Computational Cognitive Modeling

course website:
https://brendenlake.github.io/CCM-site/

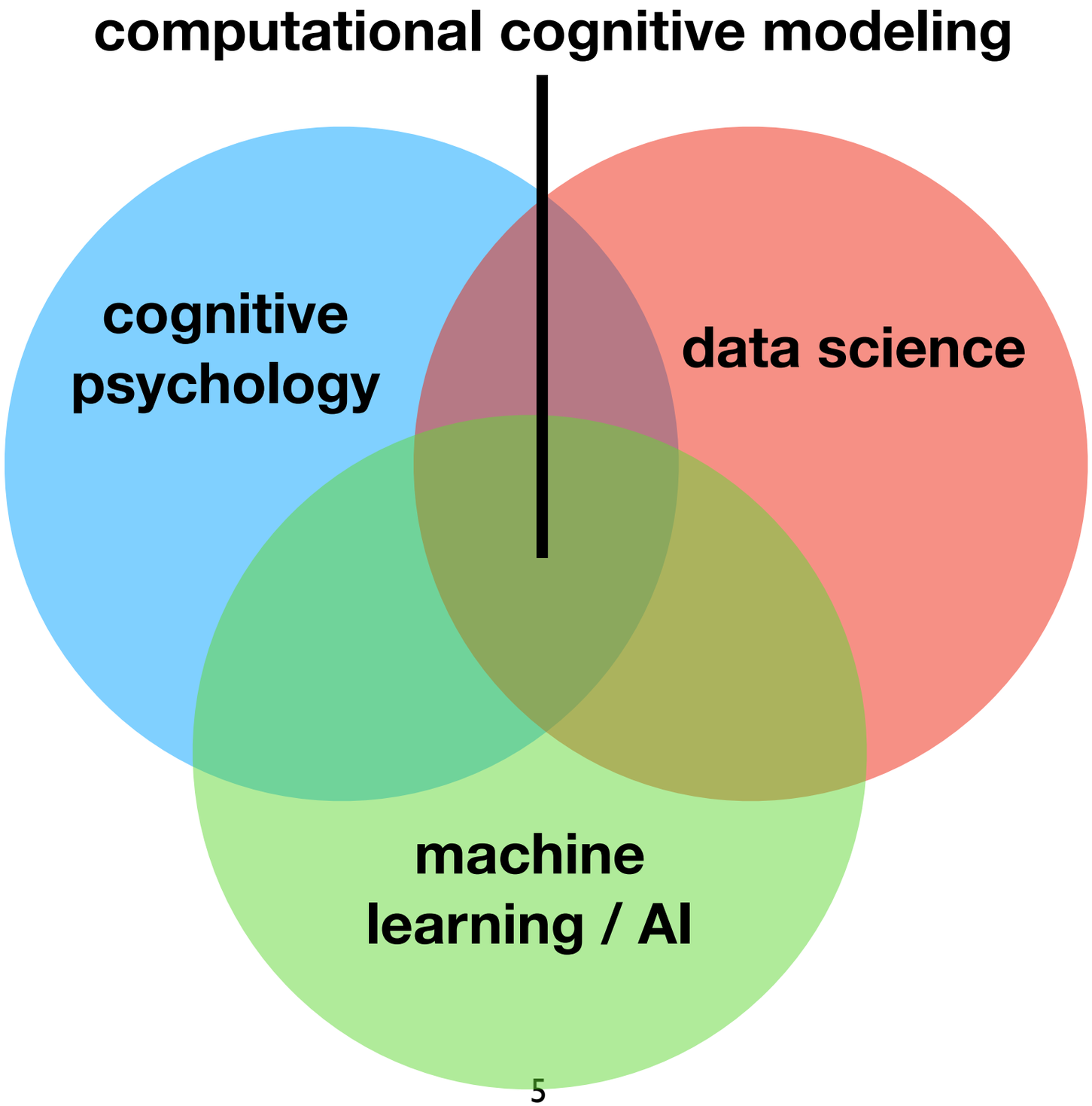
What is Computational Cognitive Modeling?

- **Computational Cognitive Modeling** is devoted to understanding the human mind and brain, in terms of their underlying computational processes.
- Building computer simulations that *mimic* the intelligent behavior of humans, and using these simulations to predict and explain human behavior.

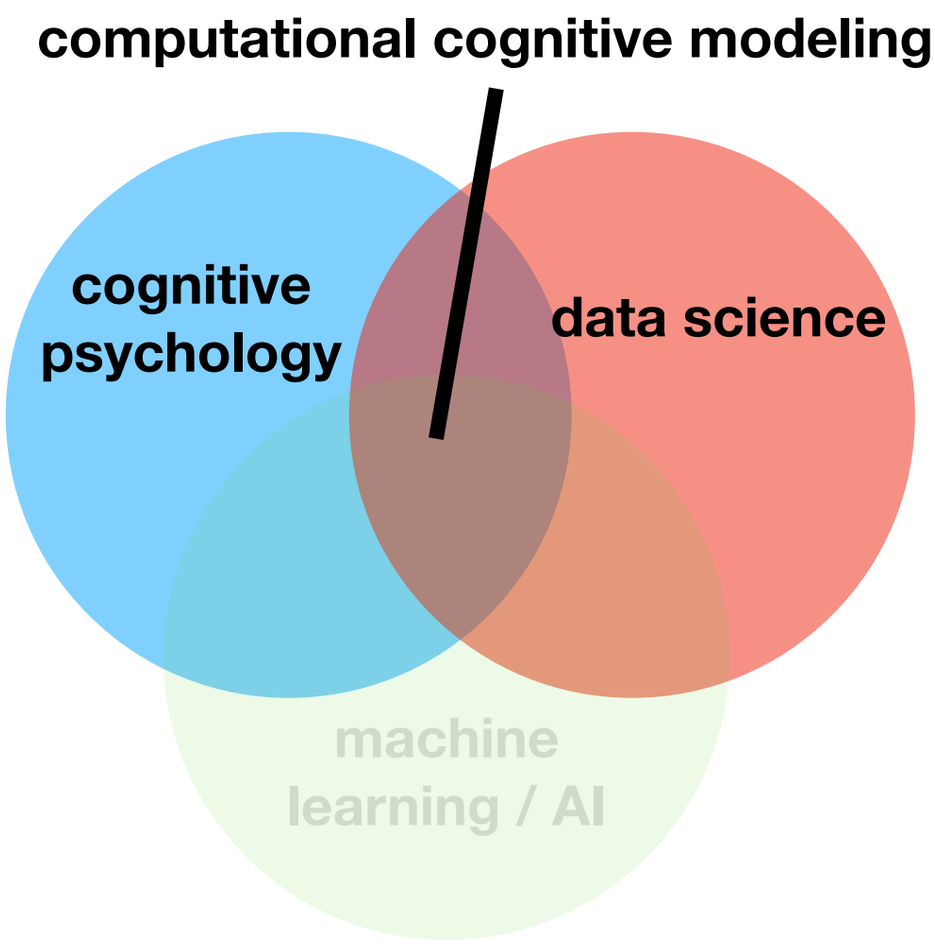
Key questions for this course

- What is intelligence?
- What kind of computer is the mind and brain?
- Can we better understand the mind/brain by building computational cognitive models?
- Can we better understand behavioral data by building computational cognitive models?
- Can we improve machine intelligence by incorporating insights from human intelligence?

At the intersection of cognitive psychology and data science

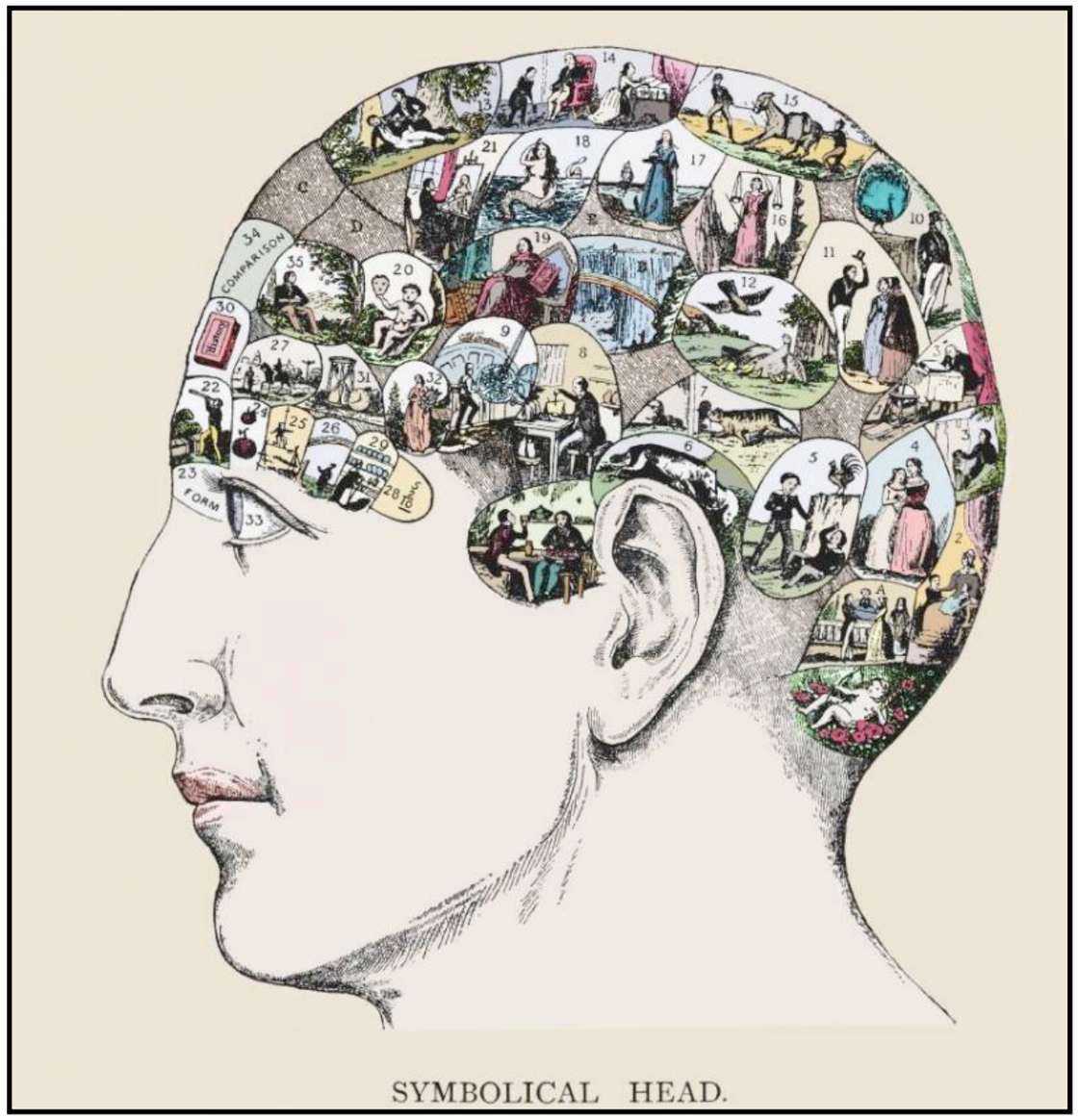


Connections between computational cognitive modeling and data science



- **Similar goals**: build computational models to explain or predict behavioral data
- **Similar computational paradigms and techniques**: neural networks / deep learning, reinforcement learning, Bayesian modeling, probabilistic graphical models, program induction
- Data science is about **extracting knowledge from data**. The human mind is the best (known) general system for extracting knowledge from data.
- There is ripe potential for even deeper connections. We hope that, by bringing together students from a variety of backgrounds, this class can help realize this potential.

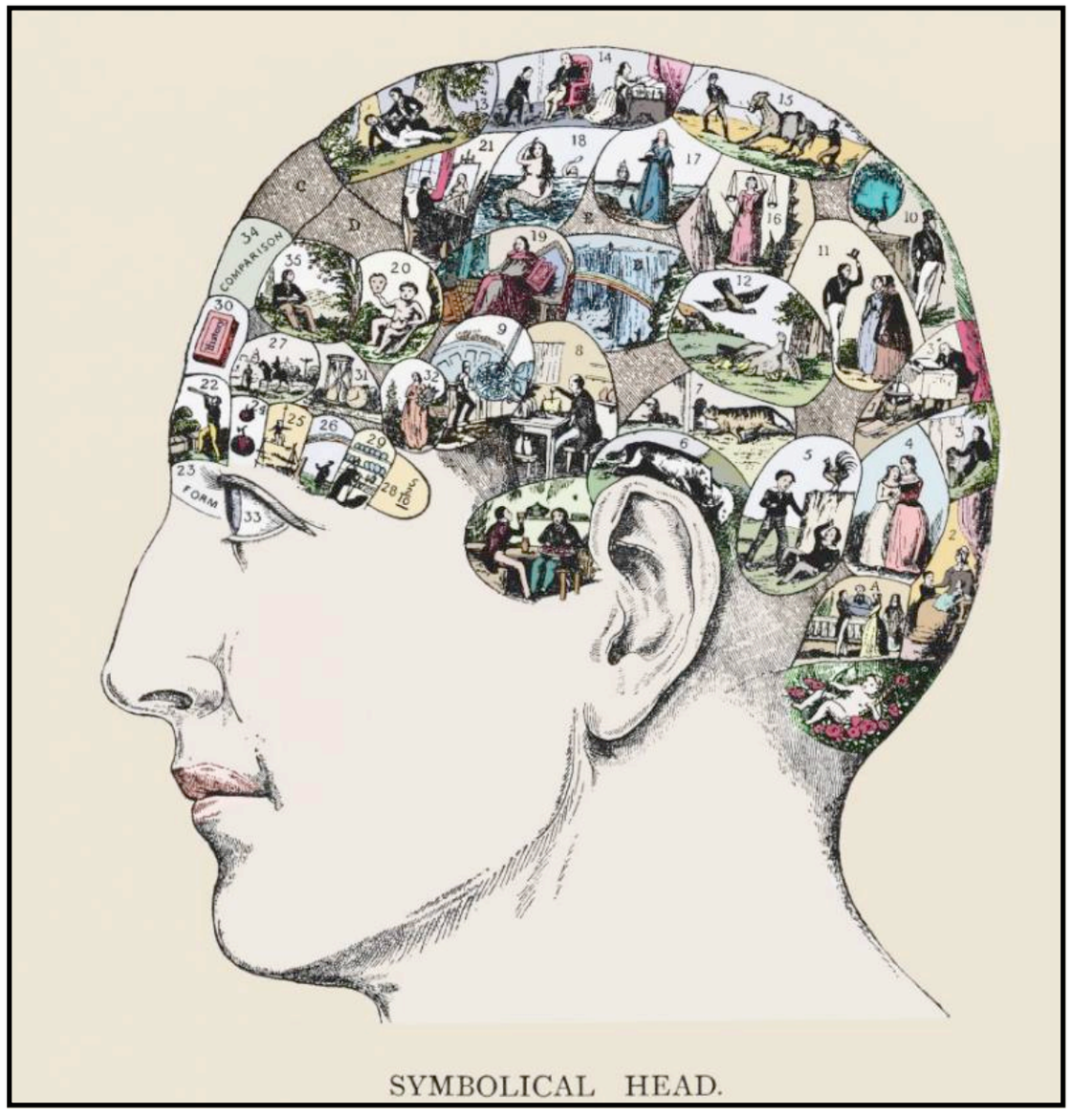
What is a mind?



SYMBOLICAL HEAD.

This has been debated for thousands of years. If you don't have an immediate answer, don't feel bad. Various proposals have been thrown around from by Plato, Buddha, Aristotle, Zoroaster…. ancient Greek, Indian, and Islamic philosophers, and even several folks at NYU.

What is a mind?

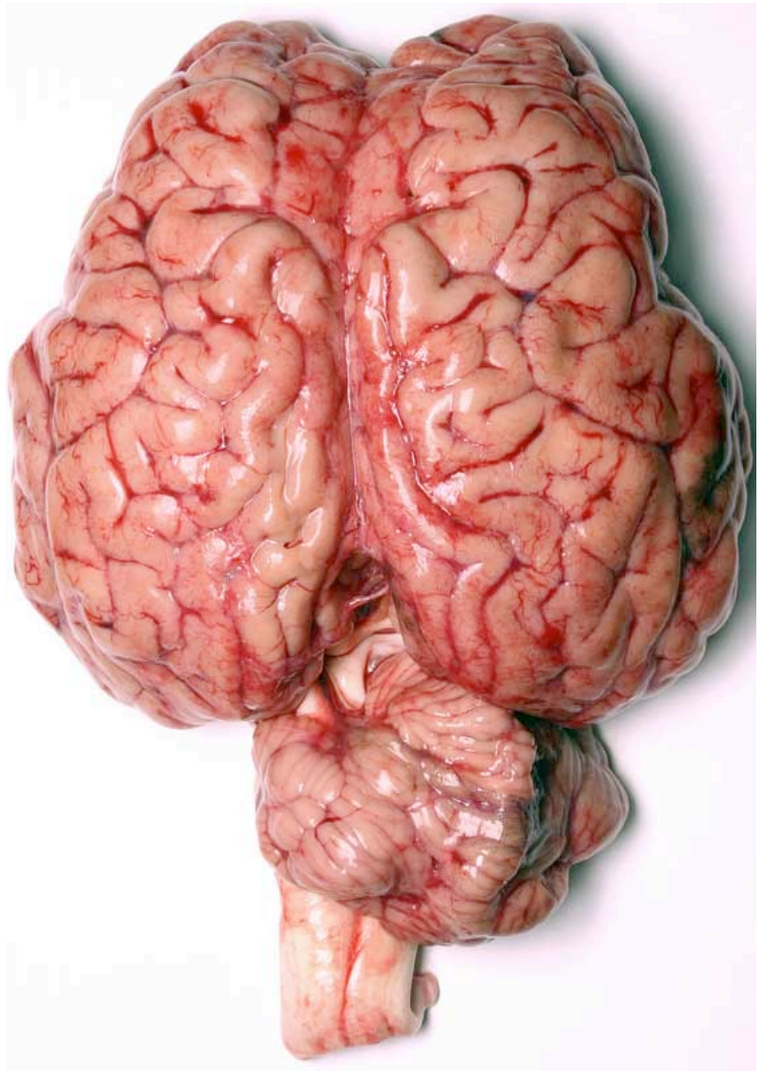


SYMBOLICAL HEAD.

What do minds do?

Minds encompass our thoughts, which are mental processes that allow us to deal with the world. These include not only explicit wishes, desires, and intentions, but also unconscious processes.

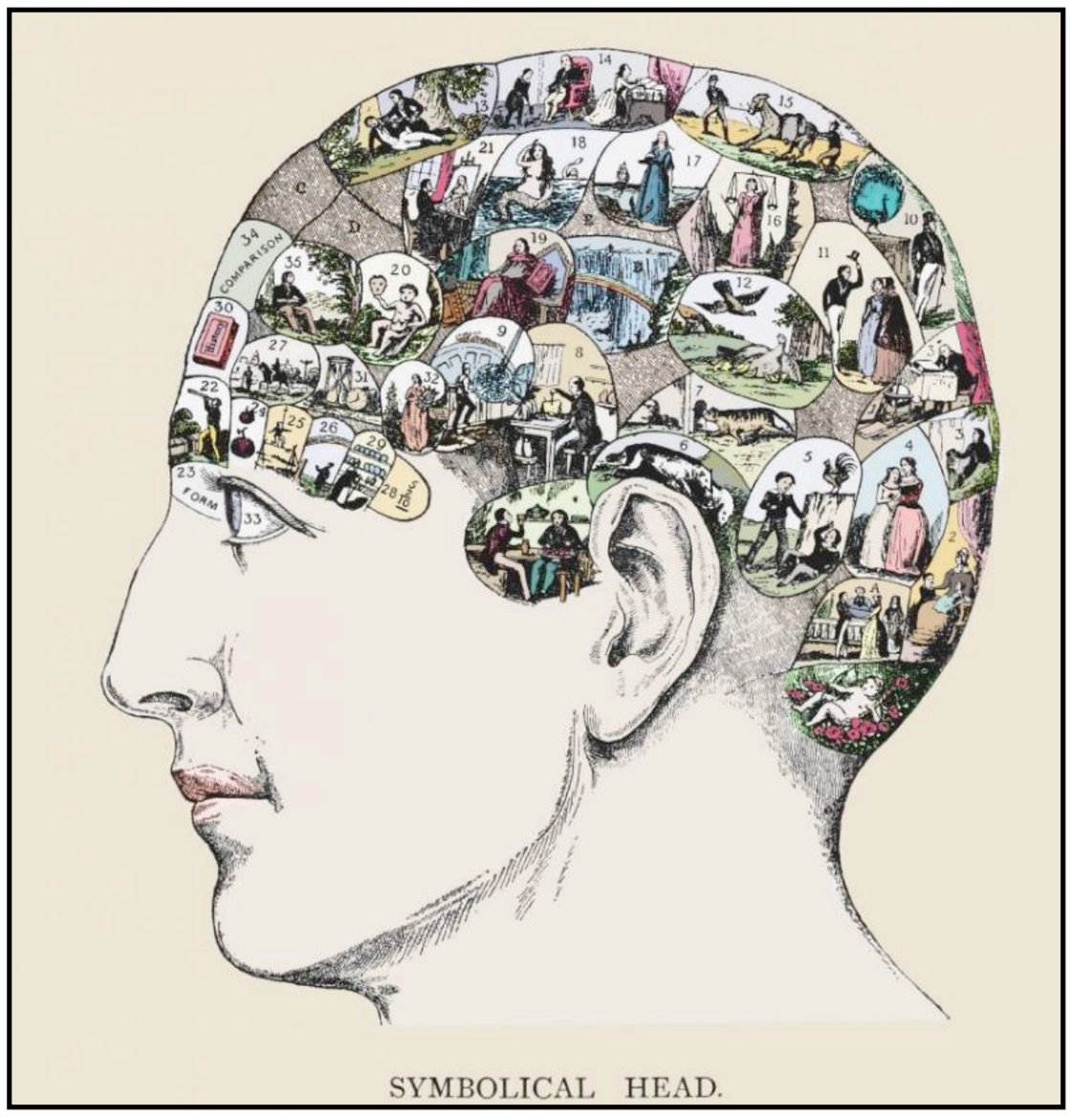
What is a mind?



Does MIND=BRAIN?

We know that we can't have a mind or thoughts without a brain, but does that mean that minds and brain are synonymous?

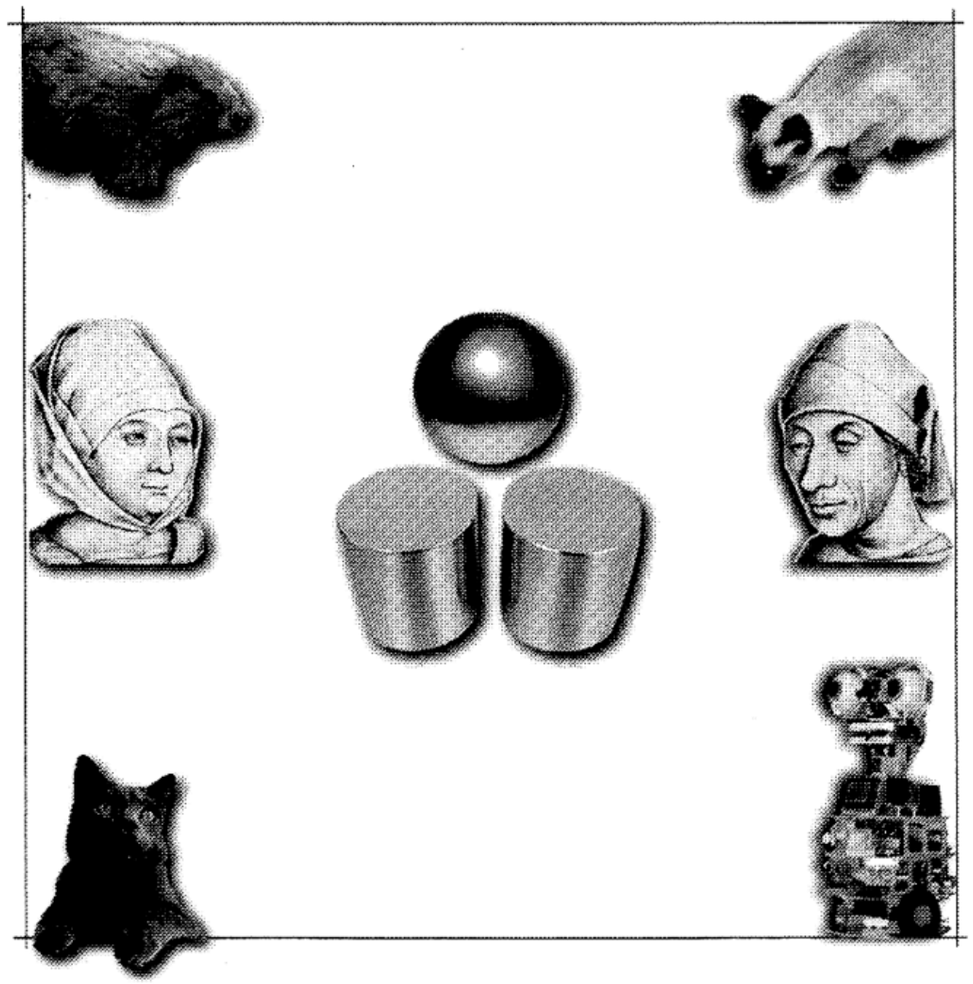
What is a mind?



SYMBOLICAL HEAD.

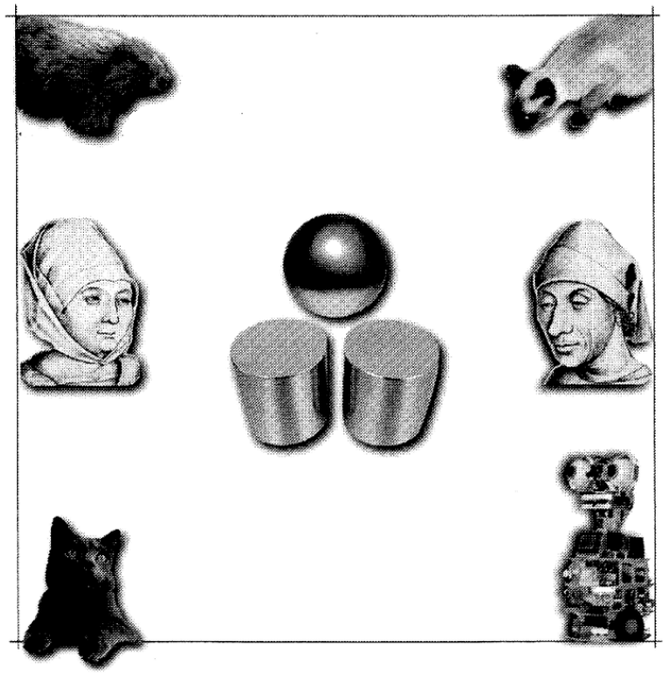
A “slippery slope” argument can convince us that minds are not literally brains, but encompass anything that is organized as representational states that accurately reflect aspects of the world.

The Brain/Mind Riddle



What is common to the various entities (person 1, person 2, cat 1, cat 2, robot, etc.) that look at this scene of two cylinders and a sphere and agree upon what is viewed?

Shimon Edelman's argument



The question: What is common to observers viewing the same scene and who agree upon what is viewed?

- Can't literally be neurons. My neurons are my own, and you can't borrow them to solve your own problems.
- Is it the literal organization of the human nervous system? We know (or at least believe) that cats have a very similar visual system and view the world much like we do. Is it the mammalian visual system? What about other animals?
- What about artificial systems formed of computers and video cameras that can accurately recognize the scene as well?
- **The key to minds is not their physical substrate, but the relations that states of the system have to one another, and to the external environment.**

Minds as computers

- Minds aren't human neurons or cat neurons or robot parts. They are dynamic, continually evolving systems that relate ongoing internal (i.e., mind) states and external (i.e., world) states
- Correspondences can be made between two systems by describing what they do, independent of their exact physical substrate.
- **We can describe these correspondences through the language of computation, simply because the THEORY OF COMPUTATION offers formal insights into how ostensibly dissimilar systems can be formally identical.**

Why build computational cognitive models? (As a psychologist)

"Verbally expressed statements are sometimes flawed by internal inconsistencies, logical contradictions, theoretical weaknesses and gaps. A running computational model, on the other hand, can be considered as a sufficiency proof of the internal coherence and completeness of the ideas it is based upon." (Fum, Del Missier, & Stocco, 2007)

Some famous psychological theories…

- Attention is like a spotlight
- A child learning about the world is like a scientist theorizing about science
- Language influences thought
- Working memory is having 7 +/- 2 slots to store items
- Categorization happens by comparing novel instances to past exemplars
- Categories influence perception

Each of these theories benefits from formalization with a computational model to…

- **Make predictions explicit**
- Implications often **defy expectations**
- **Aid communication** between scientists
- Support **cumulative progress**

“Formal (i.e., mathematical or computational) theories have a number of advantages that psychologists often overlook. They force the theorist to be explicit, so that assumptions are publicly accessible and reliability of derivations can be confirmed...” (Hintzman, 1990)

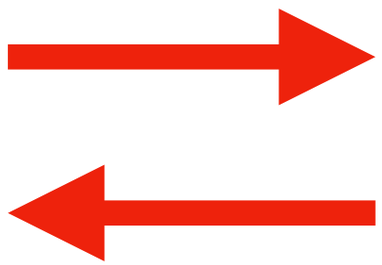
Rich history of connections between fields

cognitive science / psychology

machine learning / AI / data science

Bi-directional exchanges of computational methods and paradigms

cognitive science / psychology



machine learning / AI / data science

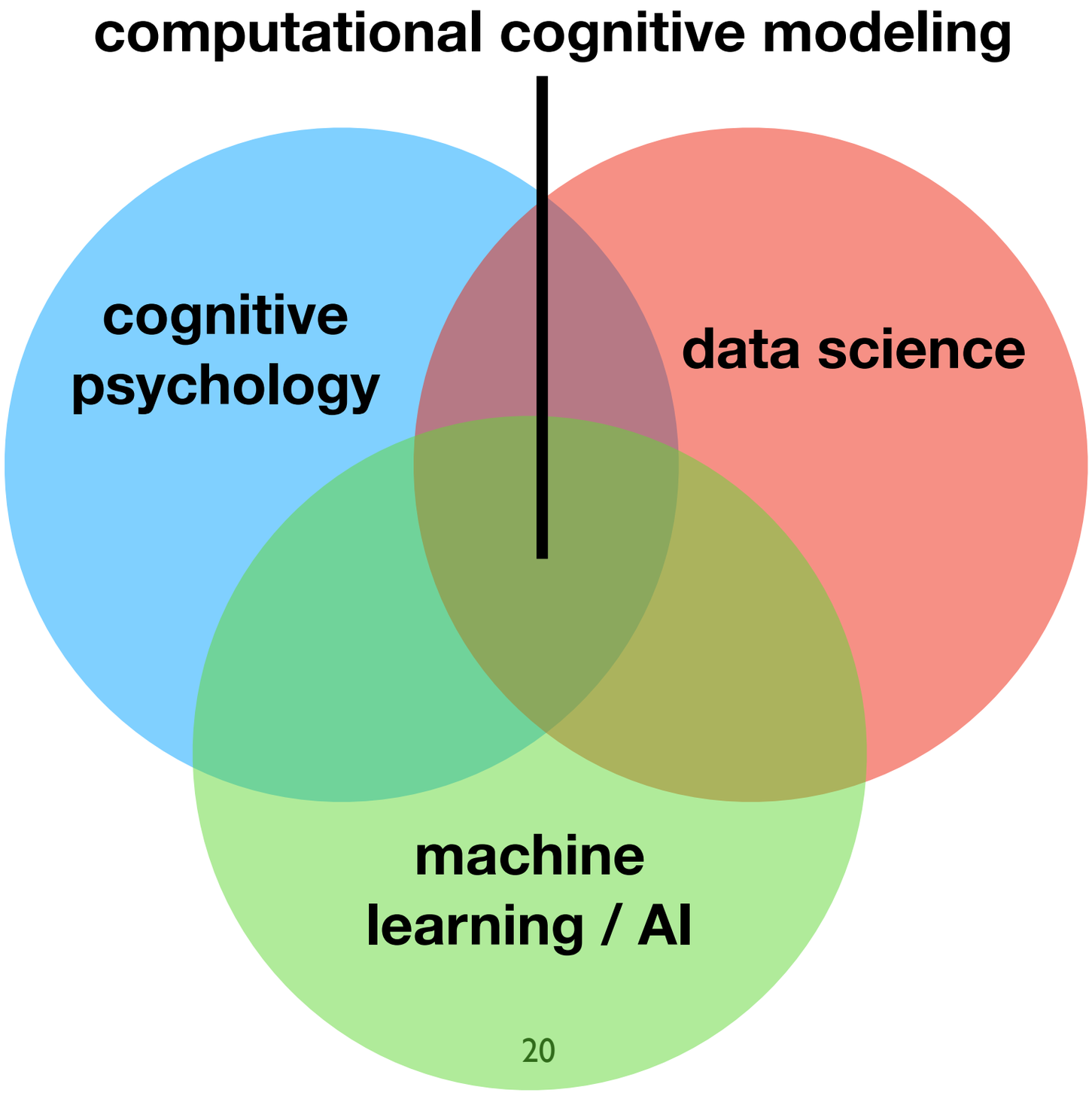
- Artificial neural networks
- Temporal difference learning
- Factor analysis
- Multi-dimensional scaling
- Probabilistic graphical models
- Structured Bayesian models
- Bayesian non-parametric models
- Probabilistic programming
- Recurrent neural networks
- …

Computational cognitive modeling can help make more powerful machines with more human-like learning capabilities

cognitive science / psychology

machine learning / AI / data science

Data science is about **extracting knowledge from data**. The human mind is the best general system we know of for **extracting knowledge from data**.



question asking

compositional learning

one-shot learning

scene understanding

concept learning

transferring to new tasks

language acquisition

inventing new tasks

computational problems that are easier for people than for machines

creativity

language understanding

Special opportunities for improving machine learning and AI through both engineering and REVERSE engineering.

general purpose problem solving

commonsense reasoning

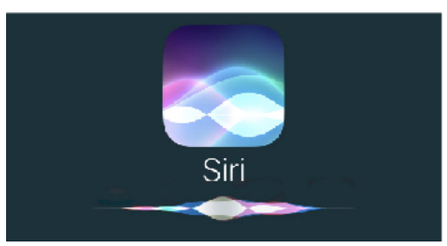
self-assessment

forming explanations

curiosity and motivation

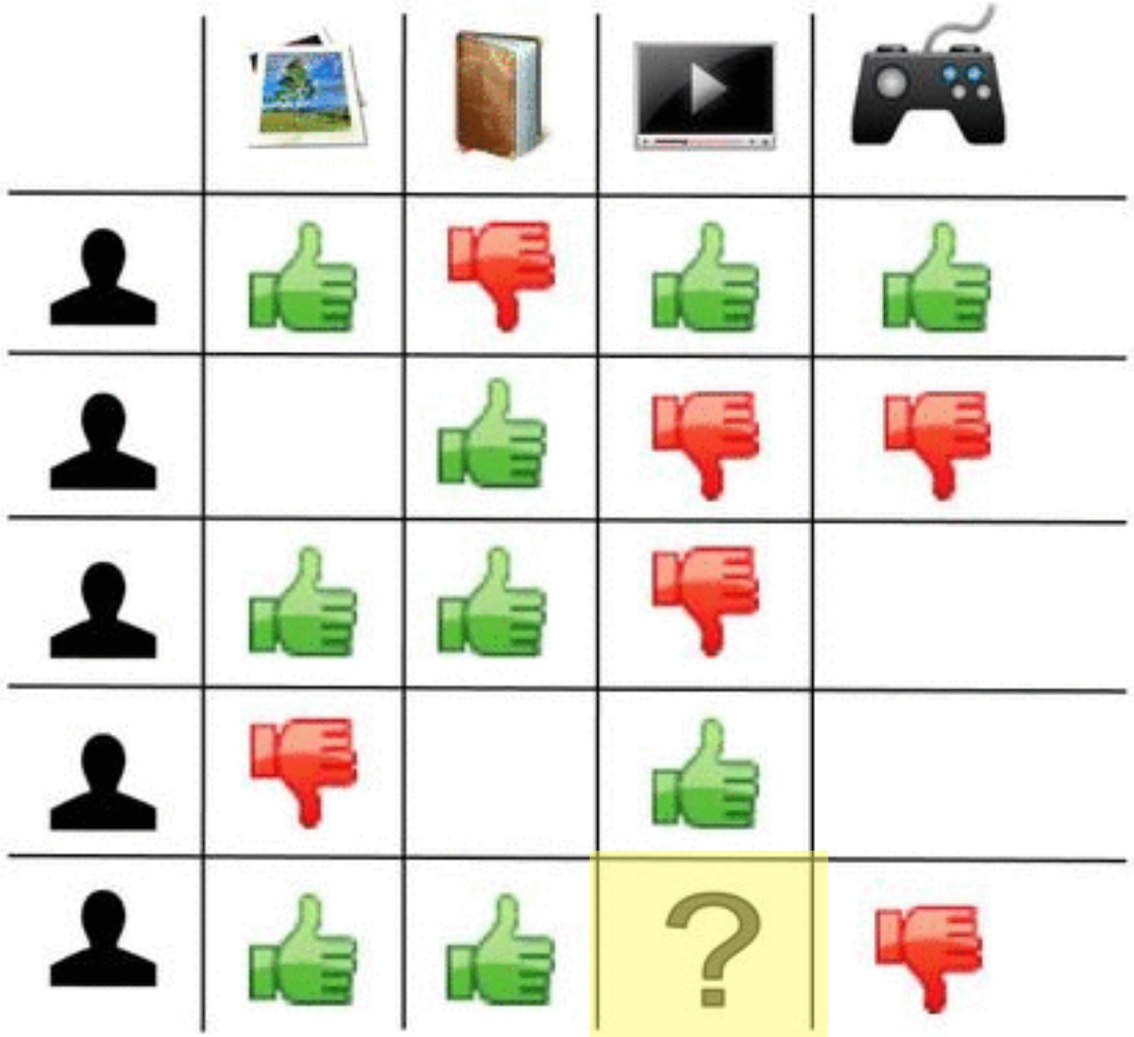
Can we better understand behavioral data by building computational cognitive models?

- In practice, data scientists deal with huge quantities of behavioral data..



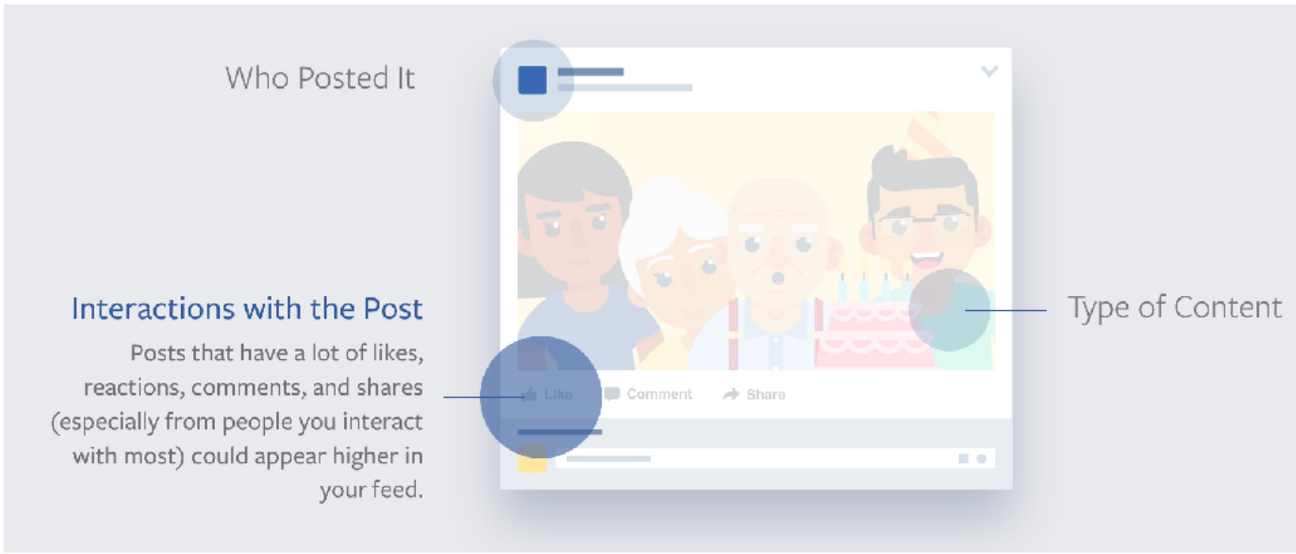
popular applications with behavioral data

collaborative filtering



churn modeling

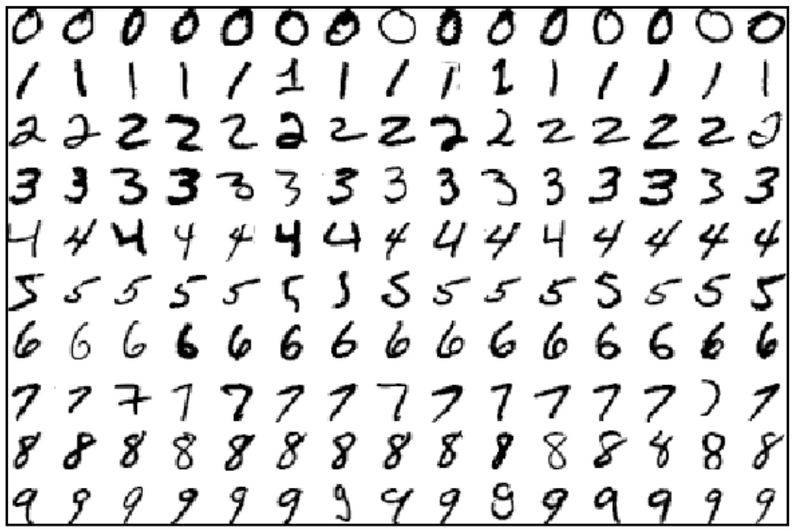
adaptive content (e.g., news feed)



popular challenges for developing machine learning / AI algorithms

object recognition (ImageNet)

digit recognition (MNIST)

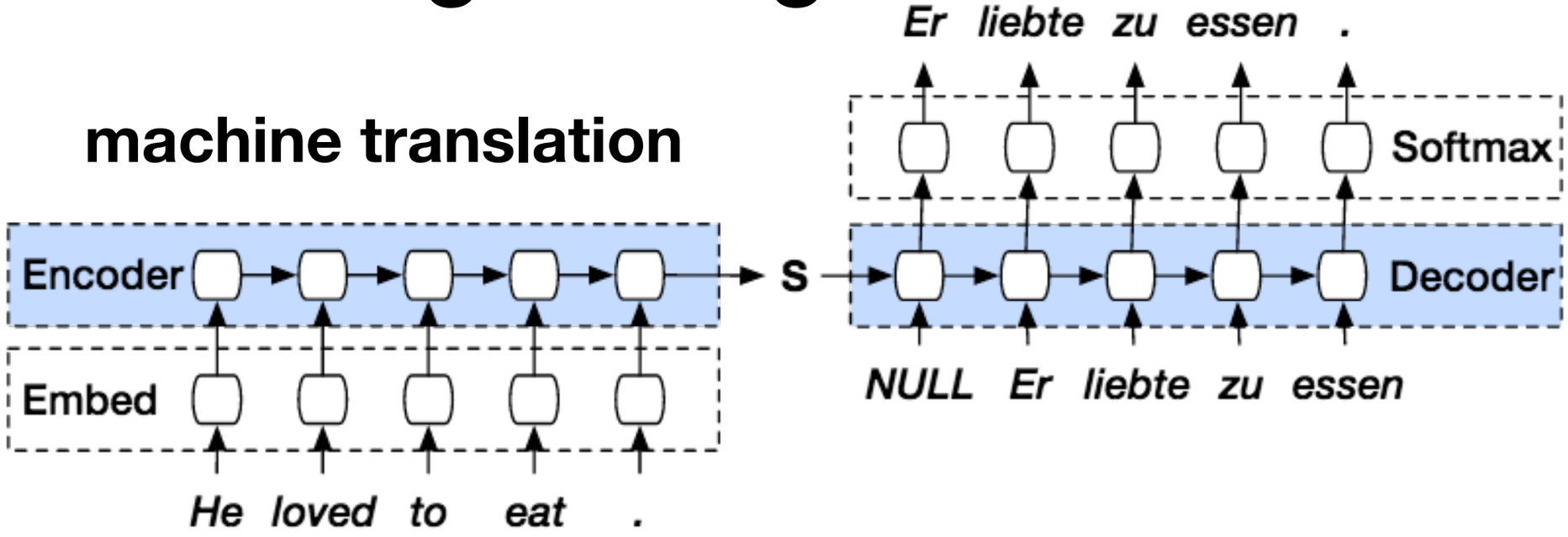


caption generation (MSCOCO)

- Datasets consist of photos taken by PEOPLE, or of digits actually drawn by PEOPLE
- Task is to predict labels and sentences produced by PEOPLE, identifying objects and events that are meaningful to PEOPLE. In many cases the labels identify concepts invented by PEOPLE

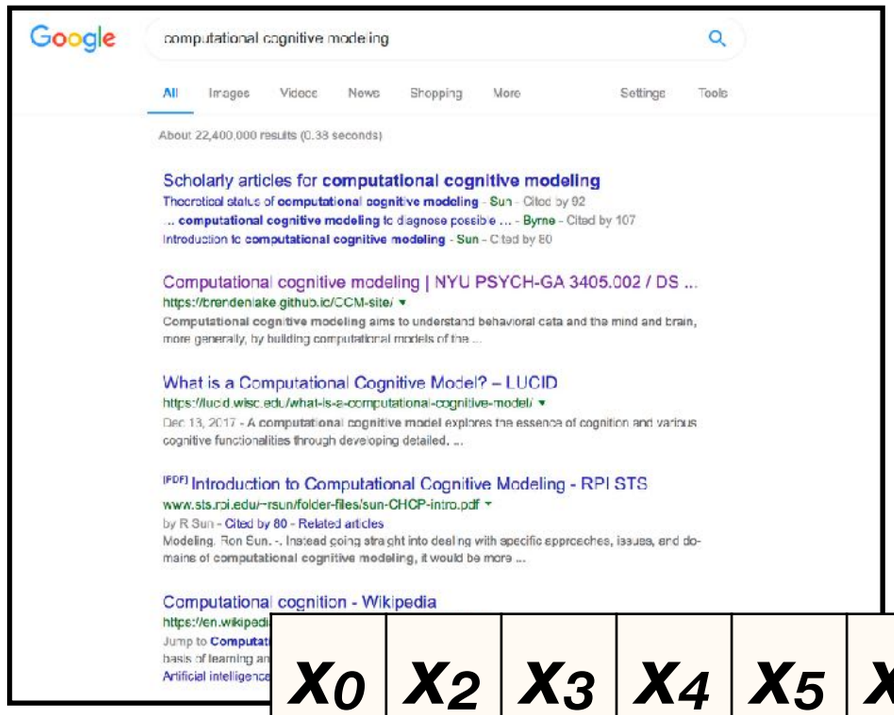
popular challenges for developing machine learning / AI algorithms

machine translation



language modeling and natural language understanding

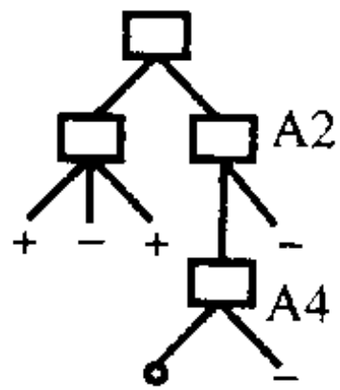
positing a mind to explain and predict behavior



x_0	x_2	x_3	x_4	x_5	x_6	x_7
0	0	0	1	0	0	0
0	1	0	0	1	0	1
1	0	0	1	0	0	0
1	1	1	1	0	1	1

rather than trying to predict clicks directly from browser history…

$p(y|x;\theta)$

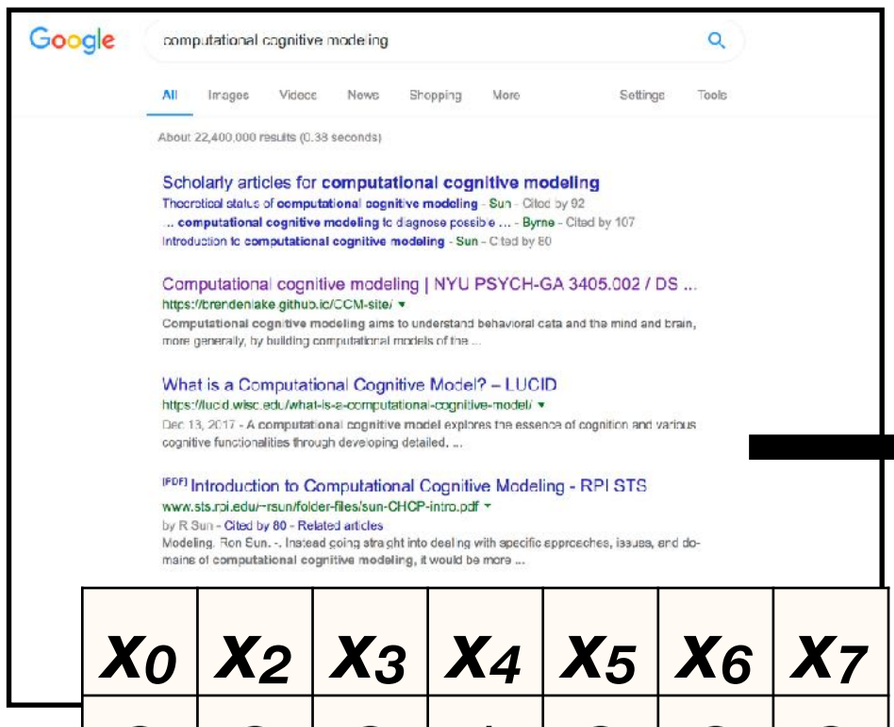


y
0
0
1
1

see Griffiths (2014). Manifesto for a new (computational) cognitive revolution.

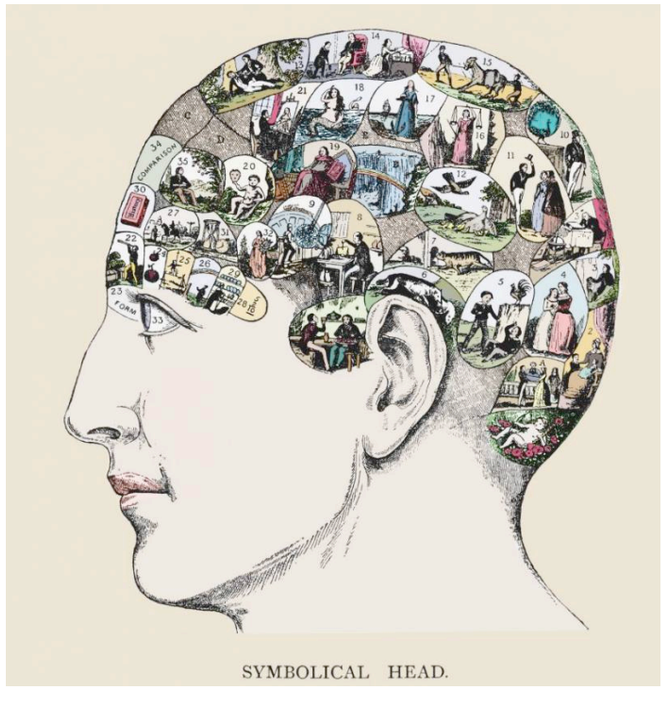
positing a mind to explain and predict behavior

- This course aims to show the value of positing mental processes to explain and predict behavior, and that mental processes are readily modeled with familiar computational tools to a data scientist.
- **Important caveat: This perspective is not yet mainstream in data science. This course is will teach you the right tools, but it's up to you to make the connections to practice!**



x_0	x_2	x_3	x_4	x_5	x_6	x_7
0	0	0	1	0	0	0
0	1	0	0	1	0	1
1	0	0	1	0	0	0
1	1	1	1	0	1	1

computational
cognitive modeling



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see Griffiths (2014). Manifesto for a new (computational) cognitive revolution.

Critical connections with neuroscience also, but this class is about modeling **higher-level cognitive rather than neural processes**

cognitive science / psychology

machine learning / AI / data science

****not this class!**

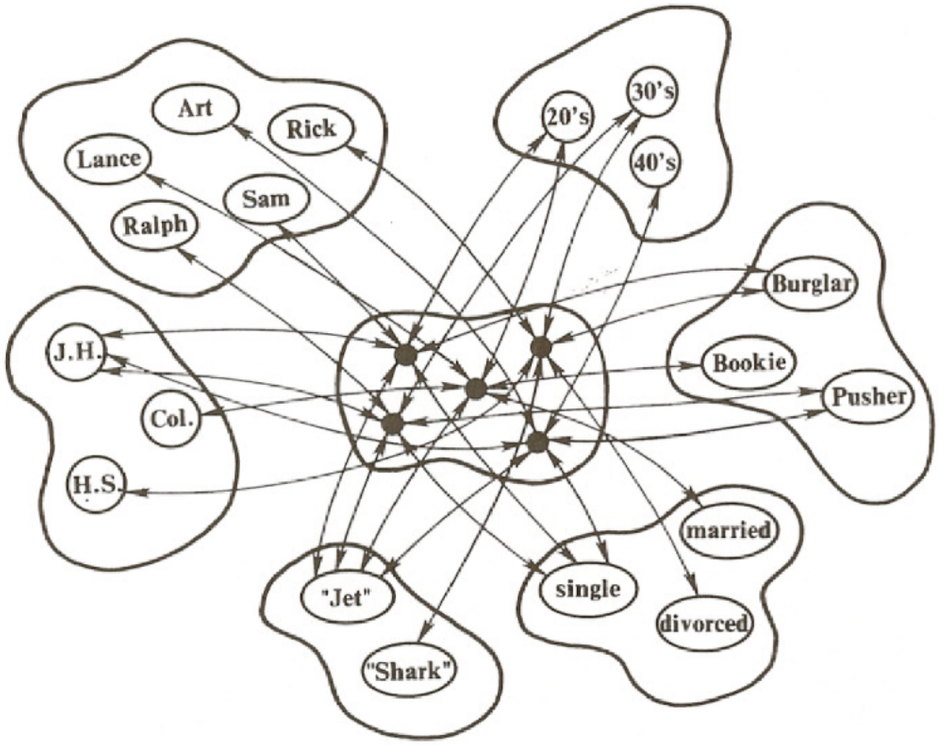
We will spend most of our time diving into various computational modeling paradigms

- Neural networks / deep learning
- Reinforcement learning
- Bayesian modeling
- Classification/categorization
- Probabilistic graphical models
- Program induction and language of thought models

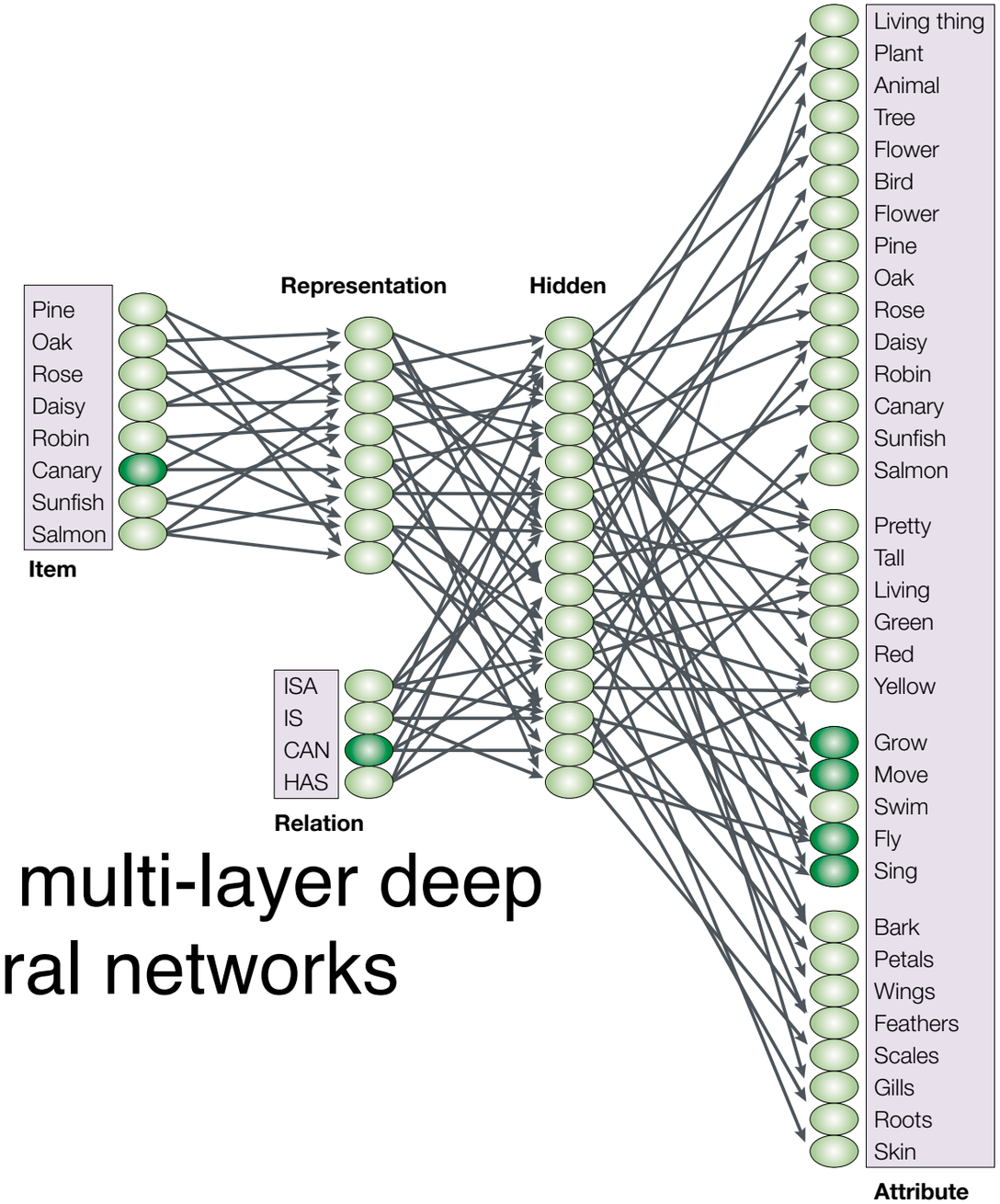
Notice synergy with contemporary machine learning / data science!

Neural networks / deep learning

Retrieving information
from memory



Learning about
objects and their properties;
modeling cognitive development

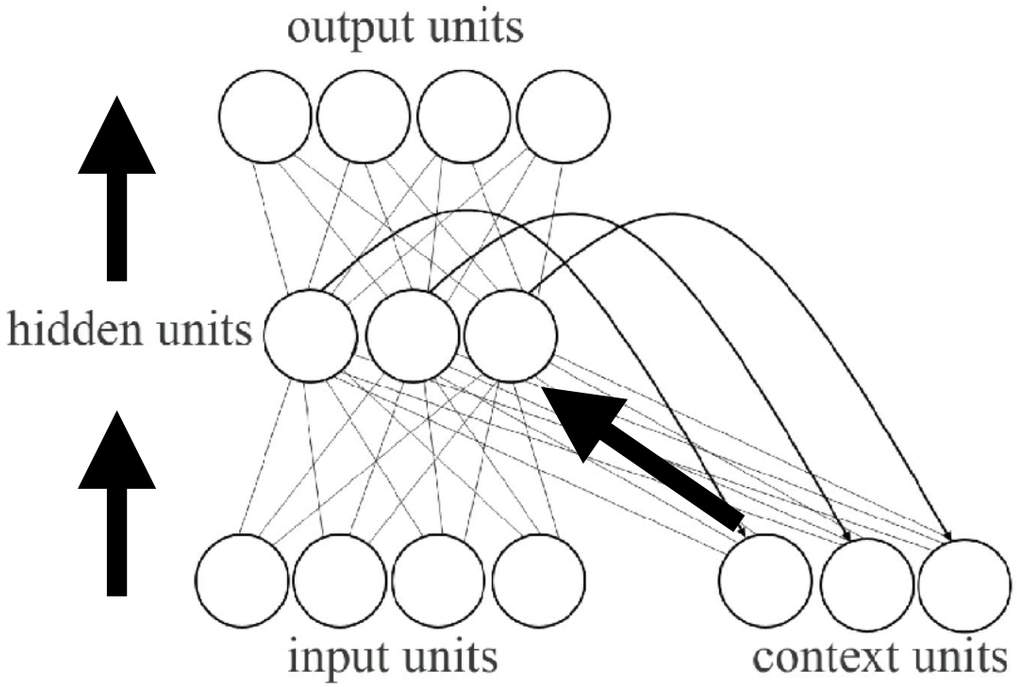


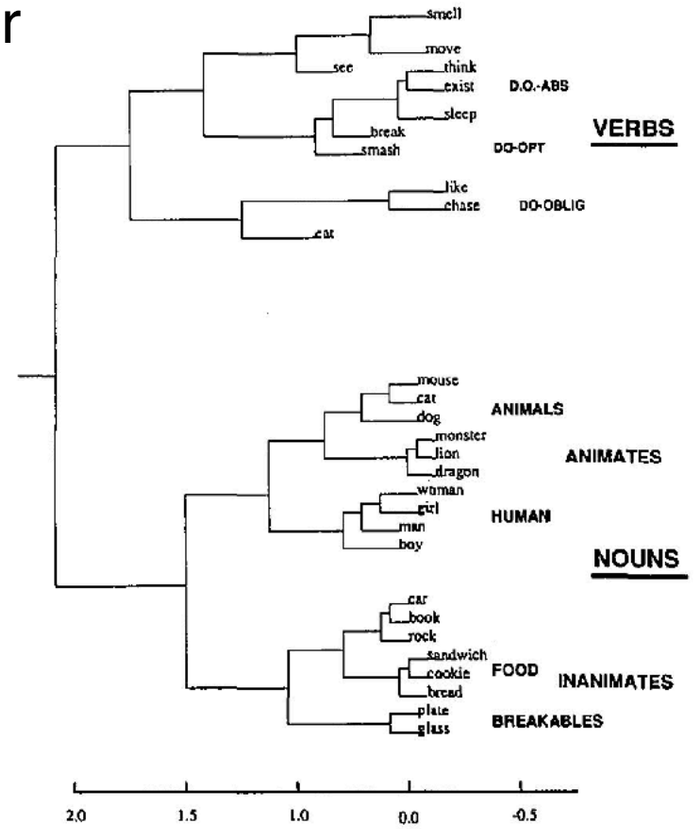
Training multi-layer deep
neural networks

Neural networks / deep learning

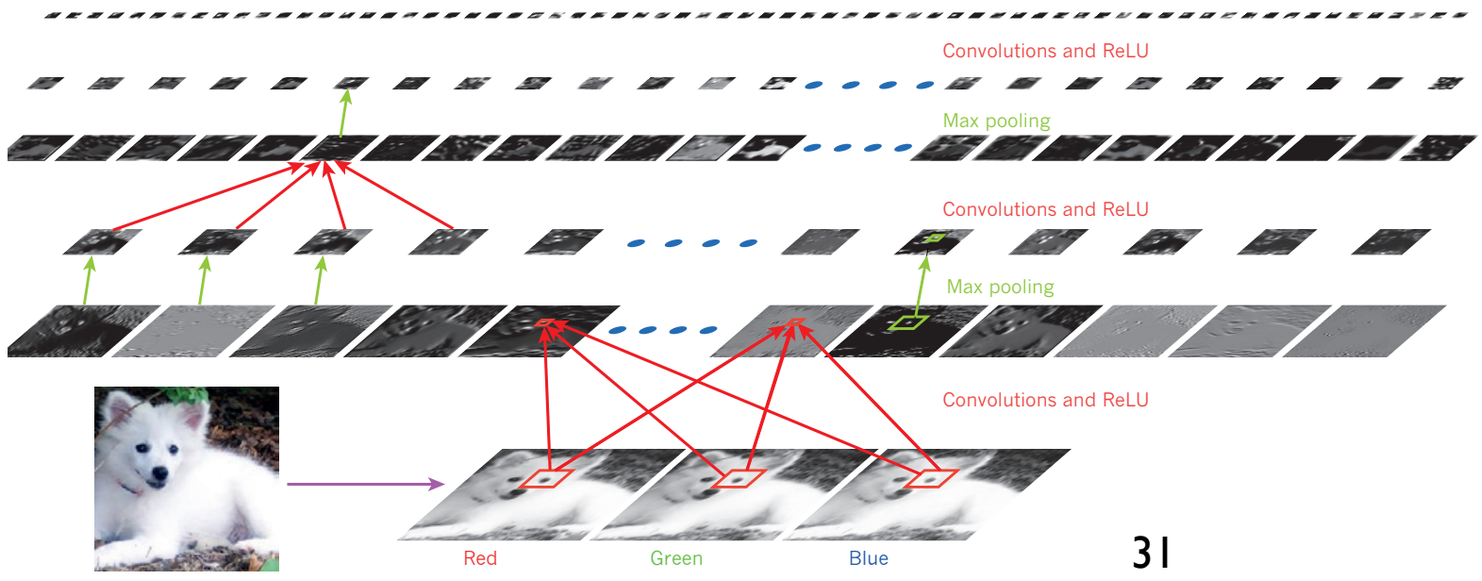
Recurrent neural networks

(Training RNNs with backpropagation was first done for computational cognitive modeling!)

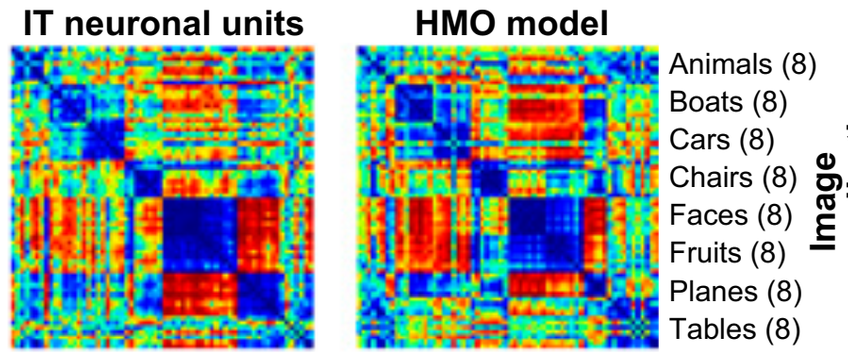




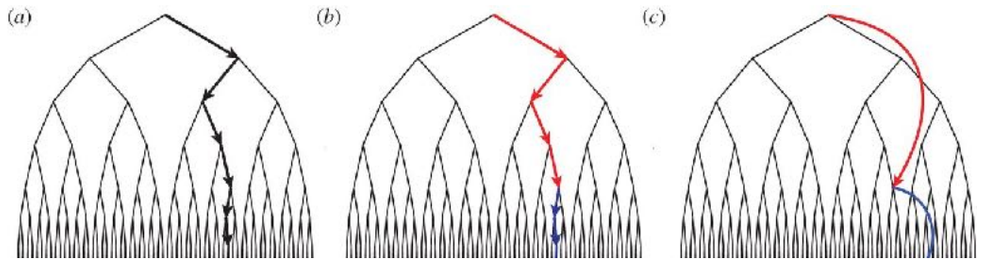
convolutional neural networks

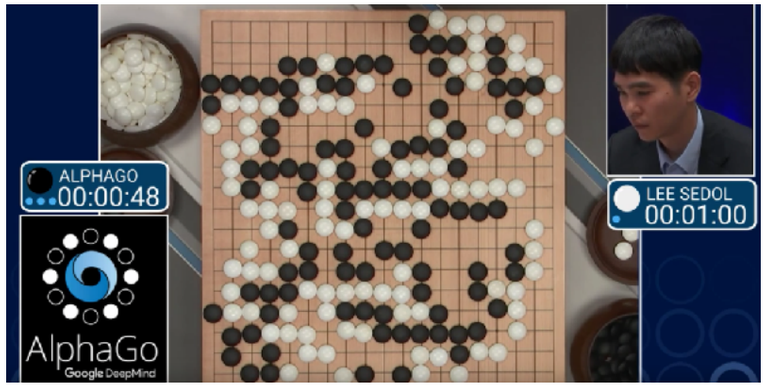


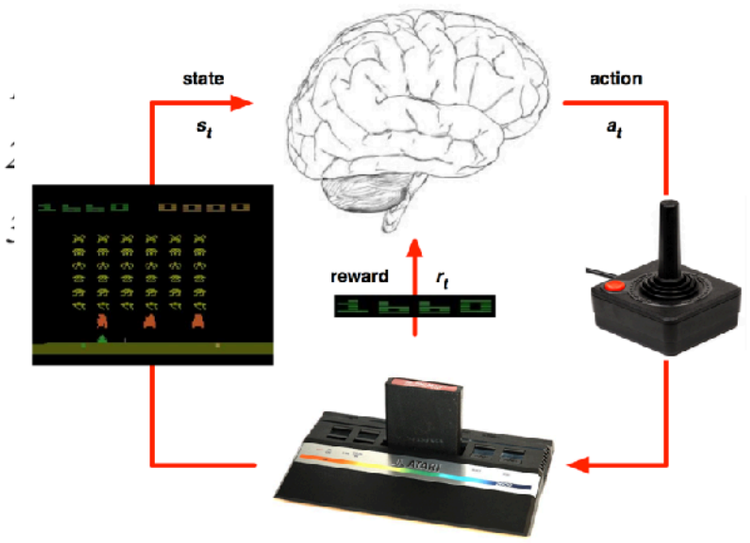
applications in cognitive science (and a bit of neuroscience)

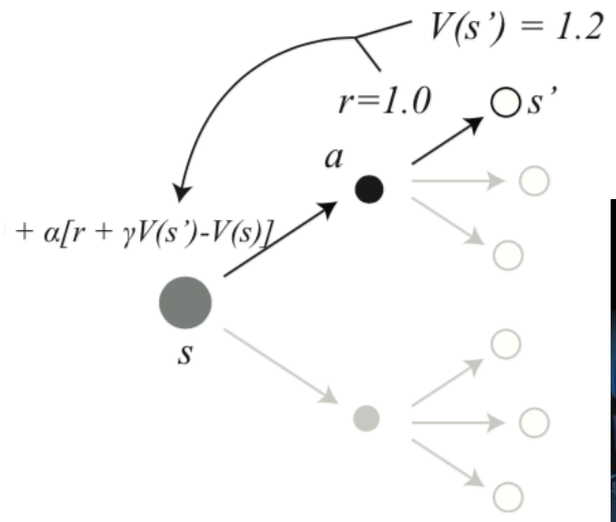


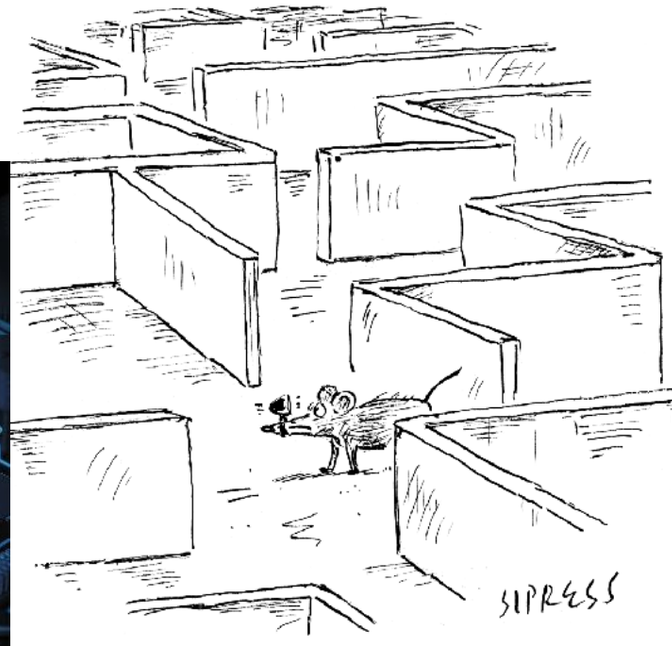
Reinforcement learning



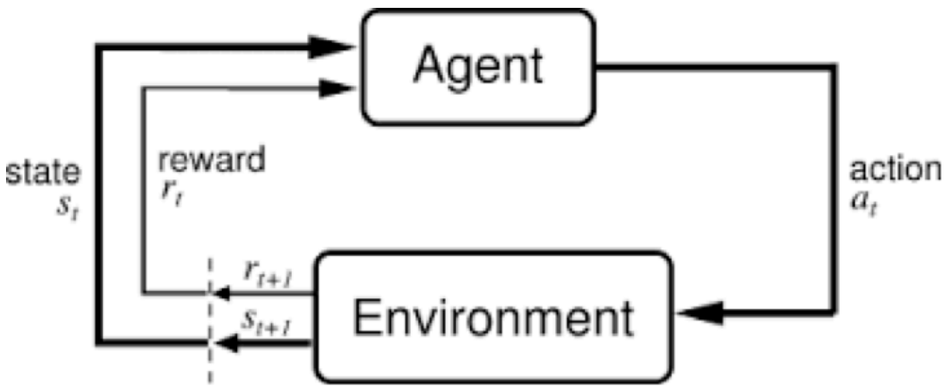


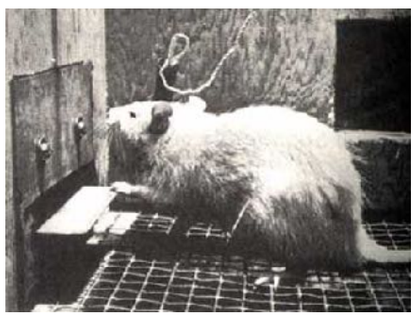






"Recalculating ... recalculating ..."





Bayesian modeling

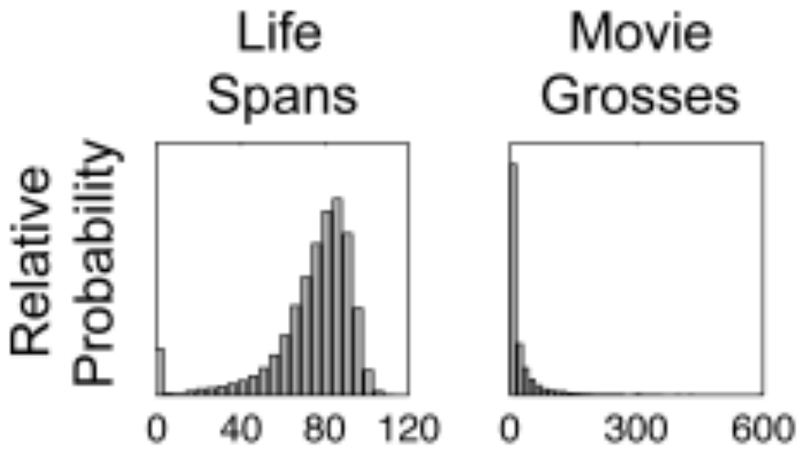
$$P(h|D) = \frac{P(h)P(D|h)}{\sum_{h_i} P(h_i)P(D|h_i)}$$

h : hypothesis D : data

Predicting the future

You meet a man who is 75 years old. How long will he live?

A movie has grossed 75 million dollars at the box office, but you don't know how long it's been running. How much will it gross total?

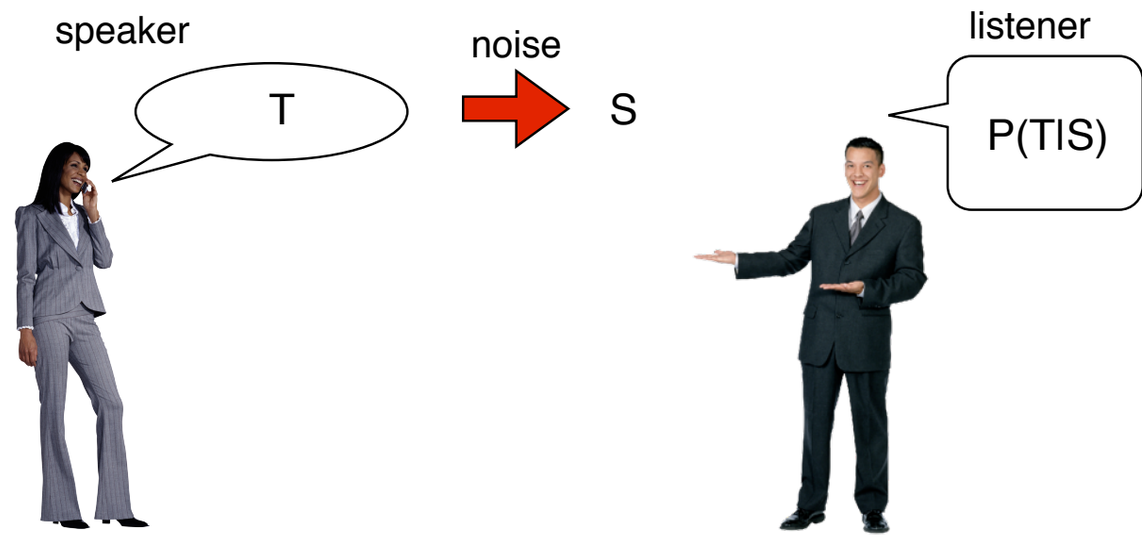


Property induction

Cows use biotin for hemoglobin synthesis
Seals use biotin for hemoglobin synthesis
—Therefore—
All mammals use biotin for hemoglobin synthesis

How strong is this inductive argument?

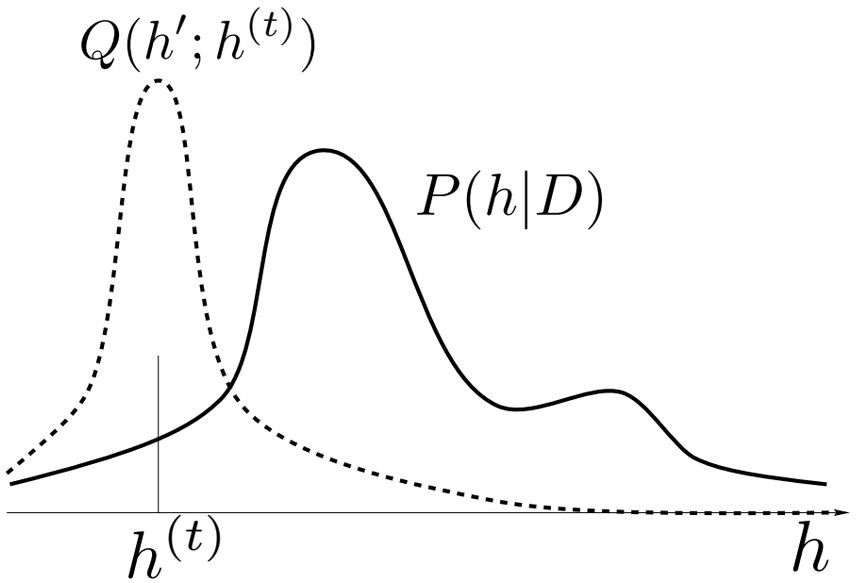
Speech perception under noise

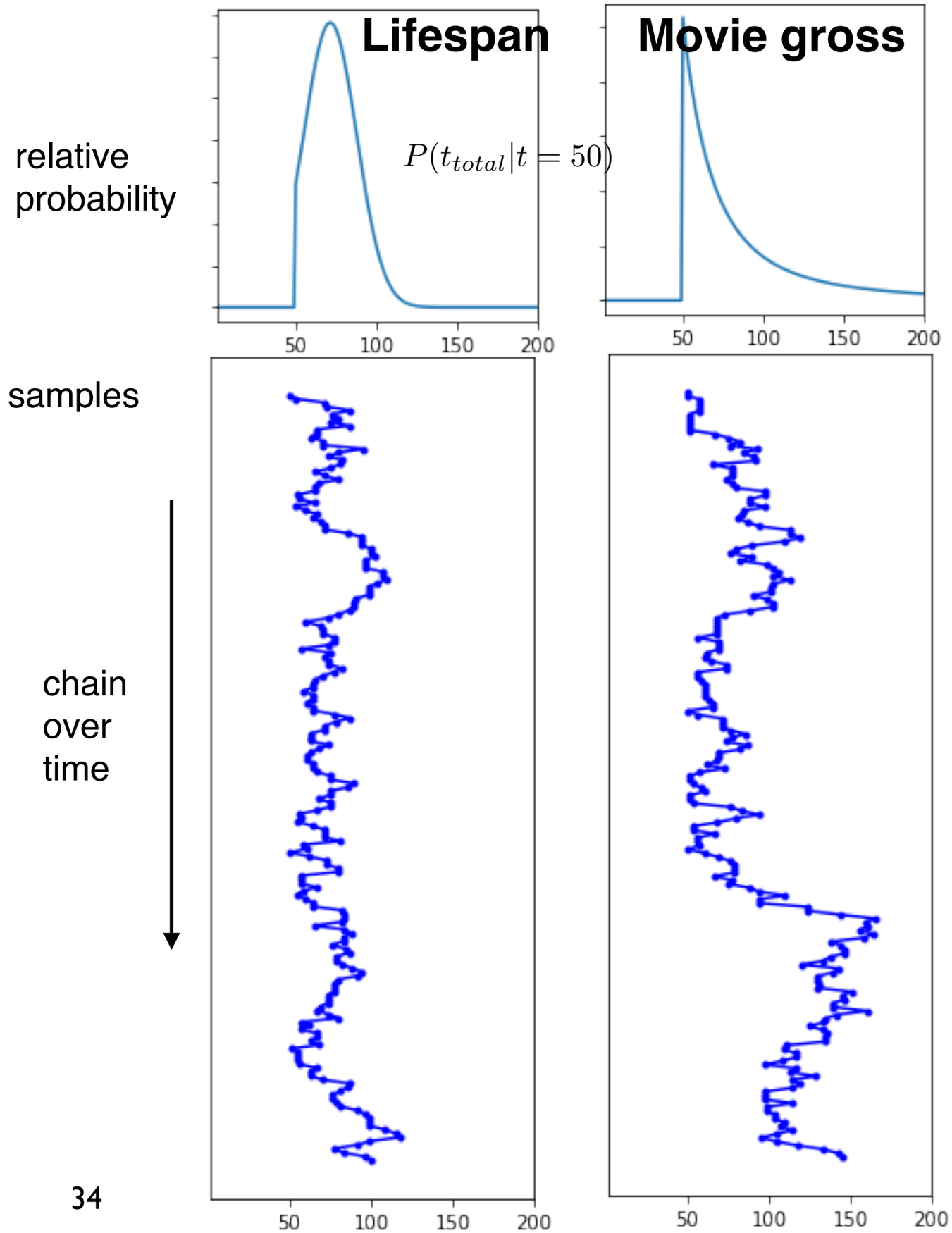


Inference in Bayesian models

- Exact inference
- Monte Carlo methods
  - Importance sampling
  - Markov Chain Monte Carlo

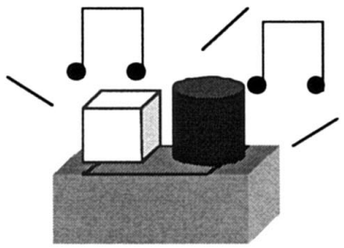
$$E[\phi(h)|D] \approx \frac{1}{T}\sum_t \phi(h^{(t)})$$



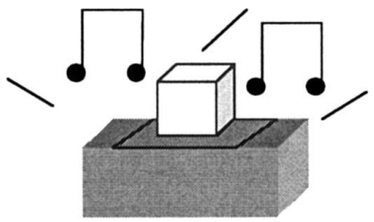


Probabilistic graphical models

Causal learning as structure learning

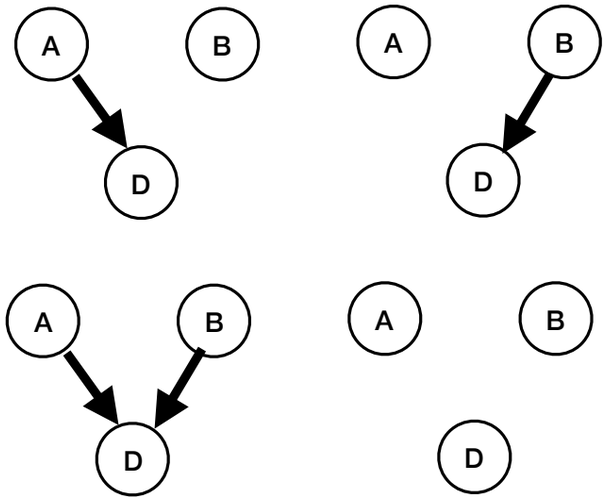


Both objects activate the detector

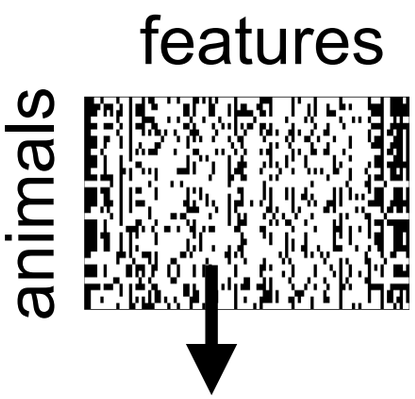


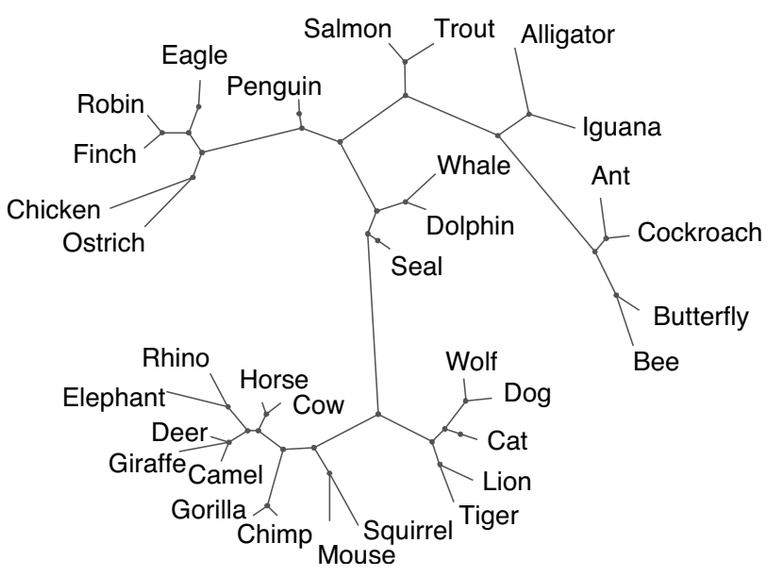
Object A activates the detector by itself

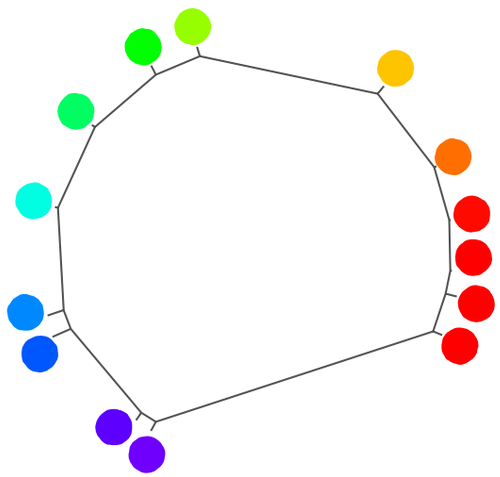
Children are asked if each is a blicket, then they are asked to make the machine go



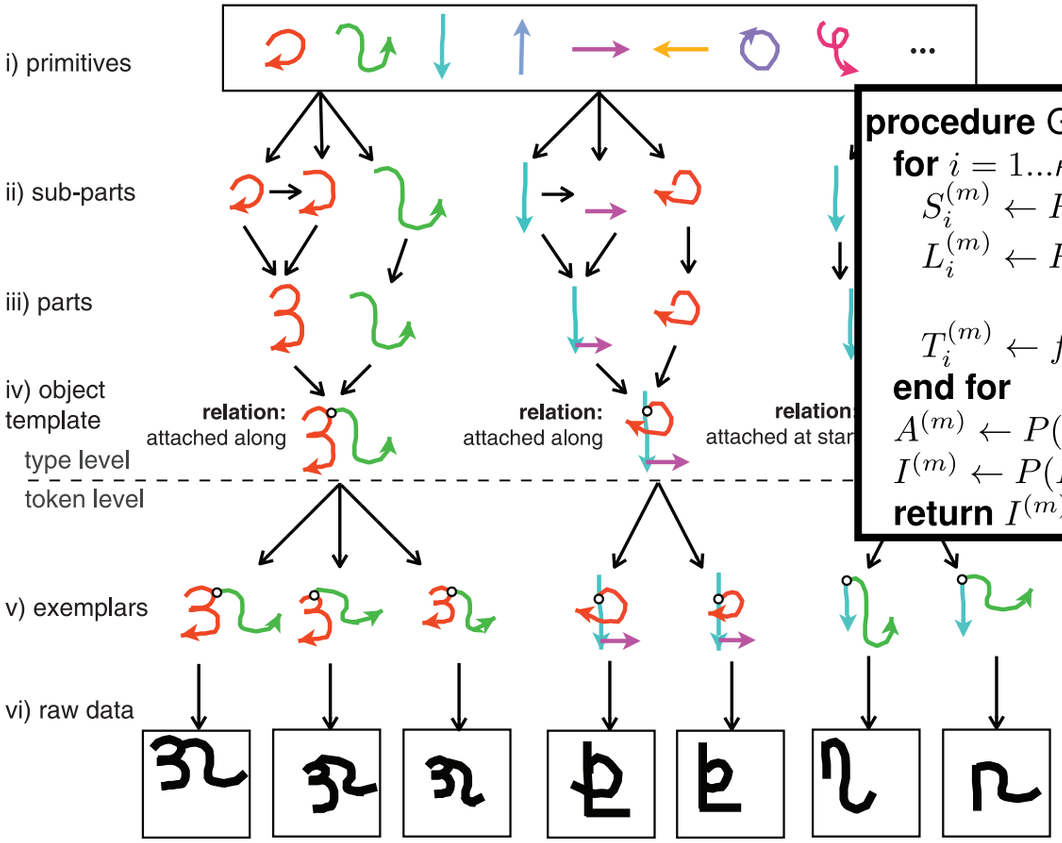
Structure discovery and evaluating inductive arguments



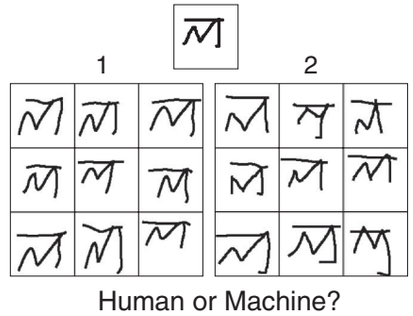




Program induction and language of thought models

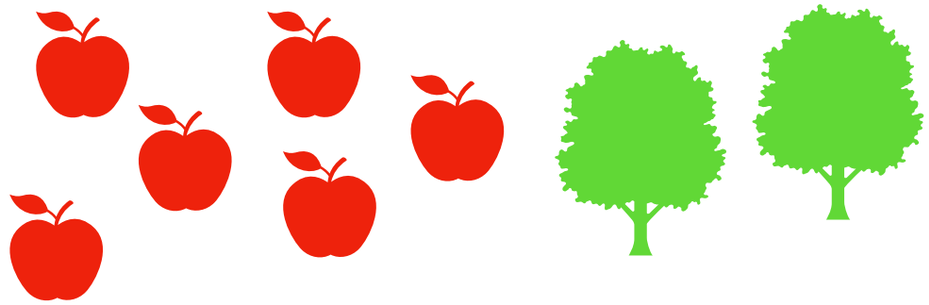


procedure GENERATETOKEN(ψ)
  for $i = 1...\kappa$ **do**
    $S_i^{(m)} \leftarrow P(S_i^{(m)}|S_i)$ ▷ Add motor variance
    $L_i^{(m)} \leftarrow P(L_i^{(m)}|R_i, T_1^{(m)}, ..., T_{i-1}^{(m)})$ ▷ Sample part's start location
    $T_i^{(m)} \leftarrow f(L_i^{(m)}, S_i^{(m)})$ ▷ Compose a part's trajectory
  end for
  $A^{(m)} \leftarrow P(A^{(m)})$ ▷ Sample affine transform
  $I^{(m)} \leftarrow P(I^{(m)}|T^{(m)}, A^{(m)})$ ▷ Sample image
  return $I^{(m)}$

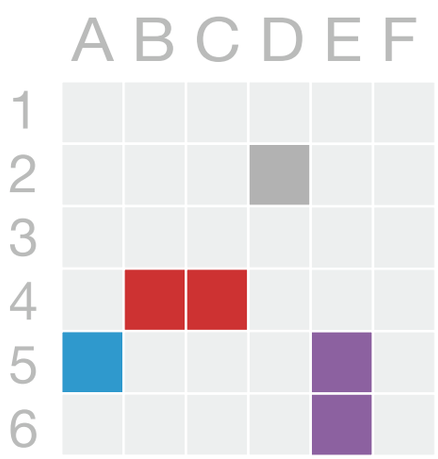


"six"

"two"



$\lambda\, S\, .\, (if\ (singleton?\ S)$
  $\text{“}one\text{”}$
  $(if\ (doubleton?\ S)$
    $\text{“}two\text{”}$
    $undef))$



What is the top left of all the ship tiles?

```
(topleft (setDifference (set 1A ... 6F) (coloredTiles Water)))
```

Are all the ships horizontal?

```
(all (map (lambda x (== H (orient x))) (set Blue Red Purple)))
```

Are blue and purple ships touching and red and purple not touching (or vice versa)?

```
(== (touch Blue Purple) (not (touch Red Purple)))
```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Is this course a substitute for machine learning?

- **No. It's not a substitute, it's complementary.**
- This course does survey different computational paradigms (deep learning, reinforcement learning, Bayesian modeling, classification, graphical models, etc.), and there is some overlap with ML classes in terms of technical content.
- But unlike ML classes, this is also a cognitive science class. **Our examples and applications aim to understand human learning, reasoning, and development, and to understand intelligent behavior more generally.**
- We get into some mathematical background, but ML courses take a more formal approach than we do here. We aim for an accessible introduction to the technical content.
- You will get hands on experience with running and analyzing complex models, implementing some (but not all) models, and analyzing behavioral data with computational models. Extensive final project.

Thank you