COGSCI 108f: “Natural Computation”

Instructor:
Jochen Triesch
triesch@cogsci.ucsd.edu

TA:
Patrick Gallagher
pwgallag@cogsci.ucsd.edu

Course web page:
http://cloudbreak.ucsd.edu/~triesch/courses/108f/
Textbooks

S. Haykin
D.H. Ballard
H.R. Wilson
P. Dayan & L.F. Abbott
Course Overview by Week (tentative)

Topics:
• Introduction, Review of probability theory, Bayes rule
• Unsupervised Learning: K-means, Self-organizing maps
• Principal Component Analysis
• Information Theory: Independent Component Analysis
• Graphical Models
• Optimization, Support Vector Machines
• Neurodynamics: non-linear dynamics and chaos
• Associative memory: Hopfield net and applications
• Self-supervised Learning
• Reinforcement Learning
• Evolutionary Learning, review session
Format and Grading

- course is “hands-on” with *bi-weekly homeworks*

- homeworks require programming in *Matlab*, teams of up to three o.k., i.e. there can be up to 3 names on one solution

- homeworks: 30% of overall grade

- final exam: 70% of overall grade
Rules

Cheating: is prohibited. In particular, no copying of assignment solutions, matlab code, etc.

Due Time: homework is due at the beginning of class.

“Late”-policy: If homework is handed in up to a week late: only get 50% of points you would usually get. After a week, the homework will earn no more credit.
Whitman Richards (coined term \textit{natural computation}): “Biological systems have available through theirs senses only very limited information about the external world. Yet these systems make strong assertions about the actual state of the world outside themselves. These assertions are of necessity incomplete. Clearly, a replica of an object and its qualities cannot be embodied within the brain. How can an incomplete description, encoded within neural states, be sufficient to direct the survival and successful adaptive behavior of a living system?”

We will be looking for answers in terms of \textit{formal models} (mathematical models, information processing, computation).
Different “Perspectives” on the Brain

**Perspective A:** The brain is a computation device. It finds solutions to certain computational problems. Sometimes these solutions are only approximate. (“top-down view”)

**Perspective B:** The brain is a complex dynamical system with many non-linearly interacting parts. The behavior emerging from these interactions is often difficult to predict (“bottom-up view”)

Jochen Triesch, UC San Diego, http://cogsci.ucsd.edu/~triesch
Spatial Scales

nervous systems span a range of spatial scales; at every scale there is interesting structure that we would like to understand

figure from Churchland and Sejnowski (1992)
Temporal Scales

- $10^{-3}$: action potential
- $10^{-1}$: object recognition
- $10^1$: infant habituation
- $10^3$: LTP, LTD
- $10^4$: percept. learn.
- $10^6$: learn skill
- $10^8$: infant walks
- $10^{10}$: human life
- $10^{12}$: growing up
- $10^{13}$: neuroevolution

1 day = $8.6 \times 10^4$ s, 1 year = $3.2 \times 10^7$ s
Models of a Neuron

Structure, structure, structure!

Is it necessary to model the detailed spatial structure? It depends...

Is it necessary to model the detailed temporal structure? It depends...

Is it necessary to explicitly model the various conductances and transmitter systems? It depends...

A: cortical pyramidal cell; B: Purkinje cell of cerebellum; C: stellate cell of cerebral cortex
### Classes of Neuron Models

<table>
<thead>
<tr>
<th>a: compartmental vs. point model</th>
<th>b: cont. activation vs. spiking</th>
</tr>
</thead>
<tbody>
<tr>
<td>highest realism, most difficult to simulate</td>
<td>lowest realism, most easy to simulate</td>
</tr>
</tbody>
</table>

Our focus will mostly be here
The need for studying cognition from a computational perspective

David Marr:

“Trying to understand perception by studying only neurons is like trying to understand bird flight by studying only feathers: it just cannot be done. In order to understand bird flight, we have to understand aerodynamics; only then do the structure of the feathers and the different shapes of birds’ wings make sense.”
Marr's levels of analysis (1982)

Computational theory: 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?

Representation and algorithm: 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?

Hardware implementation: How can the representation and algorithm be realized physically?
“Ballard’s Laws of Computation”

Brain does computation → it must obey fundamental laws of computation from theoretical computer science: (Turing machines etc.)

1. *(Computability)* “You cannot compute nearly all the things you want to compute.”

2. *(Complexity)* “The things you can compute are too expensive to compute.” (e.g. optimal solution to a travelling salesman problem)

**Indeed:** brains not necessarily built to find optimal solutions to all/most difficult problems but rather to quickly find very good solutions to survival relevant problems. (Tiger example, time enters the objective function)
The Brain as a Computing Device

The brain is organized very differently from today’s mainstream computers:

- $10^{11}$ neurons, parallel processing
- Individual neurons slow (and noisy)
- $10^4$ connections each, every other neuron only a “few synapses away”: immense connectivity
- Enough “wire” in the brain to go to the moon and back
- Learning takes place when neurons and synapses change properties
- Memory and processing not as nicely separated
Why Make Mathematical or Computational Models?

- helps understand the brain at the level of detail required for re-building it (neural prosthesis, AI)
- Some examples:
  1. Hippocampus chip
  2. Vision aids for the blind
  3. Silicon Retina for robots
  4. Cochlea Implants
Benefits of Computational Models

• come up with new explanations for cognitive phenomena

• tie explanations of cognitive phenomena to underlying biological mechanisms

• bridge gaps between vastly different spatial and temporal scales

• forces explicitness about any assumptions; such explicitness helps uncover flaws in other less formal theories

• make precise predictions that can be tested and falsified
Issues with Computational Models
(or any formal theories in the sciences)

- it is easy to account for just any one set of data
- it is even easier to account for no data
- sometimes, it is almost impossible to account for all available data
- what is the right level of abstraction?
  1. if too simple: may lose essential aspects
  2. if too complex: analysis may become unpractical

“Make everything as simple as possible, but not simpler.”

Albert Einstein
Studying real brains:
- since brain produces intelligent behavior, robotics researches can learn from better understanding of brain function.
- biological research inspiring new architectures/algorithms

Building artificial brains:
- helps us better understand the problems that the brain is solving
- allows to ask more general questions
- When do we “understand” the brain? When we can rebuild it!?
Where will this lead us?
When will we be able to build intelligent robots?

- brain’s processing power (difficult to estimate!):
  - naïve guess: every neuron has to sum its $\sim 10^4$ inputs every millisecond: $10^{11} \times 10^4 \times 10^3 = 10^{18}$

- today’s computers: 3 GHz processor, $\sim 3 \times 10^9$ ops

- Moore’s law: computer processing speed doubles around every 18 months

So how many years will it be until we’ll have the necessary processing power on our desktops?
So you want to play god...

**T1:** Robots will be smarter than humans, the only question is when.
**T2:** Robots will be as conscious as we are, the only question is when.
**T3:** Robots will have emotions if we decide to build them that way.

**Some Thought Questions:**
- how will this change the way we see ourselves?
- what do we do when they can do all our work better than we do?
- can we trust them / how can we control them?
- will they deserve to have rights (we give them to animals)?
- will they replace us?
- will we form a symbiosis with them?