An Introduction to Learning

Lecture 2/15

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What is learning?

I think we all probably have some idea about what learning is. However, as soon as you try to define it, you can quickly find yourself stuck.

Learning is the acquisition of a new behavior or a change in behavior over time, which is dependent on experience, is not entirely transitory, and which is for the most part adaptive.
The Learning Game!

Which of the following examples are or are not learning?
Learning?

Students in a classroom follow a lab report to perform and experiment and write a report of their results.
A rat is rewarded with food each time it presses a lever on one side of its cage while a red light is on. Over time the rat starts to immediately run over to the level and press it as soon as the light turns on.
Learning?

A child doesn’t like members of the opposite sex, but over time their opinion changes somewhat.
Learning?

A child goes from only eating macaroni and cheese and frozen peas to liking swiss cheese and caviar as an adult.
Learning?

A drug user develops a tolerance to a particular substance in the course of abuse.
Learning?
The Dynamics of Associative Learning in Evolved Model Circuits

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<table>
<thead>
<tr>
<th>Environment A</th>
<th>Environment B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food 1</td>
<td>Food 1</td>
</tr>
<tr>
<td>-&gt; Edible</td>
<td>-&gt; Not Edible</td>
</tr>
<tr>
<td>Food 2</td>
<td>Food 2</td>
</tr>
<tr>
<td>-&gt; Not Edible</td>
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</tr>
</tbody>
</table>

All agents can smell (S) to distinguish food, open-close mouth (M), and receive reward (R).
Figure 2  The structure of an individual trial. A trial is divided into five phases. First, a smell signal is applied. Second, the state of the mouth is evaluated relative to the correct action for the current environment (bold line). Third, there is a variable random delay. Fourth, a reinforcement signal proportional to the correctness (cross-hatched region) of the previous action is applied. Fifth, there is another variable random delay before the next trial begins.
Continuous Time Recurrent Neural Network (CTRNN) with NONPLASTIC Weights

- $N^2 + 4N$ parameters to fully specify
- Activation of any neuron depends only on weighted inputs from other neurons
- Recurrent because A can influence B which can in turn influence A

\[
\tau \dot{y}_i = -y_i + \sum_{j=1}^{N} w_{ij}\sigma(y_j + \theta_j) + s_i S(t) + r_i R(t)
\]

$i = 1, \ldots, N$
Possible “strategies”

- Always open mouth or close it, best is 50%
- Strategy depends only on smell/food type, best 50%
- “Law of effect” if last opened mouth and rewarded, then open mouth again, etc... best 50%
- Associative learning strategy... depending on environment, best is 50%
Best evolved non-plastic three neuron network had fitness of 99.99% at end, and on a generalization test got 99.97% correct!

Figure 3  A plot of the best fitness versus generation for the best evolved three-neuron nonplastic circuit. Transitions between stages of our incremental shaping protocol are marked with dashed lines and labeled by the length of the trial sequences used in that stage. Transitions occur when the best fitness reliably exceeds 0.95 (horizontal gray line). Note that the fitness drops sharply after the 2→3 and 3→6 transitions before the circuit can generalize to sequences of arbitrary length. Indeed, the 6→7 and the 7→8 transitions occur so close together that they appear as a single line.
Figure 4  Activity of the best three-neuron nonplastic circuit on a typical trial sequence. From top to bottom the traces correspond to the reinforcement signal (R), the smell sensor (S), the mouth state (M, given by the output of neuron 1) and the outputs of the remaining neurons (o). Small rectangles mark the time during which the mouth state is evaluated and the state that the mouth should be in during this time, with correct actions denoted by black rectangles and incorrect actions denoted by gray rectangles. Transitions between environments are marked by dashed lines. Note that the circuit takes an incorrect action and receives negative reinforcement after each environment transition before modifying its action map to be appropriate to the new environment.
Figure 6  The nonautonomous dynamics of the best three-neuron nonplastic circuit during the trial sequence $\uparrow O+\uparrow O-\uparrow \bullet +$, which switches from environment A to environment B after the first trial. As the input signals change throughout this sequence, the circuit's autonomous dynamics is switched between the different phase portraits shown in Figure 5 and its state is attracted to the stable equilibrium point in whose basin it finds itself at each point. The change in action map from environment A to environment B is accomplished by shifting the circuit's operating region from the neighborhood of the right stable equilibrium point of $\mathcal{P}_0$ to the neighborhood of the left stable equilibrium point of this phase portrait.
Learning?
Conclusions: Adaptive learning without adaptive weights!

“Despite the fact that the basic CTRNN model lacks synaptic plasticity, an evolutionary algorithm was able to shape the network dynamics so that the agent could both generate bites in response to edible food while ignoring inedible food and learn which food was edible through the reinforcement it received from its interactions with its environment. In the best evolved circuits, this learning ability generalized to much longer trial sequences than they were evolved on.” (page 391)
Is learning synonymous with changes in weights?

“Although many view synaptic plasticity as definitional of learning, strictly speaking, learning is a behavioral phenomena, whose underlying mechanisms remain to be empirically investigated” (page 378)

• The term learning is, in fact, a very misleading one, and one that is perhaps best abandoned as a relic of an earlier age, and an earlier misunderstanding. (Noam Chomsky, *On the nature, use, and acquisition of language*, 1999, p43)
Historical Perspectives

“Those who cannot learn from history are doomed to repeat it” - George Santayana
A little history....

Progress (hopefully)
A little history....

Psychoanalytic Theory! \rightarrow \text{SCIENCE!} \rightarrow \text{COMPUTERS!} \rightarrow \text{Cognitive “Revolution”}

Reality?
A little history....

The BRAIN!

Cognitive Neuroscience!

Genes!
Epigenetics!
Quantum Theory!
String Theory!

Reality?
A little history....

Progress (yes, actually***)

** particularly in the area of learning where there is a very clear arc of incrementally more complex and detailed science
A little history....

Key Movements

Philosophical Views
Natural Science
Experimental Psychology
Behaviorism
Cognitivism

Observational studies
Manipulation/experimentation
Mathematical Psychology
Computational Approaches
Cognitive Neuroscience

Key technical/conceptual developments
Philosophical Approaches

(note philosopher’s beard)

http://xkcd.com/675/
Philosophical Approaches
(note philosopher’s beard)

http://chaospet.com/2009/12/14/164-it-goes-both-ways/
Philosophical Approaches

- **Aristotle** (384-322 BC)
- **Plato** (427-347 BC)
Philosophical Approaches

Most of knowledge is inborn and acquired during past lifetimes.
Philosophical Approaches

Nature!

Aristotle

Plato

Nurture!

Memory is associations which depend on continuity, frequency, and similarity.
Nature!

Philosophical Approaches

Aristotle

Plato

Memory is associations which depend on continuity, frequency, and similarity.

Contributions:

This is still a topic of endless discussion!
Nice work guys on getting the early cite on that one.
Nature versus Nurture
ala Pinker (2004)

• English speakers speak English, Japanese speakers speak Japanese

• We acquire novel concepts quickly (smartphone, computer)

• Individual experience largely shapes who we are, the experiences we draw on for wisdom, problem solving, etc...

• Twin studies show remarkable heritability of personality and other behaviors

• Genetic markers correlate with various basic cognitive behaviors
Nature versus Nurture

or...

Waddington’s epigenetic landscape
De novo establishment of wild-type song culture in the zebra finch

Olga Fehér¹, Haibin Wang², Sigal Saar¹, Partha P. Mitra² & Ofer Tchernichovski¹
Critical periods

Duration of critical period depends on species and seems to scale with lifespan
Critical periods in language?
Newport, Bavelier, & Neville (2001)

- Age of exposure highly predicts eventual language proficiency (decreasing with age)
- Effects both first and second languages - accent, production and syntax, speed/accuracy
- Possibly due to interference from first language? ASL speakers show age effects on grammar in ASL despite not mastering a first language (see also feral and abused children case studies)
- Critical period, if they exist, seem not to effect semantic processing or vocabulary but formal properties and grammaticality judgements
Critical periods in language?
Newport, Bavelier, & Neville (2001)

- **Maturation versus interference:** Limited early experience may sharply restrict the set of stimuli the organism finds interesting/important, limiting later learning.

- This latter idea may be better viewed as an attack on the idea of critical/sensitive periods but as an explanation of why they happen.

- Issue may be obscured because language depends on a complex set of cognitive skills (semantic memory, working memory, reasoning, attention, etc...).
A linkage between pairs of events, sensations, or ideas such that the activation or elicitation of one (EVENT A) results in the retrieval or anticipation of the other (EVENT B).

Three key principals

- **Contiguity**: Events experience at similar point in time or space are more easily associated.

- **Frequency**: the more often we experience something, the more strongly we associate them.

- **Similarity**: when two things that are similar, thinking of one can trigger the other (e.g., chair/table, dog/cat, iPad/awesomeness)
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**Contribution:**

Amazingly these are still among the key principles of associative learning that we study today!!

Aristotle: 2
Plato: 1
**Descartes and Cartesian Dualism**

- **Dualism**: A distinction between the material, physical *body* and the ephemeral *mind*.

- The body worked according to mechanical principals. The most famous explanation of this was Descartes description of *reflexes* as being innately specified mechanisms for behavior that operate according to mechanical principals.

- What about free will then? That’s all in the spirit-world of the “mind”
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**Contribution:**
In some ways some extreme advocates of computational cognitive science advocates a similar "dualistic" view of the mind (this time grounded in the theory of computation), although subtle (see also the Mind-Body problem, embodied cognition, connectionism).
John Locke and Tabula Rasa

- Drew inspiration from advances in chemistry and advocated the concepts and ideas are built out of similar experiences (red is built of ‘cherry’, ‘apple’, and ‘sunset’ experience). Early idea of COMPOSITIONALITY.

- Suggested an important role for experience in learning (children were Tabula Rasa or blank slates)

- Politically motivated by ideas of individualism, reformation
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**Contribution:**

Inspired a popular television show.
Home Town Hero: William James

- **Associationism** elaborate the Aristotelian view of associations to include networks of interrelated concepts (precursor to connectionist “Rumelhart” networks)

- Initiated study of habits and automatic associations

- Aimed to eventually detail the nature of his networks directly in the brain
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**Contribution:**

Claimed to be first psychologist. A rock star in his age and now. Most of modern psychology can be traced to his ideas.
Ever heard of **evolution of species**? Yeah, more or less first to strongly and coherently propose that idea.

How about **natural selection**, ever heard of that? Yeah, discovered that too.

Most influential theory in contemporary science. The standard by which your dissertation will definitely be held. No formal training, took 20 years to write... you have a computer.

Relevance for learning: The key is that evolution is not Lamarckian. Your experience can’t be passed directly to your children through genes. Instead, your *capacity* for learning can be passed/selected for!!
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The Darwins

Contribution:

Fairly well known scientist who made modest contributions to human knowledge.
Francis Galton (a Darwin grandson)

- Nativist, father of eugenics an idea he never quite lived down.
- Amazing empiricist who set to measuring everything he could get his hands on
- Examined variability and inheritability of traits (including some of the first intelligence tests)
- Father of modern statistics (correlational studies, bell curve)
- Wisdom of the crowds effects
Francis Galton (a Darwin grandson)

Inheritability of traits including mental abilities (IQ). Modern statistical methods and correlational study designs.

Contribution:
Ebbinghaus: Founder of memory research

- A wandering vagabond after his PHD, moved from university to university exploring ideas, tutoring for money

- Had no money so found a cheap subject: HIMSELF!

- First person to look at memory for abstract meaningless strings (DAX, KEZ, BAP, etc...) to avoid prior associations. Modern experimental methods with humans
Ebbinghaus: Founder of memory research

- One experiment: Read list of 20 words, waited for a while, then tested his memory (recording which he got right and wrong).
- Repeated until perfect memory
- LEARNING, DELAY, TEST, RELEARNING... all variables of importance in studies today
Ebbinghaus: Founder of memory research

Most famous contribution may be the reporting the shape of the FORGETTING CURVE
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**Ebbinghaus: Founder of memory research**

Founder of modern science of memory. Advocated EXPERIMENTAL (as opposed to CORRELATIONAL) approaches to learning and memory. The study of memorizing nonsense words!
Ivan Pavlov (1849-1936)

- Studying digestion and salivation in dogs
- Noticed that the dogs started salivating before the daily feeding (e.g., when they saw the bowl or heard the research assistants coming via footsteps)
- Started an empirical lab focused on studying how animals learn such associations (CLASSICAL CONDITIONING or PAVLOVIAN CONDITIONING)
- Also introduced the idea of EXTINCTION (unlearning or suppression of a previously learned response).
- Looked at how animals GENERALIZE response from one cue to another (e.g., a metronome at 80bpm to 90bpm)
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Edward Thorndike and the Law of Effect

“Of several responses made to the same situation, those which are accompanied or closely followed by satisfaction to the animal will, other things being equal, be more firmly connected with the situation, so that, when it recurs, they will be more likely to recur; those which are accompanied or closely followed by discomfort to the animal will, other things being equal, have their connections with that situation weakened, so that, when it recurs, they will be less likely to occur”  (Thorndike, 1911)
Edward Thorndike and the Law of Effect

- Basically, repeat what works and is rewarding more, and stop doing things that lead to pain/punishment!

- Influenced by Darwinian ideas of natural selection (in this case certain behaviors within an organism are adaptively selected by the environment using a fitness function related to reward)

- The first reinforcement learning RL researcher (now a pretty large and growing area of neuroscience and computer science)

- His work really set the stage for behaviorism
Edward Thorndike and the Law of Effect

Contribution:

Along with Pavlov a key player in making learning and behavior a quantitative natural science. Rigors methods and control in behavioral experiments. Importance of reward in shaping behavior.
Drawing from work of Pavlov and Thorndike was the leading proponent of behaviorism a movement in psychology during the middle part of the last century to do away with ideas from philosophy and psychoanalytic theory.

Focus on observable behavior and stimulus-response associations rather than on internal processes like thoughts, representation, feelings, emotions.

Advocate for the idea that psychology was a “purely objective experimental branch of natural science. It’s theoretical goal is the prediction and control of behavior.” (Watson, 1913)

Strong nativist, studied classical conditioning in humans (e.g., Little Albert experiment). Also did (controversial) work on rats showing habit formation/control of behavior absent sensory input.
Give me a dozen healthy infants, well-formed, and my own specified world to bring them up in and I'll guarantee to take any one at random and train him to become any type of specialist I might select – doctor, lawyer, artist, merchant-chief and, yes, even beggar-man and thief, regardless of his talents, penchants, tendencies, abilities, vocations, and race of his ancestors. I am going beyond my facts and I admit it, but so have the advocates of the contrary and they have been doing it for many thousands of years. [Behaviorism (1930), p. 82]
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Behaviorism (1930), p. 82

Watson and Behaviorism

Contribution:

Founder of behaviorism, stood on the shoulders of Pavlov and Thorndike to advance modern theories of learning. Quit academics and went into advertising (much scarier than his experiments).
Fewer of the general public knows about Watson compared to Skinner who was a bonafide celebrity scientist (appearing on the cover of Time magazine).

Advocate of the so called “RADICAL BEHAVIORISM” perspective which argued that all things (including for instance language) could be understood in behaviorist (stimulus-response) terms

A number of important empirical findings about learning (intermittent feedback), etc..

Unfortunately strongly remembered as the foil for Chomsky’s influential book review of Skinner’s “Verbal Behavior” book which ushered the cognitive revolution
What’s wrong with behaviorism?

- The focus on establishing psychology as a hard, quantitative science. Behaviorism excluded much possible data and denied much of our mental lives.

- The enthusiasm that the early success in basic learning (Pavlov, Thorndike, etc...) lead to an over enthusiasm that other problems (such as language) would fall in a similar way.

- However, the focus has squarely shifted to cognitive and computational approaches which emphasize the structure of internal mental processes and how the brain represents the external environment.
Edward Tolman

- An early “cognitivist” in a way
- Argued that the behavior of rats was not simply stimulus-response pairings but of purposeful, goal-directed behavior
- Showed evidence of “problem solving” by rats who could find new routes to a goal in a single trial when blocked on a preferred route
- Could navigate to a goal starting from a novel start location in the maze
- A model of the environment - COGNITIVE MAP
- Latent learning (exploring a structured environment leads to creation of this map which can support later learning)
Clark Hull (1884-1952) and William Estes wanted to bring quantitative precision to studies of behavior and learning.

Sought formal equations that would relate probability of response to things like strength of stimulus and reinforcement schedule.

Credited with first attempts to develop theories that compare to those in physics ($E=mc^2$) to explain behavior.

Estes made a number of important theoretical contributions including STIMULUS SAMPLING theory, probabilistic modeling, memory models (exemplar approaches), etc., and also is credited with the CONDITIONED EMOTIONAL RESPONSE paradigm for studying fear learning.

Estes was Skinner’s student who hated his work and thought he went crazy doing too much math!! (Note: Don’t know how true that is)
Herbert Simon and Symbol Manipulation Models

- The death of behaviorism led to increased interest in ideas of cognitive representation, unobservable mental processes, thinking & reasoning, etc...

- Paralleled developments in computers at the time (symbolic AI systems)

- Simon and Newell were the originators of the idea that the mind could work by manipulation SYMBOLIC REPRESENTATIONS (i.e., representations that stand for something in the external environment)

- Emphasize planning, reasoning, decision trees, search processes in solution spaces, etc...

- Paralleled work by Chomsky on symbolic representations in language (grammar learning, etc...)
While symbolic AI systems were useful metaphors there was a lack of biological plausibility to the kind of computations they perform.

The brain isn’t much like a traditional von Neumann computer architecture (i.e., the one in your laptop), but instead is instantiated in neural hardware.

CONNECTIONISM is a branch of cognitive science devoted to the study of how interconnected, neural-like assemblies might give rise to human thought.

Key idea of DISTRIBUTED REPRESENTATION whereby multiple unit contribute to the representation of a thought or idea.

Figure 1. Interactive Activation Network Model (after McClelland and Rumelhart, 1981).
Interim Summary

- Progress in the scientific study of learning has been slow and steady... NOT characterized by successive movements which blast each other into oblivion. Indeed, early philosophical ideas still hold considerable weight.

- Rediscovering ideas that people found 100-1000 years early is a sure path to fame and glory... Plato, Aristotle, Darwin, and Galton are the winners of our survey. Everyone else made a career referencing their ideas. :)

- Arguing about nature vs. nurture is sure to give some mileage.

- Learning is a detailed and quantitative science informed by multiple sources of evidence (neuroscience, philosophy, psychology).

- The history of learning science shows how at each stage research has been shaped by compelling technological developments of the time (mechanical systems, pipes, flowing water, symbolic computers, parallel machines).
Levels of Analysis: An Example from Owls

<table>
<thead>
<tr>
<th>level</th>
<th>issues</th>
<th>the barn owl example</th>
</tr>
</thead>
<tbody>
<tr>
<td>computational theory</td>
<td>What is the goal of the computation, why is it appropriate, and what is the logic of the strategy by which it can be carried out?</td>
<td>Use timing [and intensity] differences measured at two locations to pinpoint the source.</td>
</tr>
<tr>
<td>representation and algorithm</td>
<td>How can this computational theory be implemented? In particular, what is the representation for the input and output, and what is the algorithm for the transformation?</td>
<td>Use coincidence detection and delay lines to transform time difference into a place code in the brain.</td>
</tr>
<tr>
<td>hardware implementation</td>
<td>How can the representation and algorithm be realized physically?</td>
<td>Arrange the neurons spatially and wire them up to reflect the algorithmic solution.</td>
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Table 4.2 — Marr's levels of understanding, exemplified on sound localization in the barn owl.
Key Principals for the Semester

- Learning and memory are closely related and intertwined states of information processing

- Major insights about learning and memory have come from studies of the brain

- The concept of multiple memory systems unifies the study of learning and memory

- The underlying bases of learning and memory are the same in humans and animals

- Our theoretical approaches to studying learning are always closely tied to technological advances that are unfolding in general society (e.g., today - machine learning)
Readings

Textbook reading: Gluck, Ch. 1 - *The psychology of learning and memory*


Additional Reading:

Optional Reading (discussed in lecture):
References for Slides


Lecture notes from Yael Niv (http://www.princeton.edu/~yael/PSY338/index.html)

The interweb.