Part XXX

Future of Informatics - Chapter 7

Chapter 7. Human brain and mind

understanding, modeling and simulation

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PROLOGUE

Since there is a real danger that computers will develop intelligence and take over we urgently need to develop direct connections to the brain so that computers can add to human intelligence rather than be in opposition.

Stephen Hawking

BASIC POSTULATES

This is to present non-trivial and not obvious postulates on which our optimism for future is based:

- We are able to use our own thinking to understanding our own thinking.
- Our intelligence is just above the critical threshold necessary to for us to scale our own ability to unrestricted heights of creative power.
- Understanding the human brain and mind is one of the metachallenges of 21-st century science and technology and convergence of ICT/Informatics and biology and neurology create grounds for a belief that ICT-inspired search for development of understanding of human brain and mind is a feasible goal.

GROUNDS for OPTIMISM - I.

There are good reasons to believe that we are at a turning point, and that it will be possible within the next two decades to formulate a meaningful understanding of brain functions.

This optimistic view is based on several measurable trends, and on a simple observation which has been proven in the history of science: scientific advances are enabled by a technology advance that allows us to see what we have not been able to see before.

At about the turn of the 21-st century, we passed a detectable turning point in both neuroscience knowledge and computing power.

For the first time in the history, we collectively know enough about our own brains, and have developed such advanced computing technology, that we can now seriously undertake the construction of a verifiable, real-time, high-resolution models of significant parts of our brains.

Lloyd Watts, neuroscientist

- Brain of giraffe is remarkably similar to the human brain - in spite of the fact that it seems to be far bellow the level required for self-understanding.
- Genetic difference between chimpanzees and humans is only few hundred thousands bites of information.
- The ability to reduce everything to simple fundamental laws does not imply the ability to start from these laws and reconstruct the universe.

P. W. Anderson.

HOW POWERFUL are BRAINS CONCERNING INFORMATION PROCESSING

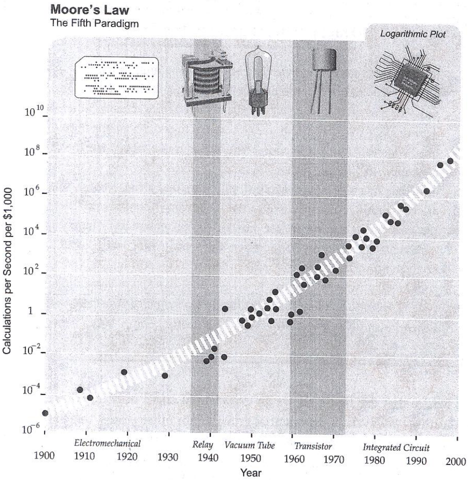
How powerful are brains

concerning information processing?

New computation paradigms as a background for overcoming brains power and for reaching human levels of intelligence

FIRST FIVE COMPUTATIONAL PARADIGMS

First five modern computational paradigms are, as already discussed in Chapter 3: electromechanical, rely, vacuum tubes, transistors, integrated circuits.



SIXTH NEW COMPUTATIONAL PARADIGM

In order to design computers with information processing power larger than that of human brain, a new computational technology - a sixth paradigm of it is needed.

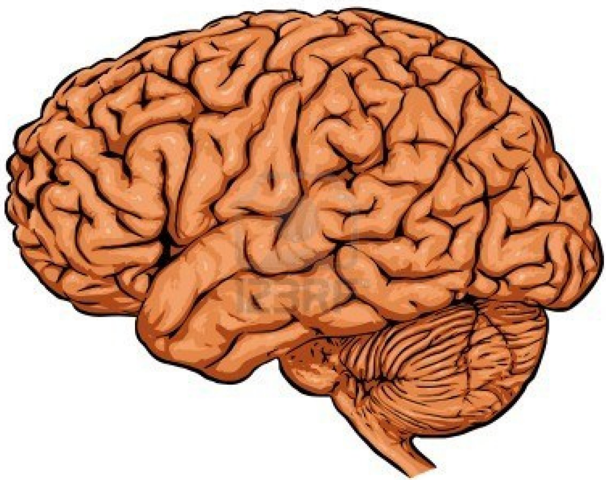
As discussed below, there has already been compelling progress in all of the enabling technologies required for the sixth paradigm to act in full power.

The sixth paradigm seems to be **3D Molecular computing**

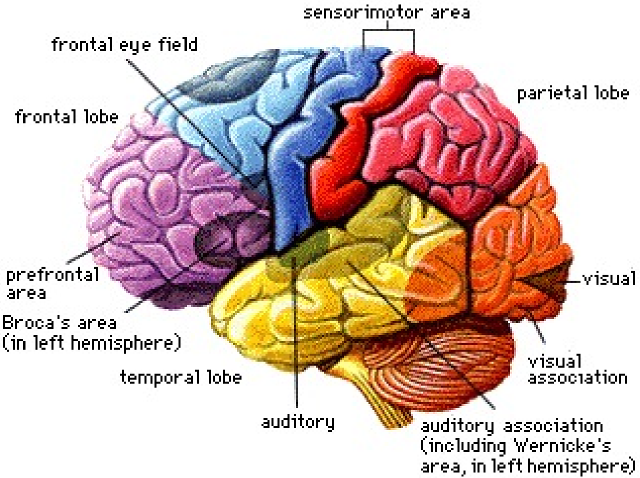
HUMAN BRAIN PROJECT - I.

- In January 2013 European Commission launched a huge 10 years long project to simulate the human brain (with 1.2 milliard of euros).
- Underlying assumptions: the convergence between ICT and biology has reached a point where we can achieve a genuine, multi-level understanding of the human brain - an understanding that could have big impact on treating brain diseases and to develop revolutionary new, brain-inspired computing and brain-like intelligence.
- Another goal is to get fundamental insights into what it means to be human.

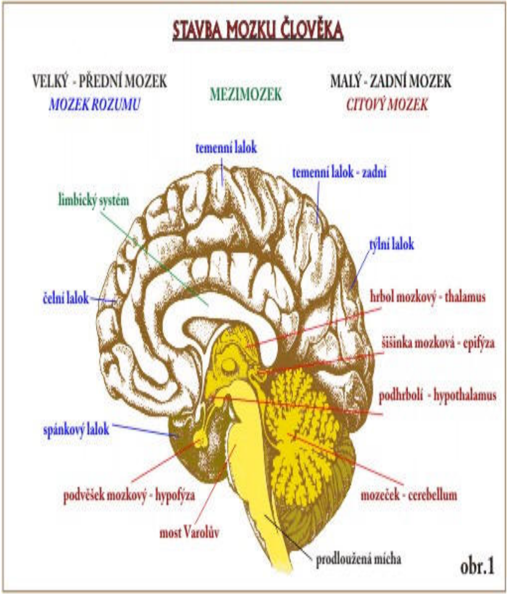
BRAIN PICTURE



BRAIN PICTURE - I.



BRAIN PICTURE - II.



- This is one of the largest and most ambitious from current scientific projects with finances 1/6 of the price of "Large Hadron Collider" in physics, 80 institutions, 250 scientists.
- It is broadly seen as a breathtaking ambition. It is broadly seen as having potential to bring very interesting and important outcomes. Though the ability to achieve a complete simulation of human brain is met often with some pessimism.

- Main grounds for optimism; the amount of already accumulated data, knowledge and models; progress in brain scanning; dramatically accelerating progress in ICT and, finally, dramatically increasing the pace of scanning the brain.
- Main grounds for pessimism: Computing technology is not yet powerful enough and it is unlikely be so in due time for the project. Project put too much emphases on physical understanding of human brain and not enough on functional understanding. Our current knowledge of activities of 80 billions of neurons and 100 trillion of synapses is currently not sufficient.

HUMAN BRAIN PROJECT - IV.

- Currently, the project is supported by the BlueGene/P IBM supercomputer with 16384 processors, 56 Teraflops of peak performance, 16 Terabytes of distributed memory and 1 Petabyte file system. At the end of the project an exascale computer should be available.

NEW TECHNOLOGIES LEADING to 3D MOLECULAR COMPUTING

- Nanotubes and nanotube circuitry.
- Self-assembly in nanotube circuits.
- Molecular computing - computing with few molecules
- Biological circuits emulating circuit assembly.
- DNA computing
- Spintronics (computing with spins of electrons).
- Optical computing
- Quantum computing.

It can be expected that some of these technologies will be integrated into system capable far outpace the computational capacity of human brains.

SILICON LITHOGRAPHY 3D CIRCUITS

One approach being currently explored is to build 3D circuits using "conventional" silicon lithography.

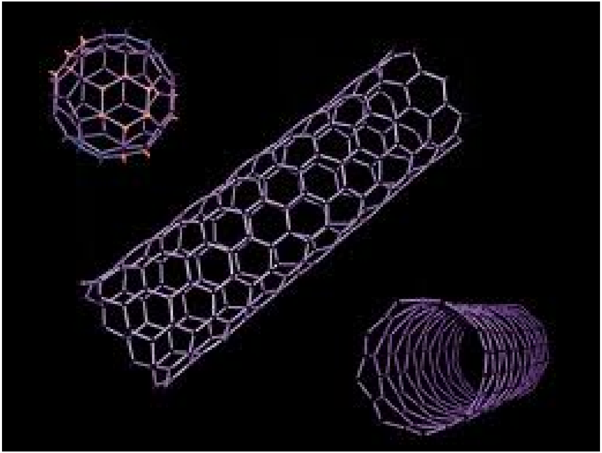
- Matrix semiconductor company is already selling memory chips that contain vertically stacked planes of transistors rather than one flat layer - this way the overall cost per bit is reduced. They want to compete with flash memory in portable electronics.
- Fujio Masuoka, inventor of flash memory, claims that his novel memory looking like a cylinder, reduces the size and cost-per-bit of memory by a factor of ten compared to 2D chips. Such silicon chips have already been demonstrated.
- NTT (Nippon Telegraph and Telephone) Corporation has demonstrated a dramatic 3D technology using electron-beam lithography, which can create arbitrary 3D structures with transistors as small as ten nanometers. Technology should be applicable to nano-fabrication of semiconductors.

NANOTUBES

Nanotubes belong to main candidates for 3D molecular computing.

- Nanotubes use molecules organized in 3D to store bits and to act as logic gates.
- Nanotubes, first synthesized in 1991, are tubes made up of a hexagonal network of carbon atoms that have been rolled up o make a seamless cylinder.
- Nanotubes are very small - one nanometer in diameter.
- Nanotubes are potentially also very fast. Nanotube circuits have been demonstrated at U of California, Irvine, operating at 2.5 GHz and their speed limit should be teraherz (that is about 1000 times faster than modern computer speed.
- In 2001 a nanotube-based transistor (1×20 nm) using a single electron to switch between on and of states was reported in *Science* and IBM demonstrated an integrated circuit with 1, 000 nanotube based transistors.
- In 2004 created in Berkley and Stanford an integrated memory circuit based on nanotubes.

NANOTUBES - PICTURES



LINING UP NANOTUBES

Lining up nanotubes is a big challenge because they tend to grow in any direction.

- In 2001 IBM demonstrated that nanotubes transistors could be grown in bulk, similarly as silicon transistors and that outcome was seen as "passing a major milestone on the road to toward molecular-scale chips".
- In 2003, Nantero company took the process a step further demonstrating a a single chip wafer with 10 billion nanotube junctions, all aligned in a proper direction.
- Nantero design provides random access and refinement of data when power is off and therefore it could replace all primary forms of memory (RAM, flash and disk).

COMPUTING WITH FEW MOLECULES

Major progress has been made recently in computing with one or few molecules.

- The idea of computing with molecules was first suggested in the early 1970s by IBM's Avi Aviran and Northwestern University Mark A. Ratner. However at that time enabling technologies were not available.
- In 2002 at U. of Basel and Wisconsin created "atomic memory drive" that seems to have potential to lead to systems capable to store millions of times more data on a disk of comparable size.
- Nanoscale molecular transistor created at U. of Illinois runs at frequency more than half a terahertz.
- A special molecule, called "rotaxane" was found that is suitable for computing. it can switch states by changing the energy level of a ringlike structure contained within the molecule. Rotaxane memory and electronic switching devices have been demonstrated with potential of storing one hundred gigabits (10^{11} bits) per square inch.

DNA AND MOLECULAR COMPUTING

- DNA computing has been developed already for quite a while as a form of computing that uses DNA, biochemistry and molecular biology to do computation.
- For example, in 2002 a programmable molecular computer composed of enzymes and DNA molecules was announced (by scientists from Weizmann Institute of Science in Rehovot);
- In 2004 a DNA computer was announced by, E. Shapiro et al., that was coupled with an input and output module which would theoretically be capable of diagnosing cancerous activity within a cell, and releasing an anticancer drug upon diagnosis;
- In 2009 bio-computing systems were coupled, by scientists from Clarkson University, with standard silicon based chips for the first time.[1]

[1] L. Cardelli's web site is one of the best places for informaticians to look for papers and talks on molecular computing.

POTENTIAL of DNA COMPUTING

- DNA in each cell contains 3 to 5 millions of base pairs;
- It can be seen as 2m long and 2nm thick and with 750 MegaBytes;
- In a human body we have 3 billions of cells, DNA as 5×10^9 km long and with 7.5 OctaBytes.
- Nature uses DNA in certain ways, mainly using proteins.
- However, there is no reason not to assume that we can use DNA/RNA in different ways than nature and to build nano-devises including nano-computers. Indeed,
- DNA computing has been developed already for quite a while as a form of computing that uses DNA, biochemistry and molecular biology to do computation.

SELF-ASSEMBLING of NANOSCALE CIRCUITS

Self-assembling of nanoscale circuits that allows improperly formed components to be discarded automatically is another big problem and several enabling technology for that have appeared.

Without such automated techniques it would hardly be possible for potentially trillions of circuit components to organize themselves.

- In U of Purdu have already demonstrated, in 2002, selforganizing nanotube structures, using the same principle that causes DNA strands to link together into stable structures.
- In 2004, at U. of South California and NASA' Arms Research Center demonstrated a method for self-organization of of extremely dense circuits. Technology has storage capacity of 258 gigabits of data per square inch.
- Several research teams tried to perform self-organisation and/or self-assembling using biological elements, say proteins or DNA molecules.s reported in *science* in 203.

DNA COMPUTING

A potential to use DNA molecules to solve hard problems was demonstrated in 1994 by Adleman (to solve traveling salesman problem on a 7-node graph) and later by Shapiro in 2003.

Their methods allow to use enormous number of DNA "computers" doing the same in parallel. A computation is performed by manipulation with tubes and enzymes and though it can demonstrate enormous massive parallelism it is very slow and as calculated by J. Hartmanis, it would require enormous number of energy to solve practically important problems.

DNA computing in the form demonstrated by Adleman and Shapiro could be of some interest to solve problems that are inherently suited for massive parallelism of SIMD type.

Of importance, in the context of this lecture, is the fact that for modeling certain aspects of functionality of the brain the SIMD architecture may be appropriate.

OPTICAL COMPUTING

This is again a type of computing suitable for solution of problems that fits very much SIMD architecture.

- The basis is to use multiple beams of laser light in which information is encoded in each stream of photons.
- Optical elements can then be used to perform logical and arithmetical operations on the encoded information streams.
- For example, Israeli company Lenslet uses 256 lasers and can perform eight trillion calculations per second by performing the same calculation on each of the 256 streams of data.
- The system can be used for such applications as performing data compression on 256 video channels.

- The main difference between classical and quantum computers, computing and information processing systems, is in the way information is stored, transferred and processed.
- In classical computers, information is represented on a macroscopic level by bits, which can take on only one of the two values, 0 or 1.
- In quantum computers, information is represented on a microscopic level, using so-called *qubits* (quantum bits), which can take on a continuum of values.
- They can take on any value from uncountable many superpositions

$$\alpha|0\rangle + \beta|1\rangle,$$

where α, β are arbitrary complex numbers such that $|\alpha|^2 + |\beta|^2 = 1$ and $|0\rangle$, $|1\rangle$, so-called basis vectors, can be seen as the representations of the classical bit values 0 and 1.

QUANTUM COMPUTING II.

Quantum computing has several enormous advantages but faces also several enormous difficulties.

- Computation with n qubits allows a really massive parallelism, in 2^n dimensional Hilbert space - to perform 2^n computations in one step - in a way.
- It is hard to separate, store for longer time, and to manipulate qubits due to the impacts of environment. Currently maximum number of qubits used is around 14.
- Some of very basic quantum operation produce non-local correlations between particles that are processed what is very hard to achieve reliably.
- It has been shown that quantum error correction can be used and quantum fault-tolerant computation is feasible in unlimited time and space if basic elements with sufficient reliability are found - what is still an open problem.
- It is far from clear how big will need to be classical overhead when larger number of qubits are to be manipulated.
- Currently design of small quantum processors for simulation of quantum processes seems to be a realistic goal and not a more powerful quantum computer.
- Optical computing can be seen as a very special case of quantum computing and so it is the case concerning computing with spins discussed afterwords.

- It has been shown that solution of so-called Deutsch-Jozsa problem classically requires n queries and quantum algorithm can do that with 1 query only.
- Shor has shown that factorization of integers can be done in polynomial time on quantum computers.
- Grover proved that a search in an unordered set of n elements requires quantumly only $\underline{O}(\sqrt{n})$ queries though classically one needs, in the worst case, $n-1$ queries.
- It has been shown that so-called Hidden subgroup problem for Abelian groups can be solved quantumly in polynomial time.

Given: An (efficiently computable) function $f : G \rightarrow R$, where G group and R a finite set.

Promise: There exists a subgroup $G_0 \leq G$ such that f is constant and distinct on the cossets of G_0.

Task: Find a generating set for G_0 (in polynomial time (in $\lg |G|$) in the number of calls to the oracle for f and in the overall polynomial time).

SPINTRONICS

To use spins of electrons is one way to implement a qubit. Spins can be visualised as magnets that can have many orientations and two orthogonal ones are used to represent two basic states $|0\rangle$ and $|1\rangle$ and their superpositions can be used to represent a general qubit state.

The exciting property of spintronics is that no energy is required to change the electron's spin state. Moreover, the spin of the electron can be transported without loss of energy. In addition, this occurs at room temperature in materials already widely used in semiconductor industry.

A form of spintronics is already used: magnetoresistance is used to store data on magnetic hard disks.

COMPUTATIONAL CAPACITY of HUMAN BRAIN

HOW TO ESTIMATE COMPUTATIONAL CAPACITY of HUMAN BRAIN

- A number of estimations have already been made - they are reasonably similar with respect to the order-of magnitude estimations.
- Estimations are based on replications of the functionality of brain regions that have already been reverse engineered (that is their functionality understood) at human levels of performance.
- Estimation of the computational capacity of a region is then multiplied by the number of regions.
- Estimations are based on functional simulations of a region and not on simulations of each neuron and interneural connection in the region.

- **Key note** The prediction that the Singularity - an expansion of human intelligence by a factor of trillions through a merge with non-biological intelligence - will occur within several decades does not depend on exactness of these estimations.
- Even if estimations of the amount of computation required to simulate human brain would be low by a factor of thousands, what is very unlikely, that would delay coming of Singularity only by about 10 years.
- Moreover, a factor of million would lead to a delay of about 21 years.

HANS MORAVEC's ESTIMATIONS

- He analyzed transformations by neural image-processing circuitry contained in the retina (2cm wide, 0.5mm thick).
- Most of retina's depth is to capture images, but 1/5 is for image processing - to distinguish dark and light and to detect motion in about million small regions of the image.
- He estimates that retina performs 10^7 edge and motion detections per second and based on his robotics experience he estimates that execution of hundred computer instructions is needed to re-create each such detection at human levels of performance.
- Replication of the image-processing functionality of this portion of retina requires 1,000 MIPS.
- Since human brain is about 75,000 times heavier than the 0.02 grams of neurons in this portion of retina, the overall estimation is 10^{14} cps for the entire brain.

LLOYD WATTS' ESTIMATION

- Estimations of Watt's group are based on functional simulations of regions of human auditory system derived from reverse engineering outcomes.
- They estimate that 10^{11} cps are required to achieve human level localization of sounds.
- The auditory cortex regions for this processing comprise at least 0.1% of the brain's neurons.
- In total that gives $10^{14} = 10^{11} \times 10^{3}$ cps.
- There are also estimation leading to 10^{15} cps and so, to be on the safe side, we will use in the following analysis a more conservative estimation 10^{16} cps.

POWER of FUNCTIONAL SIMULATIONS

- A natural question is whether functional simulations can/will be sufficiently good.
- They have been very successfully used when various implants have been designed and implemented.
- We have therefore good reasons to believe that analysis of all neurons and neural connections is not needed in order to determine computational performance of brain regions.
- Functional simulation is therefore believed to be sufficient to recreate human power of pattern recognition, intellect and emotional intelligence.

- To "upload" a particular person's personality (to capture his/her knowledge, skills,...) we may need to simulate neural processes at the level of individual neurons and their portions, such as the soma (cell body), axon (output connections), dendrites (trees of incoming connections) and synapses (regions connecting axons and dendrites).
- To do that we need to consider a detailed model of neurons (10^{11}), their fan-outs (10^3). With a reset time of five milliseconds that comes to about 10^{16} synaptic transactions per second.
- Since about 10^3 calculations per synaptic transactions are needed, to capture nonlinearities, this results in the overall estimation 10^{19} for simulation of he human brain at this level.

AVAILABILITY of HUMAN LEVEL LAPTOPS

- Current laptops achieve performance 10^9 cps.
- Current best supercomputer,"Titan"-computer, has top performance 17×10^{15} cps.
- There is a possibility of harnessing unused computational capacity of other computers on Internet that can increase performance by a factor $10^3 - 10^4$.
- It is therefore reasonable to expect human brain computational capacity laptops around 2020 - 2025.
- Availability of human-level-performance laptops could also be speed up by using transistors in their native "analogue" mode, especially because many of the processes in human brain are analogue. Simulation of analogue processes with digital one is MUCH costly.

HUMAN MEMORY CAPACITY

- Let us analyze human memory requirements.
- Number of "chanks" (patterns or items) of knowledge mastered by an expert in a domain is about 10^5 for a variety of domains.
- World-class chess master is estimated to have mastered about 100,000 board positions; Shakespeare used 29,000 of words with total about 100,000 meanings of them. Development of expert systems in medicine indicate that humans can master about 100,000 of concepts in a domain.
- If we estimate that professional knowledge represents only 1% of the overall pattern and knowledge store of a human we arrive to an estimate of 10^7 chunks.
- Experiences, from expert systems, show that 10^6 bits are needed to store one chunk and that provides as a reasonable estimate 10^{13} bits of for a humans functional memory.
- A higher estimate, namely 10^{18} bits, we get when we model human memory on the level of individual inter-neural connections.

- The hardware capable to emulate human-brain functionality should be available for approximately 1,000 dollars by around 2020-2025.
- The hardware capable to emulate all unaided human-brains functionality should be available for approximately 1,000 dollars by around 2045-2050.

OBSERVATION

Observe that most of the complexity of human neurons is devoted to maintaining its life-support functions, not its information-processing capabilities!!

We should therefore be able to port our mental processes to a more suitable computational substrate and our minds won't be so small

THE ROLE of MIND SUBSTRATE

Type of the substrate for mind is morally irrelevant, assuming it does not affect functionality or consciousness.

It doesn't matter, from a moral point of view, whether somebody runs on silicon or biological neurons (just as it does not matter whether you have dark or pale skin).

On the same grounds, that we reject racism and specieism, we should also reject carbon-chauvinism, or bionism.

Giulio Gioreli

ULTIMATE PHYSICAL LIMITS of COMPUTATION - I.

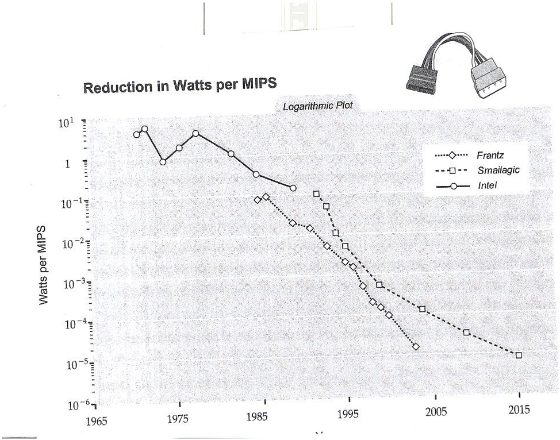
- Energy consumption started to be the key issue after the experience with first supercomputers when it started to be clear that removal of heat is the main issue in attempts to design faster computers.
- Limits for energy consumption. This is a simple and great case. Concerning energy consumption the limit is zero. Due to outcomes of Landauer (1961) and Bennet (1973), consumption of energy converges to zero if computation is performed in a reversible way (and this can always be done) and sufficiently slowly.
- The practical reality is, however, a bit different. To get outcomes of computation outside of computation devices requires an energy proportional to the number of bits that need to be outputed. However, fortunately, this amount is mostly vastly less than the amount of computation needed to produce outcomes.

ULTIMATE PHYSICAL LIMITS of COMPUTATION - I.

- Computational capacity of universe. Seth Lloyd calculated that, on the basis of current physical laws, the capacity of the universe to support intelligence is only about 10^{90} calculations per second,[2] and that the whole universe could produce during its existence not more than 10^{122} elementary physical operations (interactions) and could not store more than 10^{92} bits.
- Computational capacity of "ultimate laptops" Seth Lloyd also calculated that no laptop of weight 1kg and volume of 1 litter could perform more than 10^{51} elementary operations per second.

[2] A universe saturated with intelligence at 10^{90} cps would be trillion trillion trillion trillion trillion times more powerful than all human brains today.

REDUCTION in WATTS per MIPS



Observation 1: It seems to be clear that Moore law cannot be valid infinitely

Observation 2: It is quite clear that computer performance that would be more than trillion times larger than that of human brain is (quite soon) feasible.

LIFE AS INFORMATION PROCESSING PROCESS

- Science's understanding of life is is based on Darwinian evolution by natural selection, and selection is, in essence, information processing.
- Virtually all forms of life, including humans, are descendants from their ancestors, by the transmission of DNA.
- DNA information storage function alone is reason enough to regard life, as in essence, an information processing process.
- In a deep biological sense, computing is as much a part of life as eating and breathing.

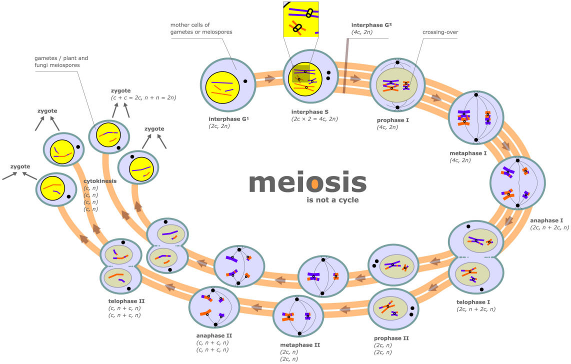
CELLS and INFORMATION PROCESSING

- Cell's do not need humans to perform computations. They are full of computational tricks of their own.
- Cells are actually tiny chemical calculators.
- Compared to even the best of human computers, the living cell is an information processor extraordinaire.
- However, cells are much more than computers. They make proteins needed for all life's purposes.
- Cells need to to copy DNA's genetic information for two reasons; one is to make proteins, the other is to pass important life information to new generations.
- The DNA in a cell contains enough information not only to make human (animal) body, but also to operate it for lifetime.
- Molecules within certain cells of living humans contain fruitful information about the history of human species.
- A cell's computational skills allow simple life forms to respond to their environment successfully - bacteria have no brain, yet they somehow figure out how to swim toward food and away from poison.
- Cells guide life not merely by exchange of energy among molecules - that is, simple chemistry -but by the sophisticated processing of information.
- By understanding cellular information processing, medical researchers can come up with better strategies.

SEX and INFORMATION PROCESSING

- Getting a new organism is a complicated process, requiring the formation of sex cells by meiosis.
- After a cell divides by meiosis, each new cell contains only half the normal supply of genes.
- Meiosis is followed by fertilization, the merging of male and female sex cells to restore a full supply of genetic material.
- In this process of meiosis and fertilisation, DNA from two parents is cut up and recombined, giving the offspring's cells a set of DNA information that contains many similarities while still differing from both parents.
- To make kids is just complicated information processing.

MEIOSIS PICTURE



DNA AND INFORMATION PROCESSING

- Genetic information is encoded along DNA strands using four kind of "bases" (molecular fragments that connect the two DNA strands). The basis are known/denoted by their initial letterers: adenine, thymine, guanine and cytosine.
- DNA strands stick together in a special way: A is always opposite to T and G with C.
- When it is time for DNA to divide e and reproduce, the two strands split and the master enzyme comes along to build to each strand a new partner.
- When Watson and Crick discovered DNA, in 1953, they immediately realized that the secret of transmitting genetic information had been exposed.
- A gram of dried-out DNA stores as much information as maybe a trillion CD-ROM discs.
- DNA origin is believed to be close to the origin of life itself.

- The blueprint for any given protein is called a gene and DNA is the stuff that genes are made of.
- A gene holds the instructions for producing a protein.

BRAIN and INFORMATION PROCESSING

- There are little doubts that brain performs sophisticated information processing and that main progress in understanding the brain came recently from the researcher that view the brain as an information processing system.
- There is a lot of controversy whether brain is a computer in the usual (Turing machine) sense - or it is just "a dynamical systems" where a lot of information processing interactions go on.
- von Neumann was perhaps the first to explore these issues in a scientific depth.
- Computer and computer models are nowadays main tools to get in depth into brain information processing.

- Information precessing ideas clearly help scientists to understand how the brain's nerve cells conspire to create thoughts and behaviour.
- Design of computational models of brain activities is currently perhaps the main and most successful way to study brain.

OBSERVATIONS of NEUROSCIENTISTS

- Scientific advances are enabled by technology advances that allow us to see what we have not been able to see before.

  L. Watts

- Now, for the first time, we can observe the brain at work in a global manner with such a clarity that we should be able to discover programs behind its magnificent power.

  J. C. Taylor, B. Horowitz, K. J. Friston

- The brain is good: It is an existence proof that a certain arrangement of matter can produce mind, perform intelligent reasoning, learning and a lot of other important tasks of engineering interest.
  The brain is bad. It is an evolved, messy system where a lot of interactions happen because of evolutionary contingencies.

  A. Sandberg

- The interactions within a neuron are complex, but on the next level neurons seem to be somewhat simple objects that can be put together flexibly into networks.
  Cortical networks are locally a mess, but on the next level the connectivity is not that complex.

  A. Sandberg

REVERSE ENGINEERING of BRAINS

GOALS, PROBLEMS and STATE of the ART of REVERSE ENGINEERING of BRAINS

Reverse engineering of the brain is of large importance because:

- Understanding of the functionality of brains is a mega-challenge of curiosity driven research.
- It is expected that understanding of functionality of brain could lead to new computation and problem solving technologies.
- It is expected that a combination of human-level intelligence with computer superiority in information processing would have formidable effects, especially for development of information processing and intelligence demonstrating tools.
- It is expected that reverse engineering of brain could enormously increase our capability to deal with neurological problems (Alzheimer, Parkinson,...)
- So far our tools to peer into the brain and to observe its working from inside have been very crude. However, this keeps changing exponentially.

BRAIN SCANNING, IMAGING and MODELLING TOOLS

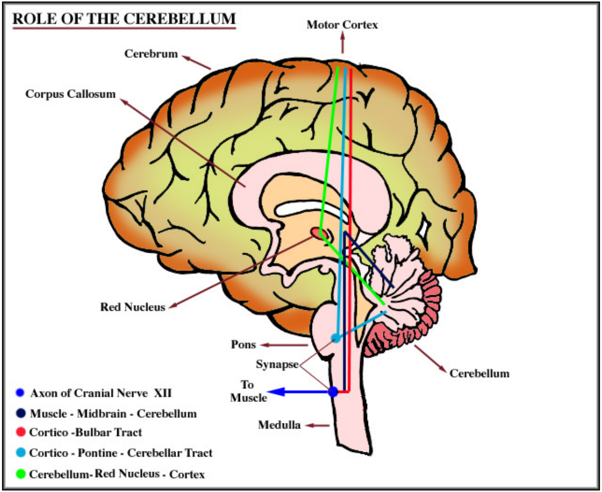
- So far our tools to peer into the brain were (very) crude.
- However, this keeps radically changing.
- A lot of new scanning technologies have been developed recently that are greatly improving spatial and temporal resolution, price-performance and bandwidth of scanning.
- Consequently, we are rapidly gathering data on particular brain subsystems (regions) and processes - ranging from individual synapses to large regions such as cerebellum, which comprises more than half of the brain's neurons.
- Extensive databases are systematically cataloging our exponentially growing knowledge of the brain
- Much progress in scanning of the brain and its processes, through scanning from inside, is expected when nanobots start to be used for scanning.
- There are no inherent barriers known to our capability to reverse engineer brain and the operating principles of human intelligence and replicate these capabilities in more powerful computational substrates.
- The human brain is a complex hierarchy of complex systems, but it does not represent a level of complexity beyond our capabilities.

The structure and processes of brain are enormously complex. For example, the information contain in a human brain contains about 10^{16} bits. However, there are several important facts why it seems that making functional models of the human brain is feasible.

- Self-organizing structures have been used to develop brains.
- In spite of the brain complexity, the initial design of the brain is based on the rather compact human genome. It consists of about $8 \cdot 10^8$ bytes, or, after redundancies are removed, less than 10^9 bits.

- There is a lot of repetitive patterns in each brain region and therefore there is no need in reverse engineering of brain algorithms to capture each particular detail of the brain structures and processes. (For example, the basic wiring pattern of the cerebellum is described in the genome only once but repeated 10^7 times.)
- Brain is massively parallel - most of its neurons work in parallel resulting in up to 10^{14} computations carried out simultaneously.
- The pace of designing brain models and performing their simulations is only slightly behind the availability of brain-scanning and neuron-structure information gathering. There are more than 50,000 neuroscientists

CEREBELLUM


ROLE OF THE CEREBELLUM
Motor Cortex
Cerebrum
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Red Nucleus
Pons
Synapse
To Muscle
Medulla
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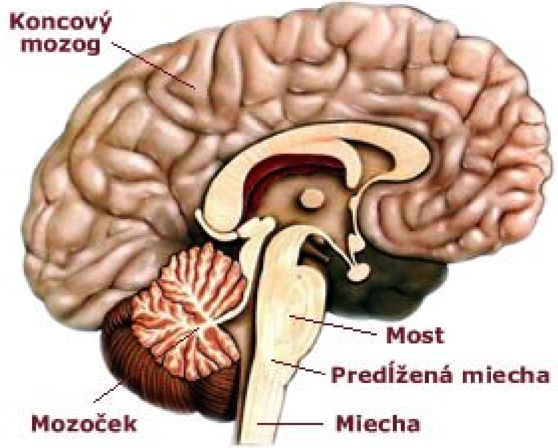
Axon of Cranial Nerve XII
Muscle - Midbrain - Cerebellum
Cortico -Bulbar Tract
Cortico - Pontine - Cerebellar Tract
Cerebellum- Red Nucleus - Cortex

CEREBELLUM - I.



- In contemporary neuroscience brain models are designed using various resources of information and knowledge: brain scanning, models of neurons and of interneural connections, psychological testing and so on.
- As several scientists envisioned, simulation of functional models of the brain would require about 1,000 less computation than would be required if we would simulate all non-linearities of subneural structures.
- A lot of the brain components and processes are to keep the brain itself "alive" and do not have to be taken into account when its functionality as an information processing system is simulated.

KEY DIFFERENCES BETWEEN BRAIN and CURRENT COMPUTERS - I.

- Brain's circuits are very slow - comparing to current computers ones.
- Brain is massively parallel - still far from current supercomputers.
- Brains combine analogue and digital phenomena.
- Brains revise themselves.
- Most of details in brains are random
- Brains use emergent and evolutionary properties - intelligent behaviour is an emergent property of brain's chaotic and complex activities.

KEY DIFFERENCES BETWEEN BRAIN and CURRENT COMPUTERS - II.

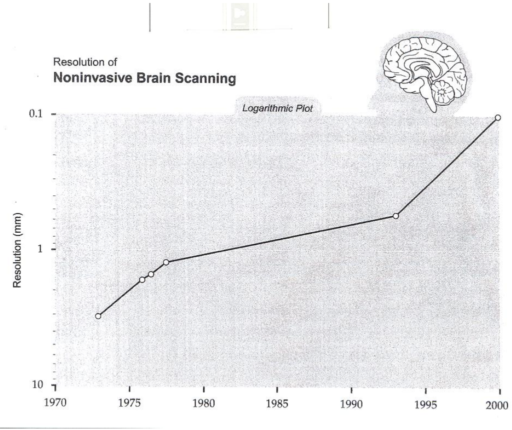
- The patterns are large importance - information is not found in specific nodes or connections, but rather in distributed patterns.
- Brains are holographic and deeply connected.
- Designs and models of brain regions are simpler than those of neurons.

MODERN PRE-HISTORY of ATTEMPTS to UNDERSTAND our THINKING

- The first deep insight into the brain is from 1928 when E. D. Adrian demonstrated that there are electrical processes taking place inside the brain and by measuring electrical impulses and potential we can identify processes in the brain.
- In 1943 W. S. McCulloh and W. Pitts develop a simplified model of neuron and neuron nets that was then refined in 1943 by A. L. Hodgkin and A. F. Huxley.
- In 1949 D. Hebb developed a theory of neural synaptic learning that resulted in so called connectionism movement.

Till fairly recently non-invasive brains sensoring technology has been very crude with not sufficiently good spatial and temporal resolutions.

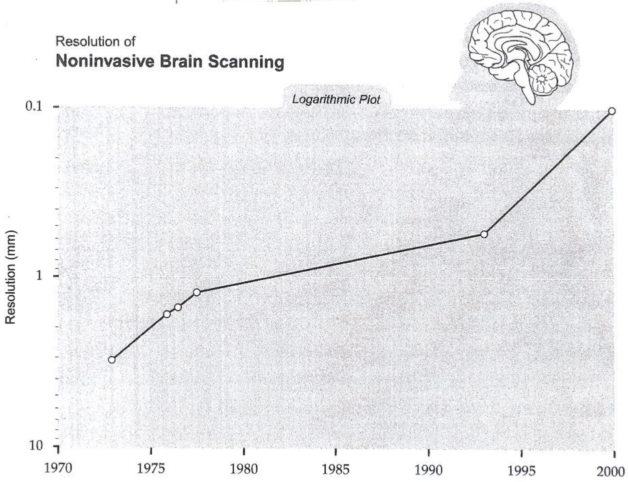
This keeps improving. The resolution of non-invasive brain scanning devices is doubling every year



PEERING INTO THE BRAIN - II. BASIC TECHNIQUES

- Non-invasive techniques have been developed that allow to map brain regions that are only a fraction of millimeter wide and capable to detect tasks that take place in milliseconds.
- Non-invasive techniques are being developed that allow to detect changes in brain states.
- An interesting invasive technique, applied already to animals, is "optical imaging" that involves removing a apart of the skull, staining the living brain tissue with a dye that fluoresces upon neural activity, and then imaging emitted light with a digital camera.
- Various high-resolution technologies have been developed to scan brains in case they can be destroyed or to scan dead brains.
- At Carnegie Mellon U. they had destructive scanner that could scan brain of mouse with a resolution of two-hundred nanometres approaching resolution quality needed for full reverse engineering of human brains.
- **At Texas U. they were able to scan an entire mouse brain at a resolution of 250 nanometers in one month.**

DEVELOPMENTS in NON-INVASIVE BRAIN SCANNING



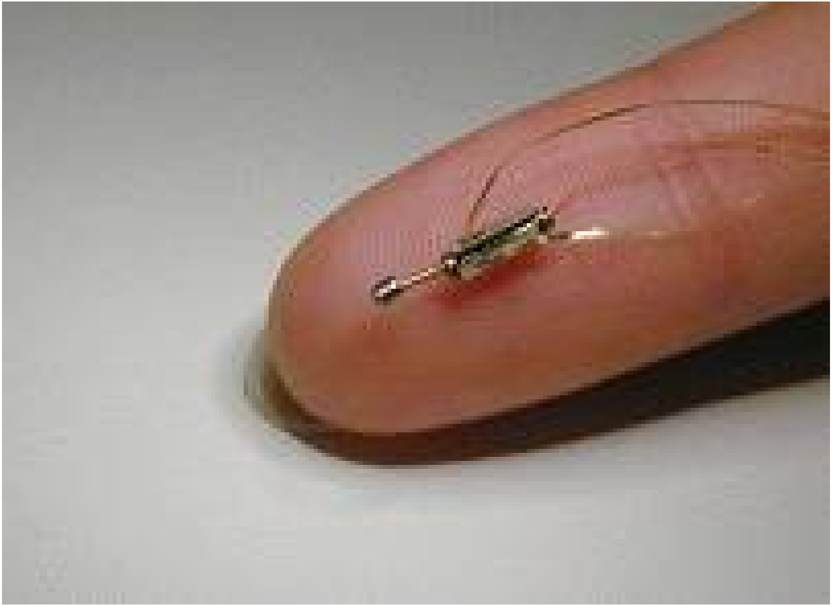
- Cameras for invasive techniques are being developed to image individual neurons, to record their firing, to image 1,000 cells at a distance of 150 microns. That will allow to scan tissue in vivo while animal is engaged in a mental task.
- **Methods have been developing, for example using "two-photon laser scanning microscopy", to noninvasively activate neurons or their parts in a temporary and spatial precise manner. (The technique has also been used to perform ultra-precise intracellular surgeries.)**

- Technique called "multielectrode recording" uses an array of electrodes to record simultaneously the activity of large number of neurons with submilisecond temporal resolution.
- **Technique called "optical coherence imaging" uses coherent light to create holographic 3-d images of cell clusters.**

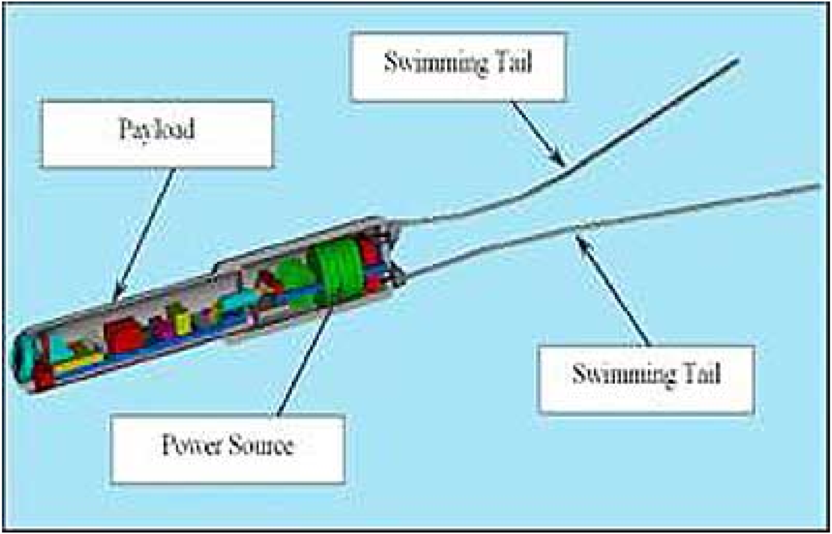
PEERING INTO THE BRAIN - IV. USING NANOBOTS

- Using huge amount of nanobots to scan brain from inside is currently seen as the most promising technique of brain scanning.
- Such nanobots are robots of the human blood cell size (few microns) that could travel through every brain capillary, scanning each neural feature in details, use high-speed WiFi to communicate with one another and with computer compiling the brain-scan database.
- Nanobots are expected to be available by the 2020s. There are currently four major conferences about nanobots.
- A key technical challenge for interfacing nanobots with biological brain structures is BBB (Blood-Brain Barrier) that protects the brain from various potentially harmful substances in the blood.
- Once nanobots-scanning becomes a reality we should be able to place highly sensitive and high-resolution sensors (as nanobots) at millions/billions locations in the brain and witness in breathtakingly details living brains in actions.

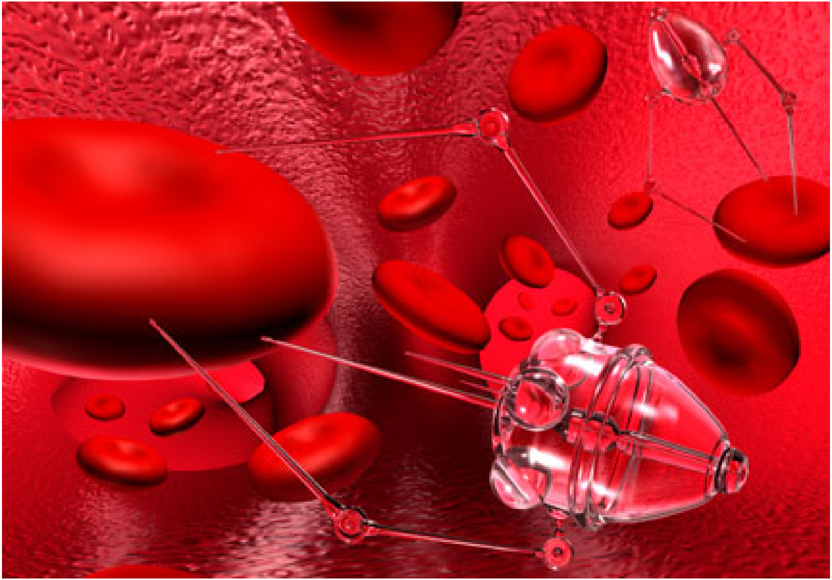
ENLARGED MODEL of a NANOBOT



COMPONENTS of a NANOBOT



NANOBOT in a BLOOD CELL



BUILDING MODELS of BRAIN - I. BASIC OBSERVATIONS

- A good news is that experiences show that for complex structures of nature models on higher level are quite simple and sufficiently good.
- However, understanding of such structures on lower levels is quite important prerequisites for building higher level models.
- Example 1. Behaviour of single molecules in a gas is unpredictable but the gas itself, consisting of trillions of molecules, has many predictable properties.
- Example 2: A pancreatic islet cell is enormously complicated, in terms of its biochemical functions. Yet modelling what pancreas does, with its millions of cells, in terms of regulating level of insulin and digestives enzymes, is considerably less difficult to model well.
- Example 3: Functional models of brain regions are mostly far more simple than mathematical description of a single cell or even a simple synapse.

BUILDING MODELS of BRAIN - I. BASIC OBSERVATIONS

- It starts to be clear that brain reverse-engineering will have to proceed by iterative refinement of both top-to-bottom and bottom-to-top models and simulations - as each level of description is refined.
- Although models have long history in neuroscience, it is only recently that they become good enough that simulations based on them perform like actual brain experiments.
- If we were magically shrunk and put into someones brain while she was thinking, we would see all the pumps, pistons, gears and levers working and we would be able to describe their workings completely, in mechanical terms, thereby completely describing the thought process of the brain.
- However, such a description would nowhere contain any mention of thought!
- It would contain nothing but description of pumps, pistons, levers.

G. W. Leibniz (1646-1716)

BUILDING MODELS of the BRAIN - III. WHY?

From Lloyd Watts:

I believe that the way to create a brain-like intelligence is to build a real-time working model, accurate in details to express the essence of each brain action being performed ...

Models should be able to contribute fundamentally to our advancing of the understanding of systems, rather than to mirror the existing understanding.

Due to such great complexity [of life systems] it is possible that the only practical way of understanding such systems is to build their working models, from the sensors inward, building on our newly enabled ability to visualize the complexity of systems as we advance into them.

Such an approach could be called *reverse-engineering of the brain*.

BUILDING MODELS of the BRAIN

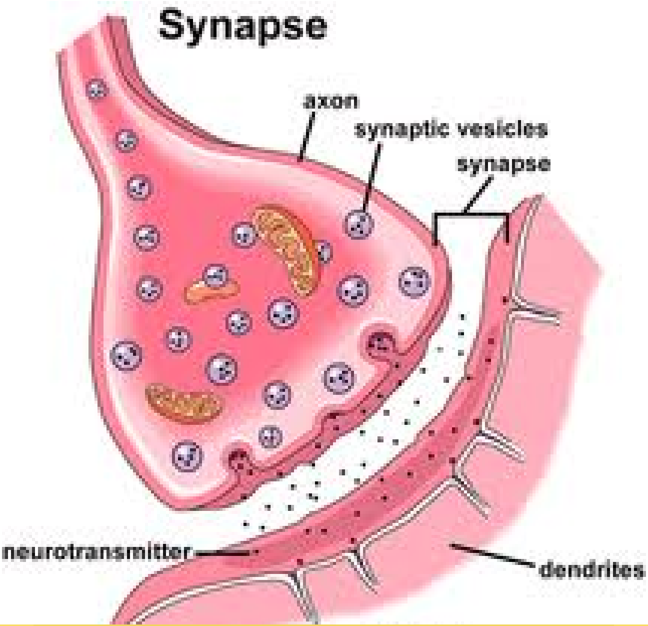
Let us list models of the main parts and regions of the brain - from the lowest level to upper ones.

- Subneural models: synapses, spikes and spines
- Models of neurons.
- Models of brain plasticity
- Models of regions of the brain.
- Models of the cerebellum
- Models of auditory regions.
- Models of brain vision
- Models of very high level functions: imitations, predictions and emotions.

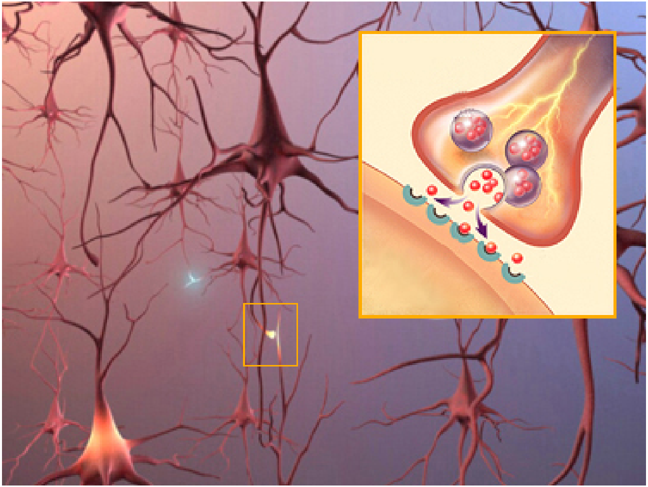
MODELS of SYNAPSES

- Synapses are interfaces through which neurons communicate with each other and they are also the physical structures in which memories are encoded.
- Synapses are low in the brain hierarchy but pretty important.
- The self is the sum of the brain's individual subsystems, each with own "memory" together with complex interactions among subsystems.
- Without the ability of synapses to alter ways they transmit signals, from one neuron to another, the changes in those systems, that are required for learning, would be impossible.
- Well substantiated models, based on non-linear differential equations, exist for biophysics of neuron bodies, synapses and various networks of neurons.
- The idea how synapses work goes back to Hebb's pioneering work, who addressed the question how short-term memory function.
- Recent discovery show that synapses and connections they form are continually changing.
- The study of synapses put a lot of light on formation of human memories.
- For example, it turns out that information is encoded in the brain in such a diffuse way that even if a large parts of the brain are destroyed the overall image is basically intact and only its resolution is diminished.

SYNAPSES PICTURE



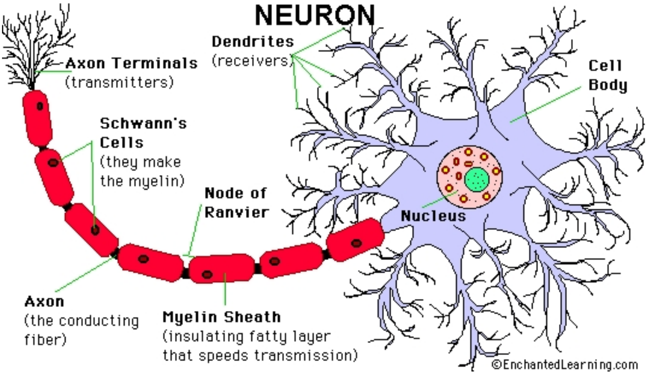
SYNAPSES PICTURE - I.



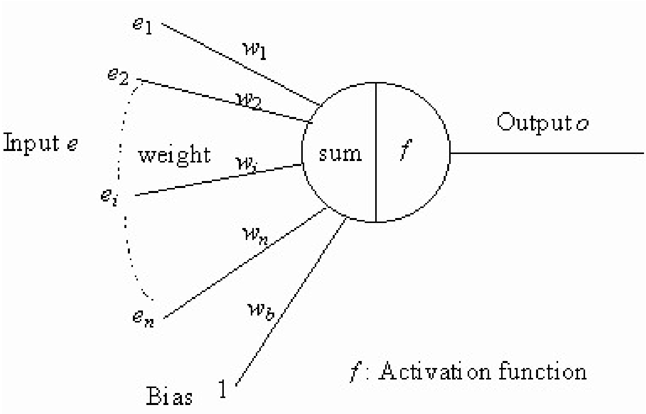
MODELS of NEURONS

- The first functional model of neurons, developed W. S. McCullough and W. Pitts in 1943, can be nowadays seen as a milestone in the development of models of brain components.
- The model introduced several important features: weights for synapses (representing strength of their connections), and non-linearity (through firing thresholds).
- The basic idea is to model the following activities of neurons: a neuron body waits until the weight on all input synapses reaches a threshold value and then the neuron "fires".
- This model can be seen nowadays as a too simplified model of neurons and neuron nets. The model was then refined in 1952 by A. L. Hodgkin and A. F. Huxley.
- The original model initiated an enormous amount of research in many areas, for example neural networks, neural learning and so on. It created the whole field of research known as *connectionism*.
- This model also inspired first steps in the development of modern theory of automata, by M. Rabin (1950) and was behind the paradigm of self-organisation introduced into informatics - into its models of computation.

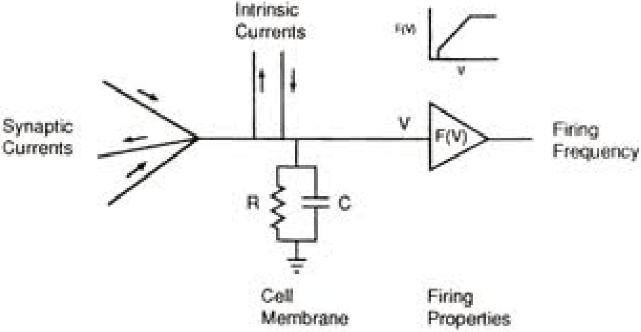
NEURON PICTURE



NEURON MODEL



NEURON MODEL - I.



NEURAL NETWORKS

- The field of neural networks, much initiated by the original neural model, is still broadly developed though it lost some momentum it had in 1980's.
- The field experienced a setback in 1969, when M. Minsky and S. Papert published, in the book *Percepton* a proof that the most common (and simplest) type of neural network used at that time (called *Percepton*) was not able to solve a very simple problem.
- The field started to flourish again in the 1980's when so called "back-propagation method" was introduced. The idea was that the strength of each simulated synapse is determined using a learning algorithm that adjusts the weight of a neuron output after each training trial so the network can "learn" to match the right answer.
- The resulting model turned out to be of some use and had justification as a computation model, but not as a model of biological neurons because the backward connections do not appear to exist.

SOME DISCOVERIES CONCERNING NEURONS

- There are about 80 billions of neurons in the brain.
- A neuron receives in average a thousand of synapses, but so called Purkije cells in cerebellum about 200, 000.
- The smallest neurons are packed about 6 millions per mm^2.
- Specific neurons perform specific recognition tasks.
- Each neuron acts in an essentially unpredictable fashion and therefore exhibit *chaotic behavior*.
- On the other side, when a network of neurons receives an input, the signaling among them appears at first to be frenzied and random. However, over a fraction of time the chaotic behaviour dies down and a stable pattern of firing emerges.
- In case a neural network is performing a pattern-recognition task the emerging pattern represents the appropriate recognition.
- In San Diego they tried to connect biological neurons (of lobster) with electronic ones and could see that biological neurons could "accept" electronical ones.

BRAIN PLASTICITY - BRAIN ADAPTIVNESS

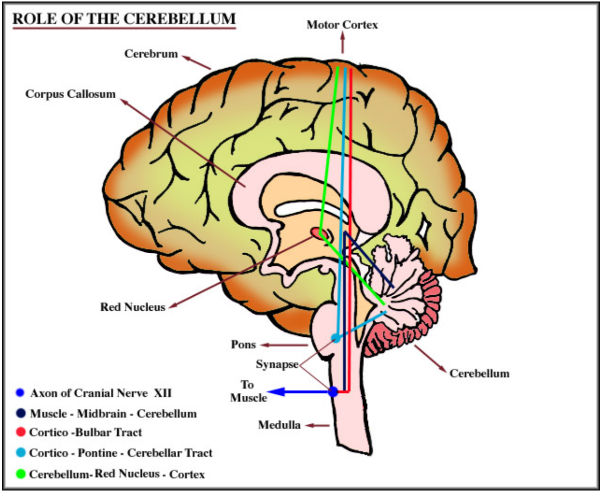
- It has been discovered that though different regions of brain seem to be assigned different functions, brain has a capability to rearranged itself in case of some injuries.
- A detailed arrangement of synapses in a given region depends also much on how extensively is that region used. (This gives a new meaning to Descartes' dictum "I think therefore I am". Not only an extensive use of a part of body but also an extensive thinking in some area can influence brain regions connectivity. Various experiments have been performed to confirm such hypothesis.
- Neurons have been intensively explored also in order to understand creation of short-term and long-term memories. Long-term memories are created after a sufficient number of repetitions of some stimuli.
- In addition to generating new connections between neurons, the brain can also make new neurons from "neural stem cells".

The following observations can characterize current trend to brain modeling

- Modeling human-brain functionality on nonlinearity-by-nonlinearity and synapse-by-synapse basis is not necessary and also not useful.
- Researchers should create many models of brain regions and an understanding has emerged that a combination of two approaches:the top-down (experimental verification of models implications and their comparison with experimental findings) and bottom-up (abstraction to models of physical findings on neuron and synapses levels) are necessary for creation of better and better models.

- Cerebellum is grey and white, baseball-sized, been-shaped region of the brain that contains more than half of brain's neurons.
- Cerebellum's cell organization is very consistent, uniform, its basic wiring method repeats billion times, contains only several types of neurons, and in spite of that it performs a broad range of functions.
- Cerebellum takes care for sensorimotor coordination, balance, control of muscle movements and the ability to anticipate the results of actions (our own as well as those of other persons or things).
- Some of the outputs of cerebellum go to about 200,000 alpha motor neurons, which then sends signals to the body's approximate six hundred muscles.

CEREBELUM


ROLE OF THE CEREBELLUM
Motor Cortex
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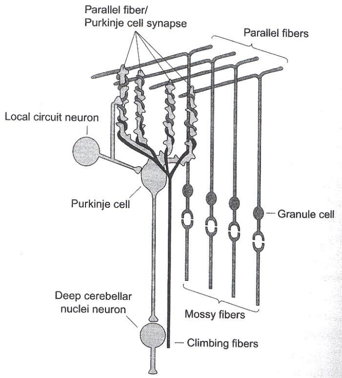
Corpus Callosum
Red Nucleus
Pons
Synapse
To Muscle
Cerebellum
Medulla
Axon of Cranial Nerve XII
Muscle - Midbrain - Cerebellum
Cortico -Bulbar Tract
Cortico - Pontine - Cerebellar Tract
Cerebellum- Red Nucleus - Cortex

REPEATED CEREBELLUM WIRING PATTERN

Massively Repeated Cerebellum Wiring Pattern



Some of the outputs of the cerebellum go to about two hundred thousand
lpha motor neurons, which determine the final signals to the body's approxi-

U. of TEXAS' CEREBELLUM MODEL

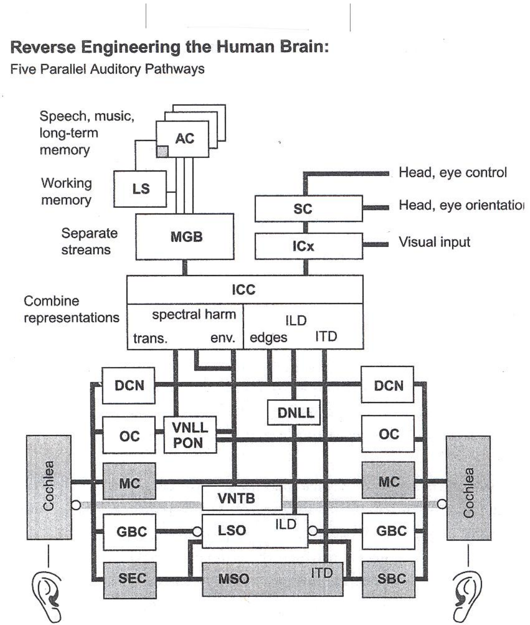
- Detailed cells and animal studies have already culminated in an impressive mathematical description of physiology and organization of the synapses of cerebellum.
- At Medical school of U. of Texas they already in 1996 designed a bottom up simulation of cerberum that features more than 10,000 of neurons, 300,000 of synapses and it includes all of the principal types of cerberum's cells.
- The researchers then applied classical learning experiments to their simulations and compared outcomes with those on actual human conditions - with very satisfactory outcomes.

MODELS of AUDITORY and VISUAL REGIONS

Impressive progress has been done in modelling auditory and visual regions.

- For example so called Watt's model (2003) is capable of matching the intricacies that have been revealed in subtle experiments on human hearing and auditory discrimination. Watt used his model as a preprocessor in his speech recognition system.
- In spite of various progress our understanding of the visual brain regions and precessing of visual information lags behind our knowledge of auditory regions.
- We have preliminary models of two (in 2005) visual areas - there are 36 others.
- Too main activities of visual systems are the identification and categorization.
- Identification is much simplee. There are, for example, already vision systems well identifying human faces.
- Categorization, the ability to differentiate between a dog and a cat, or a person and an auto, is much more difficult task.
- A lot of success has been recently also in this area to emulate the ability of our visual systems to build representations of the world. A part of that is due to much more powerful computers available. As the result a new goal seem to be reachable: vehicles without drivers, robots navigated through unknown complex environment,....

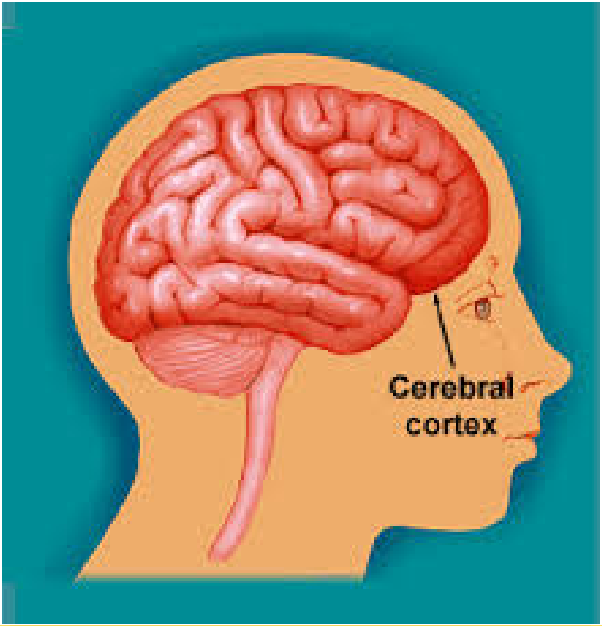
FIVE PARALLEL AUDITORY PATHWAYS



MODELING CEREBRAL CORTEX - I.

- At the top of the neural hierarchy is the cerebral cortex, the part of the brain least well understood. The cortex is responsible for perception, planning, decision making and most of the "conscious thinking".
- This region consists of 6 thin layers in the outermost areas of the cerebral hemisphere and contains billions of neurons. Its single mm^3 should contain on the order of 5 billions of synapses.
- In this region is located our puzzling capability to use language for communication and cooperation.
- Even far less understood activity, for which the cerebral cortex is to be responsible, is our ability to make predictions, even of our own actions and decisions.
- The most complex capability of human brains is our emotional intelligence. This includes our capability to perceive, and respond appropriately to, emotions, to interact in social situations, to have a moral sense, to understand jokes,...
- An important way to understand human brain is to see in what human brains differ from brains of animals.

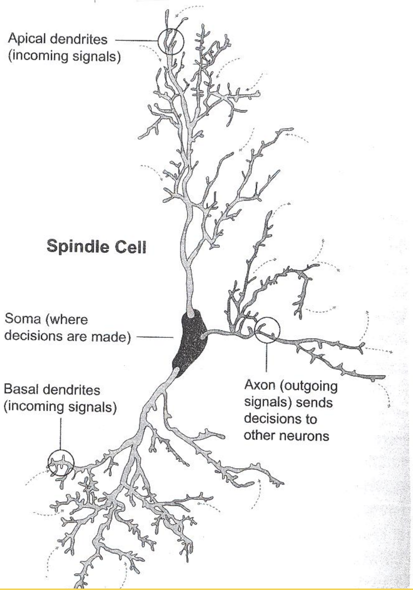
CEREBRAL CORTEX



MODELING CEREBRAL CORTEX - II.

- For example, it seems that emotional situations are handled in special cells, called *spindle cells* which have been found only in humans and some great apes.
- Humans have about 80,000 of such cells, gorillas about 16,000, chimpanzees about 1,200.
- Anthropologists believe that spindle cells made their first appearance about 15 millions years ago in as-yet-undiscovered family of common ancestors to apes and homonoids (the early family of humans).
- Spindle cells do not exist in newborn humans, and begin to appear at the age of 4 months and increase significantly between the age of 1 to 3 years.

SPINDLE CELL



INTERFACING BRAINS and MACHINES

An understanding of brains will allow not only to design biologically- and brain-inspired machines, but also, and much sooner, to build interfaces between brains and computers.

There have already been remarkable successes along these lines and expectations, concerning potentials, are very high. Especially for medical treatments and arms control.

- One line of US army supported research concentrates on the transmission of images directly into human brains.
- In Duke university they succeeded to implant sensors into brains of monkeys in the way that allowed monkeys to control robots through thoughts alone.
- Research is done in several places on direct interfaces of nerves and electronic devices and on building for this purpose "neurochips".
- Creating interfaces between surgically installed implants and electronic devises is making remarkable progress.
- There are attempts to develop communication by-thoughts-only among people through implants - this is done by the "cyborg" Ken Warwick and his wife at U. of Reading.
- Possibilities of using implants with the potential of uploading new software using non-surgical means to control some brain diseases are being explored.
- Already more than 30,000 patients with Parkinson disease have neural implants.
- Research along these lines is usually very carefully controlled by ethical committees in order not to go "too far", into hard to control developments for mankind.

CYBORGS - I.

- The term Cyborg (Cybernetics organism) refers to an organism that has enhanced abilities due to (internally implanted) technology.
- The term was coined in 1960 by M. Clynes and N. S. Kline.
- Other way to see cyborgs is as humans with bionic or robotics implants that are connected to human brain so through them brain can control even distance systems and can be also under outside control.

CYBORGS - II.

- In the current prosthetic applications, so called C-Leg system, developed by Otto Bock Health Care, are used to replace a human leg that has been amputated because of injury or illness. Such prostheses are seen as first very important real-world cyborg applications.
- W. Dobelle used, since 1978, a brain implant (68 electrodes) to treat acquired blindness. A more sophisticated system is, since 2002, in commercial applications.
- US military explores possibilities to use cyborg animals (insects, bees, rats or even sharks) and remotely manage that they perform some (spy) actions.
- In 2010 the *Cyborg Foundation* was established to help humans to be cyborgs

FIRST CYBORG - KEVIN WARWICK

- Kevin Warwick, professor at the University of Reading, is perhaps most known cyborg.
- Warvick contributed to many fields, but he is most known for his Human enhancement experiments.
- For example, by means of the implant, Warwick's nervous system was connected onto the internet of Columbia University in New York. From there he was able to control the robot arm in the University of Reading and to obtain feedback from sensors in the finger tips.
- Through the implant to his wife they demonstrated first direct and purely electronic communication between nervous systems of two humans.
- Warwick was also helping to design the next generation of Deep brain stimulation for Parkinson's disease.
- Warwick is know for saying There is no way I want to stay a mere human.
- Warwick's experiment are often under consideration of Ethic committees.

UPLOADING the HUMAN BRAIN/MIND

- A more controversial goal than the scanning-brain-to-understand-it is the goal of the scanning-brain-to-upload-it.
- Uploading a human brain means scanning all its details and then reinstalling them into a new sufficiently powerful substrate - the process would capture a person entire personality, memory, skills, and history.
- In order to fully capture a particular person's mental processes, then the reinstantiated mind will need a body, real or virtual, say human body version 2.0. - this can happen at the end of 2030's by Kurzweil's estimates.
- Of importance for uploading of mind is also the fact that a person's personality and skills do not reside only in the brain - our nervous system extends through the body and hormonal system has an (small) influence as well.
- A very nontrivial problem is whether we will be able to do scanning in the continuously changing brain fast enough.
- Final problem is whether or not uploading of your brain will really produce you, especially due to the fact that the original will keep existing.

- The world is real. Consciousness is the illusion.

  Craig Bruce

- If consciousness can function independently of the body during one's lifetime, it could be able to do the same after death.

  Stanislav Grot

- The great mystery of of our consciousness is beyond our grasp.

  W. Shatner

- In this electronic age we see ourselves being translated more and more into the form of information moving forward the technological extension of consciousness.

  Marshal McLuhar

Development of basic standpoints:

- Consciousness is not the subject for scientific study.
- Consciousness may be a legitimate subject for scientific study.
- Conscious is legitimate subject of scientific study by both experiments, (information processing) modeling and (speculative, philosophical, ...) theory.

HOW FAR WE SHOULD GO? - BASIC OBSERVATIONS and WORRIES

- We know what we are, but know not what we may be.

  W. Shakespeare

- The most important thing is to be able at any moment to sacrifice what we are for what we could become.

  Ch. Dubious

- Homo sapience, the first truly free species, is about to decommission natural selection, the force that made us ... [Soon] we must look deep within ourselves and decide what we wish to become.

  E. O. Wilson, 1998

HOW FAR WE SHOULD GO? - CRITICISM and RESPONSES

- Criticism of attempts to make non-biological brains and to enhance *too much* human brains is based on worries that our designs can get out of our control and destroy subtle balance between mankind and nature with catastrophic consequences.
- Responses are based on observations that such worries have always turned out not fully justified and so far mankind was able always to stop when it got too far in breaking balance with nature - moreover, all advances and their potential impacts are very carefully scrutinized.

COMMON SENSE

- Common sense is nothing more than a deposit of Prejudices laid down in the mind before you are eighteen.
- Common sense is not a simple thing. Instead, it is an immense society of hard-earned practical ideas - of multitudes of life-learned rules and exceptions, dispositions and tendencies, balances and checks.

Marvin Minsky

HBP

EUROPEAN HUMAN BRAIN PROJECT - GENERALITIES I.

Goals are:

- to provide neuroscientists with the tools to integrate data from different sources as well as to identify and fill gaps in their knowledge;
- to be able to trace intricate casual relations across multiple levels of brain organizations;
- to ask questions and to address them that are not accessible with current knowledge and methods;
- to identify complex cascades of events leading from genes to cognition and back;
- to explore biological mechanisms responsible for perception, emotion, memory and learning;
- to increase understanding of the relationships between brain structure and functionality.

EUROPEAN HUMAN BRAIN PROJECT - GENERALITIES II.

Goals are:

- to understand the neural structures and architectures responsible for specific cognitive and behavioral skills;
- to build various predictive models to detect statistical regularities in the relationships between data representing different regions and levels of brain organisation and to estimate the values of parameters that are difficult or impossible to measure experimentally;
- to build models of brain activities that would allow to perform *in silico* experiments that are impossible *in vivo* - in laboratories;
- to work out theoretical foundations needed to overcome the fragmentation of neuroscience data and research;
- to open doors for research into biological mechanisms of human consciousness.

HUMAN BRAIN PROJECT - PILLARS of ACTIVITY I.

- 1. Molecular neuroscience The goal is to collect strategically selected data of molecular systems in animal and human brain cells and to integrate the data in molecule level models of neurons, glia and synapses, making it possible to connect genes and the genome to cells and cell types, circuits and psychology, behaviour and disease.
- 2. Cellular neuroscience The goal is to obtain strategic biological data from animal brains to fill gaps in our current knowledge and to generate predictive models of hard to measure features of the brain. Recent advances in molecular, genetic, 3D-imaging, computer graphic and predictive modeling have much facilitated design of biologically-accurate brain models and wiring maps.
- 3. Cognitive neuroscience The goal is to collect *quantitative behavioral and brain imaging data* on the normal human brain and to use them to understand functional and structural organizational principles underlying cognitive functions behaviour in sufficient detail to be simulated. Unlike data from previous two pillars, which will provide *bottom-up constraints* for modeling, the date from this pillar will provide data for *top-down constraints*.

HUMAN BRAIN PROJECT - PILLARDS of ACTIVITY - II.

- 4. Theoretical neuroscience The goal is to extract mathematical concepts of brain-style computation that can contribute to research in the Cognitive Neuroscience, Simulation and HPC pillars and contribute to the development neuromorphic and neurorobotics applications. This activities n mathematical modeling have history at least 100 years.
- 5. Neuroinformatics The goal is to federate neuroscience data from first three pillars, the community and literature making hem available for subsequent analysis, modelling and simulation and developing the necessary ontology's, workflows and data access methods. Modern neuroscience research generates huge volumes of data - from genes and molecules to microcircuits, systems and behaviour - and the goal is to provide tools for their integration, analysis and exploitation.
- 6. Brain simulation The goal is to design software required to systematically integrate biological data into computer models and simulations of the brain and to use these models to explore diseases of the brain.

HUMAN BRAIN PROJECT - PILLARS of ACTIVITY - III.

- 7. Medical informatics The goal is to use data gathered in previous pillars and from clinics to characterize normal human brains and brains of patients with neurological or psychiatric disorders. Mining such data will allow to identify biologically homogeneous "disease constructs".
- 8. High performance Computing (HP) The goal is to provide HP with computing and storage potential to simulate human brains and by that to revolutionize ICT and HP. (Top current computers could simulate 100 millions of neurons - roughly the number found in the mouse brain).
- 9. Meromorphic computing The goal is to establish a brain-inspired computing paradigm building highly configurable meromorphic computation systems to operate with the ability to operate at speeds ranging from biological real time to ten thousand times faster and with number of neurons equivalent to the human brain.
- 10. Neurotics The goal is to create a "testing ground" for experimental setups in which brain models are coupled to robot bodies in a closed loop. Such setups will be used for experiments demonstrating that the brain models developed in the project could drive biologically realistic and purposeful behaviour, and for the investigation of the lower level brain mechanisms responsible for such behaviour.

ETHICAL ISSUES

Both Human Brain Project and related projects in US, including all Singularity related research and education institutions, play big attention to ethical issues related to brain exploration, modelling and simulation, as well as to problems related to strong AI, to uploading minds and to the vision of Singularity.

They realise that these issues may be for society very sensitive and for progress in AI and in the brain research it is very important that society is comfortable with goals and methods.

THREE OTHER BIG IMPACTS of HBP

- To develop a shift in the main paradigm for dealing with brain diseases: from symptoms and syndrome-based to biology-based classification of brain diseases and to develop biological signatures of brain diseases. That would allow to diagnose diseases at their early stages, before they make irreversible changes, and to accelerate development of new and personalised treatments.
- To contribute much to brain drugs developments: to speed-up their development, to cut cost and to improve success rate for drugs development (current estimate for a drug development is 1 billion EUR).
- To contribute to development of neuromorphic brain-inspired computing technology making use of the brain-inspired techniques for energy-efficient information storage, mining, transmission and processing techniques and also development of interactive (super)computing. The idea is to integrate meromorphic devices with conventional supercomputing.

Appendix

- Rolf Landauer was expert in condense-matter physics and in physics of computation.
- Around 1970, when first supercomputers were built, it got clear that main problem is extraction of the heat.
- Landauer started to explore ultimate physical limits of computation concerning energy consumption that do not depend on a particular technology.
- Landauer discovered that computation in principle does not require any energy. The key in that is a realisation that a computation could in principle be carried out more and more slowly to reduce any friction that would generate waste heat (if computation is done in a reversible way).

LANDAUER and its PRINCIPLE - II.

- Landauer's principle can also be stated as follows: Any process that erases a bit in one place must transfer the same amount of energy somewhere else. In short: "erasing information requires dissipation of energy".
- Landauer also discovered that energy is necessary to erase information. That erasing information always produces a heat that escapes into environment. This understanding is now called as "Landauer's principle".
- Landauer's determined that to erase one bit one needs to release of an amount $kT \ln 2$ of heat, where k is the Boltzmann constant.
- Landauer's principle sounds deceptively simple. But its implications are immense. It identifies the only true limit on the ability of computers to process information. It is also a concrete example of the connection between physical reality and the idea of information as measured by bits.

ULTIMATE COMPUTATIONAL POWER - ULTIMATE LAPTOP

- For determining ultimate limit concerning the maximal rate a bit can flip, so-called Margolus-Levitin theorem is useful, that says that the maximal rate at which a physical system can move from one state to another is proportional to the system's energy.
- The Margolus-Levitin theorem sets the limit on the number of elementary operations that a bit can perform in one second.
- From that one can derive that no laptop that has weight 1 kg and volume of one litter, so called ultimate laptop, can perform more than 10^{51} operations per second.
- In case performance of laptop keep increasing according to Moore's law, no laptop can reach the above performance sooner than in 2205.