

Thinking about Thought

- Introduction
- Philosophy of Mind
- Cognitive Models
- Machine Intelligence
- Life and Organization
- Ecology
- The Brain
- Dreams and Emotions
- Language
- Modern Physics
- Consciousness

"Any kid in the streets of Gottingen knows Mathematics better than him"

(Hilbert on Einstein, circa 1915)

**Session Nine: Language
for Piero Scaruffi's class
“Modern Physics”
at UC Berkeley (2014)**

Roughly These Chapters of My Book “Nature of
Consciousness”:

20. Self-organization and the Science of Emergence

21. The New Physics: The Ubiquitous Asymmetry

Self-organization

Or

The Science Of Emergence



Entropy: the Curse of Irreversibility

- Thermodynamics studies macroscopic systems that cannot easily be reduced to their microscopic constituents.
 - Energy cannot be created or destroyed, only transformed
 - The entropy of an isolated system can never decrease
 - The entropy of a perfect crystal is zero at the temperature of absolute zero

Entropy: the Curse of Irreversibility

Entropy

- Sadi Carnot:
 - Heat flows spontaneously from hot to cold bodies, but the opposite never occurs
 - Any transformation of energy has an energetic cost
 - There are no reversible processes in nature
- “*I propose to name the quantity S the entropy of the system, after the Greek word [τροπή trope], the transformation*” (Rudolf Clausius, 1865)
- Natural processes generate entropy
- Clausius’ definition: the ratio between absorbed energy and absolute temperature



$$\Delta S = \frac{\Delta Q}{T}$$

Entropy: the Curse of Irreversibility

Entropy

- Ludwig Boltzmann's statistical definition
 - Many different microscopic states of a system result in the same macroscopic state
 - The entropy of a macrostate is the logarithm of the number of its microstates
 - Entropy = the number of molecular degrees of freedom
 - Entropy is a probability function
 - A system tends to drift towards the most probable state, which happens to be a state of higher entropy



$$S \propto \log \Omega$$

Entropy: the Curse of Irreversibility

Entropy

- Boltzmann realized that the molecules of an isolated gas tend to scatter until they are as randomly distributed as they can be, and that's the state of thermodynamic equilibrium.
- This randomness turns out to correspond to Clausius' entropy, and this randomness can be expressed mathematically as the number of microstates that can create a macrostate.
- (Boltzmann, living in the age of the slide rule, took the logarithm because in this way the randomness of a combined macrostate is simply the sum of the randomness of the individual macrostates).



$$S \propto \log \Omega$$

Entropy: the curse of irreversibility

- The second law of Thermodynamics (1852)
 - Some processes are not symmetric in time
 - Change cannot always be bi-directional
 - We cannot always replay the history of the universe backwards
 - Some things are irreversible



$$dS \geq 0$$

The Second Law

- Entropy can never decrease
- Transformation processes cannot be run backwards, cannot be "undone"
- Young people age, elderly people cannot rejuvenate
- Buildings don't improve over the years, they decay
- Scrambled eggs cannot be unscrambled and dissolved sugar cubes cannot be recomposed



Entropy: the Curse of Irreversibility

- Murray Gell-Mann
 - The reason that nature prefers disorder over order is that there are many more states of disorder than of order, therefore it is more probable that the system ends up in a state of disorder.
 - The probability of disorder is much higher than the probability of spontaneous order, and that's why disorder happens more often than order.



Heat Death

- William Thompson's eternal doom (1862): the universe must evolve in the direction of higher and higher entropy
- The universe is proceeding towards the state of maximum entropy
- Henri Poincare's eternal recurrence (1890): every closed system must eventually revert in time to its initial state
- Arthur Eddington (1939): not in an expanding universe



$$\mu(\{x \in E : \text{there exists } N \text{ such that } f^n(x) \notin E \text{ for all } n > N\}) = 0.$$

Every point of E returns to E infinitely often

The Origin of Irreversibility



- Irreversibility was deduced from reversibility
- Ilya Prigogine: inherent time asymmetry in chaotic processes at the microscopic level, which could cause entropy at the macroscopic level
- Irreversibility originates from randomness

Entropy

Entropy and Information

- Order is directly related to information
- Entropy is therefore related to information
- Entropy = a measure of disorder = a measure of the lack of information

Entropy and Information

- Entropy can also be understood as “missing” information
- Entropy measures the amount of disorder in a physical system; i.e. entropy measures *the lack of information* about the structure of the system

$$\text{Entropy} = - \text{Information}$$

Design Without a Designer

- Why do all living things have to grow
- Why do all living things have to evolve
- Darwin's intuition: the target can be reached not by designing it and then building it, but by taking a primitive object and letting it evolve
- The target object will not be built: it will emerge
- Everything in the universe was not built, it developed slowly over time
- How they happen to be the way they are depends to some extent on the advantages of being the way they are and to some extent on mere chance



The Origin of Order

- Classical physics: order can be built only rationally, by application of a set of fundamental laws of physics
 - Order needs to be somehow created by external forces
- Darwin: order can build itself spontaneously, e.g. Evolution
 - Spontaneous "emergence" of order.



$$\cancel{dS \geq 0}$$

The Origin of Order

- Physics: splitting the atom and observing distant galaxies
- Darwinian approach: focus on the evolutionary process that gradually built the universe the way it is
- Physics: study how things are modified when a force is applied
- Darwinian approach: study how things modify themselves spontaneously



The Origin of Information

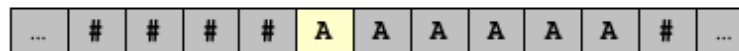
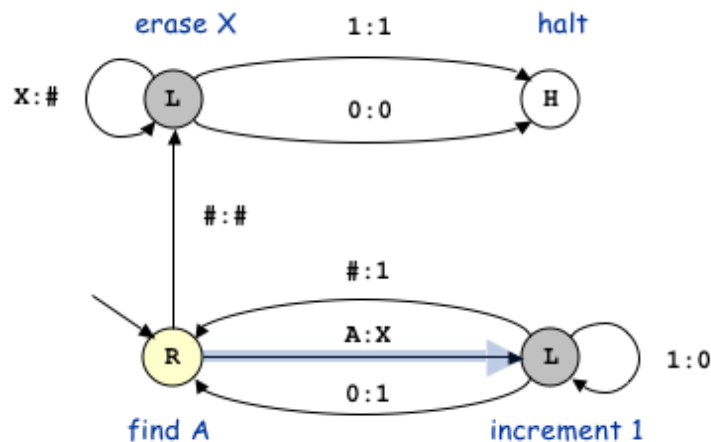
- Classical Physics: a study of forces
- Darwin's theory: the creation of information
- Classical Physics: a study of motion, gravitation, electricity...
- Darwinian approach: a study of information

The Origin of Information

- Classical Physics: differential equations

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Darwinian approach: algorithms



The Origin of Organization



- Algorithms are discrete, occur in steps, and can refer to themselves
- A science based on algorithms would be inherently different from a science based on equations.

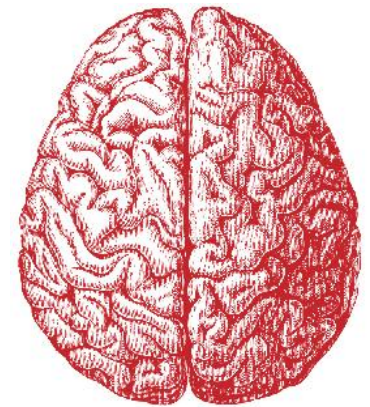
The Origin of Organization

- Darwinian approach: explain organization
- The concept of organization is deeply rooted in the physical universe.
- Darwin's treatise on the origin of species was indeed a treatise on the origin of order



The Origin of Organization

- Nature is able to obtain far bigger and more complex structures than humans can ever dream of building by design
- Nature uses much simpler mathematics
- Humans have developed a system that is much more complex than anything nature has ever dreamed of using
- Example of a complex self-organizing systems that grows: the brain



Chaos and Complexity

- Need for a new science:
 - A mathematical model of phenomena of emergence (the spontaneous creation of order)
 - A justification of their dynamics (which violates classical Physics)

Chaos and Complexity



- Henri Poincaré's "chaos" theory (1900s): a slight change in the initial conditions results in large-scale differences
- Very "disordered" systems spontaneously "crystallize" into a higher degree of order
- Complexity: a system must be complex enough for any property to "emerge" out of it
- Complexity can be formally defined as nonlinearity

Chaos and Complexity

- Chaos theory = nonlinear dynamics
 - In a linear system an action has an effect that is somewhat proportionate to the effect.
 - In a nonlinear system an action has an effect that causes a change in the action itself.
 - The world is mostly nonlinear. The “linear” world studied by classical Physics (Newton’s laws) is really just an exception to the rule.

$$F = \frac{d(mv)}{dt}$$

$$F = m a$$

$$F = G \frac{m_1 m_2}{r^2}$$

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Chaos and Complexity

- Chaos theory = nonlinear dynamics
 - Nonlinear equations canNOT be reduced to simpler equations: the whole is literally more than its parts.
 - A slight change in the initial conditions of nonlinear systems have devastating consequences
 - A small change in the initial conditions can grow exponentially quickly, the so called “butterfly effect” (Edward Lorenz, 1972).
 - Strange attractors: shapes that chaotic systems produce in phase space

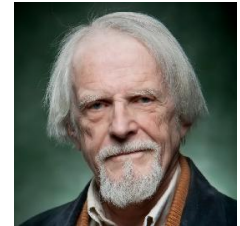


The Science of Emergence

- Theories that deal with self-organization and provide a unified view of the universe at different levels of organization
 - At every level of science, the spontaneous emergence of order, or self-organization of complex systems, is a common theme
 - Processes of emergent order and complexity
 - How structure arises from the interaction of many independent units

The Science of Emergence

- Theories that complexity entails hierarchical organization
 - Arthur Koestler
 - Stanley Salthe



The Science of Emergence

- Theories that extend Physics to dynamic systems:
 - Paul Weiss (1925): “As a system we want to define each complex that, when parts of it are modified, displays an effort to stay constant with regard to its outside”
 - Ludwig Von Bertalanffi's general systems theory
 - Hermann Haken's synergetics
 - Ilya Prigogine's non-equilibrium thermodynamics



Holarchies

- Arthur Koestler: a unified theory of open hierarchical systems (holarchies)
 - Each intermediary entity ("holon") functions as a self-contained whole relative to its subordinates and as one of the dependent parts of its superordinates
 - Each holon tends to persist and assert its pattern of activity.
- Wherever there is life, it must be hierarchically organized

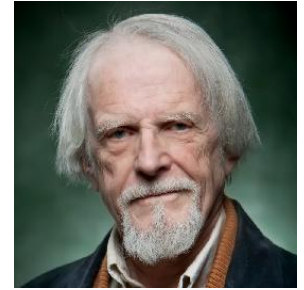


Holarchies



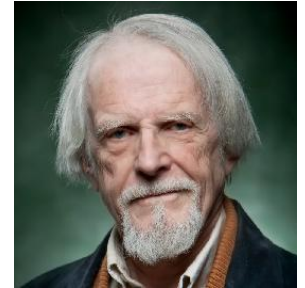
- Arthur Koestler
 - In nature there are no separated, indivisible, self-contained units- an "individual" is an oxymoron
 - An organism is a hierarchy of self-regulating holons (a "holarchy")
 - Consciousness should be analyzed in the context of a multi-levelled hierarchy (degrees of consciousness)

Hierarchies From Complexity



- Stanley Salthe's theory of everything
 - An ontology of the world
 - A formal theory of hierarchies
 - A model of the evolution of the world
- The world is a determinate machine of unlimited complexity
- Within complexity, discontinuities arise

Hierarchies From Complexity



- Stanley Salthe
 - Hierarchical structure turns out to be a consequence of complexity
 - Differentiation interpolates levels between the original two
 - The new entities aggregate in such a way that affects the structure of the upper levels
 - Every time a new level emerges, the entire hierarchy must reorganize itself

General Systems Theory

- Ludwig von Bertalanffy: to provide a unified view on all types of systems
- Classical Physics is feasible under two conditions:
 - 1. interaction among the parts of the system be negligible
 - 2. behavior of the parts be linear



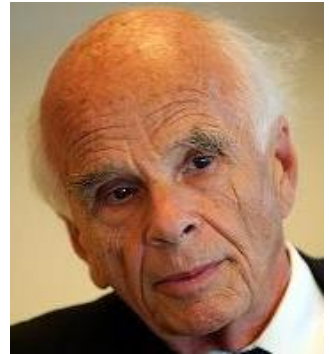
General Systems Theory

- Ludwig Von Bertalanffy
 - “Organized complexities” consist of interacting parts
 - General systems theory
 - Looks for an isomorphism of law in different fields
 - Studies "wholes", which are characterized by such holistic properties as hierarchy, stability, teleology
 - A living organism is a hierarchical order of open systems, where each level maintains its structure thanks to continuous change of components at the next lower level



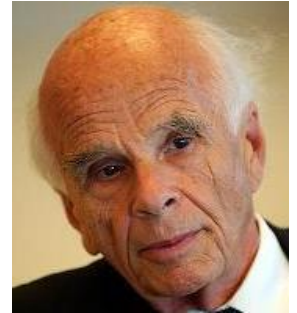
General Systems Theory

- Ervin Laszlo's "theory of natural systems"
 - A theory of the invariants of organized complexity
 - "Ordered whole"
 - Cybernetic principle: any isolated natural system subject to constant forces is inevitably inhabited by "organisms" that tend towards stationary or quasi-stationary non-equilibrium states
 - The combination of internal constraints and external forces yields adaptive self-organization.



General Systems Theory

- Ervin Laszlo's "theory of natural systems"
 - Natural systems evolve towards increasingly adapted states, corresponding to increasing complexity
 - Natural systems sharing an environment tend to organize in hierarchies
 - The set of such systems tends to become itself a system, its subsystems providing the constraints for the new system



Synergetics

- Hermann Haken's theory of pattern formation in complex systems
 - To explain structures that develop spontaneously in nature
 - Behavioral attractors of changing stabilities
 - The appearance of new forms as non-equilibrium phase transitions
 - The dynamic equations of the system reflect the interplay between stochastic forces ("chance") and deterministic forces ("necessity")



Synergetics

- Hermann Haken's theory of pattern formation in complex systems
 - Synergetics applies to systems driven far from equilibrium
 - Order can arise from chaos
 - Order can be maintained by flows of energy/matter



Hypercycles



- Manfred Eigen's cyclic reaction networks
 - Focus on very fast chemical reactions
 - A hypercycle is a cyclic reaction network, i.e. a cycle of cycles of cycles
 - Life is the product of a hierarchy of hypercycles
 - Basic catalytic cycles can be organized into an autocatalytic cycle, i.e. a cycle that is capable of self-reproducing
 - A set of autocatalytic cycles gets, in turn, organized into a catalytic hypercycle
 - This catalytic hypercycle represents the basics of life

Hypercycles



- Manfred Eigen's cyclic reaction networks
 - The dual process of unity (due to the use of a universal genetic code) and diversity (due to the "trial and error" approach of natural selection) in evolution started even before life was created
 - Evolution of species was preceded by an analogous stepwise process of molecular evolution
 - Natural selection is a mathematical consequence of the dynamics of self-reproducing systems

Dissipative Systems

- Ilya Prigogine's non-equilibrium thermodynamics (1960s)
 - Classical physics: the world is a static and reversible system that undergoes no evolution, whose information is constant in time
 - Classical physics is the science of being
 - Thermodynamics describes an evolving world in which irreversible processes occurs
 - Thermodynamics is the science of becoming
 - Irreversible processes are an essential part of the universe



Dissipative Systems

- Ilya Prigogine's non-equilibrium thermodynamics (1960s)
 - Furthermore, conditions far from equilibrium foster phenomena such as life that classical physics does not cover at all
 - Irreversible processes and non-equilibrium states may turn out to be fundamental features of the real world



Dissipative Systems

- Ilya Prigogine (1960s)
 - The science of being and the science of becoming describe dual aspects of nature
 - “Conservative” systems vs “dissipative” systems (subject to fluxes of energy and/or matter)
 - Dissipative systems give rise to irreversible processes



Dissipative Systems

- Ilya Prigogine (1960s)
 - Order can come either from equilibrium systems or from non-equilibrium systems that are sustained by a constant source (by a persistent dissipation) of matter/energy
 - All living organisms are non-equilibrium systems
 - The distance from equilibrium and the nonlinearity of a system drive the system to ordered configurations, i.e. create order



Dissipative Systems



- Ilya Prigogine (1960s)
 - Non-equilibrium and nonlinearity favor the spontaneous development of self-organizing systems, which maintain their internal organization, regardless of the general increase in entropy, by expelling matter and energy in the environment
 - Nonlinear systems driven away from equilibrium can generate instabilities that lead to bifurcations (and symmetry breaking beyond bifurcation)

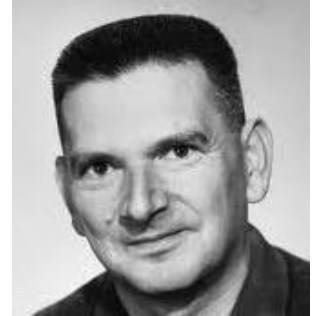
Dissipative Systems



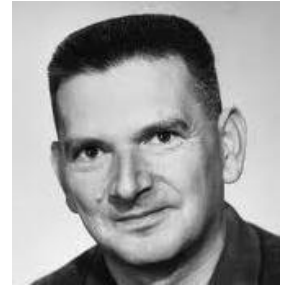
- Ilya Prigogine (1960s)
 - When the system reaches the bifurcation point, it is impossible to determine which path it will take next: chance
 - Once the path is chosen, determinism resumes
 - The multiplicity of solutions in nonlinear systems can be interpreted as a process of gradual "emancipation" from the environment

Catastrophe Theory

- Rene' Thom's catastrophe theory (1967)
 - General laws of form evolution
 - A form is defined, first and foremost, by its stability: a form lasts in space and time
 - Life itself is, ultimately, creation, growth and decaying of form
 - Every physical form is represented by a mathematical quantity called "attractor" in a space of internal variables
 - If the attractor satisfies the mathematical property of being "structurally stable", then the physical form is the stable form of an object



Catastrophe Theory



- René Thom's catastrophe theory (1967)
 - Changes in form, or morphogenesis, are due to the capture of the attractors of the old form by the attractors of the new form
 - All morphogenesis is due to the conflict between attractors

Catastrophe Theory



- Rene' Thom's catastrophe theory (1967)
 - The universe of objects can be divided into domains of different attractors
 - Such domains are separated by shock waves
 - Shock-wave surfaces are singularities called "catastrophes"
 - A catastrophe is a state beyond which the system is destroyed in an irreversible manner
 - In a 4-dimensional space there exist only 7 types of elementary catastrophes
 - The form of an object is due to the accumulation of many of these "accidents"

Complex Systems



- Per Bak (1987)
 - The collapse of a pile of sand under the weight of a new randomly placed grain is unpredictable
 - However, when it happens, the pile reorganizes itself
 - While it is impossible to predict if a particular grain will cause an avalanche, the size of these avalanches is distributed according to a "power law".
 - No external force is shaping the pile of sand: it is the pile of sand that organizes itself.



Complex Systems

- Chris Langton (1989)
 - When ice turns into water, the atoms have not changed, but the system as a whole has undergone a phase transition
 - The state between order and chaos (the "edge of chaos") is sometimes a very "informative" state, because the parts are not as rigidly assembled as in the case of order and, at the same time, they are not as loose as in the case of chaos.
 - The system is stable enough to keep information and unstable enough to dissipate it.
 - The system at the edge of chaos is both a storage and a broadcaster of information.



Complex Systems



- Chris Langton (1989)
 - The edge of chaos is where the system can perform computation, can metabolize, can adapt, can evolve
 - In a word: these systems can be “alive”
 - Phenomena such as life can only exist in a very narrow boundary between chaos and order

Complex Systems

- Stuart Kauffman (1993)
 - There exists a fundamental force that counteracts the universal drift towards disorder
 - Darwin was only half right: systems do evolve under the pressure of natural selection, but their quest for order is helped by a property of our universe, the property that "complex" systems just tend to organize themselves
 - Systems on the boundary between order and chaos have the flexibility to adapt rapidly and successfully.



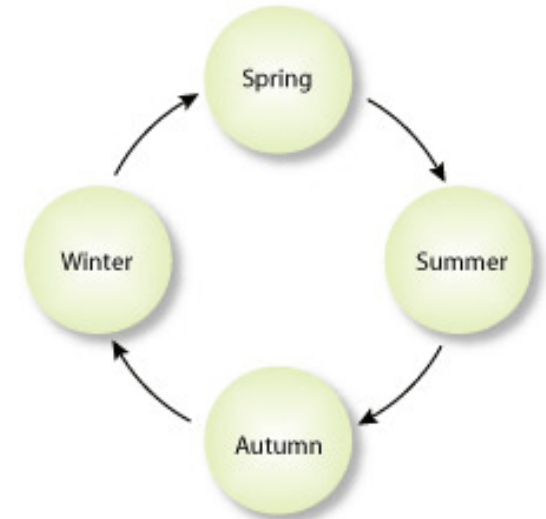
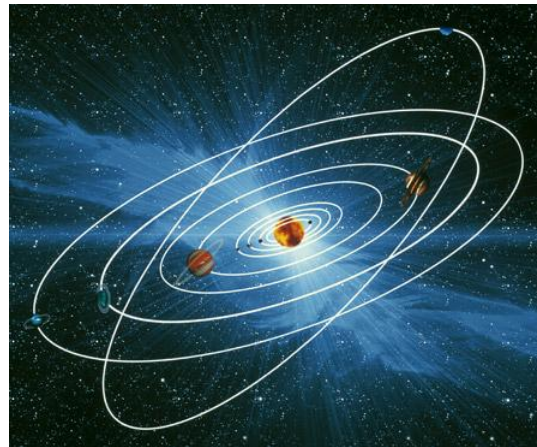
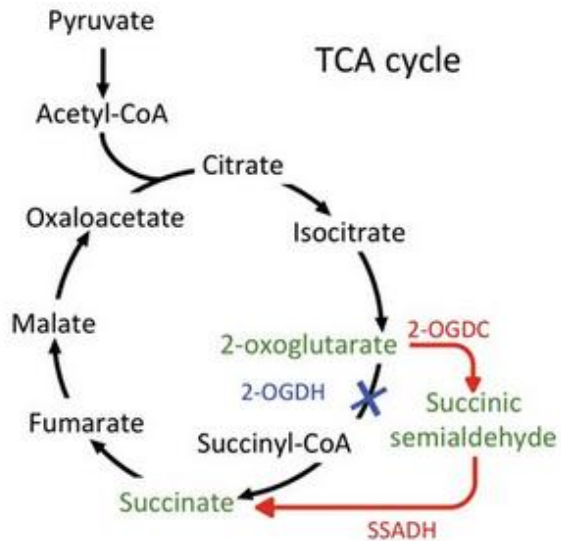
Complex Systems

- Stuart Kauffman's self-organizing systems
 - Living organisms are a particular type of complex adaptive systems.
 - Natural selection and self-organization complement each other: they create complex systems poised at the edge between order and chaos, which are fit to evolve in a complex environment



Synchronized Oscillators

- Clocks and cycles are pervasive in our universe, from biological clocks to the cycles of electrons around the nucleus



The tricarboxylic acid (TCA) cycle includes a series of chemical reactions that are used for metabolism by most forms of life,

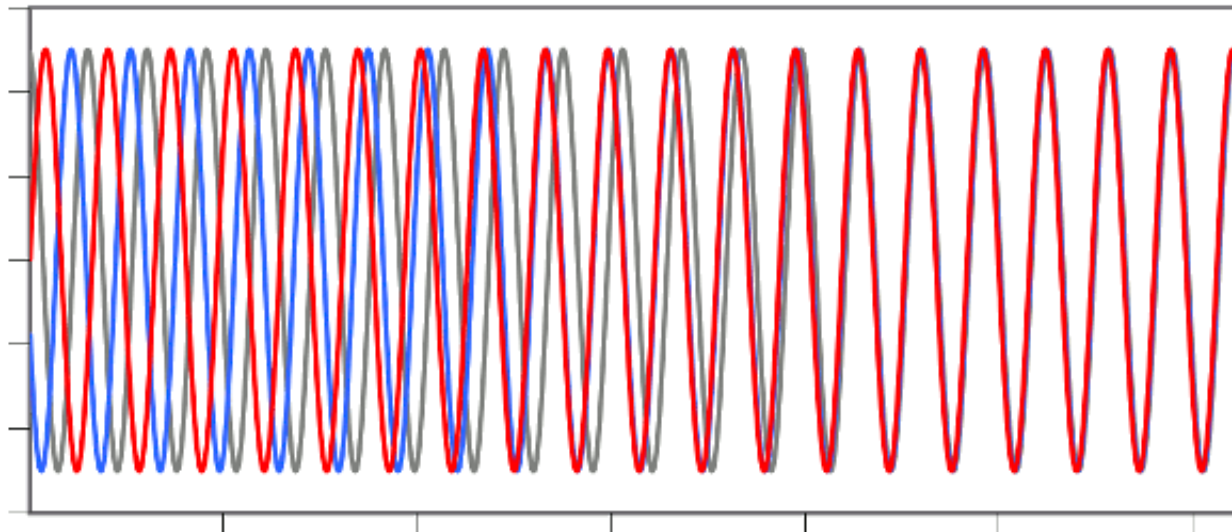
Synchronized Oscillators

- Populations of synchronized oscillators are pervasive in nature
 - Biological clocks are regulated by populations of interacting neurons
 - The rhythm of the heart is set by the collective behavior of a group of cells
 - The suprachiasmatic nucleus is made of a large population of independent oscillators
 - At low temperatures all bosons behave like one (Bose-Einstein)
- The population does not need any leader in order to achieve synchronization



Synchronized Oscillators

- Order emerges from the synchronized behavior of "coupled oscillators"
- The advantage of having a population of clocks: fault tolerance



Synchronized Oscillators

- Phase transition of a substance: all the molecules of that substance have to "cooperate" in order for the substance to change state
- Organizing a population of oscillators is similar to organizing a population of molecules, except that the former gets organized in time and the latter gets organized in space

Synchronized Oscillators

- Yoshiki Kuramoto (1984): There is a threshold value for a chaotic system of oscillators, below which a solution of complete synchronization exists and above which it does not exist
- John Hopfield (1994): A system of synchronized oscillator is a self-organizing system
- Steven Strogatz (2003): Synchronicity "will" emerge at some point in any system that exhibits partial synchronicity above the threshold



Synchronized Oscillators

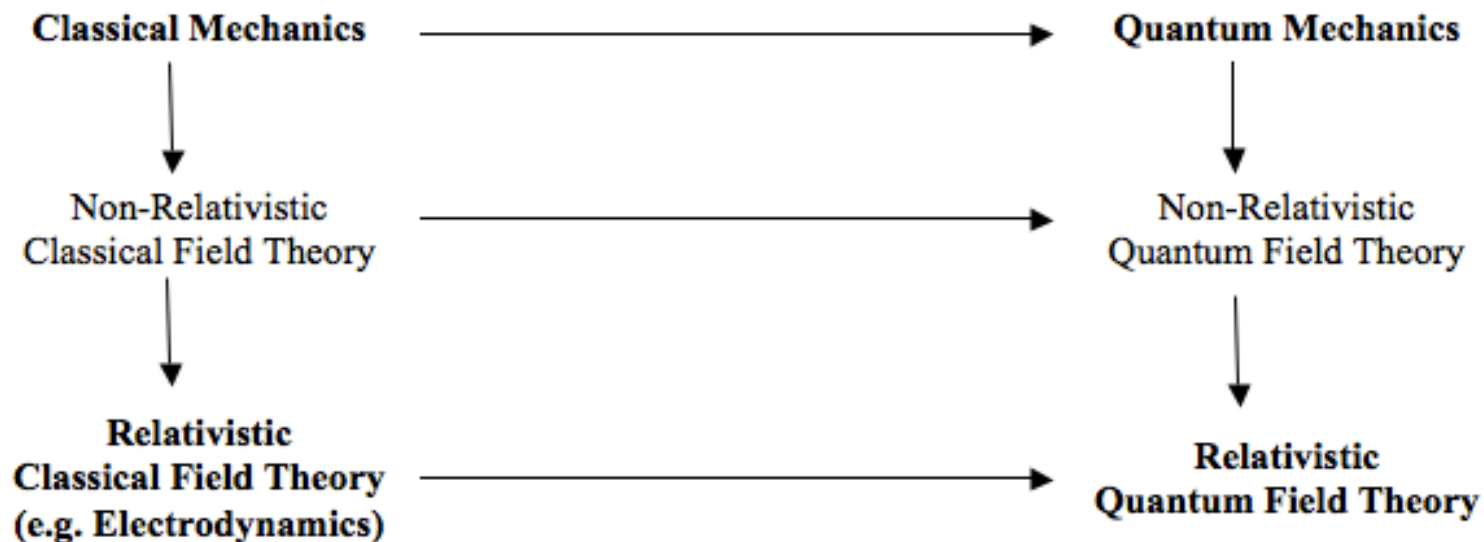
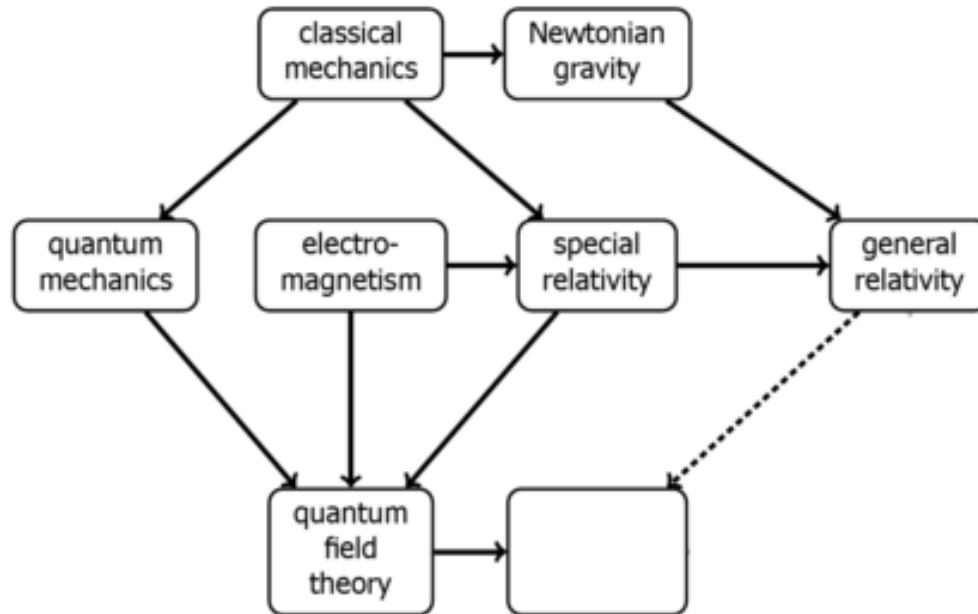
- Self-organization can be achieved in time or in space.
 - Some interacting molecules, cells and atoms achieve self-organization in space through spontaneous reorganization
 - Some coupled oscillators achieve self-organization in time through spontaneous synchrony

Break



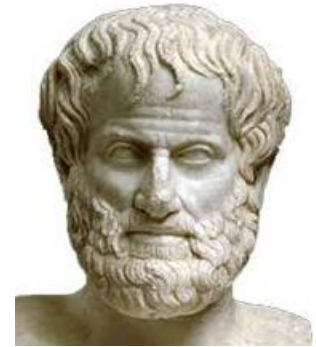
*"The beaver told the rabbit as they stared at the Hoover Dam:
No, I didn't build it myself, but it's based on an idea of mine"
(Charles Townes)*

Quantum and Relativity Theories



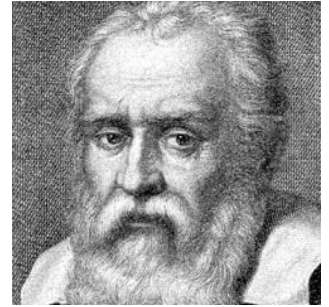
The Classical World: Utopia

- Aristoteles
 - There is a reality that exists apart from anyone experiencing it, and human senses are capable of accessing it
 - The natural state of things is rest
 - The natural state of the heavens is uniform circular motion
 - Heavier bodies of a given material fall faster than lighter ones



The Classical World: Utopia

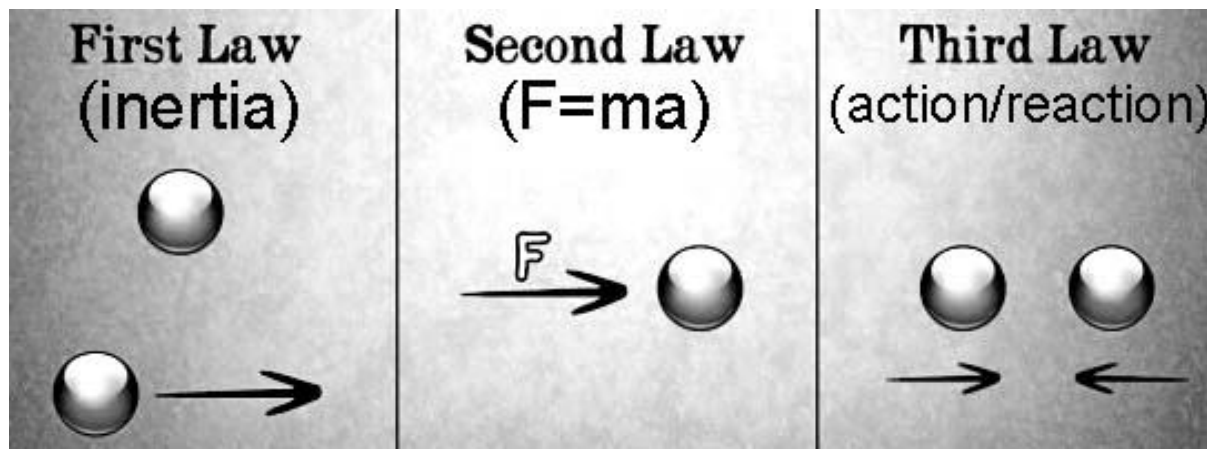
- Galileo Galilei
 - A body in free motion does not need any force to continue moving: the natural state of things is uniform linear motion
 - If a force is applied, then what will change is the acceleration, not the velocity
 - All bodies fall with the same acceleration
 - Space and time are independent



The Classical World: Utopia



- Isaac Newton
 - Differential calculus and Euclid's geometry
 - Three fundamental laws
 - Exact mathematical relationships
 - The dynamic equation that mathematically describes the motion of a system
 - Newton's world is a deterministic machine

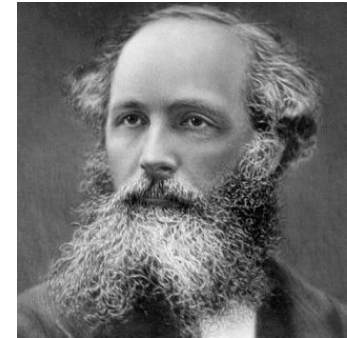


The End of Utopia

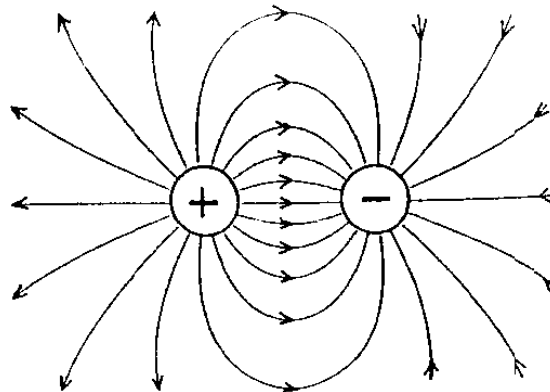
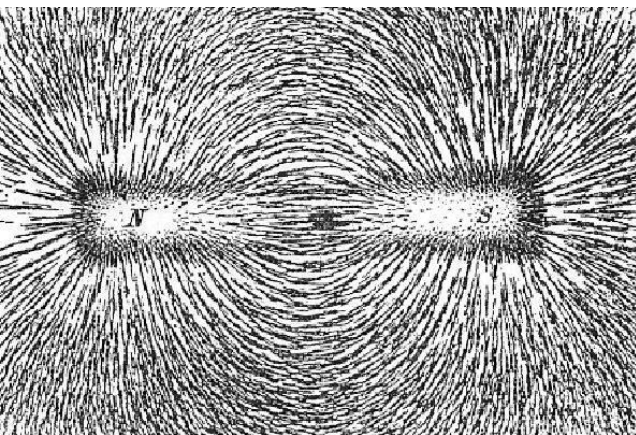
- Gas
 - Gas: a system made of many minuscule particles in very fast motion and in continuous interaction
 - Classical approach abandoned in favor of a stochastic approach
 - All quantities that matter (from temperature to heat) are statistical quantities



The End of Utopia



- Electromagnetism
 - Electric bodies radiate invisible waves of energy through space (fields)
 - James Maxwell (1873): field equations (distribution of electric and magnetic charges)
 - The number of coordinates needed to determine a wave is infinite



Maxwell's Equations

$$1. \quad \nabla \times \underline{B} = \underline{j} + \frac{\partial}{\partial t} (\underline{aE})$$

$$2. \quad \nabla \times \underline{E} = -\frac{\partial \underline{B}}{\partial t}$$

$$3. \quad \nabla \cdot \underline{B} = 0$$

$$4. \quad \nabla \cdot \underline{E} = \frac{\ell_c}{a}$$

here $\underline{D} = \underline{aE}$ and $\underline{B} = \mu \underline{H}$

$\underline{B}$ is the magnetic induction. $\underline{E}$ is the electric field.

$\underline{D}$ is the electric displacement. $\underline{H}$ is the magnetic field.

$\underline{j}$ is the electric current. ℓ_c is the charge density.

μ and a are constants.

The End of Utopia

- Time's arrow
 - Classical Physics is reversible in time
 - Classical Physics can not distinguish the past from the future
 - All of Classical Physics' equations are symmetrical in time

The End of Utopia

- Erwin Schroedinger: classical science relies on two fundamental postulates:
 - object and subject can be separated (i.e., the subject can look at the object as if it were a completely disconnected entity);
 - the subject is capable of knowing the object (i.e., the subject can look at the object in a way that creates a connection, one leading to knowledge)

Relativity: the Primacy of Light

- Special theory of relativity (1905)



"On the Electrodynamics of Moving Bodies".

**3. Zur Elektrodynamik bewegter Körper;
von A. Einstein.**

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng voneinander zu trennen sind. Bewegt sich nämlich der Magnet und ruht der Leiter, so entsteht in der Umgebung des Magneten ein elektrisches Feld von gewissem Energiewerte, welches an den Orten, wo sich Teile des Leiters befinden, einen Strom erzeugt. Ruht aber der Magnet und bewegt sich der Leiter, so entsteht in der Umgebung des Magneten kein elektrisches Feld, dagegen im Leiter eine elektromotorische Kraft, welcher an sich keine Energie entspricht, die aber — Gleichheit der Relativbewegung bei den beiden ins Auge gefaßten Fällen vorausgesetzt — zu elektrischen Strömen von derselben Größe und demselben Verlaufe Veranlassung gibt, wie im ersten Falle die elektrischen Kräfte.

Relativity: the Primacy of Light



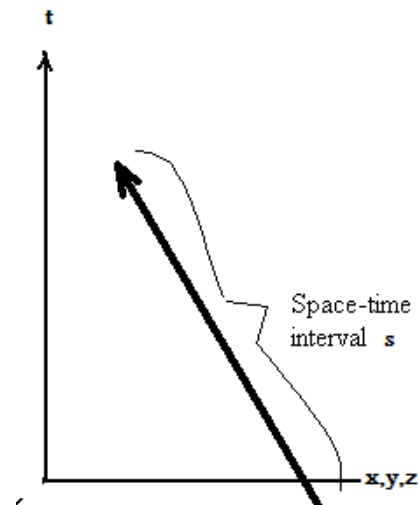
- Special theory of relativity (1905)
 1. Laws of nature must be uniform
 2. Laws must be the same in all frames of reference that are "inertial"
 3. The speed of light is always the same

Relativity: the Primacy of Light



- Unify Newton's equations for the dynamics of bodies and Maxwell's equations for the dynamics of electromagnetic waves in one set of equations
- Space and time are simply different dimensions of the same 4-dimensional spacetime continuum (Hermann Minkowski)
- All quantities must have four dimensions, a time component and a space component (e.g., energy-momentum)

$$s^2 = x^2 + y^2 + z^2 - (ct)^2$$



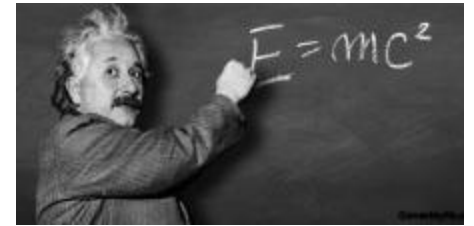
Relativity: the Primacy of Light



- Different observers see different things depending on their state of motion
- All quantities are decomposed into a time component and a space component, but how that occurs depends on the observer's state of motion.

Relativity: the Primacy of Light

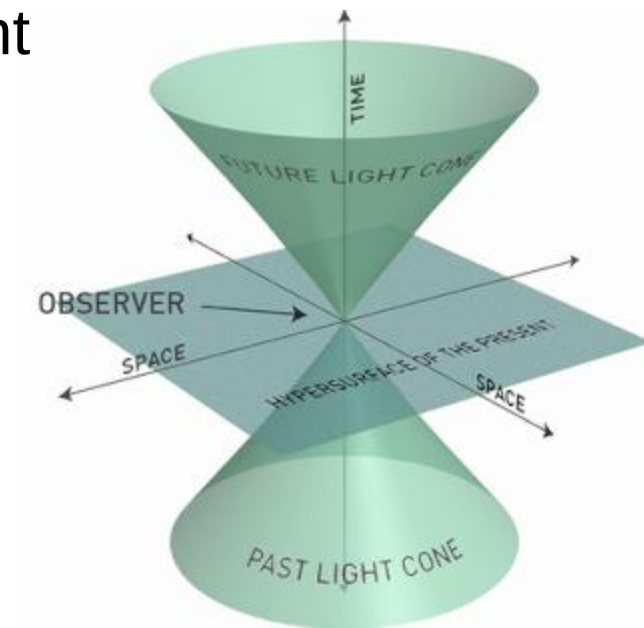
- Distortions of space and time
- "Now" is a meaningless concept
- The past determines the future
- Matter = energy
- Nothing can travel faster than light



Life on a World Line



- The “light cone”
 - The set of all points that can be reached by all possible light rays passing through that point
 - The potential future of the point
 - Light cone for the past
 - No event located outside the light cone can influence the future (“event horizon”)



Life on a World Line



- “World line”: spatiotemporal path that an object is actually traveling through space-time
- “Proper” time is the spacetime distance between two points on a world line (the time experienced by an observer traveling along that world line)
- No provision in relativity for free will...
- ...but everything is relative to the observer

General Relativity: Gravity Talks



- Relativity theory is ultimately about the nature of gravitation
- Relativity explains gravitation in terms of curved space-time, i.e. Geometry
- Gravity is canceled in a frame of reference which is free falling
- The laws of nature in an accelerating frame are equivalent to the laws in a gravitational field
- Free falls as natural motions, as straight lines in spacetime

CURVATURE

= ENERGY-MOMENTUM

$G_{\mu\nu}$

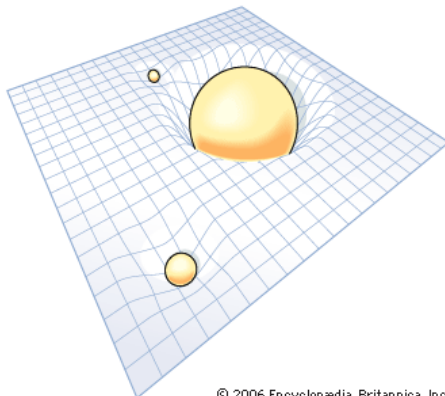
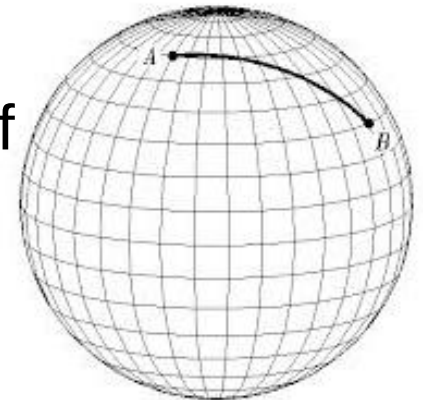
=

$8\pi T_{\mu\nu}$

General Relativity: Gravity Talks

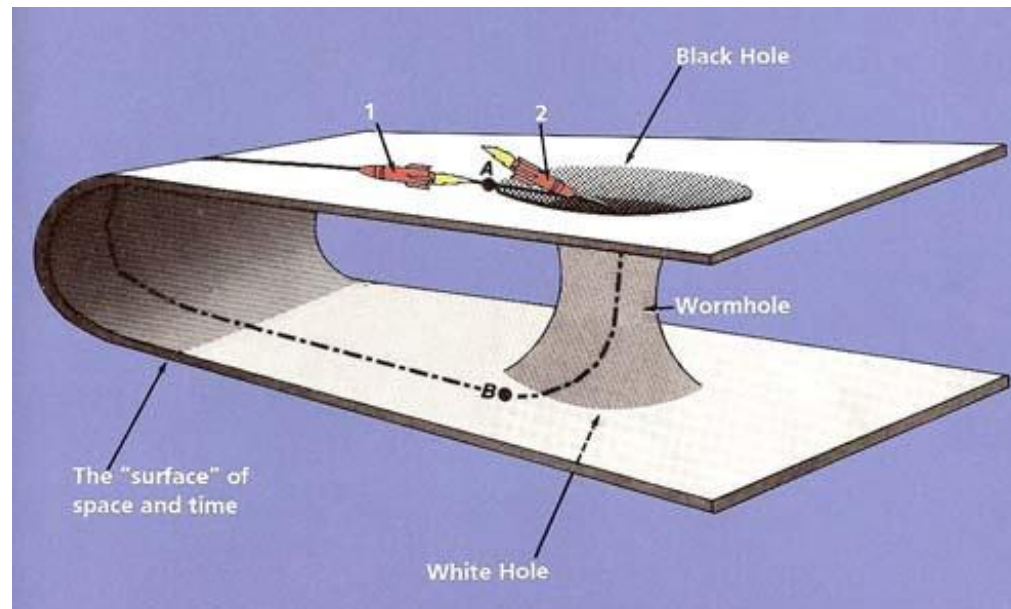
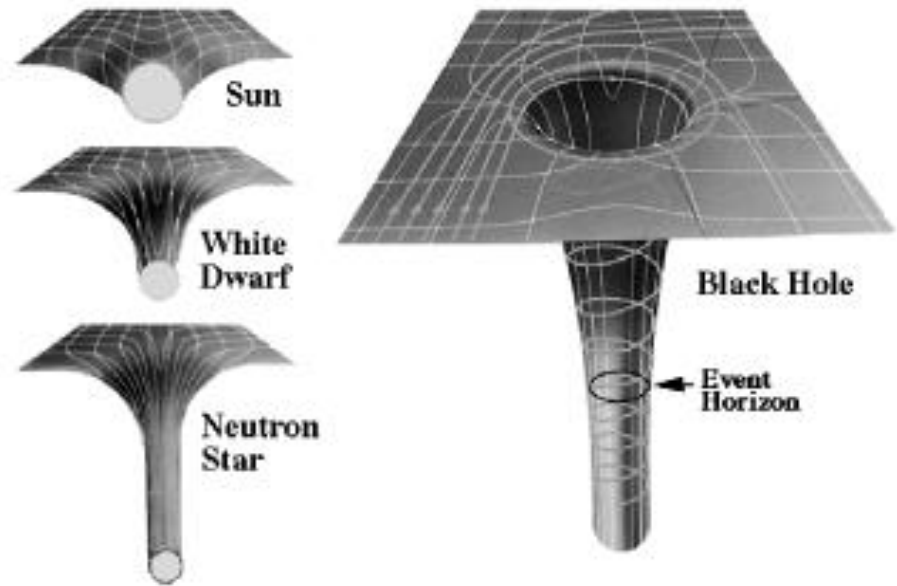
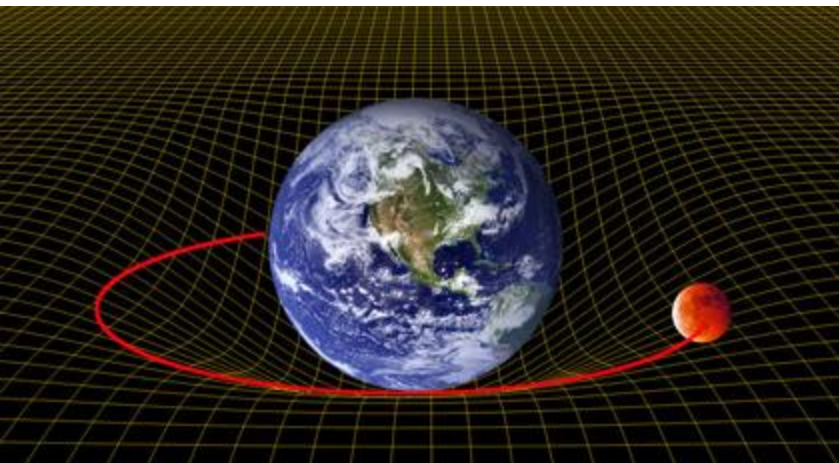
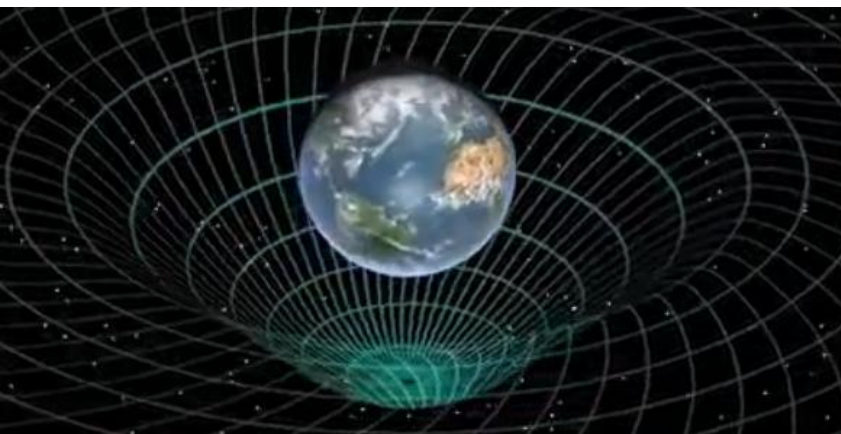


- The effect of a gravitational field is to produce a curvature of spacetime
- The straight line becomes a “geodesic”, the shortest route between two points on a warped surface
- Bodies not subject to forces other than a gravitational field move along geodesics of spacetime



General Relativity: Gravity Talks

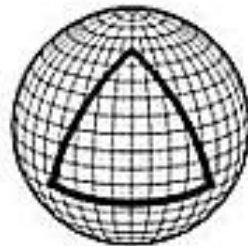
- Spacetime warp



General Relativity: Gravity Talks



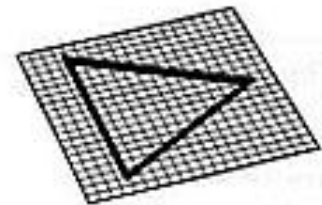
- The curvature of space-time is measured by a “curvature tensor”
- Each point is described by ten numbers (metric tensor)
- Bernhard Riemann’s geometry
- Euclid's geometry is one of the infinite possible metric tensors (zero curvature)



Closed Geometry



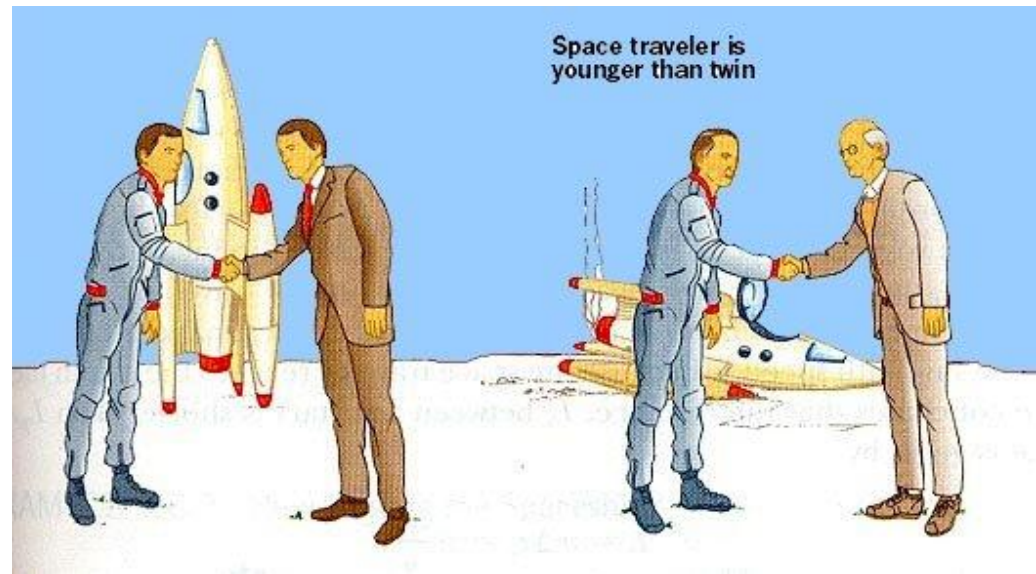
Open Geometry



Flat Geometry

General Relativity: Gravity Talks

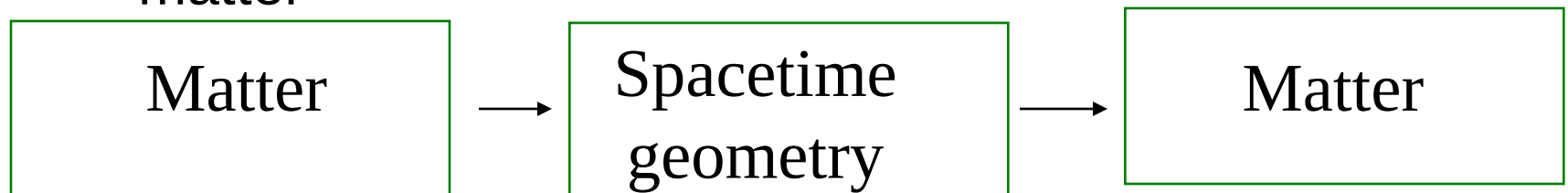
- What causes the “warps” is energy-mass
- "Force" becomes an effect of the geometry of space
- A "force" is the manifestation of a distortion in the geometry of space
- Clocks are slowed down by “gravity” (i.e. by spacetime warps)



Summarizing Einstein...



- The dynamics of matter is determined by the geometry of space-time
- Geometry is in turn determined by the distribution of matter
- Space-time acts like an intermediary device that relays the existence of matter to other matter



Summarizing Einstein...



- Special relativity: the laws of nature be the same in all inertial frames (i.e. invariant with respect to the Lorentz transformations)
- Consequence: everything is relative to the observer, clocks slow down, bodies contract, nothing travels faster than light
- General relativity: laws of nature be the same in all frames, inertial or not (i.e. "covariant" with respect to a generic transformation of coordinates)
- Consequence: further erosion of the concept of time (clocks slow down just for being in the wrong place)

Quantum Theory

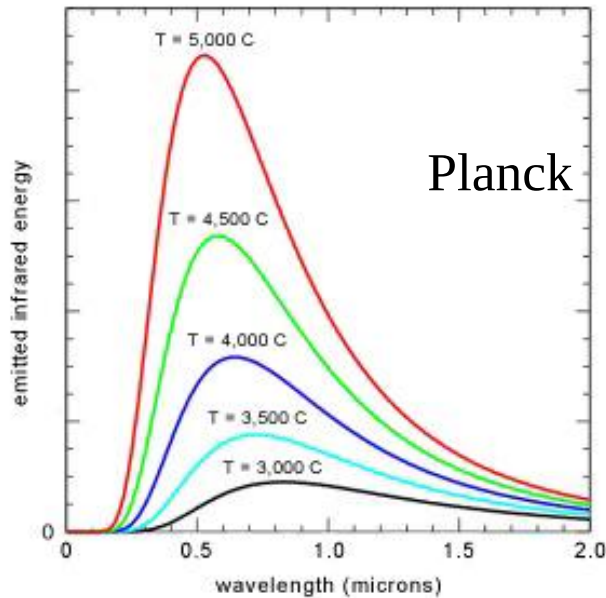


“About your cat, Mr. Schrödinger—I have good news and bad news.”

New Yorker

Quantum Theory: Enter Probabilities

- Any field of force manifests itself in the form of discrete particles (“quanta”)



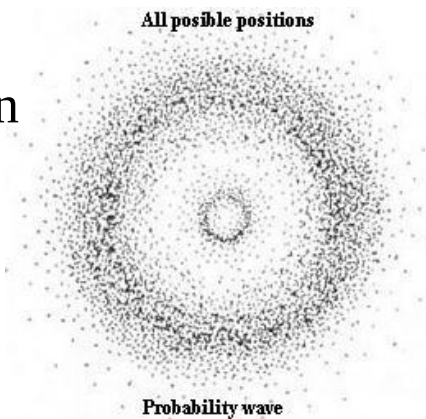
$$mc^2 = h\nu$$

DeBroglie

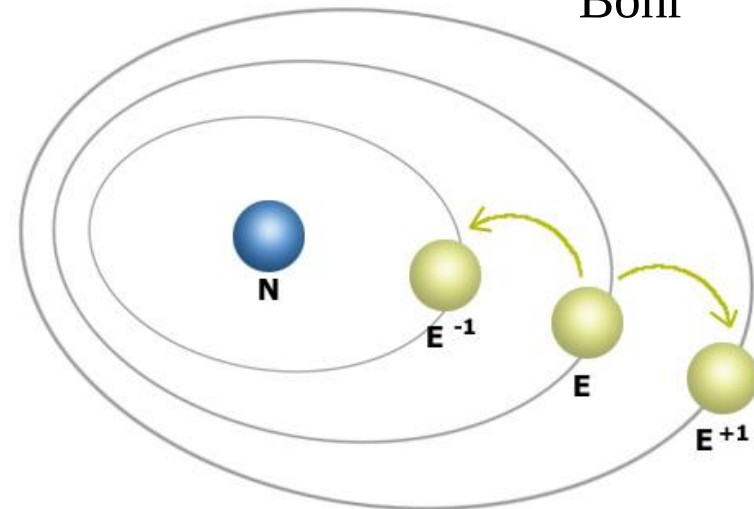
$$E = h\nu$$

Einstein

Born



Bohr



Quantum Theory: Enter Probabilities

- Forces are manifestations of exchanges of discrete amounts of energy (Max Planck, 1900)
- Equivalent descriptions: energy and mass, frequency and wavelength (Einstein, 1905)
- Electrons are permitted to occupy only some orbits around the nucleus (Niels Bohr, 1913)
- Waves and particles are dual aspects (Louis de Broglie, 1923)
- The wave associated to a particle is a wave of probabilities (Max Born, 1926)



Quantum Theory: Enter Probabilities

- 1925 equations to replace Newton's (or, better, Hamilton's) equations and predict the state of the system at a later time given the current state
 - Werner Heisenberg's equation (based on matrix algebra): the result of a physical experiment depends on the order in which the calculations are performed
 - Erwin Schroedinger (based on wave mechanics): an object is a wave spread in space

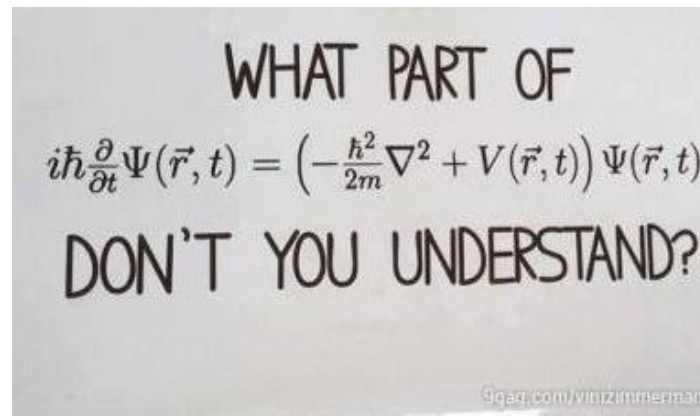


$$X_{nm}(t) = e^{2\pi i(E_n - E_m)t/h} X_{nm}(0) \quad i\hbar \frac{\partial}{\partial t} \psi(\mathbf{r}, t) = -\frac{\hbar^2}{2m} \nabla^2 \psi(\mathbf{r}, t) + V(\mathbf{r}, t) \psi(\mathbf{r}, t)$$

Quantum Theory: Enter Probabilities



- The state of a particle is a “superposition” of alternatives
- The state of a particle is described by a “wave function” which summarizes (superposes) all the alternatives and their probabilities
- Erwin Schroedinger's equation describes how this wave function evolves in time
- The wave function describes a set of possibilities



Quantum Theory: Enter Uncertainty

- An observable quantity can assume a range of values (its “eigenvalues”), each one with a given probability
- An observer can measure at the same time only observables which are compatible: indeterminacy of incompatible observables
- Werner Heisenberg’s “uncertainty principle”: there is a limit to the precision with which we can measure quantities
- The degree of uncertainty is proportional to the Planck constant



$$\Delta E \Delta t \geq \frac{\hbar}{2} \quad \Delta \chi \Delta \rho \geq \frac{\hbar}{2}$$

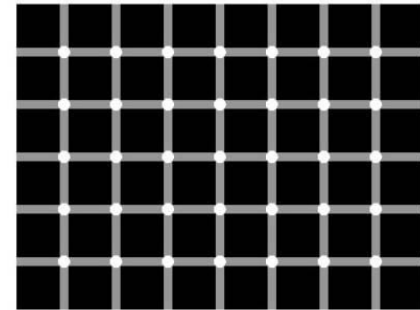
Quantum Theory: Enter Uncertainty

- The degree of uncertainty is proportional to the Planck constant
- Below a quantity proportional to the Planck constant the physical laws stop working altogether
- This implies that there is a limit to how small a physical system can be



Quantum Theory: Enter Uncertainty

- The Planck constant
 - Newton and Einstein physics assumed that the most fundamental units of the universe were the point and the instant
 - Quantum Theory introduces a fundamental unit that is bigger than a point and an instant
 - There is a limit to how small an object can be and to how short an interval can be
 - Einstein had warped space and time, Quantum Theory it turned them into grids.
 - The Planck constant has a size: a length, height and width of 10^{-33} centimeters and a time interval of 10^{-43} seconds



Quantum Theory: Enter Uncertainty

- The vacuum
 - Paul Dirac (1930)
 - If you remove all particles, i.e. you have absolute certainty about the position of particles, then you know nothing about momentum and therefore about energy
 - Kinetic and potential energy cannot both be zero at the same time
 - There has to be a minimum amount of energy: the zero-point energy
 - The vacuum is not empty



$$E_0 = \int_{\omega=0}^{\omega_{cutoff}} \frac{\hbar \omega^3}{2\pi^2 c^3} d\omega$$

Energy Density from the Quantum
Vacuum Advanced Propulsion
Physics: Harnessing the Quantum
Vacuum H. White, P. March

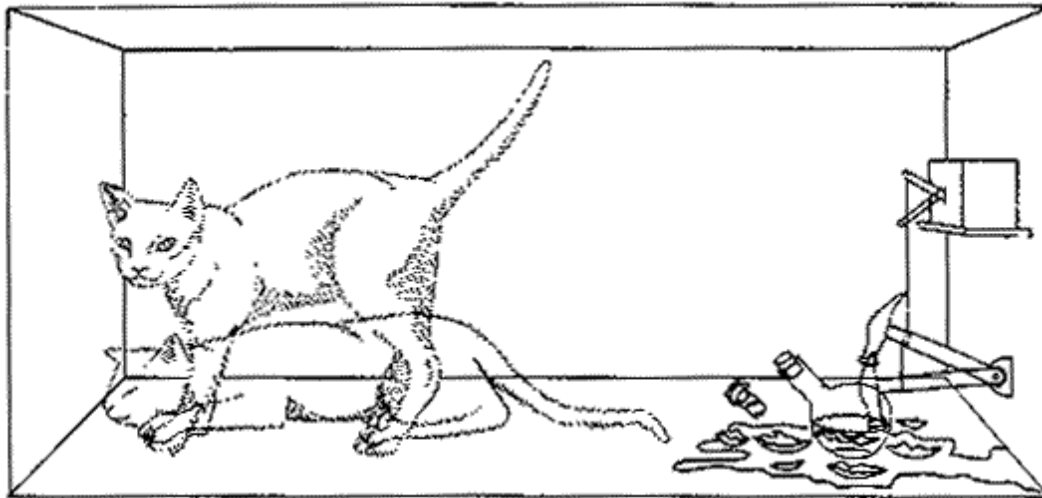
Quantum Theory: Enter Uncertainty

- The vacuum
 - Hendrik Casimir (1948): the vacuum generates a force
 - Andrei Sakharov (1968): gravitation is not a fundamental force but an electromagnetic phenomenon induced by the interaction of matter with the quantum vacuum
 - Harold Puthoff (1989): a body's inertia is due to the electromagnetic interaction that arises from quantum fluctuations of the zero-point field in accelerated frames (first rational explanation of why force and acceleration are related)

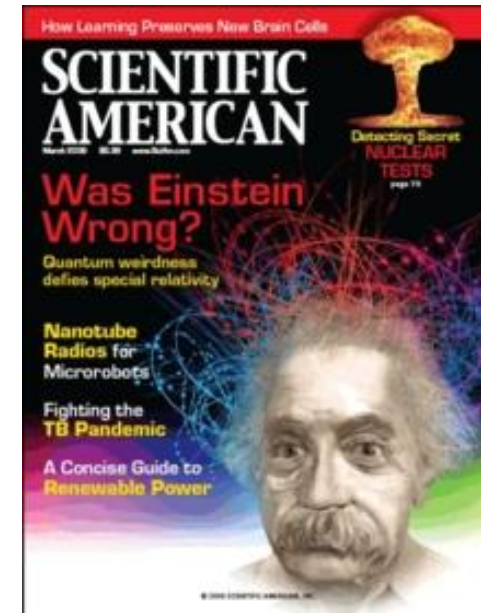


Quantum Theory: Enter Uncertainty

- Randomness
- Schroedinger's cat
- Non-locality



upscale.utoronto.ca



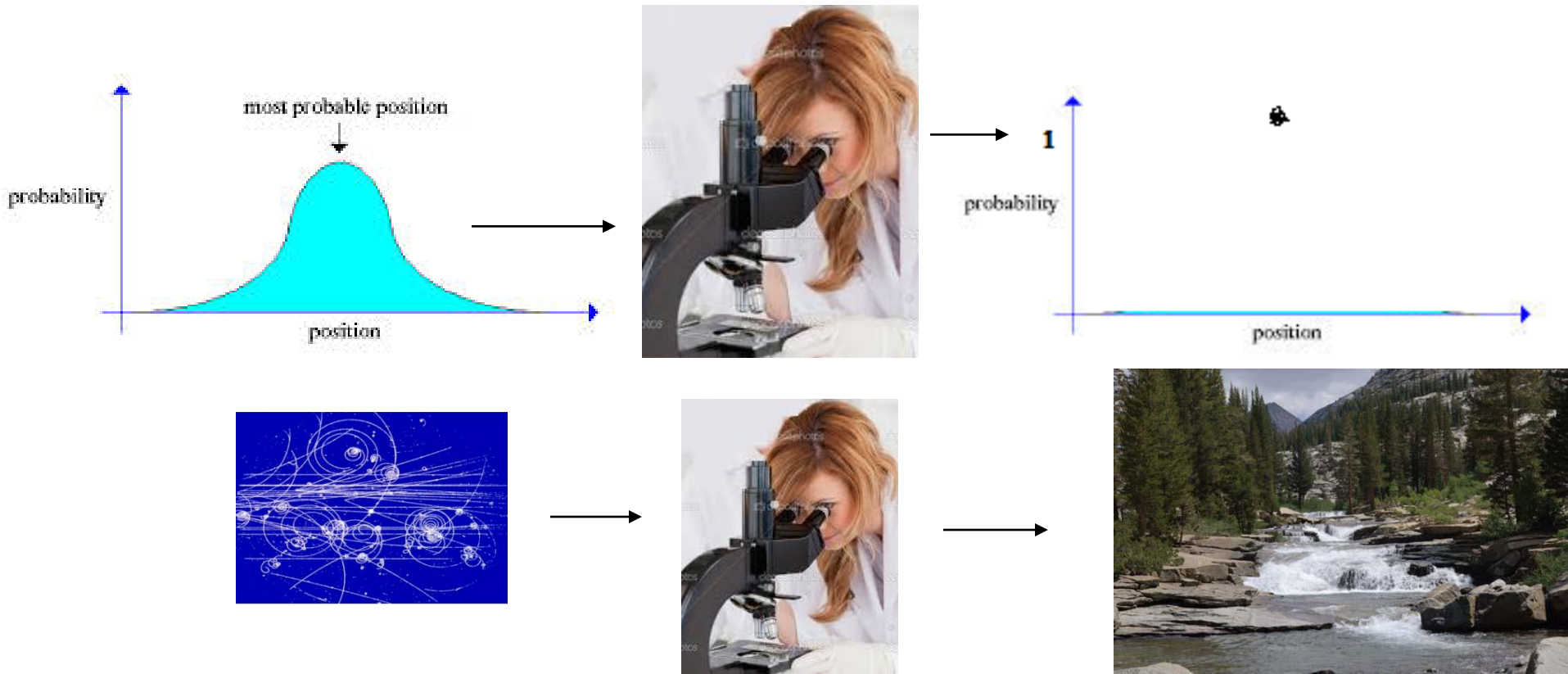
Interpretations of Quantum Theory

- Niels Bohr: only phenomena are real
- Werner Heisenberg: the world "is" made of possibility waves (particles are merely "potentialities")
- Paul Dirac: a description of our knowledge of a system
- Hugh Everett: multiverse
- etc



The Measurement Problem

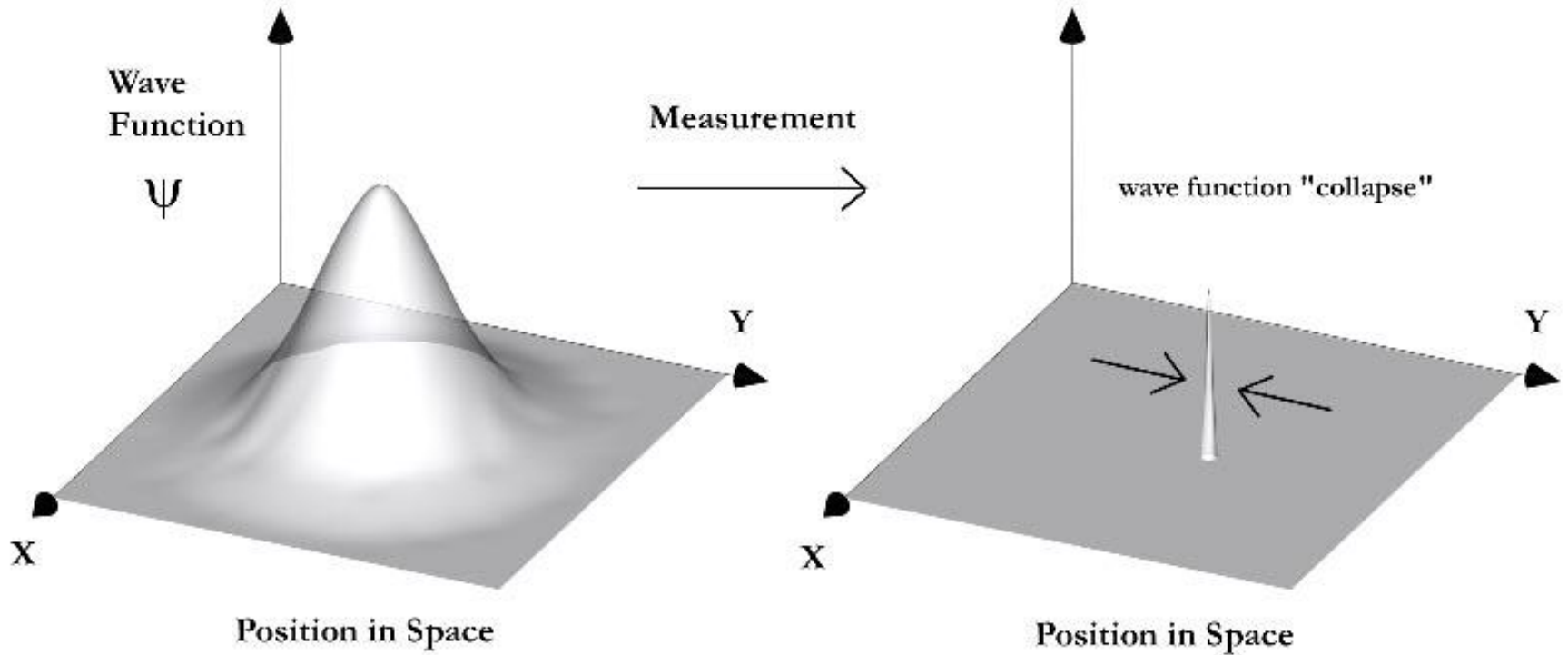
- A measurement causes a “collapse” (reduction) of the wave function: only one eigenvalue is possible after the measurement, the one that is measured
- A measurement introduces irreversibility in nature: collapse cannot be undone



The Measurement Problem

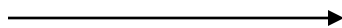
- The collapse of the wave:

The Copenhagen Interpretation:



The Measurement Problem

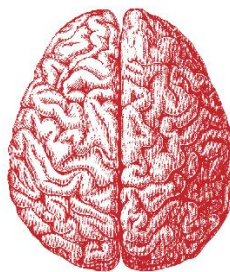
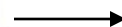
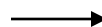
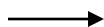
- John von Neumann (1932)
 - The flow of time is mysteriously altered by measurements
 - The classical world emerges from the quantum world thanks to measurement
 - A continuous process of the probabilistic kind gives rise to a discontinuous process of the deterministic kind



The Measurement Problem



- John von Neumann
 - Measurement of a system consists in a chain of interactions between the instrument and the system, whereby the states of the instrument become dependent on the states of the system
 - Eventually, states of the observer's consciousness are made dependent on states of the system, and the observer "knows" what the value of the observable is
 - Somewhere between the system and the observer's consciousness the "collapse" occurs



The Measurement Problem



- The objects to be observed are treated as quantum objects (or waves), while the objects that observe (the instruments) are classical objects, with no wave
- Large objects are granted an immunity from quantum laws that is based only on their size
- What attributes must an object possess to collapse a wave?

The Measurement Problem



- Is it something that only humans have?
- If not, what is the smallest object that can collapse a wave?
- What is the measuring apparatus in quantum physics?
- How does nature know which of the two systems is the measurement system and which one is the measured system?
- A privilege of the human mind?

Quantum Theory: Enter Entanglement

- **Albert Einstein (1935)**
 - **Paradox: once entangled, the states of two particles would be entangled forever, no matter how far from each other (EPR paper: 5 citations in 20 years, more than 300 in 2014)**
- **Schroedinger (1935)**
 - **Entanglement is the most fundamental feature of Quantum Mechanics**
- **John Bell (1964)**
 - **Yep, that's the way it is!**



Quantum Theory: Enter Entanglement

- **A brief history of teleportation**
 - **Impossible according to Heisenberg's uncertainty principle (the very act of measuring its state destroys it so it is impossible to make an exact replica)**
 - **William Wootters: Entanglement offers a way around it (1993)**
 - **("Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels", 1993). In 1998 the team led by US physicist Jeff Kimble teleports a photon for about one meter (1993)**
 - **Nicolas Gisin teleports a photon to 2 kms (2003)**
 - **Anton Zeilinger teleports a photon to 143 kms (2012)**

The Quest for Certainty

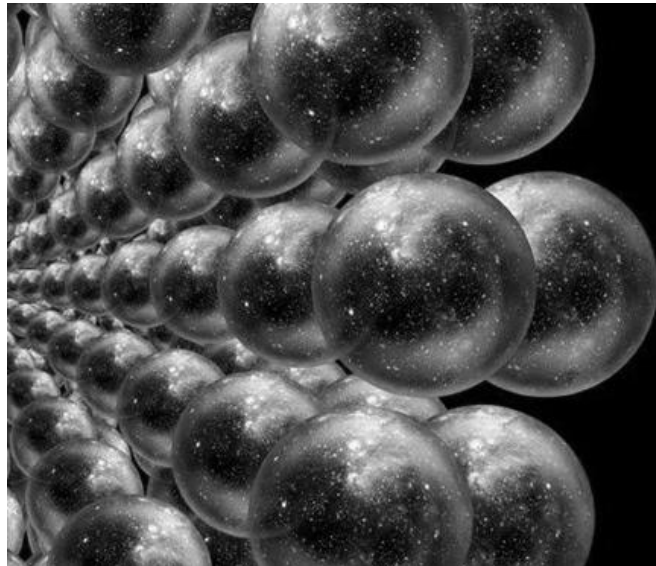


- Richard Feynman (1948)
 - All possible states allowed by a wave function exist at any moment
 - The state that is revealed by measurement is merely the state which represents the “path of least action” for the particle relative to the observer
 - An observation is an interaction between the observer and the observed system

The Quest for Certainty



- Hugh Everett's “multi-verse” (1957)
 - If something physically can happen, it does: in some universe
 - Each measurement splits the universe in many universes



The Quest for Certainty



- Hugh Everett's “multi-verse” (1957)
 - We exist in one copy for each universe and observe all possible outcomes of a situation
 - No collapse of the wave function
 - The universe can unfold in an infinite number of ways
 - Quantum theory becomes deterministic
 - The role of the observer is vastly reduced

The Quest for Certainty

Michael Lockwood (1986)

- Each measurement splits the observer, not the universe



The Quest for Certainty



- David Bohm (1952)
 - The quantum "wave" is a real wave, due to a real field, that acts upon particles the same way a classical potential does
 - This field is due to a potential that permeates the universe
 - Position and momentum of a particle are no longer incompatible
 - Bohm's wave is a real wave that guides the particle (the "pilot-wave")
 - Everything is both a particle and a wave, and is acted upon by both a classical potential and a quantum potential

The Quest for Certainty



- David Bohm (1952)
 - Bohm's potential plays the role of Einstein's "hidden variables"
 - Bohm's quantum potential acts beyond the 4-dimensional geometry of spacetime
 - The quantum field is, in turn, affected by all particles
 - Everything in the universe is entangled in everything else
 - The universe is one indivisible whole

The Quest for Certainty

- Eugene Wigner (1963) following Von Neumann:
 - Reality is just the content of consciousness
 - The evolution of the universe changed after the appearance of human beings (there was no collapse anywhere before mind appeared)



The Quest for Certainty

- Transactional Interpretation
 - Heisenberg: *"The probability wave... was a quantitative version of the old concept of "potentia" in Aristotelian philosophy. It introduced something standing in the middle between the idea of an event and the actual event"*

The Quest for Certainty

- Transactional Interpretation
 - John Wheeler and Richard Feynman (1945)
 - Maxwell's equations of electromagnetism have two possible solutions: a retarded solution and an advanced one
 - A charged particle generates both waves that will arrive after the emission as well as other, perfectly symmetrical, waves that will arrive before the emission.
 - A radiation process is a "transaction" in which the emitter of the radiation and the absorber of the radiation exchange waves

The Quest for Certainty



- Transactional Interpretation
 - John Cramer (1980)
 - The transactional interpretation derives the Born Rule
 - The measurement process corresponds with the moment when "all confirmation waves are returned to the emitter from all absorbers capable of responding"
 - Any quantum event is a "handshake" executed through an exchange of advanced and retarded waves between a present emitter and a future absorber
 - The future is affecting the past

The Quest for Certainty



- Transactional Interpretation
 - Ruth Kastner (2014)
 - The retarded and the advanced waves as being both "real"
 - David Lewis: all possible worlds are as real as the actual world
 - Possibilities exist, although not in spacetime.
 - "Physical" and "actual" are not the same thing: "actual" is a physical entity that is also experienced, but there are physical entities that are never experienced, and therefore never "actual"

The Quest for Certainty

- Wojciech Zurek (1984)
 - The progressive evolution of a system from quantum to classical behavior (the progressive emergence of reality from probability)
 - The environment destroys quantum coherence
 - Decoherence causes selection (or "einselection") of which possibilities will become reality
 - The classical state that results from a quantum state is the one that best "fits" the environment
 - Einselection: a Darwinian process



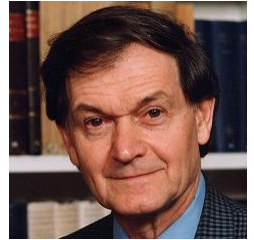
The Quest for Certainty



- James Anglin (1997)
 - The evolution of "open quantum systems" far from equilibrium
 - Similarities between the emergence of classical systems from quantum systems and the emergence of living systems from non-living systems

The Quest for Certainty

- Roger Penrose (1989)
 - Frigyes Karolyhazy (1966): Quantum mechanics of macroscopic bodies
 - Gravity (spacetime curvature) can cause a system's wave function to collapse ("objective" reduction)
 - Self-collapse occurs to everything, but the mass of the system determines how quickly it occurs



The Quest for Certainty

- John Wheeler (1994)
 - Ours is a "participatory" universe, one in which consciousness participates in creating reality
 - The observer and the phenomenon are engaged in a creative act that yields reality

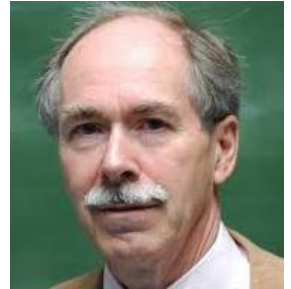


The Quest for Certainty



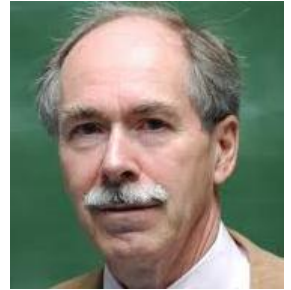
- Alwyn Scott (1995) via Einstein
 - Quantum Theory is an incomplete description of the universe because of some “hidden variable” (approximation to a not yet discovered nonlinear theory)

The Quest for Certainty



- Gerard's Hooft (1995)
 - Quantum Physics is Classical Physics after an information loss (“hidden variables”)
 - Classical variables can take any value, quantum variables can take only some values
 - A classical system gives rise to a quantum system when it loses information

The Quest for Certainty



- Gerard's Hooft (1995)
 - Different starting conditions can lead to the same results because of dissipative forces
 - If you throw two pennies from the top of a skyscraper at different speeds, air friction will cause them to reach the ground at the same speed
 - The observer will conclude that nature only allows some discrete values for the speed of the coins
 - Nature is classical at its most fundamental level, but quantum at the level of the laboratory because of “dissipation”

The Quest for Certainty



- David Deutsch (1997)
 - There is no such thing as the "flow of time".
 - Each "moment" is a universe of the manyverse.
 - Each moment exists forever, it does not flow from a previous moment to a following one.
 - We exist in multiple versions, in universes called "moments".
 - Each version of us is indirectly aware of the others because the various universes are linked together by the same physical laws

The Quest for Certainty

- Christopher Fuchs (2002)
 - The wave function describes the state of the observer, not of the system.



The Quest for Certainty

- Relativity, Quantum Physics and Thermodynamics: three disciplines that happen to pose limitations on the speed, amount and quality of information that can be transmitted in a physical process.

The Power of Constants

c

h

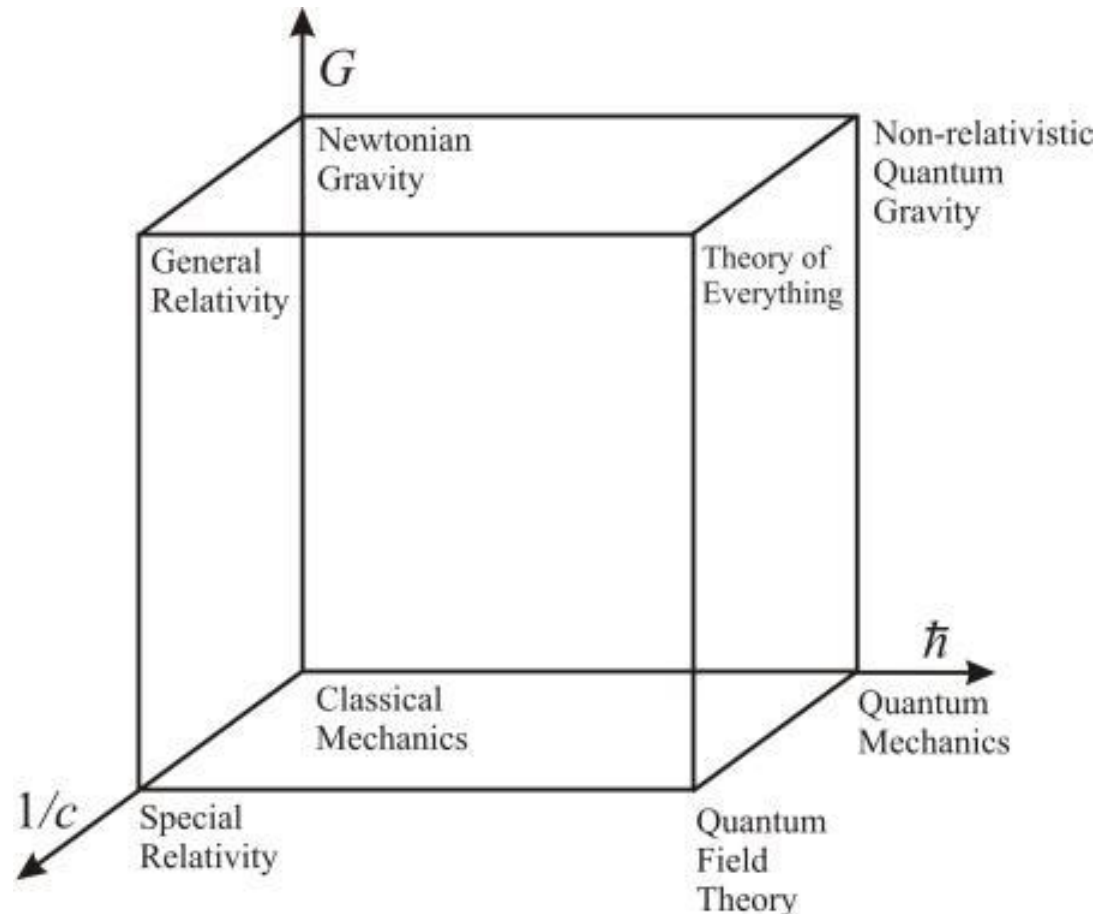
G

The Power of Constants

- Quantum Mechanics was a direct consequence of Planck's constant “ h ”: were that constant zero, there would be no uncertainty
- Relativity Theory was a direct consequence of the speed of light “ c ” being constant in all frames of reference
- The speed of light converts time into space (and vice versa)
- The Planck constant converts waves into particles (and vice versa) because it converts frequency into energy
- The gravitational constant “ G ” converts energy-momentum density into spacetime curvature

The Power of Constants

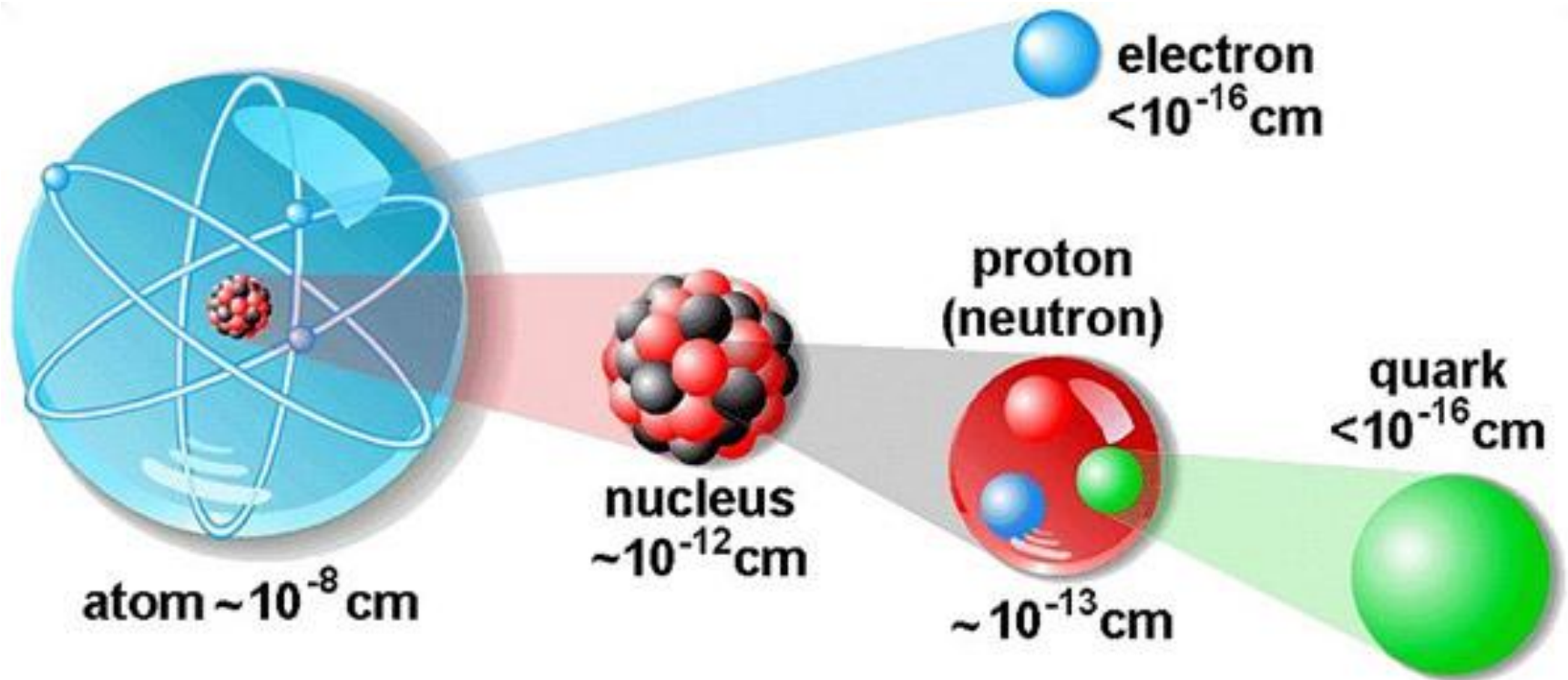
- These constants (“ h ”, “ c ” and “ G ”) are as much metaphysical as they are physical



Summary

- Relativity theory is not only about reality being "relative".
- It is about reality being beyond the reach of our senses.
- Newton: we see the universe as it is.
- Einstein: we don't always see the universe as it is.
- Newton's physics: a description of how mind perceives the universe.
- Einstein's physics: a "guess" about what the universe really is.
- Quantum theory is not only about reality being "quanta".
- It is about reality being beyond the reach of our cognitive capacity

The Physics of Elementary Particles



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The Physics of Elementary Particles

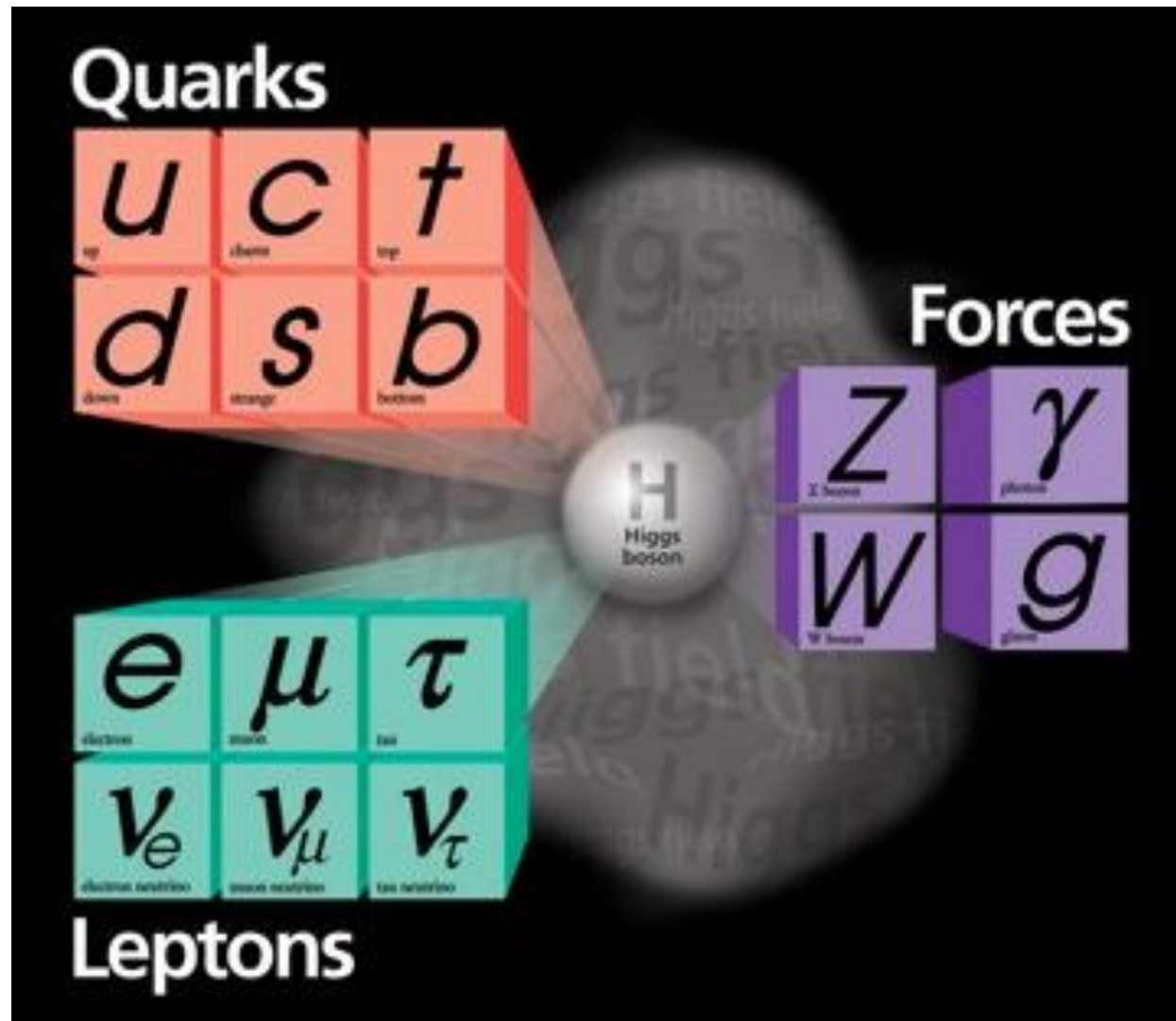
- Quantum Electrodynamics (Paul Dirac, 1928) and Quantum Chromodynamics (Murray Gellman, 1964)



The Physics of Elementary Particles

- Forces are mediated by discrete packets of energy (quanta: photon, $w^-/w^+/z$, graviton, gluons)
- Particles that make up matter belong to two families of fermions: leptons and quarks
- The world is made of six leptons, six times three quarks, four bosons for leptons and eight gluons for quarks (48 fermions and 12 bosons)
- The whole set of equations for these particles has 19 arbitrary constants

The Physics of Elementary Particles

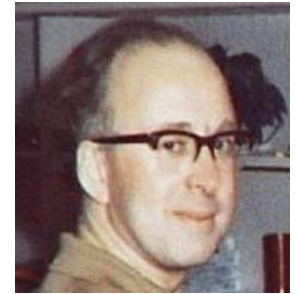


The Physics of Elementary Particles

INTERACTION	MEDIATOR	STRENGTH (gravity=1)	BEHAVIOR	RANGE (meters)	EFFECT	PARTICLES AFFECTED
Strong	Gluons (8)	10^{38}	$A/r-k_r$	10^{-15}	Creates nuclei	Quarks (36)
Electromagnetic	Photon (1)	10^{36}	$1/r^2$	Infinite	Creates atoms	Quarks (36) + Charged leptons (6)
Weak	W/Z Bosons (3)	10^{32}	$\text{Exp} (-m_w, z^r)/r$	10^{-18}	Transforms particles	Left-handed quarks (36) Left-handed leptons(12)
Gravitation	?	1	$1/r^2$ (in flat space)	Infinite	Moves masses	Quarks (36) + Massive leptons (6)

Unification: In Search of Symmetry

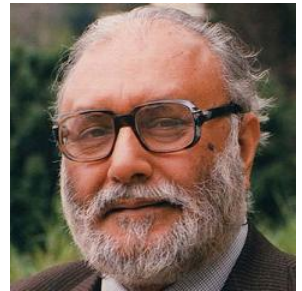
- Peter Higgs (1964)
 - The top quark is about 100,000 times “heavier” than the electron, and more than one trillion times heavier than the electron-neutrino
 - Mass measures the interaction with the all-pervasive Higgs field, mediated by the Higgs boson



	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	
				Higgs boson	

Unification: In Search of Symmetry

- Steven Weinberg and Abdus Salam (1967)
 - Each force exhibits a different form of symmetry
 - The fundamental forces exhibit striking similarities when their bosons are massless
 - Unification of the weak and the electromagnetic forces into one flavor force



Grand Unification

- The universe of Relativity is curved and continuous
- The universe of Quantum Theory is flat and granular
- Relativity prescribes that matter warps the continuum of spacetime, which in turns affects the motion of matter
- Quantum Theory prescribes that matter interacts via quanta of energy in a flat spacetime
- Quantum Theory does not explain gravity

Grand Unification

- Theodor Kaluza (1919)
 - Gravitation is due to the geometry of a four-dimensional space-time.
 - Electromagnetism is due to the geometry of a five-dimensional space-time.
 - A theory of gravitation in five dimensions yields both a theory of gravitation and a theory of electromagnetism in four dimensions
 - Light's privileged status comes from the fact that light is a curling of the fourth spatial dimension



Grand Unification



- Oskar Klein (1926): the fifth dimension is curled up in a loop the size of the Planck length
- The Kaluza-Klein theory
 - The physical world as we know it, and in particular its fundamental forces, originate from the geometry of hidden dimensions.
 - The fundamental forces appear to be “forces” only in a four-dimensional subset of the universe. They are actually just geometry.

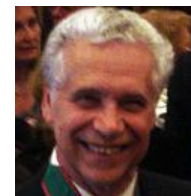
Grand Unification

- Bryce DeWitt
 - When the fifth and higher dimensions are curled up, the Kaluza theory yields the Yang-Mills fields required by Quantum Mechanics



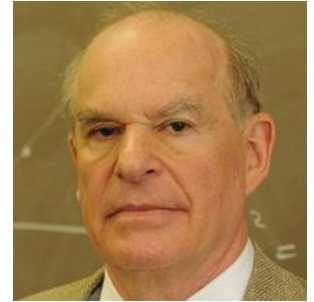
Superstring Theory

- Gabriel Veneziano (1968)
- Yoichiro Nambu (1970)
- John Schwarz (1974)
 - Particles are one-dimensional entities (or “strings”)
 - Particles are resonances (or modes of vibrations) of tiny strings
 - Each vibrational mode has a fixed energy, which means a mass, charge and so forth. Thus the illusion of a particle.
 - Matter is made of vibrating strings and each particle is due to a particular mode of vibration of the string



Superstring Theory

- John Schwarz (1974)
 - Space-time must have ten (or 26) dimensions
 - Six of them are curved in minuscule tubes that are negligible for most uses.
 - Elementary particles are compactified hyper-dimensional space

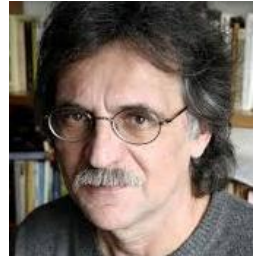


Superstring Theory

- David Gross (1985)
 - The heterotic string
 - Matter-energy arises from fluctuations in the geometry of space-time (Einstein's dream)
 - Particles emerge from geometry, just like gravity and the other forces of nature



Superstring Theory



- Peter Freund (1985)
 - The laws of nature become simpler in higher dimensions
 - The perceptual system of humans can only grasp three dimensions, but at that level the world looks terribly complicated
 - The moment we move to a fourth dimension, we can unify phenomena that looked very different (e.g. Mechanics and Electromagnetism).
 - As we keep moving up to higher and higher dimensions, we can unify more and more theories (e.g., Electromagnetism and the Weak and Strong nuclear forces)

Superstring Theory

- Edward Witten (1995)
 - The M-theory is the theory of all possible superstring theories
 - The M-theory is an eleven-dimensional theory of ten-dimensional theories.
 - A staggering 1 to the 500th power different kinds of universe are technically possible, each with its own laws of nature



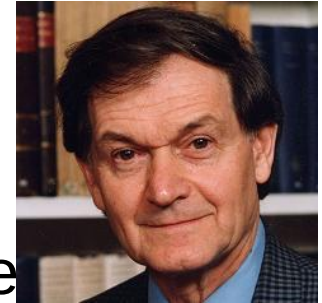
Branes

- Joseph Polchinski and Petr Horava (1989)
 - D-branes are mathematical objects that resemble membranes in a five-dimensional spacetime
 - Our universe is a D-brane extending over the three familiar spatial dimensions
 - The objects of our world are stuck to this D-brane like bugs on flypaper
 - Hence the illusion of three dimensions.



Grand Unification

- Roger Penrose
 - Quantum Gravity will explain the oddities of Quantum Mechanics, unify Quantum and Relativity Physics and explain consciousness



Superconductivity

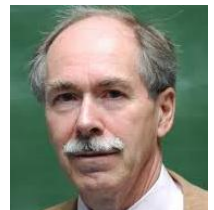
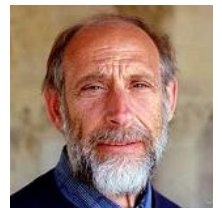
- 1911: Heike Kamerlingh Onnes discovers superconductivity (certain materials cooled to almost absolute zero exhibit no electrical resistance)
- 1925: Albert Einstein and Satyendranath Bose discover that bosons at extremely low temperatures can form a fluid that displays the bizarre properties of Quantum Mechanics at a macroscopic level
- 1957: John Bardeen et al discover that superconductors condense in a way similar to Bose-Einstein condensates

Superconductivity

- 1986: Karl Müller and Johannes Bednorz achieve the first high-temperature superconductor
- 2011: Subir Sachdev explains that near a “quantum-critical point” the process of entanglement creates entire populations of entangled electrons that can no longer be studied as independent particles.

Black Holes and Entropy

- Jakob Bekenstein (1972): Black holes store a huge amount of entropy
- Stephen Hawking (1974): The area of the event horizon can never decrease
- The entropy of a black hole is proportional to the area of its event horizon.
- Hawking (1974): Black holes evaporate
- Leonard Susskind and Gerard 't Hooft (1993): A black hole is a hologram: information about what has been lost inside the black hole is encoded on the surface of the black hole



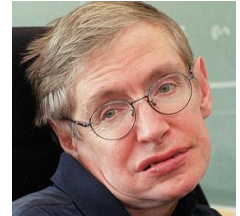
Black Holes and Wormholes

- Karl Schwarzschild (1916): The "black hole"
- Einstein: Black holes imply the existence of a "bridge" between our universe and a mirror universe which is hidden inside the black hole, and in which time runs backwards
- Kurt Goedel (1949): Space-time can curve to the point that a particle will return to a previous point in time; I.e., "wormholes" can connect two different points in time of the same universe
- John Wheeler (1950s): Two points in space can be connected through several different routes, because of the existence of spatial wormholes



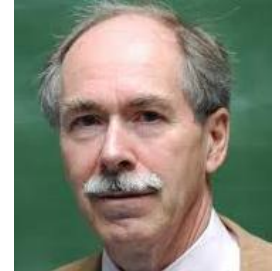
Black Holes and Wormholes

- Stephen Hawking (1988): Wormholes can connect different universes altogether
- Lee Smolin (1992): Black holes are the birthplaces of offspring universes
- Kip Thorne (1994): A time machine capable of exploiting such time wormholes
- Andrew Strominger (1996): Black holes decay into strings and strings decay into black holes



The Holographic Universe

- Gerard't Hooft (1993)
 - The horizon of a black hole (a two dimensional surface) stores all the information that ever fell into the hole
 - Generalizing: the informational content of a region of space can always be equivalently expressed by a theory that lives on the boundary of that region
 - The three-dimensional universe which we perceive might be encoded on a two-dimensional surface, like a hologram.

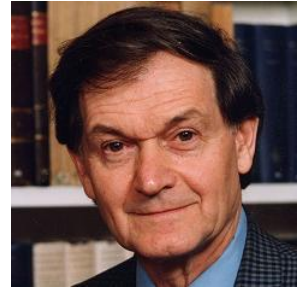


The Holographic Universe

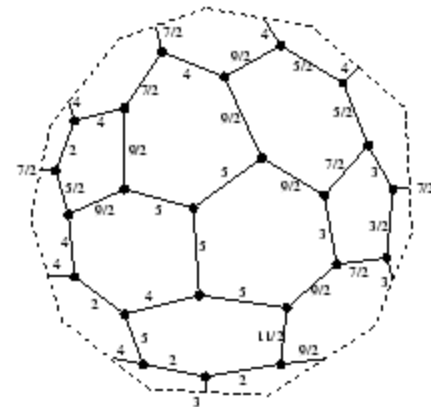
- Juan Maldacena (1997)
 - A universe described by superstring theory can be described as functioning in an anti-DeSitter spacetime (a negatively curved spacetime) with a quantum field theory operating on the boundary of that spacetime. And viceversa.



Loop Quantum Gravity



- Roger Penrose (1971)
 - A "spin network" is a graph whose edges are labeled by integers, corresponding to the possible values of the angular momentum.
 - Spin networks are the simplest geometric structures to describe space
 - Space and time are not primitive entities but are themselves constructed out of something more primitive
 - Space and time can fluctuate



Loop Quantum Gravity



- Jakob Bekenstein (1972)
 - Every horizon separating an observer from her hidden region has an entropy proportional to the information that is hidden or trapped in the hidden region (the missing information)
 - The entropy of the radiation that the accelerated observer experiences is proportional to the area of her horizon.
- Kenneth Wilson (1974): Space must be a discrete lattice (the "loops")



Loop Quantum Gravity

- Bill Unruh (1976)
 - An accelerating observer must measure a temperature where an inertial observer observes none, the temperature being proportional to the acceleration
 - The "vacuum" depends on the state of motion of the observer: an accelerating observer will never observe any vacuum
 - Every accelerating observer has a hidden region (all the photons that cannot reach her because she keeps accelerating, getting closer and closer to the speed of light) and a horizon (the boundary of her hidden region).



Loop Quantum Gravity



- Lee Smolin and Carlo Rovelli (1988)
 - Unruh + Bekenstein = If energy comes in discrete units, then space must come in discrete units
 - Just like matter is made of elementary particles, space itself must be made of elementary units

Loop Quantum Gravity

- Amitaba Sen (1982) : Time and space can be split into two distinct entities subject to quantum uncertainty (analogous to momentum and position)
- Abhay Ashtekar (1986): The solutions of Einstein's equations are quantum states that resemble loops "loop-space model"
- Lee Smolin
 - Sen + Ashtekar = A theory of loops and how they interact and combine
 - Einstein's theory of gravitation (General Relativity) becomes similar to Maxwell's theory of electromagnetism, with loops playing the role of field lines.



Loop Quantum Gravity

- Loop-states are best represented by Penrose's spin networks
- Each vertex of a spin network creates the volume of a region of space.
- The structure of spin networks generates space.
- The space that we experience is continuous.
- A spin network "creates" geometry.
- An evolving spin network is a discrete version of Einstein's spacetime
- The Big Bang turns out to be a “Big Bounce” from an imploding universe to an expanding universe



Loop Quantum Gravity

- Einstein's great intuition was that spacetime is not just a stage but an actor in the story of the universe
- Loop Quantum Gravity shows that spacetime is made of its own atoms just like matter is made of its own atoms.



Loop Quantum Gravity



- Fotini Markopoulou (1999)
 - Spin networks evolve in time in discrete steps
 - At every step, the change of each vertex of the spin network only depends on its immediate neighbors (a` la Von Neumann's cellular automata)

Loop Quantum Gravity

- The entropy of a black hole is finite
- Any volume of the universe behaves like a black hole for an observer in constant acceleration
- Thus the entropy of any portion of the universe must be finite
- Thus the amount of information contained in any volume of space, no matter how big, must be finite
- Thus a volume must be made of a finite number of points
- Thus space has an atomic structure

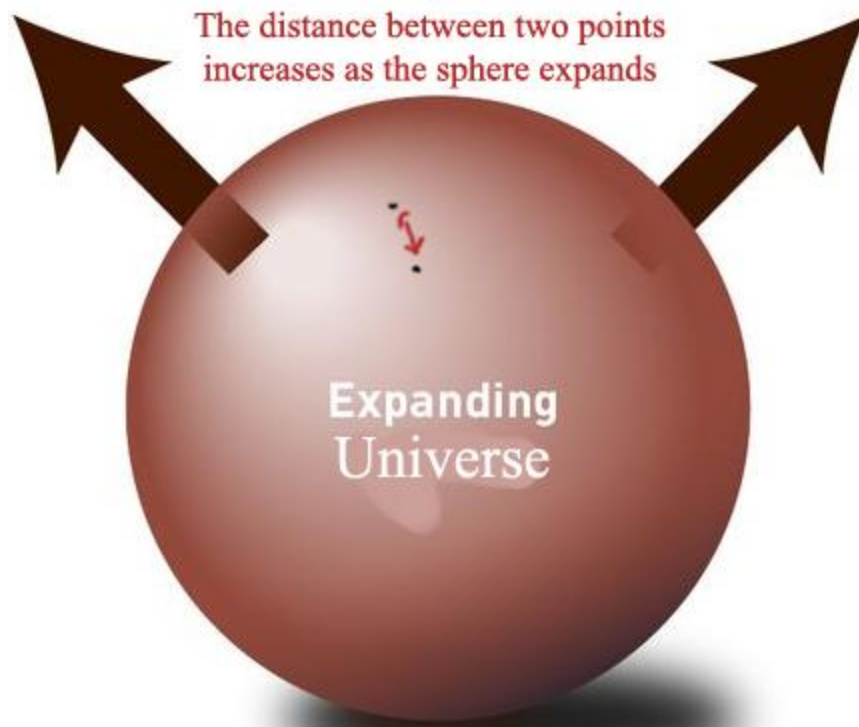
The Mathematical Universe



- Max Tegmark (1996)
 - There exists an external reality independent of human minds
 - This reality must be perceivable also by non-human minds.
 - There is only one kind of external reality that would be perceived identically by all kinds of minds: a mathematical structure
 - We are thinking equations within a complex system of equations

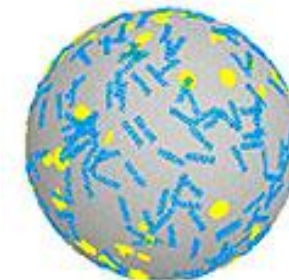
The History of the Universe

- Georges Lemaître (1927): Space-time has been expanding from an initial singularity
- Edwin Hubble (1929): The universe is expanding in all directions

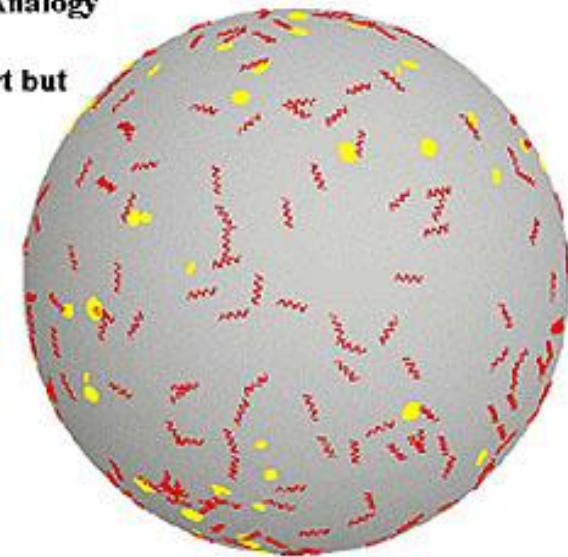


Expanding Balloon Analogy

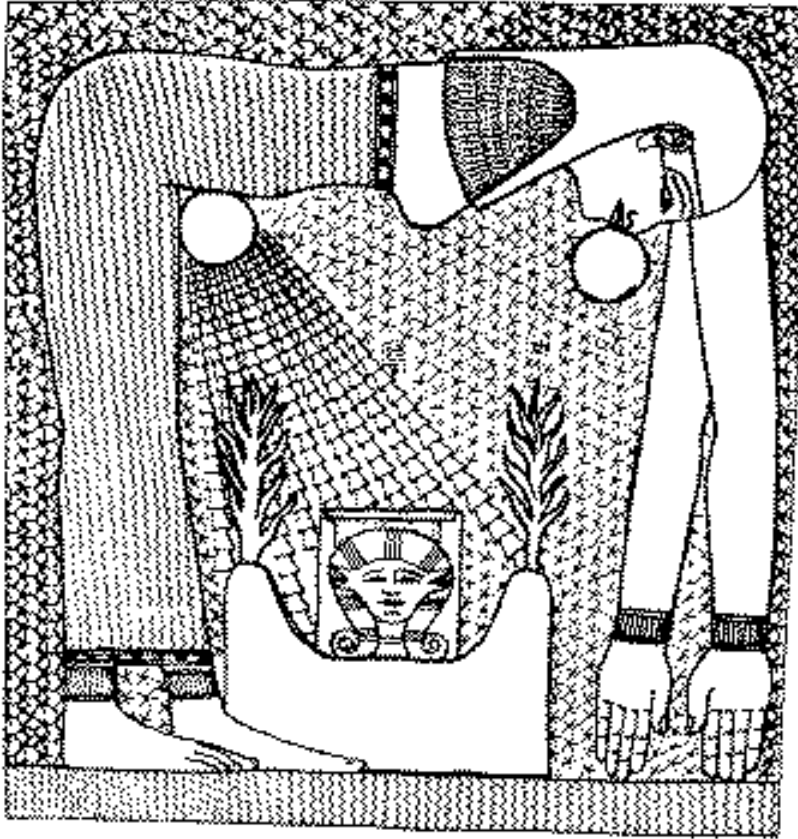
Galaxies spread apart but stay the same size



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The History of the Universe



The History of the Universe

- Quantum fluctuations in an infinitely small universe "created" the universe (space, time and matter) in a "big bang" (George Gamow, 1948)
- Spacetime started expanding (Alan Guth's "inflationary" model, 1981)
- John Wheeler
 - The universe oscillates back and forth between a big bang and a big crunch
 - Each new universe can have no memory of the old universe
- Andrei Linde's "chaotic inflationary" model (1980s)



The History of the Universe

- Tiny random quantum fluctuations in the first fraction of a second after the Big Bang created every structure that we observe in today's universe

6 parameter Λ CDM model

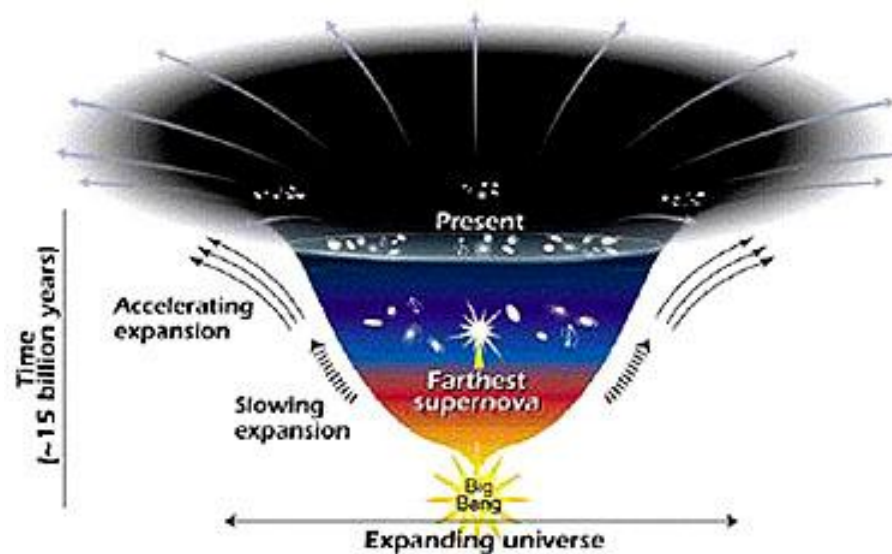
Parameter	Planck (CMB+lensing)	
	Best fit	68% limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067
τ	0.0949	0.089 ± 0.032
n_s	0.9675	0.9635 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057

(Lambda-CDM is the standard model of cosmology)

Six parameters are enough to represent the initial state of the universe in Year 380,000, when the universe stopped being opaque and became transparent (i.e. photons started traveling freely), and its future evolution

The History of the Universe

- The expansion is accelerating (Saul Perlmutter, 1998)



Status

Science cannot account for:

Dark matter (perhaps 23% of the mass-energy of the universe and five times as abundant as matter) does not interact with ordinary matter, does not emit and does not reflect light (its gravitational effect has been inferred by observing the motion of galaxies)

Dark energy (about 73% of the mass-energy of the universe) is needed in order to account for the acceleration of the expansion of the universe



Meditation

“A metaphysical interpretation and understanding of the world is neither scientifically attainable nor scientifically excluded. It is another mode of cognitive approach to the world, a transition from the (as much as possible) neutral observation of the world to a personal relationship with the world. It is a product of the freedom of humankind, and therefore interpretation and understanding define its entire stance towards the world , its mode of use of the world. Scientific observation does not simply affirm the reality of the cosmos; it constitutes it as an existential fact...,then every reality is recapitulated in the relationship of humanity with an active reason (logos) as an invitation to relationship, which is directed towards humanity alone.”

Christos Yannaras
(Postmodern Metaphysics, 2004)

Summary

- Thermodynamics introduces entropy
- Entropy is related to order and information
- Darwin's theory was really a theory of how to create order
- Complex systems create order (self-organize) in special cases
- Self-organizing systems defy the law of entropy
- Self-organizing systems only happen at the edge of chaos
- Oscillators too can self-organize, not in space but in time

Summary

- Electromagnetism introduces fields
- Relativity is based on the observer: even space and time are relative
- Quantum Mechanics is based on the observer: it is the act of measuring that creates reality
- There is a limit (uncertainty) to what we can know in Quantum Mechanics
- The result of a measurement is random
- Relativity and Quantum Physics contradict each other
- Physics is almost certainly incomplete (dark matter, dark energy)

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Modern Physics

"Time is the substance of which we are made"
(Borges)

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