ANNfk Lecture 3
Brains and ANNs

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Goals of lectures 3 & 6
- Beyond ANN as a tool
- Modern brain theory, relation to ANN
- Biorealistic model of neocortex
- Attractor networks, as CAM and for optimization
- Lessons from biology?
- Technological potential of brain-like computing
- NN hardware

ANN yesterday ... today
- First ANN wave 1945 – 1969
- Second wave 1982 – 1995
- Today
  - ANN applications
  - AI-ANN research scattered
  - E.g. paradigm shift in Computer Vision
  - Computational neuroscience expanding
  - Neuroinformatics
    - Databases, Simulators, Brain imaging and Visualising
    - "Neuro-IT"
  - EU, NSF, DARPA, ..., Japan
  - "Reverse engineering the brain"
  - Startups ...
  - Third ANN wave?
    - Truly brain-like computing and architectures?
    - Artificial Nervous Systems, Artificial Brains

Our brain = "alien technology"
- Volume: 1.5 liters, 80% cortex
- Cerebral cortex
  - Dimension: 3 mm × 2 × 1200 cm²
  - N: neurons: 20 × 10^9
  - N: synapses: 10^14, sparseness 10^-6
- Fiber length: 10 million km
  - >20 × distance Moon-Earth
  - 600 km/cm²
  - 90 nm chip: 10 km/cm²
  - N: messages/s: 10^13
  - "RAM": >10^15 bits
  - Ops/s: >10^19 Ops
  - Power consumption: 30 W
    - Light bulb, PC processor

Brain networks – multi-scale view

The synapses = memory and compute nodes

Size of real neuronal networks
- In reality
  - Several types of different neurons
  - Huge numbers
  - Modular and layered

<table>
<thead>
<tr>
<th>Neuron</th>
<th>Human</th>
<th>Manager</th>
<th>Cat</th>
<th>Rat</th>
<th>Mouse</th>
<th>Honey bee</th>
</tr>
</thead>
<tbody>
<tr>
<td>N (10⁹)</td>
<td>2.6</td>
<td>2.6</td>
<td>6.8</td>
<td>6.0</td>
<td>2.9</td>
<td>2.9</td>
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<tr>
<td>Synapses (10⁻¹⁸)</td>
<td>3.0</td>
<td>3.0</td>
<td>4.0</td>
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- Quite similar over areas and species!
- Linear scaling also of synapses
- Very sparse connectivity
**Biological nervous systems excel in ...**

- Real-time perception and control
- Sensor "technology"
- Sensor arrays, high sensitivity
- Holistic perception
- Exploits context, multi-modality
- Figure-background segmentation, information fusion
- Parallelism, distributed memory
  - Scalability (mouse to man)
  - $N = 10^{11}/10^{15}$
- Compactness
  - Low power dissipation (< 50W)
  - Slow, stochastic elements
  - Fault tolerance
- Can we understand HOW?

**Synaptic plasticity and Hebbian synapses**

Hebb D O, 1949: The Organization of Behavior

- Experience dependent connectivity
- Co-activation of nerve cells $\Rightarrow$ enhanced connection/synapse

- Hebb’s hypothesis verified!
- Synaptic long-term potentiation (LTP), 1973, Hebbian, 1978
  - LTD, long-term depression
  - "Spike-timing dependent plasticity" (STDP)?

**Hebbian cell assemblies – formation**

**Hebbian cell assemblies – dynamics**

Perceptual Pattern completion

**Hebbian cell assemblies – bistability**

Necker cube
Hebbian cell assemblies – bistability

- Mechanism?
- Synaptic depression + neuronal adaptation?

Hebbian synapses and cell assemblies

- Cell assembly = mental object
- Gestalt perception
  - Figure-background segmentation
  - Perceptual completion
  - Perceptual rivalry
- After activity ≈ 100 ms – 1 s
- Association chains
  - + Central Executive → Thinking
- Suggests kind of ANN?

Mathematical instantiation of Hebb's theory

The Hopfield network

\[ \frac{d}{dt} u_i = \sum_j w_{ij} v_j - u_i + I_i \]

\[ v_i = g(u_i) = \frac{1}{1 + e^{-\frac{u_i}{\beta}}} I_i \]

“Hebb’s learning”

\[ w_{ij} = \frac{1}{N} \sum_{t=1}^{T} e^{ij} M_{ij} \]

Applications of attractor networks

- Mathematical cortex model
  - Associative memory model
  - Content Addressable Memory (CAM)
    - Storage capacity
    - Sparse activity
    - Diluted connectivity
    - Lots of modeling done
      - Connectionist → Biophysically detailed
- Combinatorial optimization
  - E.g. TSP

CAM – different (attractor) networks

- Hopfield
  - Potts network – modular, normalization
- Willshaw-Palm
  - Binary W
- BCPNN
  - Bayesian probabilistic, modular, normalization
- How many memories can cortex store?
  - How many does it need to store? Forgetting?
Performance measure – storage capacity

- Number of retrievable (random) patterns
- Bits/connection (free parameter)
- Noise analysis
- Information theoretical analysis
- "Replica theory"

Hopfield networks – storage capacity

- Random patterns, 50% activity
- "Crosstalk", variance analysis
  \[ M_s = 0,14N \]
  
  \[ M_{\text{max}} = \frac{N}{2 \ln N} \]

- Much analysis exists

Information theoretic estimate

- N:o bits in W (symmetric)
  \[ \text{bit}_{\text{sym}} = \frac{N(N-1)}{2} \]

- N:o bits/retrieved pattern
  \[ \text{bit}_{\text{rem}} = \text{bits/pattern} = \log \left( \frac{N}{m} \right) \]

- \( k = 0.2 – 0.3 \) (bits stored by each synapse)
- Reasonable for standard Hopfield
  - … and for attractor networks generally!

Efficient memory!

Some further remarks

- Skewed random patterns
  - Common in real world data
    - E.g. varying feature detector selectivity
  - Willshaw-Palm does not work
  - Hopfield neither …
    - High utility units gets strongly connected
    - Converges to a common pattern
  - BCPNN works well
    - High utility units gets weakly connected

- "Dynamic sparsity"
  - Synaptic spine dynamics …
  - Improves bits/synapse capacity
  - Cortical modularization still uncertain

Hopfield networks – storage capacity

- Sparse activity \( a = \sqrt{N} \), \( 10^2 \) connectivity
  - Sparse activity \( \Rightarrow \) Less information/pattern …
Combinatorial optimization using attractor networks – useful at all??

- Compares Hopfield networks (and SOM) to "meta-heuristic" methods
- Hopfield and Tank, TSP, 1985
  - Energy function
  - … equivalent to the function to be minimized
  - "Constraints" included as penalty terms
  - Legal & good solutions desirable

- Wilson and Pawley, TSP, 1988
  - Could not reproduce Hopfield & Tank 1985
  - Only fraction of tours valid, not very short
  - "our simulations indicate that Hopfield and Tank were very fortunate in the limited number of TSP simulations they attempted"
  - Method in doubt! ➔ heuristic methods

Combinatorial optimization using attractor networks – improvements

- Reformulation of energy function ➔ More legal solutions
  - "Valid subspace approach"
- More optimal solutions
  - Stochastic "annealing"
  - E.g. Boltzmann-Cauchy machine
  - Units with chaotic dynamics
- Dedicated hardware, FPGA

- "The initial problems that have plagued the reputation of the Hopfield network have now been solved."

Recent TSP evaluation

- WTA modules (columns)
  - Ensuring exactly one visit/step
  - Some invalid states disabled (may have 2 ones on row)

- \( E(x) = \frac{1}{2} \sum_{i} \sum_{j} (x_{ij} + x_{ji}) + \sum_{i} \sum_{j} \delta(x_{ij}) \) \( \delta(x_{ij}) = \begin{cases} 1 & \text{if } x_{ij} = 1 - x_{ji} \\ 0 & \text{otherwise} \end{cases} \) \( W_{ij} = -(K\delta(x_{ij}) - 1) + \delta(x_{ij}) \delta(x_{ji}) - \delta(x_{ji}) \) \( \delta(x_{ij}) \) is the Kronecker delta function.

- \( K > 2d_{\text{max}} - d_{\text{min}} \)
  - Converges
  - Always valid tour
  - Solution quality improves with decreasing \( K \) ...

Recent TSP evaluation, cont’d

- \( K > 2d_{\text{max}} - d_{\text{min}} \)
- \( K < 2d_{\text{max}} - d_{\text{min}} \)
  - Never valid tour

- Table I: Performance of oridinal Hopfield model with 20 cities
- Table II: Performance of CM model with 20 cities
Recent TSP evaluation, cont’d

- Order of 10 iterations
- + Simulated Annealing

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<th>Table III</th>
<th>The performance of CCM with SA for the 21-city example</th>
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<th>Table IV</th>
<th>The performance of CCM for the 15-city example</th>
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Recent TSP evaluation, cont’d

- Larger problems ...
- Perf. ratio = minimum/average
- Other tours
- Better SA
- Map coloring problem

Possible ANNk project

Back to biology: Attractor memory and cortex

- Biological attractor memories?
  - Olfactory cortex, Hippocampus
  - Recurrent connectivity
  - Inspiration for CAM models
  - Entire neocortex: Multiple connected attractor networks?

  ➔ Biophysically detailed model of neocortex
  - Structure as "modular Hopfield network"

Units/Minicolumns, Hypercolumns

- Unit ➔ cortical minicolumn
  - 30 pyramidal cells
  - 2 "regular spiking non-pyramidal cells" (RSNP)
  - "double bouquet" ...
  - "Functional minicolumn"
- Hypercolumns with ca 100 minicolumns = 3000 cells
- Basket cells provide negative feedback within the hypercolumn ("activity normalization")

Synaptic strengths from isomorphic connectionist network trained with BCPNN

Biophysically detailed cell model
Synapse properties

- Realistic amplitude of PSP:s in largest network model
- Asymmetric cell-cell connectivity
- 2D geometry ⇒ delays, 0.1 - 1 m/s

Tsodyks, Uziel, Markram 2000

Some questions we had

- Is cortical recurrent connectivity strong enough?
- ... to support pattern completion and rivalry
- How much of spike synchronicity, gamma rhythm, theta rhythm, ... etc
- Can the model reproduce "UP/DOWN-states" observed in vitro in cortical slices?
- Model of cortex layer 2/3, horizontal connectivity

McCormick et al, 2003

Network layout

- 1x1 mm patch
- 9 hypercolumns
- Each hypercolumn
  - 100 minicolumns
  - 100 basket cells
  - 100 patterns stored
  - 29700 neurons
  - 15 million synapses

Active minicolumn (30 pyramidal cells)
Active basket cell
Active RSNP cells

One of the 9 hypercolumns

Active RSNP cells
Active minicolumn (30 pyramidal cells)

9 hypercolumns

- 1x1 mm patch
- 9 hypercolumns
- Each hypercolumn
  - 100 minicolumns
  - 100 basket cells
  - 100 patterns stored
  - 29700 neurons
  - 15 million synapses

100 hypercolumns

- 330000 neurons
- 161 million synapses
≈ 4x4 mm

8 rack BG/L simulation

- 22x22 mm cortical patch
- 22 million cells, 11 billion synapses
- 8K nodes, co-processor mode
  - used 360 MB memory/node
  - Setup time = 6927 s
  - Simulation time = 1 s in 5942 s
  - >29000 cpu hours
  - Massive amounts of output data
  - 77 % of linear speedup
  - Point-point communication slows (?)
  - Currently (unofficial) world record

The three different cell types
3 sec simulation

Pyramidal
RSNP
Basket

- 2000+ neurons
- 25000+ synapses
- 5 s = 600 s on PC

Bimodal membrane potential

Perception and associative memory performance

- Pattern reconstruction
  - Figure-background
  - Pattern completion and rivalry
- Sustained after-activity
  - 150 ms – 2 sec
- NMDA, K\textsubscript{\textsc{a}} modulation
- Robust to parameter changes and scaling
- Cortical long-range recurrent excitation strong enough to support attractor dynamics
- Spiking statistics as in vivo
- Can even reproduce cognitive phenomena...
  - ... like "Attentional Blink"

What is Attentional Blink?

- Occurs when two expected stimuli are presented < 500 ms apart
- Experimentally, stimuli are changed every 100ms; exposure 85-100ms
- Can occur in vision and audition, likely any modality
- A cognitive component of general reaction time
- Effect is diminished when interval is <= 100ms (lag-1 sparing)

Attentional blink – effect of GABA\textsuperscript{\textsc{a}}

- Attractor activation correlates with percentage of correct probe detections
- Time scales different but qualitatively similar results

Adapted from Kranczioch, Debener, Engel 2003
Ongoing and planned work

+ Add a layer 4
  - Selective feature detectors
  - V1 model
+ Add a Layer 5
  - Martinotti cells, delayed inhibition to superficial layers
  - Pyramids, cortico-cortical connections
+ Overlapping stored memories
+ Analysing dynamics, spiking statistics, conductances, intracellular potentials
+ Better synthetic VSD, BOLD signals