A Brain science perspective on Artificial intelligence and Machine learning

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About me

- Brain interest since 1970's
- Computer science PhD 1986
- Associative memory networks in cortex
  - Mathematical models and simulation
    - Short-term and Working Memory
    - Memory consolidation
  - Supercomputer simulation
- Parallel AI interest and teaching
- PhD courses and seminars in neuroscience

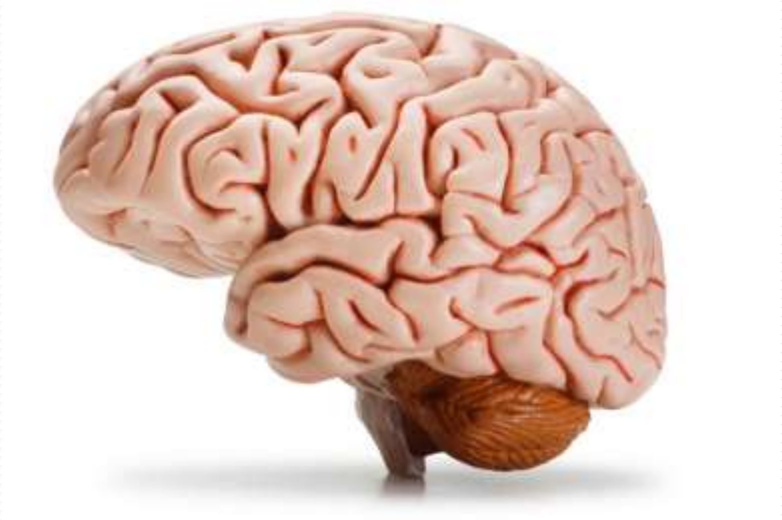
- My perspective
  - ML-DNNs etc are successful
    - Algorithm and/or Hardware progress ...?
  - ... but what comes next
    - Towards Artificial General Intelligence
    - What can a Brain-inspired approach offer?

AI,Robotics and the Brain

- Popular performance reference
- ”We don’t need to copy how the brain does it”
- Current ML uses deep neural networks …
  - ”mimics how the brain works …” – Well, do they?

- Look more deeply into how the brain works!
  - Experimental data accumulate very rapidly
    - Many new measurement technologies (molecular, imaging …)
  - Tells about fundamental mechanisms

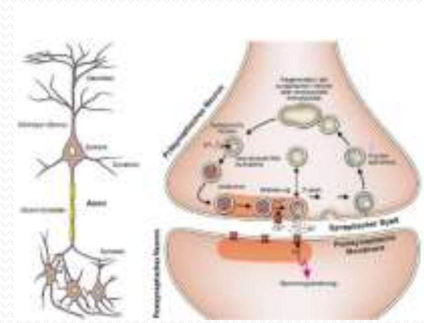
The complex Human brain



- Almost 86 billion neurons
  - Cortex, 82% of brain mass, 16 billion neurons
  - 10^{14} synapses, extremely sparse connectivity (W filling ratio = 10^{-6})
- Total length of (myelinated) axons 180000 km
  - Supercomputer total cable length order 1000 km
- Power consumption 25 W
  - Large supercomputers order 10 MW

Brain computing components

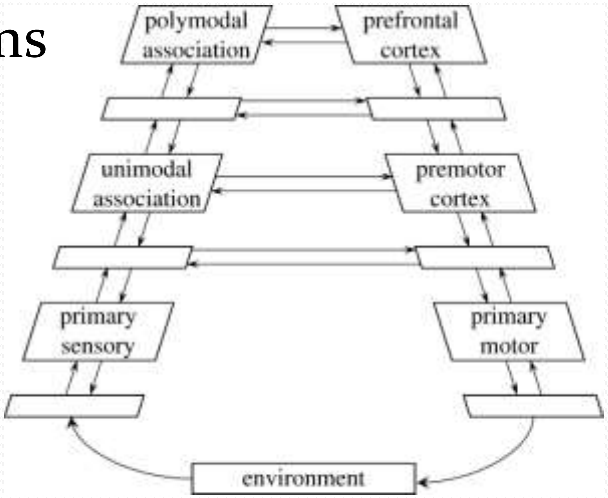
- Neurons and synapses
  - High variability, low speed, low precision (≈5 bit synapse)
  - Synaptic transmisson about 50% successful
  - 0.1 – 100 m/s conduction speed
- Synapse = molecular machine, 1000 different proteins
  - Signal transmission
  - Plasticity, strength and structure → learning
    - Multiple time-scales, life-long or short-lived
- Each synapse/neuron has only local knowledge (plus some global neuromodulation) → massive parallelism!



MPI for Biophysical Chemistry

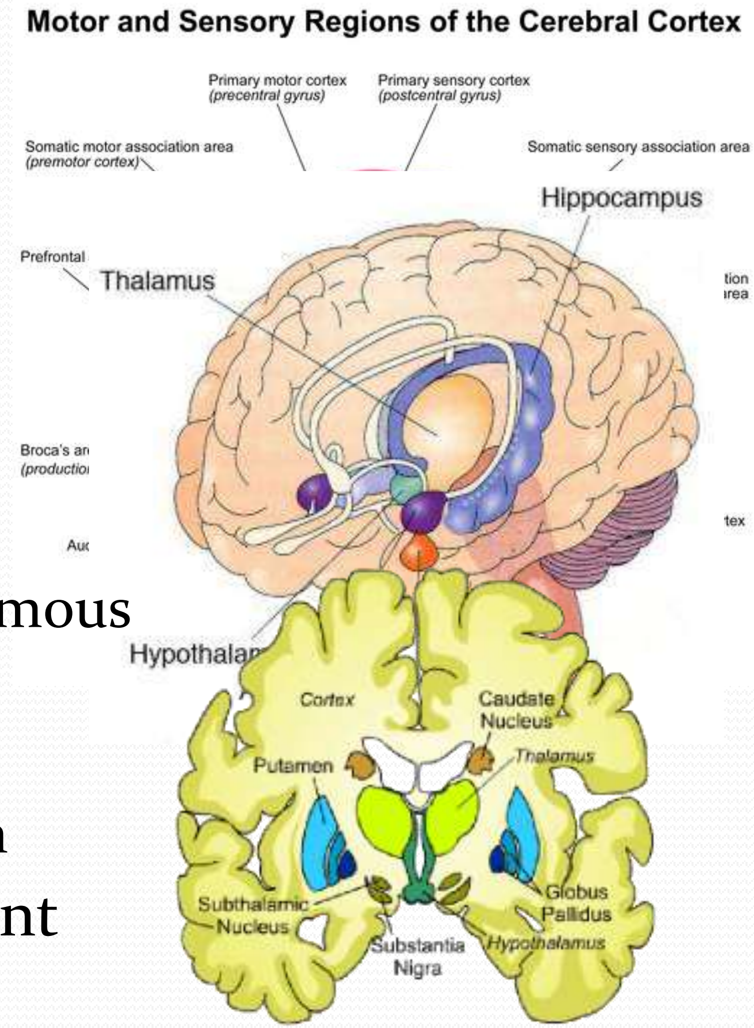
Cortical areas and connectivity

- Hierarchy of cortical areas, processing streams
  - Sparse (10^{-6}) unstructured connectivity
  - Primary sensory →higher order
    - Layers 2/3,5 → Layer 4
    - Feature extraction
  - Higher order → lower order
    - Layers 2/3,5 → Layer 5
    - Top-down expectation
  - Lateral within and between different sensory modalities
    - Layers 2/3,5 ←→ Layers 2/3,5
    - Information fusion, constraint satisfaction
- Connectivity formed mostly by learning
  - Unsupervised or Reinforcement forms
    - Benefits from abundant non-labelled data
- Feed-forward (like DNNs) 10%, Recurrently connected 90%



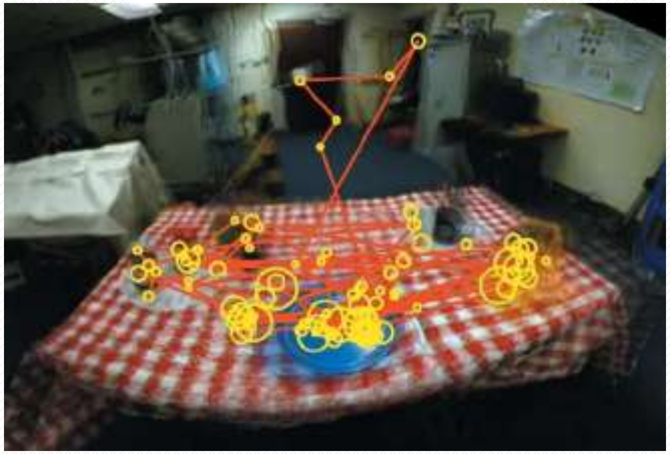
Systems integration

- Perception →… → Behavior
  - Tight integration, 20 ms latency
    - Between senses and memory areas
    - Sensory-Motor (cerebellum)
- Motivational systems
  - Drives, needs
  - Controls attention, reward learning
  - Necessary component in an autonomous system
- Decision making systems
  - Multiple goals, real-time arbitration
- AI/ML: Single/Few multi-component systems



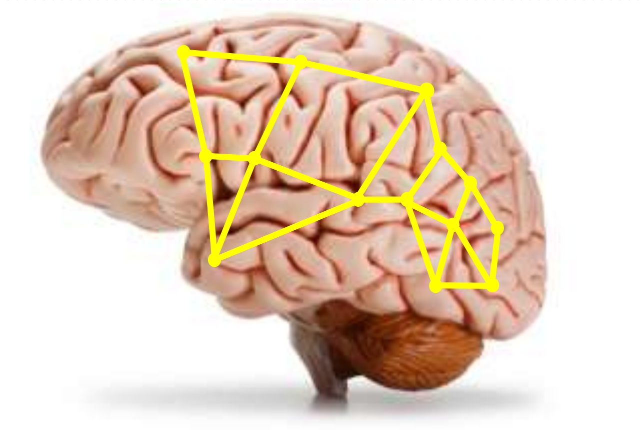
Perception

- Visual acuity low outside fovea
- Selective attention
  - saccades,fixation → scan path
- ”Invariant perception”
  - Translation
  - Size
  - Rotation
  - Learning based …?
- Co-operation and Rivalry
  - Recurrent brain connectivity
  - Figure ground, illusory contours, …
  - Alternating perception, …
  - Sensor fusion
    - Lip reading can change hearing



Memory and Thinking

- Mental representations = cell assemblies
- Multiple memory systems, long-term
  - Explicit (episodic,semantic)
  - Procedural (knowing how,skills)
  - Sequence memory allows prediction
- Short-term and working memory
  - Key to human (fluid) intelligence
    - Lacking in current ML …
  - Content of consciousness

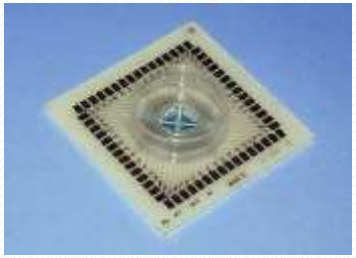


- Thinking, active memory
  - We learn a world model
    - Synaptic plasticity
  - Mental simulation by associations, ”imagination”
    - Symbolic and sub-symbolic
    - AI: Memory/Case-based reasoning

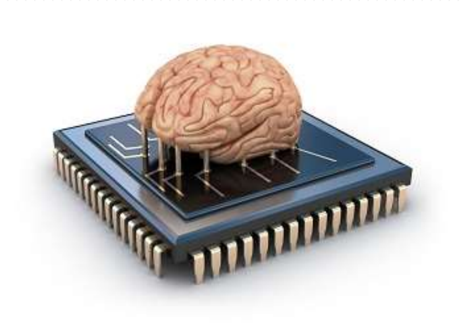
Action and Motor control

- Biological motor control
  - Spinal cord and brain stem, basic motor programs
  - Control of dynamic stability
  - Tight sensory-motor integration
    - Cerebellum, time coordination
- Robotics
  - Typically static stability
  - Biology inspired
    - Mark Raibert, MIT leg lab → Boston Dynamics Inc
      - Big dog, Atlas, Spot, and more

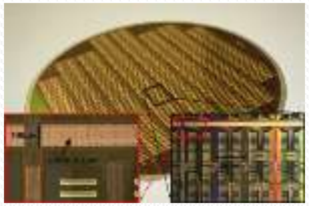
Neuromorphic hardware



- Neuron culture in a dish/rack…
  - Bi-directional communication
- Digital
  - IBM True North (2014)
  - Intel's Loihi (2017), on-chip learning
  - SpiNNaker system (Manchester U, HBP)
  - KTH custom VLSI design, human cortex sized NN, real-time, 3 kW



- Analog, mixed-signal
  - Wafer-scale system (Heidelberg U, HBP), analog neurons
  - Memristor based NN
  - IBM Phase-change-memory (PCM technology)
    - Potentially 30 W for human cortex sized NN
  - …



- In-memory-computing, massive parallelism, stochastic and low precision components, analog computing
  - Brain-like designs can exploit this!
  - Standard algorithms mostly not …

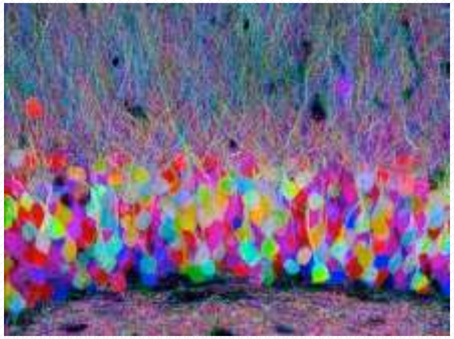
Brain ↔ AI/ML/Robotics

- Imprecise, slow components
- Unsupervised and Reinforcement learning
- Sparse, unstructured W
- 90 % recurrence,feedback W
- Multiple modalities
- Multiple drives and goals
- Multiple memory systems
- Multiple time scales, sequence
- Dynamic stability
- Autonomous operation

- Fast high precision math
- Supervised learning
- Partly sparse, structured W
- Feedforward W
- Single modality
- Single goal
- Single memory system
- LSTM …
- Static stability
- Poor autonomy

Conclusions

- Brain science has lots of useful data on the brain
  - Experimental techniques develop fast
- Need less reductionism, more synthesis and theory
  - … an engineering approach
  - Different scientific cultures, very narrow bridge
- Mathematical modeling and computer simulation
  - Only way to connect micro- with macro-scale and dynamic operation, i.e. to understand the brain
  - Enables more hyphothesis driven brain science
  - Connects neuroscience and cognitive psychology
    - Helps to better understand brain diseases
      - Improves brain health



”Brainbow”

AI/ML research with a perspective longer than 1-2 years should take very seriosly this connection to Brain science!