Neural networks

1. Announcements
   a. Exams. Most people did better. 1/3 class got As. 1/3 class got Bs. 1/3 class lower.
   b. Final projects. 14%, just like an exam. 8% written report and 6% an oral presentation. A topic of interest of maths used in cognitive science. Short paper: 1000 words. Paper should include references demonstrating that you’ve adequately researched the topic. 10 minute presentation. Start looking around for ideas. If there’s something that interests you, come talk to me, and I can help point you in the direction of something interesting.

2. Introduction to neural network unit
   a. The mathematics developed in the previous unit are useful to understand the process of computation.
   b. Cognition has been traditionally dominated by the brain as a computer.
   c. Computation is useful for certain tasks:
      i. Factory automation
      ii. Number crunching
      iii. Abstract symbol manipulation
      iv. Logical reasoning
      v. Anything that’s not going on in the real world, in real time, with real objects.
   d. Not only are humans not so good at those tasks (certainly not as good as computers), but we are much better at other tasks that are quite different in nature.
      i. Perception
      ii. Movement
      iii. Locomotion
      iv. Object manipulation
   e. Tasks that systems operating under a the computational paradigm started to proved they were particularly bad at.
   f. In the 1960s, a group of researchers started to take inspiration in the brain.
   g. The realization was, if the brains are these powerful things that do all sorts of amazing tasks:
      i. Walking, Talking
      ii. Reading, Writing
      iii. Recognizing hundreds of faces and objects irrespective of light and distance
      iv. Drinking from cups
      v. Giving a lecture
      vi. Driving cars
      vii. Climbing mountains
   h. (Even though it’s not the brain alone, it’s also because of our bodies.)
   i. Then maybe we should understand brains a little more, and try to understand cognition from the perspective of the properties of biological brains and bodies.
j. A typical human brain is composed of $10^{11}$ neurons. Neurons themselves are not all that smart. Their behavior is relatively simple. But when many of them are connected, the emergent behavior is remarkable.

k. Unlike biology, the purpose of these studies was not to understand the specifics of each neuron and each area of the brain, but the principles underlying the units that compose the brain, and the characteristics of their interconnections such that their emergent property can results in intelligent behavior.

3. **Some differences between computers and brains**
   a. Parallelism.
      i. Computers function in a sequential manner.
      ii. Brains are massively parallel. Densely connected. Each neuron has about 10000 connections to other neurons.
      iii. In computers, the units are sophisticated, complex, and there’s usually not many, and they are trivially connected.
      iv. In brains, the units are relatively simple, but there’s many of them and they are massively and complexly connected.
   b. Graceful degradation.
      i. Property of natural systems that computers lack.
      ii. Noise and fault tolerant.
      iii. Ability to generalize.
   c. Adaptability and learning
      i. Continuously learning from the environment.
      ii. Impossible not to learn: once we’ve finished this lecture we’ll all have changed forever, whether we like it or not.
      iii. Ability to remember.
      iv. Even more interestingly, ability to forget, selectively.
   v. The organization of memory, as we understand it, works completely different from computers. Computers work with precise addresses. Biological memory works in associative ways - trying to remember what happened that day, where we were, what we were listening to, etc.
   vi. Unlike computers, brains get tired. They need sleep to recover.
   d. Nonlinearity.
      i. Neurons are highly nonlinear.
      ii. This helps to solve problems that are noisy and nonlinear.
   e. Plasticity
      i. Brains are plastic.
      ii. Interesting examples: When the optic nerves of a ferret are connected to its auditory cortex, that part of the brain develops in similar structures to the visual one.
   f. Paradox of the expert.
      i. In computers, the bigger the database the longer it takes it to search for an answer.
      ii. In humans this is not trivially true. The more someone knows, it’s not necessarily true that it takes them longer to arrive at answers.
g. Context
   i. Biological organisms are particularly good at understanding context. (THE CHT), visual, auditory, in every aspect.
   ii. This is something that computers are particularly bad at.

4. From biological to artificial neural networks
   a. Human brain.
      i. Lots of neurons $10^{11}$.
      ii. Highly interconnected: each connected to 10000 other neurons. $10^{14}$ connections.
   b. Awesome complexity.
   c. For the cognitive scientist, it’s not necessarily the specific details that matter the most, but the principles of how such a system operates.
   d. Main components of a biological neuron:
      i. SKETCH
      ii. Dendrites - transmit information from other neurons to the cell body of the neuron.
      iii. Cell body of the neuron - sums, and processes the information from the other neurons.
      iv. The axon - transmits the cell body’s output, which depends on the summation of inputs, as well as it’s present state, to other neurons.
      v. Sometimes a spike is generated. Sometimes it’s just a gradual signal.
      vi. Connections between two neurons can be either inhibitory or excitatory.
      vii. Connections between two neurons can have different strengths.
   e. This is a highly simplified sketch of a neuron. There are many different types of neurons, with many different properties. This is an area of active exploration, with new exciting results being presented every single day.
   f. For theoreticians, that it is a highly simplified, abstract, idealized, version of a neuron is seen as a virtue.
      i. For example, it takes time for the signal to travel through the axon. This is simplified away in the model.
      ii. The size of the neuron, the specifics of how the neuron is connected, and the chemical channels that it has, play a major role in the specifics of what it can do. But this is usually simplified away in the simpler models.
   g. There are different interpretations for the activity of a neuron.
      i. Average firing rate of a spiking neuron.
      ii. Or gradual non-spiking neuron.
   h. There are probably as many different models of neurons as there are types of neurons, and certainly as many as there are modelers of neurons. Some, for example, are specific to spiking neurons. Some describe more closely the biophysical mechanisms of the neuron. Some try to capture the physiology of pools of neurons in specific parts of the brain.
   i. The main point for now, is that even the most simple unit can achieve a lot.
   j. *The aim of this unit will be to understand how interesting things can be achieved using such simplified elements.*
5. History
   a. 1943 McCulloch and Pitts. A logical calculus immanent in the nervous activity.
   b. 1958. Rosenblatt published his seminal work on perceptrons (binary classifier).
   c. 1969. Minsky and Papert published a mathematical proof of some limitations of the
      perceptron. Symbolic approach took over during the seventies and part of the eighties.
   d. Because of problems in AI, and the realization that the proof of the limitation could be
      easily overcome, from 1985 to 1990 there was a rebirth of neural networks -
      connectionism.
   e. Connectionism - Many simple interconnected units working in parallel.
      i. Learning systems. The systems didn’t have to be programmed to solve a specific task,
         they could be trained to solve a specific problem using training data.
      ii. Emergent properties.
         1. When analyzed, it can show that it has abstracted certain principles about the data.
         2. Or, also, when tested on different data, it can show that it’s generalized about
            certain types of data.

6. Applications
   a. Cognitive science - to understand intelligent behavior.
   b. Neurobiological modeling - to understand how neurons work.
   c. Computer science: Optimization, control, signal processing, classification problems,
      pattern recognition, stock market prediction.

7. Basic concepts
   a. There is an enormous literature on neural networks and a rich variety of neural network
      models, learning algorithms, architectures, and philosophies. Still, a few principles can be
      identified - at least as a good starting point for anyone wanting to dig deeper.
      i. The characteristics of the node/unit/neuron/processing element. How does the node
         sum the inputs? How is this activity transformed into a level of activation? How is the
         level of activation updated? How much input does it take to activate the neuron? And
         finally, how is it transformed into an output that is then transmitted along the axon?
      ii. The connectivity. It must be specified which nodes are connected to which other
          nodes.
      iii. Propagation rule. It must be specified how a given activation that is traveling along an
          axon is transmitted to the neurons which it is connected to.
      iv. Learning rule. It must be specified how the strengths of the connections vary over
          time.
      v. Embedding the network in the physical system. How are the neurons connected to the
         sensors and motors of the body.
8. Node characteristics.
   a. SKETCH -- summing and processing
   b. $y_i = g \left( \sum_{j=1}^{n} w_{ij} o_j \right) + \text{bias}_i$
   c. --- Note on notation for the activation.
      i. Biologists tend to use $v$ for voltage.
      ii. Computer scientists tend to use $a$ for activation.
      iii. Mathematicians use $y$ because they are cool.
   d. where $y_i$ is the level of activation of neuron $i$
   e. $o_j$ is the output of other neurons
   f. $g$ is an activation function
   g. $h_i$ is the summed activation of the input
   h. Most widely used activation function is the sigmoid or logistic function - a smooth version of a step function.
      i. Linear activation functions.
      ii. Step activation functions.
      iii. Sigmoid activation functions.  $g = 1 / (1+e^{-2bh_i})$
         1. where $B = 1/K_bT$, where $T$ can be understood as the absolute temperature.
      iv. Sigmoid is the most natural because of the saturation properties and the nonlinearity.
   v. $\tanh(x) = e^x - e^{-x} / e^x + e^{-x}$

9. Connectivity characteristics.
   a. Directed graphs.
   b. Matrix representation of the strengths of the network.
   c. Feedforward networks: input layer, one or more interneuron layer, output layer. No internal state. Output is a function of the input.
   d. Recurrent network. Feeds the output back into the input. Means that the output is a function of the input and itself. Dynamical system. Exhibit different phenomena: reach a stable state. Exhibit oscillations. Become chaotic. They have internal state - which one can think of as short-term memory. More interesting models of the brain. But also a little harder to understand!
   e. Fully-connected.
   f. We’ll focus only on feedforward networks.

    a. The weight of the connection determines the effect that a neuron will have on another neuron.
    b. Normally, a weighted sum is assumed.
    c. But a multiplicative connection could also be used.