# UNIVERSE AS A QUANTUM COMPUTER

Jozef Gruska

Faculty of Informatics
Brno
Czech Republik

December 13, 2010

# ABSTRACT

The goal of the lecture is to present a new view of the universe, as of a quantum information processing system (in short a quantum computer) and its main processes, such as evolution, life and ..... as quantum information processing processes.

In the first part of the lecture, we discuss previous views of the universe and their impacts on science in general.

In the second part of the lecture, we try to argue why we can and we should see universe as quantum information processing system. We demonstrate that all physical system register and process information and that by understanding how universe computes we can understand why it is so complex.

In the third part of the lecture, we discuss some consequences of such a new view of the universe.

In the last part of the lecture, some of the very basic open problems of science are discussed: what is time, space, gravitation, and some of the current approaches to them.

# PROLOGUE

# PHYSICS versus INFORMATICS

## Basic standpoints

- The main scientific goal of physics is to study concepts, processes, laws and limitations of the physical world.
- The main scientific goal of informatics is to study concepts, processes, laws and limitations of the information precessing world.

## Some very basic questions

- What are relations between physical and information worlds? Are they different or two sides of the same world?
- What is the relation between basic concepts, laws and limitations of these two worlds?
- Is the problem Information versus matter a proper version of the fundamental problem of philosophy "mind versus matter" or "body versus mind"?

## LAWS of PHYSICS versus LAWS of INFORMATION PROCESSING

- Laws of physics are used to calculate what nature will do in advance of nature's doing that.
- Do such laws have any meaning if the calculations could not be actually performed?
- In other words, laws of information processing and laws of physics have to be tightly entangled.
- Physics is looking for laws which in fact are compatible with information-handling capabilities that are really allowed in the universe.

# SCIENCE versus REALITY

- Every theory has two parts. A formal part: a formal language (or a logical-mathematical structure) and rules for manipulating its constructs and an interpretation. Secondly, it is an interpretative part, rules for connecting language constructs to "reality" (or to a "real world" or to a "perceived world").
- In a good theory, there should be a good correspondence between language constructs and perceptions of reality that these constructs should represent.
- Nevertheless, theory and its constructs remain only models or reality.
- Very often it is pretty clear that theory is only a model that does not tell the whole story.
- When theory is very successful (as Newtonian physics was/is), there is a tendency to identify model with the reality.

# SUPERPARADIGMS of MODERN SCIENCE

# PARADIGMS and SUPER-PARADIGMS

- The clock, steam engine and computer have all inspired metaphorical frameworks for science that can be called super-paradigms.
- A paradigm can be viewed as a framework of thought within which researchers in a given field practice "normal science".
- Each new paradigm leads to a different way of understanding of nature; offers new insights to old things; as well as suggesting new avenues of investigation that lead to new discoveries.
- A superparadigm is a point of view about what's ultimately fundamental in determining what happens in the world.
- Example: Newton's superparadigm described the universe in terms of the motion governed by force, the way the moving parts of a clockwork mechanism were driven by the pull of weight attached to ropes.
- The basic mechanistic view provided a convenient picture for understanding why things happen and how things change.
- The basic idea of force thus formed a foundation on which other science could be built in the Newton spirit.

## MACHINE SUPER-PARADIGMS in the HISTORY of MODERN SCIENC

**Clock** • Dominant tool in the society in the medieval time.

- Tool and metaphor for science leading to new science of Newtonian mechanics
- Metaphor for scientific world view based on force.

**Steam engine** • Dominant tool in the society during the first industrial revolution

- Object of scientific study leading to new science of thermodynamics
- Metaphor for scientific world view based on energy.

**Computer** • Dominant tool in the society in the information era.

- Tool for science and object of scientific study leading to new science of quantum information processing.
- Metaphor for scientific world view based on information.

## IMPORTANCE of MACHINES for UNDERSTANDING OF NATURE

- Many of the most general and powerful discoveries of science have arisen, not through the study of phenomena as they occur in nature, but, rather, through the study of phenomena in man-made machines, in products of technology.
- This is because phenomena in man's machines are simplified and ordered in comparison to those occurring naturally, and it is this simplified phenomena that one can understand more easily.

## CLOCK driven paradigm

- History of clocks is very old, but only after weight-driven mechanical clocks were invented the clockwork metaphor of universe started to catch on.
- Clocks were hot commodities already around 1320; around that time communal clocks began to appear in most of towns of any significant size.
- Soon some of them started to depict movements of sun, moon and some of planets - for example in the cathedral in Strasbourg in 1354.
- Nicole Oresme was first, in 14th century, who explicitly formulated a clock-like vision of universe.
- In his famous *Principia* of 1687 Newton transformed the metaphor of clockwork into something more tangible - called *force*.
- Newton's force prevailed as the central concept of physics for a century and a half.

# STEAM ENGINE driven paradigm

- The steam engine story started in 1698 when Thomas Savery in Britain patented a steam device for pumping water out of coal mines.
- A key improvement was done by James Watt in 1765 and soon Watt-style steam engines became a driving force of the industrial Britain.
- For a long time there was a very little scientific understanding of steam engines. This has changed in 1824 when Sadi Carnot formulated physical principles underlying the workings of steam engine and in doing so he identify general principles that constrained operations of any heat engine.
- Carnat's work gave rise to thermodynamics and its laws and thermodynamics description of nature led to establishment a new central concept of science - energy.
- The ideas that temperature is a measure of energy in random motion and entropy is a measure of information underlie what is called statistical formulation of thermodynamics.

## (QUANTUM) COMPUTER driven paradigm

- Pascall's calculator.
- Babbage's Difference engine and Analytical Engine.
- Turing machine
- From Zuse, through Collosus to ENIAC
- From Benioff through Bennett to Feynman
- From Deutsch through Simon to Shor

# PART II - UNIVERSE as a QUANTUM COMPUTER

# OTHER INTERESTING/IMPORTANT PARADIGMS

# OVERALL HISTORY of MANKIND

We can see the history as consisting of three eras.

**Neolithic era**: Progress was made on the basis that man learned how to make use of the potentials provided by the biological world to have food available in a sufficient amount and whenever needed.

**Industrial era**: Progress has been made on the basis that man has learned how to make use of the laws and limitations of the physical world to have energy available in a sufficient amount and whenever needed.

**Information era**: Progress is and will be made on the basis that man learns how to make use of the laws and limitations of the information world to have information available in a sufficient amount and whenever needed.

## NEXT ERA

**Security era** Progress is and will be made on the basis that man learns how to make use of the laws and limitations of the information and physical and biological worlds to have security (in a broad sense) available in a sufficient amount and whenever needed.

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**Era of hapiness** Progress is and will be made on the basis that man learns how to make use of the laws and limitations of the information and physical and biological worlds to have hapiness (in a broad sense) available in a sufficient amount and whenever needed.

# LAST THREE CENTURIES

If we try to see the development of the last three centuries we can discover, from the science and technology point of view, the following common scenarios.

**19th century** was mainly influenced by the first industrial revolution that had its basis in classical mechanics discovered, formalized and developed in the 18th century.

**20th century** was mainly influenced by the second industrial revolution that had its basis in electrodynamics discovered, formalized and developed in the 19th century.

**21th century** can be expected to be mainly developed by quantum mechanics and informatics discovered, formalized and developed in the 20th century.

To summarize, it used to take about a century that new main discoveries in science and technology started to have a decisive impact on the main society developments.

## FROM MATTER, ENERGY and ENTROPY to INFORMATION

## STRUCTURE of ATOMS - BASIC FACTS

- Atoms are typically a few billions of a metre across spheres held together by electricity.
- An atom of a compact nuclei (100 000 times smaller) consisting of (positively charged) protons and (without charge) neutrons;
- A nucleus is surrounded by a cloud of electrons whose masses are a couple of thousands times smaller that those of protons and neutrons;
- Electrons are negatively charged and there are so many neutrons as protons and therefore each atom as the whole is electrically neutral.
- Each electron has a wave associated with its position and velocity. The places where wave is big are places where electrons are likely to be found. The shorter the length of the wave, the faster electron is moving.
- The rate at which the wave wiggles up and down is proportional to electron's energy.

- Suppose we want to fit electron's wave around an atom's nuclei. The simplest wave that can fit around a nucleus is a sphere; the next simplest way has one peak, then two and so on. Each of these types of waves corresponds to an electron in a definite energy state. The more peaks in an electron's wave, more energy it has.
- When an electron jumps from a higher energy state to a lower energy state it emits a photon whose energy equals to the energy difference of two states. Similarly, an atom can absorb a photon and jump from one energy level to a higher energy level. Any atoms refuses to absorb a photon whose energy is not exactly difference of some energy levels.
- Emitting or absorbing a photon takes some time.
- Usually we take ground state (corresponding to lowest energy level) as representing $|0\rangle$ and the next exciting state as representing the state $|1\rangle$.
- Applying a laser pulse takes atom from the state $|0\rangle$ to $|1\rangle$ and vice verse.

## JOHN ARCHIBALD WHEELER (1911 - )

- A man who named black holes.
- A man who helped to explain nuclear fusion.
- A leading expert in quantum physics, relativity theory.
- Wheeler is considered among physicists as one of the greatest teachers of the last century.
- Richard Feynman was one of his students.

## WHEELER's VIEW

I think of my lifetime in physics as divided into three periods

- In the first period ...I was n the grip of the idea that
  EVERYTHING IS PARTICLE
- I call my second period
  EVERYTHING IS FIELDS
- Now I am in the grip of a new vision, that
  EVERYTHING IS INFORMATION

John Archibald Wheeler
Gems, Black Holes and Quantum Foam

## WHEELER"S VIEWS

- "I have been led to think of analogies between the way a computer works and the way the universe works. The computer is built on yes-no logic. So, perhaps is the universe ... The universe and all that it contains ("it") may arose from the myriad yes-no choices of measurements (the "bits");
- By Wheeler, information has some connection to existence, a view he advertised with the slogan "It from bit" - or, in other words, that "Everything is information".
- In other words, the black hole converts all sorts of real things into information.
- Wheeler initiated development of a view that information is the ultimate "substance" from which all things are made.
- Many scientists now conceives of information as somethings real, as real as space, time, energy and matter.

# ENTROPY

- Thermodynamics is governed by two main laws.
- First law of thermodynamics says that total amount of energy never changes.
- Second law of thermodynamics says that entropy - the amount of an un-useful energy, or of disorder - always increases.
- In other words second law of thermodynamics states that each physical system contains a certain number of bits of information - both invisible information (entropy) and visible information - and that the physical dynamics that process and transforms that information never decrease that total number of bits.
- Two laws of thermodynamics are statistical - they do not have to hold any time, they are only very likely to held.

- The two laws of thermodynamics guide the interplay between two main actors of universe: energy and information.
- It is this interplay between energy and information that makes universe to compute.
- In 1948 Claude Shannon introduced mathematical theory of information and a measure of information - entropy.
- It has been slowly realised that these two concepts of entropy are deeply related, that they are two sides of a coin.
- Entropy is information required to specify the random motion of atoms and molecules.
- Entropy is information contained in physical systems invisible to us.
- Example: to describe an $8 \times 6$ inches color photo with 1000 pixels requires $10^9$ bits; to describe all underlying atoms requires $10^{24}$ bits (of invisible information).

# STORY of ENTROPY

- Entropy was first defined in 1865 by R, Clausius as a mysterious thermodynamic quantity that limits the power of steam engines.
- Originally entropy and heat were seen as special features of matter.
- Entropy was first seen as a measure of how much disorder or randomness is present in any (hot) system.
- At the end of 19th century Maxwell, Boltzmann (especially) and Gibbs realised that entropy was a form of information - a measure of the number of bits of unavailable information registered by atoms and molecules.
- Another view: Heat is just the energy in the jiggling of atoms. To describe the motion of atoms requires a lot of bits of information - entropy is then proportional to the number of bits required to describe the way atoms are jiggling.
- Consequence: the faster the atoms jiggle, more information is needed to describe their jiggling and therefore more entropy they posses.
- The physical quantity known as entropy came to be seen as a measure of information registered by individual atoms that make up the matter.

# STORY of ENERGY

- Energy is ability to do work. Energy makes physical systems to do work.
- Since by the first law of thermodynamics energy cannot increase it seems to be puzzling where energy came from.
- Quantum mechanics describes energy in terms of quantum fields - a kind of underlying fabric of universe, whose weave makes up elementary particles.
- The energy we see around us, in the form of Earth, stars, light, heat, was drawn out of underlying quantum fields by expansion of our universe.
- As universe expands, gravity (a force that pulls things together) sucks energy out of quantum fields.
- The energy in quantum fields is almost always positive, and its almost exactly balanced by negative energy of gravitational attraction.
- As the expansion proceeds, more and more positive energy is available, in the form of matter and light.
- Information and energy play complementary role in universe.
- Energy makes physical systems to do things - information tells them what to do.

# FREE ENERGY

- Free energy is energy in highly ordered form associated with relatively low amount of energy.
- The relatively small amount of information required to describe this energy makes it available for use - that is why it is called free.
- For example energy in chemical bonds is free. (Every gram of glucose contains a few kilo-calories of free energy.)
- While one runs the free energy in the sugar is converted into motion by our muscles; after finishing running we are hot. Free energy in sugar was converted into the heat and work.
- To convert energy in the heat (which has a lot of invisible (hidden) information) into the free energy (with less information) is not easy; one has to do something with that extra information.

## INFORMATION IS PHYSICAL

- Wheeler, Zurek, Fredkin and Landauer were main protagonists of the view that information is an important physical concept, and, as formulated by Rolf Landauer, that Information is physical.
- By saying that information is physical one usually understands that physical carriers are needed to store, transform and transmit information and therefore the laws of physics determine the laws of information processing and transmission.

## LANDAUER and its PRINCIPLE

- 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 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'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 Boltzman 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.

# BRIEF STORY OF UNIVERSE

- The universe began a little less than 14 billion years ago in a huge explosion called Big Bang.
- As universe expanded and cooled down, various forms of matter condensed out of cosmic soap.
- Three minutes after the Big Bang, the building blocks for simple atoms such as hydrogen had formed.
- These building blocks clumped together under the influence of gravity to form the first stars and galaxies 200 million years after the Big Bang .
- Our own sun and solar system were formed 5 millions years ago.
- Life on earth was up a little over a billion years later.

## INFORMATION STORY of UNIVERSE

- After Big Bang universe was simple - it required few bits to describe it.
- The early universe remained simple, for a very short time. it could be described by just a few bits of information. The energy that was created was free energy.
- As universe expanded, it pulled more and more energy out of the underlying fabric of time and space.
- After a billionth of a second universe was of an order of $10^{50}$ bits.
- After that billionth of a second universe performed $10^{67}$ elementary operations on its bits; there was very little of free energy, order, at that time.
- Protons and neutrons, particles that make up the nuclei of atoms, condense out a little more than one millionth of second after Big Bang.
- After 3 minutes the nuclei of the lightweight atoms - hydrogen,... - had condensed;
- 380 000 years after the Big Bang stable atoms were formed.

## HOW ORDER ARISED from CHAOS?

- At the beginning the universe contained very little of information - it was features and uniform.
- One of fundamental questions is how could then such structures as suns, planets, solar systems, galaxies be created.
- Creation of order from chaos is due to randomized nature of quantum mechanical laws.
- In the process of creating such large structures gravity also created free energy that lining things require to survive.
- Every galaxy, star and planet owes its mass and position to some quantum accidents of early universe (and its butterfly effects).
- Chance and randomness is a crucial element of Nature.

## BLACK HOLES

- A black hole is a place where gravity is so strong that the velocity required to escape from it is greater than the speed of light.
- A black hole has a gravitation field as planets or stars.
- By Wheeler black holes keep records of information they absorb.
- A black hole can consume anything that exists and still be described in terms of how much information it has digested.
- In other words, the black hole converts all sorts of real things into information.
- Black holes are systems that can be described using laws of thermodynamics.
- An important open question: What is nature of information trapped in a black hole?
- A black hole has entropy that is proportional to the area of its horizon and measures the amount of information trapped beyond her horizon.
- Dozens of candidate black holes have been discovered.

- Most of galaxies, including our own, seem to have an enormous black hole in the centre - with a mass million times of that of sun.
- A black hole with the mass of Mount Everest would be no longer than a single atomic nucleus, but it would glow with a temperature greater than the centre of a star.
- A black hole is actually a very simple object. Once formed, it is featureless. From the outside one can measure only a few of its properties: mass, electric charge and angular momentum.

## BLACK HOLES as MICROSCOPES

- Importance of black holes is that they may act as a sort of microscopes for Planck scale.
- Ordinarily we cannot see what is happening on Planck length scale because we cannot use light to look at something which is smaller than wavelength of that light.
- However, if we can observe light coming from very close to the horizon of a black hole we may be able to see the quantum structure of space on Planck level.
- The reason is that black holes stretches the wavelength of the light coming from close to horizons of black holes.

## BLACK HOLES PARADOX

- It is known that black holes evaporate.
- It is known that information that gets into black holes cannot get out.
- All that means that information can disappear. However, quantum mechanics says that information cannot be lost.
- Quantum gravity theory therefore says that information can get lost - quantum mechanics that it cannot. Both theories turned out as excellent in describing universe or microworld.
- The above information paradox of black holes was a first example when concept of information played key role in the mainstream of physics.
- Evaporation of black holes is slow. It would take black hole the mass of the Sun about $10^{57}$ times the present age of universe to evaporate.

## INTERESTING OBSERVATIONS

- The search for the meaning of temperature and entropy of matter led to the discovery of the structure of atoms;
- The search for the meaning of the temperature and entropy of radiation led to the discovery of quanta.
- The search for the meaning of the temperature and entropy of black holes is now leading to the discovery of atomic structure of space and time.

## BIG PROBLEMS of UNIVERSE

- Does universe has beginning and end?
- Is universe finite or infinite?
- Is universe discrete or continuous? Are time and space discrete?
- How looks space on very large (small) scale? How many dimensions it has?
- How life arised?
- Why is universe so complex when laws of physics are so simple?

# BASIC POINTS Of VIEW - A SUMMARY

- The universe is made of bits.
- Every molecule, atom and particle register bits of information.
- Every interaction between those pieces of universe processes that information by altering those bits.
- Therefore universe computes and since it is governed by the laws of quantum mechanics, it computes in intrinsically quantum fashion - its bits are qubits.
- The history of universe is therefore, in effect, a huge and ongoing quantum computation.
- What universe computes? - Itself - its own behaviour!
- As soon as universe began, it began computing. At first it produced simple patterns. Later more complicated.
- Life, human beings, language and ... all owe their existence to the intrinsic ability of matter and energy to process information.

- The computational capability of universe can also explain one of the great mysteries of nature: how such complex systems as living creatures could arise from fundamentally simple physical laws.
- The digital revolution, that is under way today, is merely the last in a long line of information processing revolutions stretching back to the beginning of universe itself - to the Big Bang.

## WHAT IMPLIES UNDERSTANDING that UNIVERSE is a QUANTUM COMPUTER?

- Randomness of outcomes of quantum measurement implies that future can be determined only probabilistically;
- The existence of randomness is one of the main philosophical problem.

## PHYSICAL versus COMPUTATIONAL UNIVERSE

- Lloyd's view: The computational universe is not an alternative to the physical universe. The universe that evolves by processing information and the universe that evolves by the laws of physics are one and the same. The two descriptions, physical and informational, are two complementary ways of capturing the same phenomenon.

## HOW UNIVERSE REGISTERS and PROCESSES INFORMATION?

- Building of a quantum computer and exploring its functioning is a very important way to understand information processing of nature and universe

## MAIN INFORMATION PROCESSING REVOLUTIONS

- Creation of universe.
- Life (Genes and mechanisms for copying and reproducing gems are key information-processing technologies of life.)
- Sex
- Language
- Writing
- Digital computers with quantum computers as its avant-garde.

Each information processing revolution is associated with a new technology: particles, DNA, brain, computer.

## POWER of RANDOMNESS

- Could monkeys create something great?
- Could monkeys write Hamlet by typing into typewriter? (No, the probability of that is extremely small.)
- Could monkeys create something important by typing into a universal computer. (As Kolmogorov-Chaitin complexity indicates that has a much larger chance.)

# ROADS to THEORY of EVERYTHING

# HOW to COMPLETE QUANTUM and RELATIVITY REVOLUTION in PHYSICS

- Quantum theory (as a theory of matter on atomic scale that differs from Newton's theory on very small scales) and General relativity theory (as a new theory of space, time and cosmology that differs from Newton's theory on very large scales) created a revolution in physics - that showed that Newton physics doe not hold on atomic level and for understanding of time and space.
- A key problem of current science is that Quantum theory and General relativity theory are not compatible. They differ in two basic issues:
  - In understanding of time and space (quantum theory took Newton's view);
  - In understanding of the relation between "observers" and "systems they observe".
- Main goal now is to create a single theory, so-called quantum theory of gravity, that unifies insights coming from the Quantum theory and from the General relativity theory.
- Quantum theory of gravity should be a theory of matter, of time and space and also of cosmology.

## WHAT ARE TIME AND SPACE?

- Basic observation: Everything that exists exists somewhere, and nothing happens that does not happen at some time.
- On the one hand, space is synonymous for nothingness; on the other hand, mathematics describing space is at the heart of theories that attempt to describe everything.
- Are time and space discrete? If yes, what are their minimal amounts? Do they have beginning and end? How is space on very small and on very large scale? How many dimension does space has?

## RELATIONAL VIEW of SPACE and TIME

- Space is an aspect of the relationship that hold between things - there is no meaning of space that that is independent of the relationships among real things in the world.
- Time is described only in terms of change in the network of relationships that describes space. There is no time apart of change. Time is nothing but a measure of change.
- Space and time are discrete - that claim all major theory of cosmology. However, their discreteness has not been tested experimentally.

## CONSEQUENCES

- It is absurd to speak about universe with nothing or only one thing in it.

## THREE ROADS to QUANTUM THEORY of GRAVITY

- To start with ideas and methods developed first in quantum theory - from that comes "string theory"
- To start first with ideas and methods developed first in general relativity theory - from that comes so-called loop quantum gravity theory.
- Black holes thermodynamics is third main road to gravity.
- To develop some other, very different, approaches - this is done by those that do believe that neither quantum theory, nor relativity theory are good and compete enough to start with.
- So far it was not possible to test new theory of quantum gravity experimentally.
- Both main approaches to quantum theory of gravity agree that there is a scale, so-called Planck scale, on which the nature of time and space is very different from that we observe.
- The Planck length is $10^{-33}$ cm; the Planck time is $10^{-43}$ of the second.

## GRAVITY

1. Informally, gravity is a force that puts things together.
2. As universe expands, gravity sucks out of quantum fields.
3. In the context of general relativity theory, gravity is actually a manifestation of the structure of time and space.

## BIG PROBLEMS of COSMOLOGY - I. OBSERVERS

- In science we believe that observers have to remove themselves from the system they study in order to be objective;
- Natural sciences can do that - this is one reason they are "hard"; social sciences have problems with that - this is one reason they are called "soft".
- In cosmology we cannot remove observers from universe - this causes big problems;
- No observer can see all what is in universe - not things more than 14 billion light years away;
- Two observers can see (completely) different things; for example if one of them is in a black hole and second is not.

- Truth or false of some statements cannot be determined by particular observers - cosmology needs a special non-standard logic.
- Any scientific form of cosmology requires a radical change in the logic we use - to take into account the fact that any observer is inside the universe.
- Quantum theory as been built on the assumption that an observer is outside of the system.
- To extend quantum theory to cosmology one needs an interpretation of quantum theory that allows observers to be a part of the system.
- It is not easy to find a language to talk about universe if one believes that the notion of reality depends on one who is talking.

## BIG PROBLEMS of COSMOLOGY - II. UNIVERSE IS MADE of PROCESSES

- The illusion that the world consists of things is behind many of the constructs of classical sciences.
- Modern cosmology see the universe as consisting of (information processing) processes; what we consider as things are actually VERY SLOW processes.
- More exactly universe is seen as consisting of events - they are smallest units of processes, smallest units of change.
- The universe of events is relational universe - the most important relation is causality;
- In the relational universe there is a notion of time, but not that of a moment of time;
- This leads to a view of universe as a computer whose circuitry evolves with time as a consequence of the information flowing through it.

## HOW TO MAKE INFORMATION FROM NOTHING

- An important fact for quantum computer view of universe is that due to the laws of quantum mechanics nature can generate information from "nothing" - because of the existence of entangled states.
- Let particle $P_1$ be in state $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle$ and particle $P_2$ be in state $|0\rangle$. By applying CNOT operation both particles are in the state $\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$. All these three states are pure and therefore fully determined and therefore their entropy is $0$ - they stand for no bit. However, after CNOT operation both particles are in a complete undetermined state and therefore each of them has one full bit of entropy.

## ULTIMATE COMPUTATIONAL POWER - of 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.

## ULTIMATE COMPUTATIONAL POWER - of UNIVERSE

- Because age of universe is finite and speed of light is finite, the part of universe we can have information about (so-called "universe within horizon") is also finite.
- Seth Lloyd determined, using again Margolus-Levitin theorem, that during its existence universe could not performed more than $10^{122}$ elementary operations and could not store more than $10^{92}$ bits.

## HOW HUMANS FIT into the COMPUTATIONAL UNIVERSE?

- The innate information-precessing capacity of universe, at the most fundamental level, gives rise to all possible forms of information processing.
- After the Big Bang, as different pieces of universe tried out all possible ways of producing information, sooner or later, some of them, seeded by quantum accidents, some pieces of universe succeeded to develop an algorithm to reproduce itself - such an accident led to life.
- Life evolved by processing genetic information to try new strategies for survival and reproduction.
- After trying billions of strategies, some living organism discovered sex - a technique that much increases the rate at which new evolutionary strategies and algorithms can be explored (because it speeds up the rate of genetic information processing).
- After billions of years of sex - living creatures had evolved various tools of getting and processing information - eyes, ears, brains and so on.
- During the last 100 000 years humans developed language that allowed distributed information processing, what in turned allowed cooperation, association.
- It is the richness of our information receiving, processing and communication of information that brought human beings so far.

## CITATIONS

- If we could find the answer to the question why we and universe exist, it would be an ultimate triumph of human reason - for then we would know the mind of God.

Stephen Hawking: A brief history of time

## INTERESTING OBSERVATIONS

- The search for the meaning of temperature and entropy of matter led to the discovery of the structure of atoms;
- The search for the meaning of the temperature and entropy of radiation led to the discovery of quanta.
- The search for the meaning of the temperature and entropy of black holes is now leading to the discovery of atomic structure of space and time.

## BASIC PRINCIPLES of MODERN COSMOLOGY

- There is nothing outside of universe. (Everything in universe has to be described in terms from the universe only.)
- In the future we will know more. (We get information from longer distances.)
- There is one universe, but many observers (that can see different, even disjoint, things).
- The universe is made from processes, not from things.
- Time and space are discrete - smallest items of space are at Planck scale.
- The world is nothing, but evolving network of relations.

## GENERAL RELATIVITY as a RELATIONAL THEORY

- General relativity is a theory of fields.
- The field involved is called the gravitational field.
- To visualise gravitational field three sets of lines are needed.
- The gravitational field defines a network of relationships having to do with how the three sets of lines link with one another (for example, how many times one of the three kind of lines knot around those of another kind).
- The above relationships are all it is to the gravitational field

## WHY NOT TO SEE UNIVERSE AS CYBERSPACE?

- Critics of the quantum computer view of the universe, and of the informatics as a new and fundamental science, bringing also a new methodology, can ask why is such a view not so short-sided as the recent attempts to see universe as a cyberspace and cybernetics as a new fundamental methodology for science.
- Wiener introduced cybernetics as a new scientific method that could frame a "unified science" and this view was adopted by quite a few. Why this failed?
- We can see now that such a view of the role of cybernetics in science was prematured. Wiener and other tried to impose it on science. It did not grew out of science itself. It was not sufficiently general. Only one aspects of what informatics is bringing was emphasized.

## LAWS of PHYSICS versus LIMITATIONS OF INFORMATICS

- What are the laws of physics if not recipes for performing computations (Landauer)?
- Physical laws are used to calculate what nature will do in advance of nature's doing it.
- Would physical laws have any meaning in case calculations could not be performed?
- Ultimate physical laws have to be limited to what actually can be, in principle, computed in the universe we inhabit.
- The laws of physics we have today come from continuous mathematics that provide such a simplified view of the world as Newton's view of the world with fixed and continuous time and space - this view has already been proved to be of limited usefulness.

# STORY of RANDOMNESS

## DOES RANDOMNESS EXIST? - I

One of the fundamental question of science has been whether randomness really exist or whether the term *randomness* is used only to present objects and events with unknown lawfulness. Two early views are:

The randomness is the unknown and Nature is determined in its fundamentals.

Democritos (460 - 370 BC )

By Democritos, order conquers the world and this order is governed by unambiguous laws and the world randomness is used when we have incomplete knowledge of some phenomena.

The randomness is objective, it is the proper nature of events.

Epikurus (341 - 270 BC )

By Epikurus, there exists a true randomness that is independent of our knowledge. Einstein also accepted the notion of randomness only in the relation to incomplete knowledge.

## VIEWS on RANDOMNESS in 19th CENTURY

Main arguments before 20th century why randomness does not exist:

**God-argument** There is no place for randomness in the world created by God.

**Science-argument** Success of natural sciences and mechanical engineering in 19th century led to a belief that everything could be discovered and explained by deterministic causalities of cause and resulting effect.

**Emotional-argument** Randomness used to be identified with chaos, uncertainty and unpredictability what was always related to fear.

There are only two possibilities, either a big chaos conquers the world, or order and law.

Marcus Aurelius (121 - 181 AC)

## EINSTEIN versus BOHR

God does not roll dice.

Einstein, a strong opponent of randomness.

The true God does not allow anybody to prescribe what he has to do,

Famous reply by Niels Bohr

## DOES GOD PLAY DICE? - NEW VIEWS

God does play even non-local dice.

An observation due to N. Gisin, on the basis of experiments.

God is not malicious and made Nature to produce, so useful, (shared) randomness.

What the outcomes of informatics imply.

# MERITS of RANDOMNESS in CURRENT INFORMATICS

Randomness plays currently key role in informatics in several ways.

- Randomized algorithms are often much more efficient and much easier to design.
- Random walks are important algorithm design methodology.
- Randomness seems to extend the class of problems that have feasible solution - from $\mathbf{P}$ to $\mathbf{BPP}$.
- Only randomized encryptions can be perfectly secure.
- Randomized proofs can be provably more efficient.
- Zero-knowledge proofs are important cryptographic tool.

## BIOLOGY and INFORMATICS

- Biology and informatics - life and information processing - are related. I am confident that at their interfaces great discoveries await those who seek them.

  Leonard Adleman in "Computing with DNA

- Biology had become the science how cells use information contained in genes.
- In a way, thanks to DNA and genetic code, information processing superparadigm entered life sciences sooner than computers brought it to the physical sciences.

## EVOLUTION AS an INFORMATION PROCESSING PROCESS

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## 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 precessing

- 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

Meiosis is the process by which one diploid eukayetic cell deviates to generate four heploid cells often called gamates
Meiosis is essential for sexual reproduction - and therefore occurs in all eukanyates, including singlecell organisms, that reproduce themselves sexually.

## 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.

## GENES AND INFORMATION PROCESSING

- 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 mail tools to get in depth into brain information processing processes.
- It seems getting clear that brain has to be seen as a computer with ever evolving hardware and with special (no) distinction between hardware and software.

## COMPUTATIONAL NEUROSCIENCE

- 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.

## CONSCIOUS AND INFORMATION PROCESSING

Development of basic standpoints:

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

## QUANTUM LOOP GRAVITY

- It is the view of spacetime discovered when, in 19??, Ashtekar discovered a simpler way to write Einstein's equations for general relativity, and a way to solve them.
- In a way, quantum loops generalize loops from the field theory.
- In 1995, L. Smolin and C. Roveli showed how the geometry of space can be determined by how Ashetekar's loops link up.
- As a consequence of how these loops link, space cannot come in any size you want, but only in certain allowed amounts.
- It has then turned out that different ways such loops must be able to link correspond to structures called "spin networks" introduced by R. Penrose in 1960s.

## SUPERSTRING THEORY

- First view of a string was a lop in drawn in space. Later strings started to be seen as consisting of string bits (each of which carries a discrete amount of energy and momentum) or even of branes.
- Superstrings are tiny one-dimensional objects that may be basic building blocks of everything.
- In superstring theory, point particles become tiny loops of vibrating strings.
- Different particles correspond to different modes of vibration.
- Mathematics behind superstring theory required the existence of a peculiar particle that physicists soon realised was graviton - the particle form of gravitation.

- It has been shown that certain black holes can condense into a superstring particle.
- String theory is the only known way of consistently unifying gravity with quantum the other forces of nature - at a background dependent level.
- Mathematics of superstring theory says that space is 9 or 10 dimensional.
- Second supersting theory cane in 1996 when M-theory was introduced by E. Witten - it brought a unifying view on 5 different superstring theories - basic objects are supermembranes.

## WHERE RANDOMNESS COMES FROM

There are several sources of randomness:

- Heisenberg uncertainty principle - no particle can have fixed position and velocity.
- Even we could remove all energy from a particle there would remain some intrinsic random motion.
- The same applies to fields - there exists so called random fluctuations.
- There are entangled pairs of particles with one of the particle beyond the horizon of an observer, in his hidden region, and therefore the particle visible by him exhibits random behaviour, with respect to him.

## THREE IMPORTANT LAWS of COSMOLOGY

**Unruh's law** : Accelerating observers see themselves as embedded in a gas of hot photons at a temperature proportional to their acceleration.

**Bekenstein's law** With every horizon that forms a boundary separating an observer from a region which is hidden from them, there is associated an entropy which measures the amount of information which is hidden behind it. This entropy is always proportional to the area of the horizon.

**Hawkin's law** The temperature $T$ of a black hole is inversely proportional to its mass, $m$. That is

$$T = \frac{k}{m},$$

where the constant $k$ is very small.

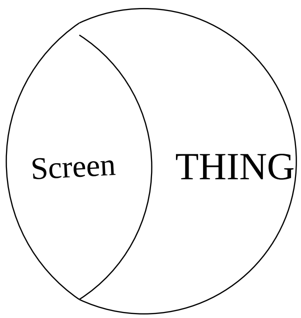
## INFORMATION PROCESSING SYSTEMS

- Computers - the concept of computer keep changing with computers and their applications getting more complex.
- Dynamic systems - Newton's idea
- Interactive systems - cellular automata as an important model
- Computing using chaotic systems
- Information processing by nature
- Brain computing
- Computing and conscious

# HOLOGRAPHIC PRINCIPLE

This principle is inspired by Bekenstein bound (that is a consequence of second law of thermodynamics).

Consider any physical system - call it The Thing - and require that The Thing is enclosed within a finite boundary, called The Screen.




- Bekenstein bound says that there is a general limit to how many yes/no questions e can answer about The Thing by making observation only through The Screen - the number has to be less than one-quarter of the area of the screen.
- If we ask more questions than either the area of The Screen will increase or the answers to some previous questions stop to be valid.
- Weak holographic principle says that we are mistaken to think that the world consists of Things that occupy regions of space. Instead that all there exists are Screens, on which the world is represented.

- Theory says that nothing exists except processes by which information is conveyed from one part of the world to another. The area of a screen is then nothing but the capacity of that surface as a channel of information.
- According to weak holographic principle space is nothing but a way of talking about all the different channels of communication that allow information to pass from observer to observer.
- Geometry, as measured in terms of area and volume, is nothing but a measure of the capacity of these screens to transmit information.
- History of universe is nothing but the flow of information.

# APPENDIX

## GRAND CHALLENGES

- (*Problem of the theory of everything.*) To unify general relativity theory and quantum theory into a single theory (that could be then seen as a complete theory of nature).
- (*Problem of the interpretation of quantum theory.*) To solve the problem of foundation of quantum theory either by finding a clear interpretation of current theory or by finding a new theory without current inconsistencies.
- (*Problem of the unification of particles and forces.*) To find out whether all particles and forces could be described by a single theory that could explain all of them as following from a single fundamental entity.
- (*Problem of the constants.*) To explain how nature chooses values of constants in the standard model of nature.

- (*Problem of the black matter and energy*) Explain the nature of black matter and black energy or, if they do not exist, explain how and why is gravitation modified for huge sizes.

P. Smolin

## IDEAS of Carver Mead

- It is my firm belief that the last seven decades of the twentieth [century] will be characterized in the history as the dark edges of theoretical physics.
- Matter is not composed of particles, rather of waves. Electron can be a mile long,....

Carver Mead is one of the most prominent scientists: Nobel Lauerat, inventor of a crucial high frequency transistor, author of dominating chip design techniques, propagator of the movement toward dynamically programmable logic chips, developer of radical advances in machine-aided perception,...considered as the most important practical scientis of the late twenty century,..