volumes I and II. John Wiley and Sons, New York.

Feller is one of the most referenced texts in probability, and although the word "introduction" is in the title, it contains a lot of material that is quite advanced for the non-mathematician. Volume I covers the foundational results concerning random variables and distributions in more detail than Papoulis, with particular emphasis on combinatorial analysis. Volume II reviews measure theory, which is the "language" of modern probability. The volumes are generally less useful than Papoulis when seeking the answer to a particular question, but they are important references since they contain many mathematical details and examples.

Computer Science

The Theory of Computation

• John Hopcroft and Jeffrey Ullman (1979) **Introduction to automata theory, languages, and computation.** Addison-Wesley, Reading.

The creation of algorithms and computer programs for solving problems has evolved into a science in its own right, and Hopcroft and Ullman is a standard and clearly written reference. There is nothing remotely "neural" in this book, but the ideas it presents can still be useful without suggesting any equivalence between brains and computers. Anyone interested in neural computation should have a passing knowledge of the basic ideas of deterministic and non-deterministic automata, formal languages and grammar, and polynomial-time algorithms.

• Aho, A., Hopcroft, J. and Ullman, J., (1974) **The design and analysis of computer algorithms**, Addison-Wesley.

Another computer science book by the same (mostly) authors. This text focusses more on the practical issues of solving problems with computers, and less (relatively) on the mathematical and formal aspects of computation.

• Michael Garey and David Johnson (1983) **Computers and intractability: a guide to the theory of NP-completeness.** W.H. Freeman, New York.

The classification of algorithms into categories of P, NP, NP-hard, etc., has provided a useful formal framework with which to judge the tractability of computational problems. The letters refer to how long a particular problem may take with respect to the "size" of that problem, and Garey and Johnson provides an extremely readable introduction to these ideas. Although some of the problems studied by computer scientists (e.g. graph partitioning, map coloring, etc.) seem far removed from the problems of neural computation, rather surprising connections exist at the abstract level.

Numerical Methods and Optimization

• William Press *et al.* (1988) **Numerical recipes in C: the art of scientific computing.** Cambridge University Press, New York.

This book has rapidly become the bible of scientific computing. Although the "C" edition is popular and ubiquitous, versions of the book exist for other programming languages (e.g. Pascal, FORTRAN) as well. Whether your problem calls for sorting, minimizing or maximizing functions, solving simultaneous equations, or integrating differential equations, this book will have algorithms, explanations, *and* bug-free C code for you.

Engineering and Information Theory

• Paul Horowitz and Winfield Hill (1989) **The art of electronics.** Cambridge University Press, Cambridge.

For a totally self-contained introduction to electrical circuit design, Horowitz and Hill cannot be beaten. Starting with the ideas of voltage and current, the book develops passive and active corcuit analysis, transistors and their use in operational amplifiers and filters, and precision and low-noise techniques. Additional sections deal with digital circuits, microprocessors, and high-speed, high-frequency techniques. A lab manual can be purchased as well, making the set a complete teach-yourself guide to electronics.

• Claude Shannon and Warren Weaver (1963) **The mathematical theory of communication.** University of Illinois Press, Urbana.

This monograph (reprinted and expanded from 1948) introduced the foundations of what is now called information theory: the formal study of coding and communication. This is not a textbook, but it is useful to see the original form in which notions like channel, mutual information, and capacity were expressed. Sections giving intuitive background to the crucial concept of entropy are also notable.

• Thomas Cover and Joy Thomas (1991) **Elements of information theory.** Wiley, New York.

There are fewer good modern textbooks on information theory than one would hope. Cover and Thomas is certainly up-to-date and comprehensive, although it moves a bit quickly and formally at times. The standard topics of data compression, channel capacity, and rate distortion are covered well, and in addition chapters on harder-to-find topics such as Kolmogorov complexity, hidden Markov models, gambling, and the stock market are included. The index and reference list are quite extensive, with many topics and references from the last ten years of research.

• Mead, C. (1989) **Analog VLSI and neural systems**, Addison-Wesley.

The basic book for CNS 182, this book tells about the Mead lab's efforts towards building an electronic brain in a chatty style full of interesting observations. Chapter 2 is an electronics primer, chapter 3 a transistor physics primer, and chapter 4 a neurons and neuroscience primer.

• Gersho, A. and Gray, R. (1992) **Vector Quantization and Signal Compression**, Kluwer Academic.

This is an excellent text on vector quantization. It starts out from basic stochastic modeling, talks about scalar and vector quantization and efficient searching techniques.