More is different

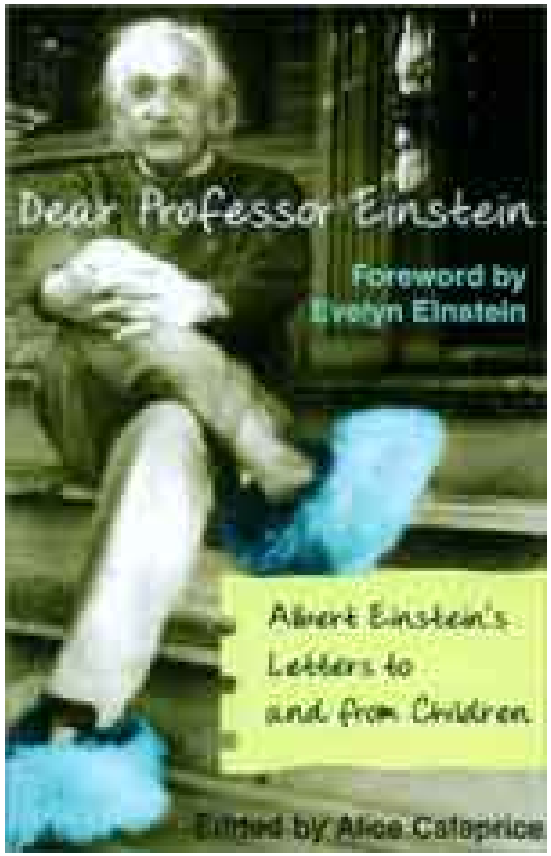
Science’s second frontier

1905: The miraculous year

March:	On a Heuristic Point of View concerning the Production and Transformation of Light. (*the photoelectric effect*)
May:	On the Movement of Small Particles Suspended in Stationary Liquids Required by the Molecular-Kinetic Theory of Heat. (*Brownian motion*)
June:	On the Electrodynamics of Moving Bodies. (*special relativity*)
September:	Does the Inertia of a Body Depend upon Its Energy Content? ($E = mc^2$)
December:	On the Theory of Brownian Motion. (*refined mathematical treatment*)

One day during his tenure as a professor, Albert Einstein was visited by a student. "The questions on this year's exam are the same as last year's!" the young man exclaimed.

"Yes," Einstein answered, "but this year all the answers are different."



Dear Professor,

. . . We are in sixth grade. In our class we are having an argument. The class took sides. We six are on one side and 21 on the other side. Our teacher is also on the other side so that makes 22. The argument is whether there would be living things on earth if the sun burnt out or if human beings would die. . . . We believe there would be living things on the earth if the sun burnt out. Will you tell us what you think. . . .

We would like you to join our Six Little Scientists, only now it would be Six Little Scientists and One Big Scientist. . . .

Love and lollipops,
Six Little Scientists
[1951]

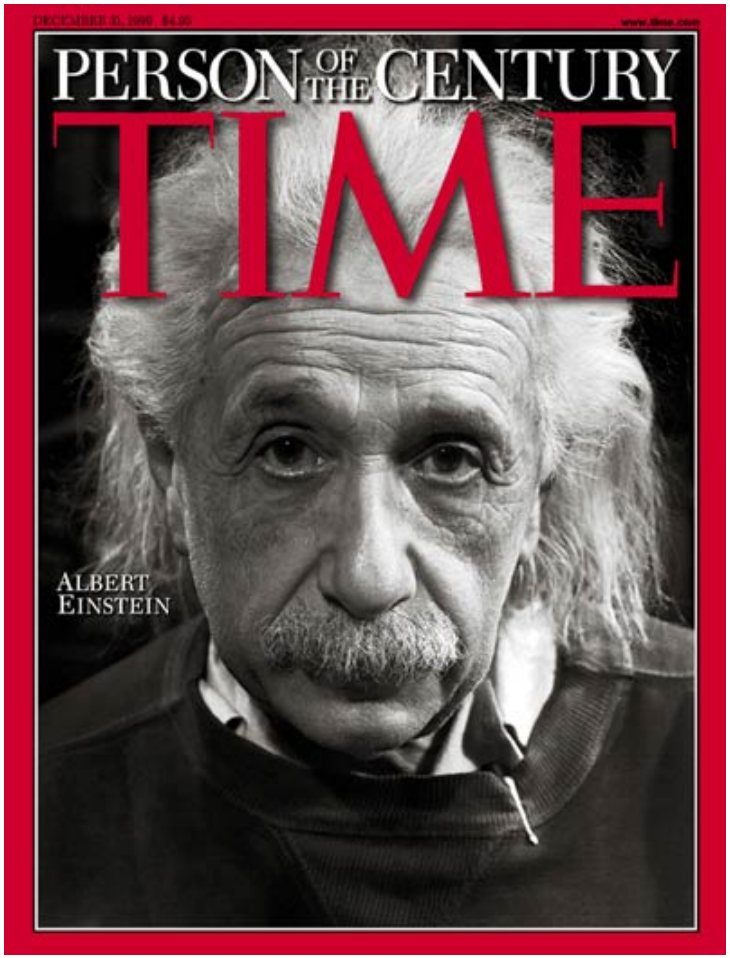
Dear Children:
The minority is sometimes right — but not in your case. Without sunlight there is :
no wheat, no bread,
no grass, no cattle, no meat, no milk, and everything would be frozen.
No LIFE.
A. Einstein
December 12, 1951

20th Century Physics:

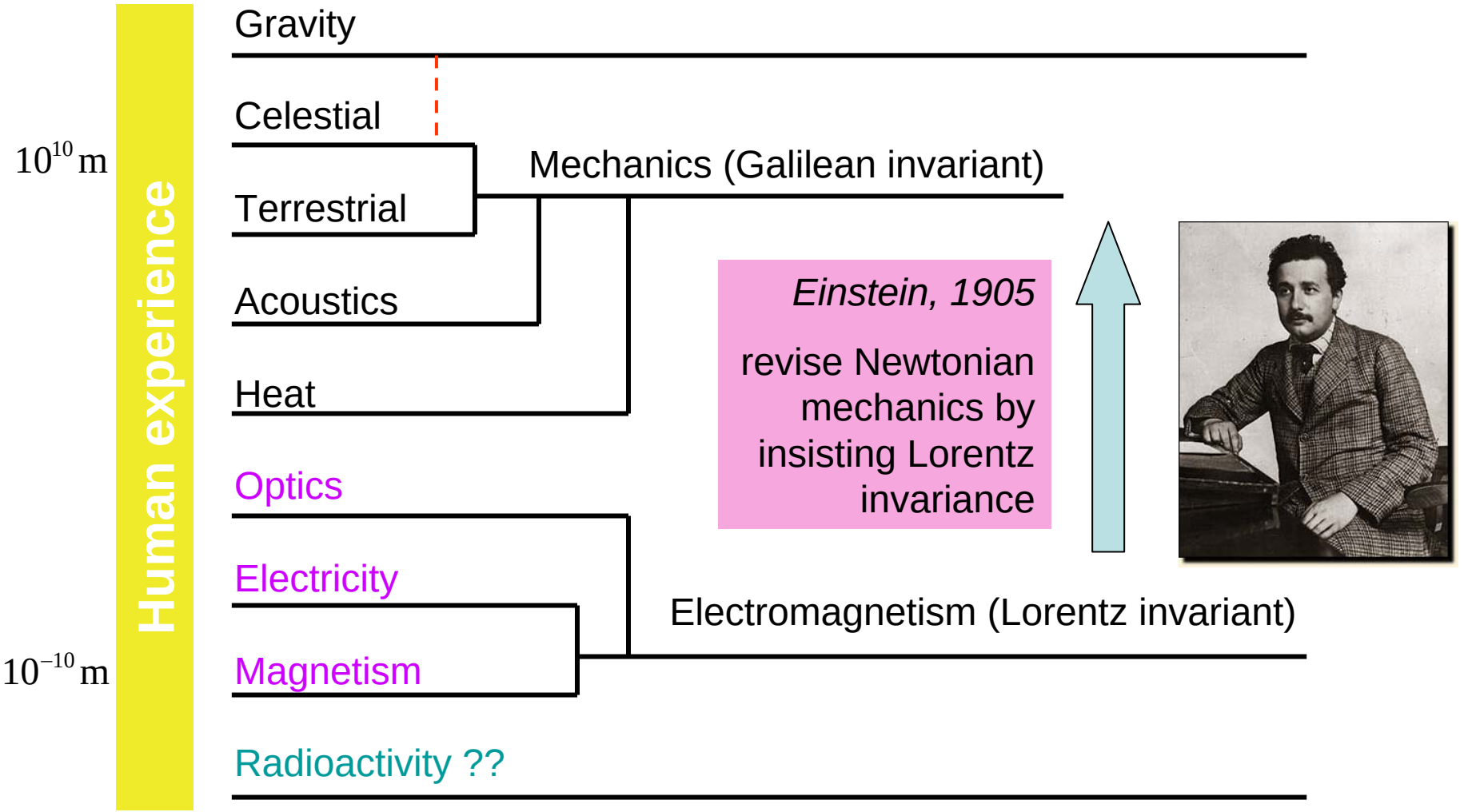
The story of symmetry with Einstein leading the way

21st Century Physics:

Science of organization?

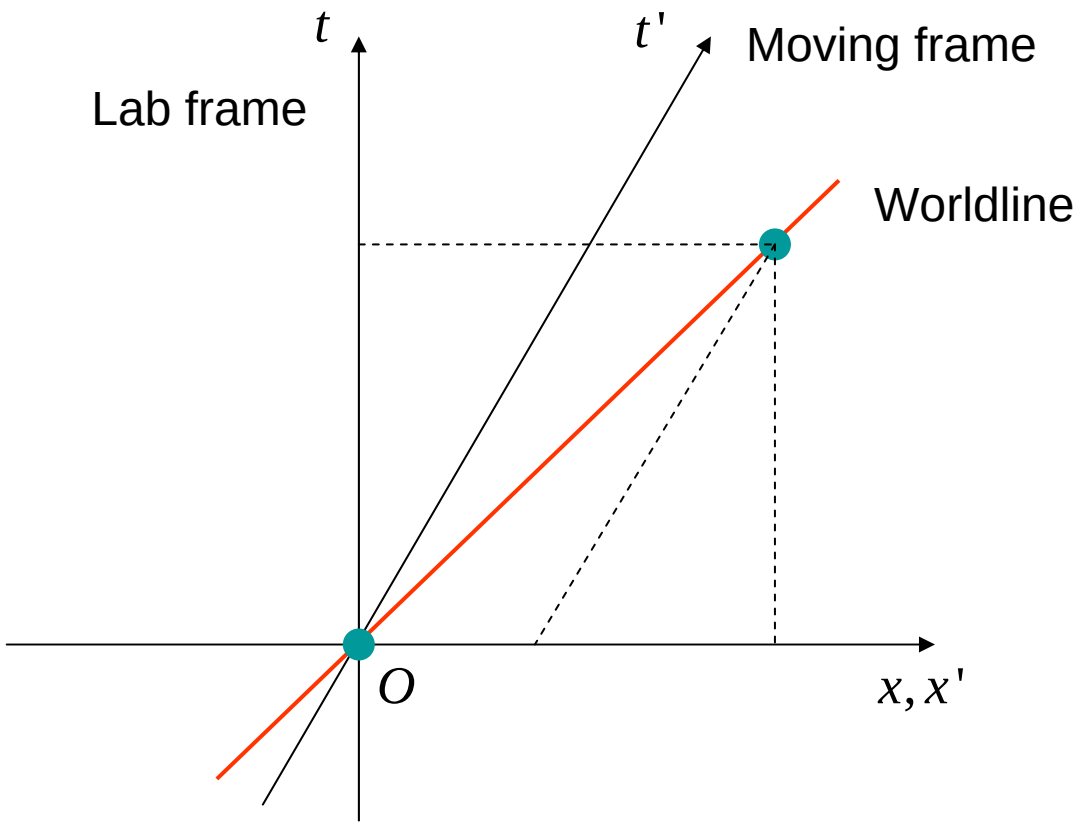


Physics at 1900



A. Zee, *Fearful Symmetry*, 1986

Galileo's spacetime

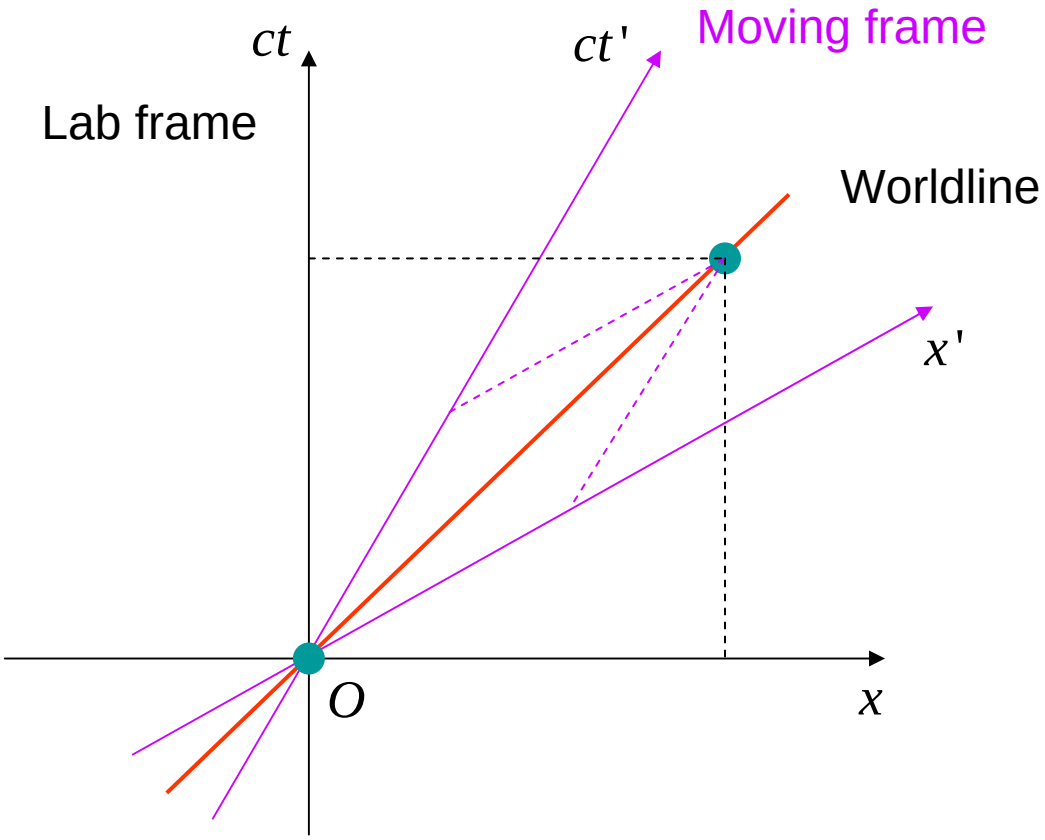


$$t' = t$$

$$x' = x - vt$$

Space and time asymmetry in the transformation

Einstein's spacetime

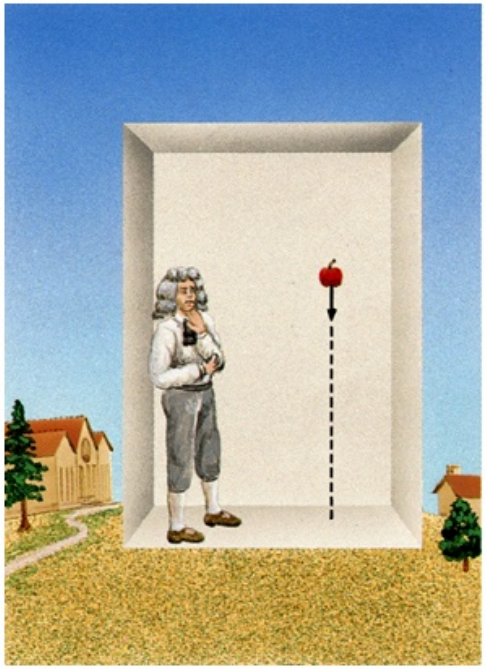


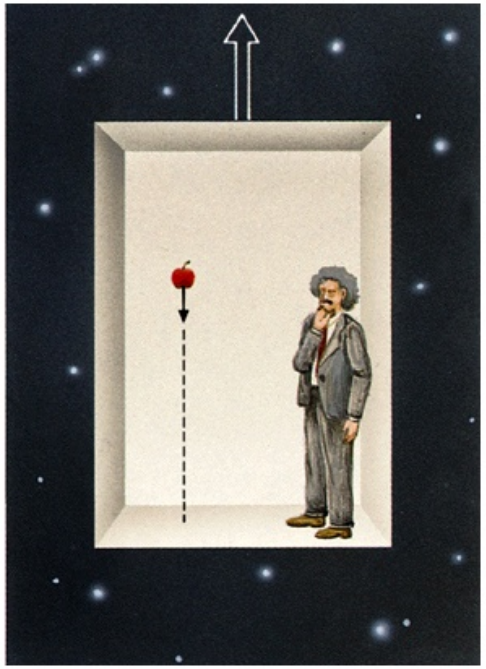
$$ct' = \gamma\left(ct - \frac{v}{c}x\right)$$

$$x' = \gamma\left(x - vt\right)$$

$$\gamma = 1/\sqrt{1 - v^2/c^2}$$

Equivalence principle





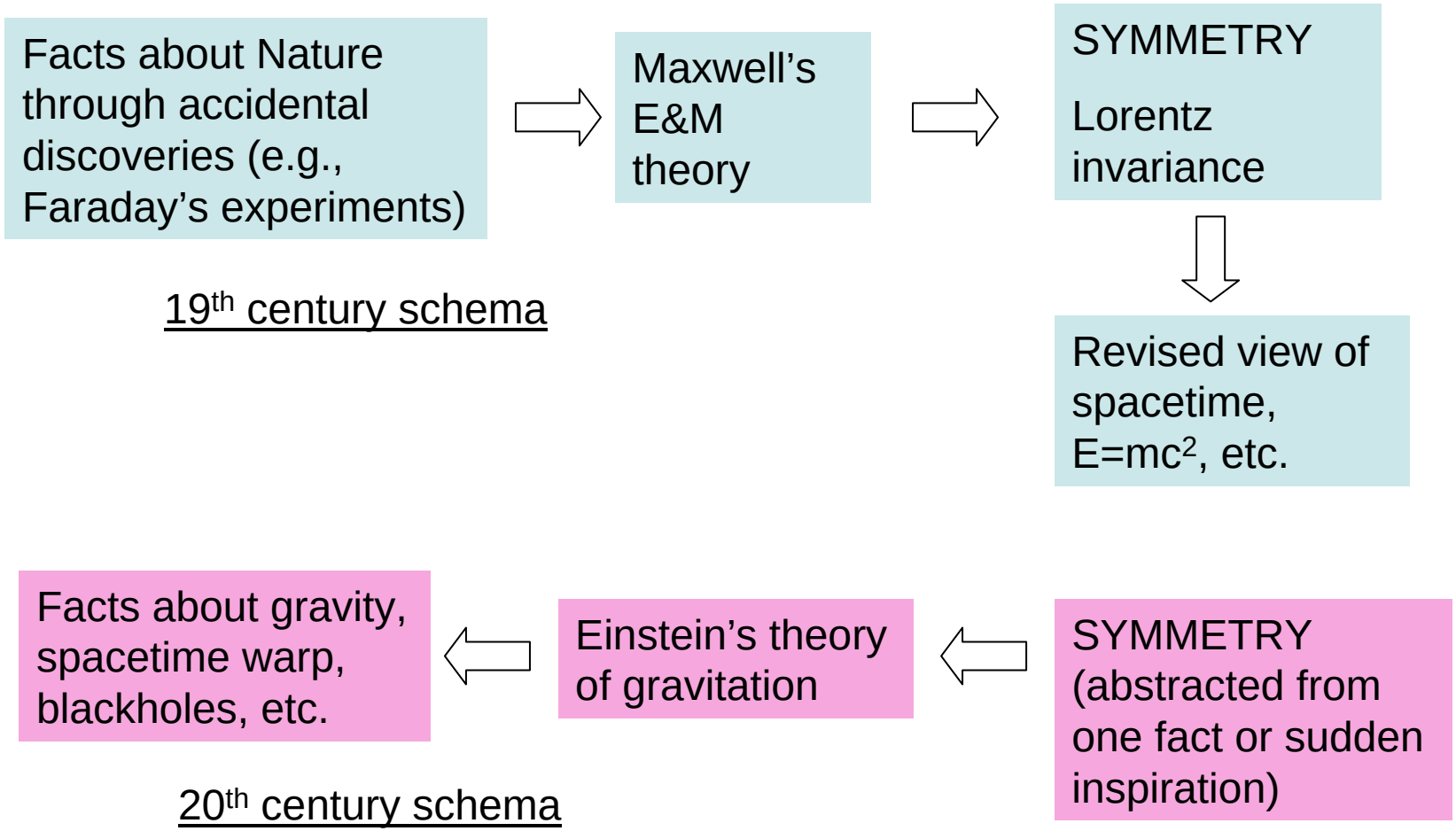
1907: While daydreaming in the patent office in Bern, Einstein had the *happiest thought of his life*: gravity can be accounted for by a space-time transformation!

1916: Published the mathematical theory of warped spacetime known as *General Theory of Relativity*

1919: Observation of bending of starlight by the solar gravitation field by Arthur Eddington brought Einstein to instant world fame.

Weightlessness is just an illusion, or is it not?

The new way of doing physics



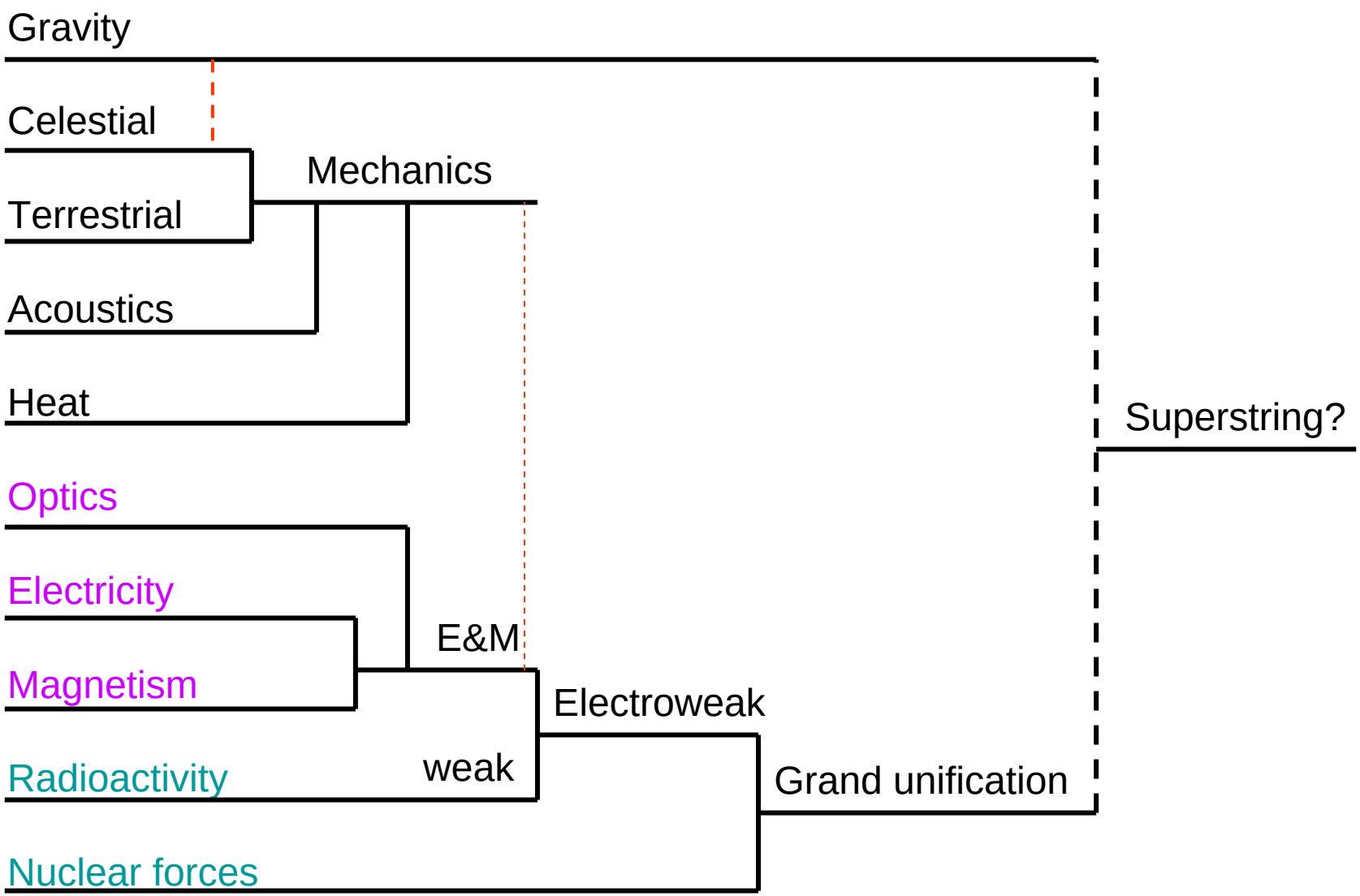
A. Zee, *Fearful Symmetry*, 1986

Lesson #1

Symmetry dictates design

Extremely successful in guiding the exploration of the sub-nuclear world, as re-accounted in A. Zee's book, *fearful symmetry: The search for beauty in modern physics*

Physics late in the 20th Century



A. Zee, *Fearful Symmetry*, 1986

"Millennium Madness"

Physics Problems for the Next Millennium

1) Size of dimensionless parameters

2) Origin of the Universe

3) Lifetime of the Proton

4) Is Nature Supersymmetric?

5) Why is there 3+1 Space-time dimensions?

6) Cosmological Constant problem

7) Is M-theory fundamental?

8) Black Hole Information Paradox

9) The weakness of gravity

10) Quark confinement and the strong force

David Gross, Nobel Prize in Physics, 2004

Some wonder whether some day we will arrive at a theory of everything, and run out of new problems to solve - much as the effort to explore the earth ran out of new continents to explore.

While this is conceivably possible, I am happy to report that there is no evidence that we are running out of our most important resource - ignorance.

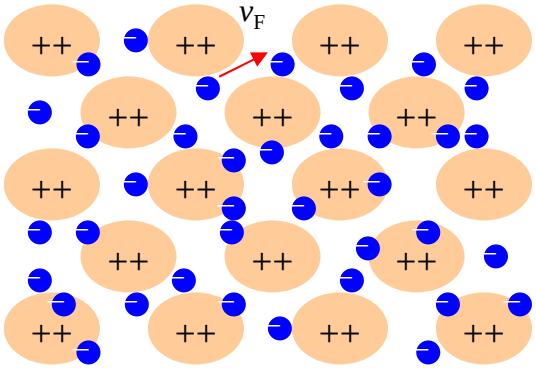
How lucky for science.
How lucky for scientists.
And, how lucky for the Nobel Foundation.

The frontier of science according to particle physicists:

Exploration of fundamental forces of Nature

$\Rightarrow$ *Theory of Everything*

In the backdrop, Solid State Physics was born

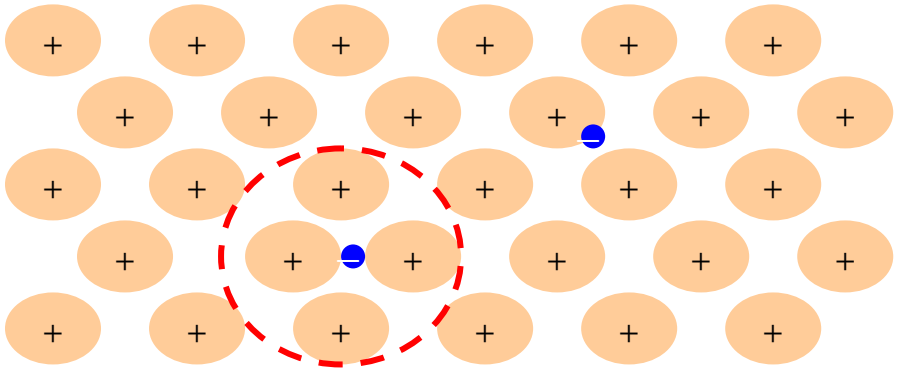


obey laws of quantum mechanics with E&M interactions

Bloch theorem $\Rightarrow$ band theory

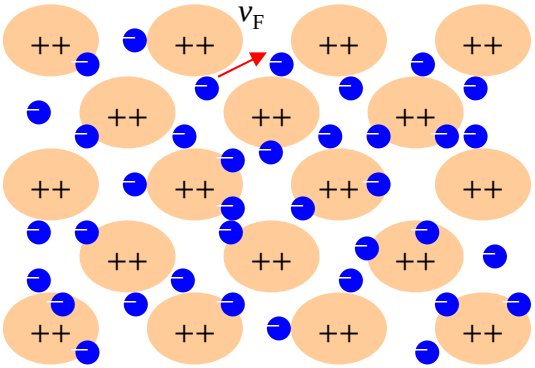
Provides underpinning of electrical conduction, light absorption and emission, structural and thermal properties of crystalline solids

Surprise at low temperatures



1. Pairing of electrons mediated by the lattice or other many-body effects
2. Condensation of paired electrons leads to a broken symmetry which, among other things, gives rise to the Meissner effect.

Emergent phenomena



Laws of quantum mechanics with E&M interactions

- Magnetism
- Charge density wave
- Superconductivity
- Mott insulator
- QHE
- Supersolid

Lesson #2

higher order organization
principles equally fundamental

Millennium Debate

— challenge to the reductionists' viewpoint by condensed matter physicists

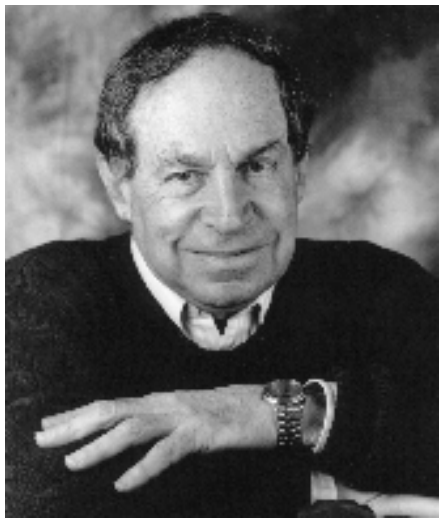
Q1: Knowing how electrons and nuclei interact, can we predict properties of a solid without invoking additional principles?

Q2: Is it possible that the theory discovered based on symmetry are themselves emergent organized behavior rather than being truly fundamental?

P.W. Anderson

More is different,

Science **177,** 393 (1972)



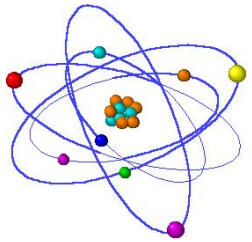
R. B. Laughlin and D. Pines

The Theory of Everything, PNAS **97**, 28 (2000)

The middle way, PNAS **97**, 32 (2000).

21st century physics: the mesoscopic frontier

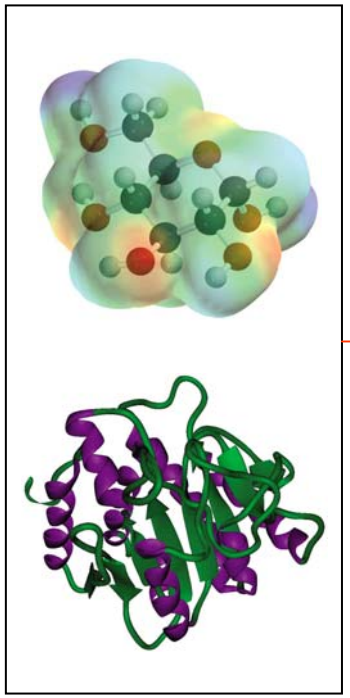
atom



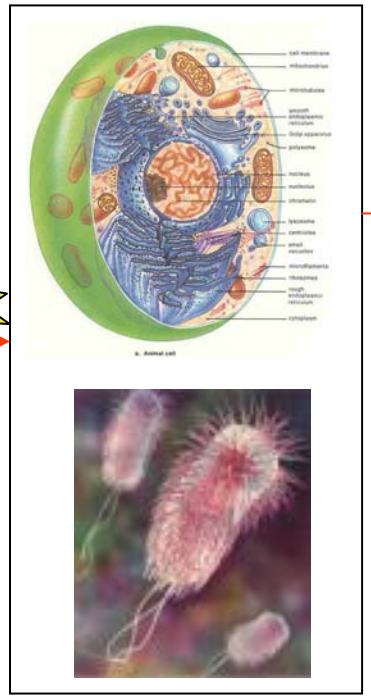
"homogeneous"

Simple matter: gas, liquid, solid

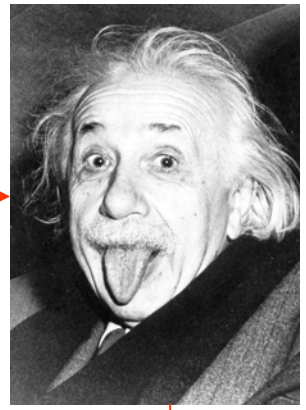
"organized"



Complex molecules



cell



people

society

Biotech revolution

Restriction enzymes (cut and paste)

PCR (copy machine)

Gel electrophoresis (read-out)

cDNA/oligonucleotide microarray (attendance check) (e.g., 6000 genes under over 1000 conditions)

Two-hybrid protein-protein interaction (who talks to who)

RNAi (circuit test)

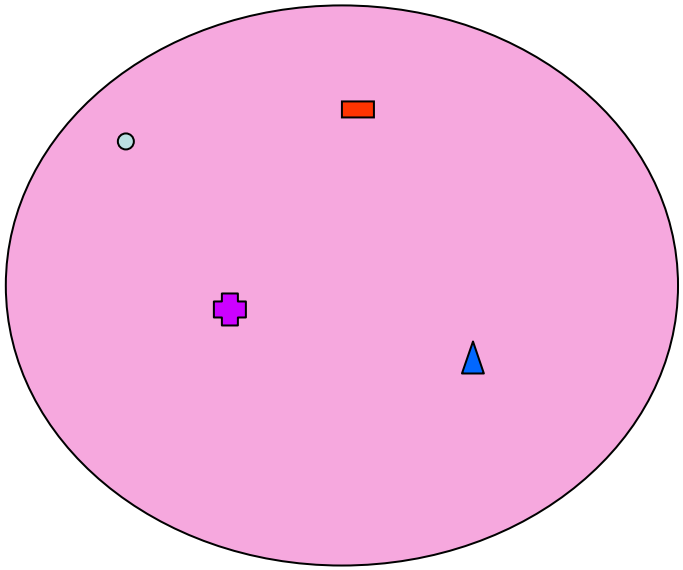
Bio-sensors (tracing individual players)

$\Rightarrow$***massive data on the genomic scale***

Too much information?

Erwin Schrödinger: What is life?

Cell = bag of molecules following laws of physics and chemistry



Molecule: 10^{-4}-10^{-3}μm

Cell: 1-10 μm

Question of scale: why are atoms so small?

Question of order: how is it maintained, inherited, and protected against deleterious mutations?

Life guarded against chance events

Randomness at the molecular scale

Solved by

law of large numbers

Orderly procession of cellular events

Life guarded against continuous drift of atomic motion

- Experiments on fruitfly: gene size < 300Å^3
- Classical mechanics: such a cluster of atoms will constantly change its structure
- Quantum mechanics: by forming macromolecules, stability of the *aperiodic crystal* is assured through chemical bonding

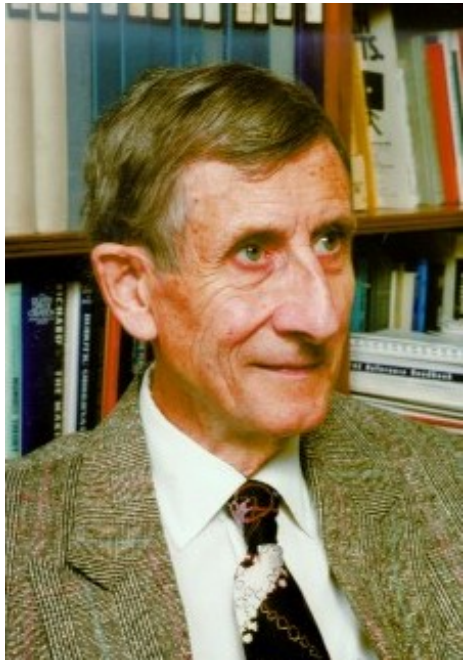
Life guarded against the 2nd law of thermodynamics

- Living organisms are nonequilibrium systems supported by a constant flow of material and energy (metabolism)
- Order maintained through importing *negative entropy* from the environment

Q: Life is possible (for a physicist), but why does it have to be so complicated?

A: May be it started simple…

Freeman Dyson: Origins of life



Life as we know it

1) Metabolism (inter-conversion and recycling of chemical compounds catalyzed by proteins)
2) Replication (duplication of the genetic blueprint)

Reductionist again: Do they need to be there simultaneously?

von Neumann came to rescue

Autonomous machines

1) Metabolism: hardware, information processor
2) Replication: software, information carrier

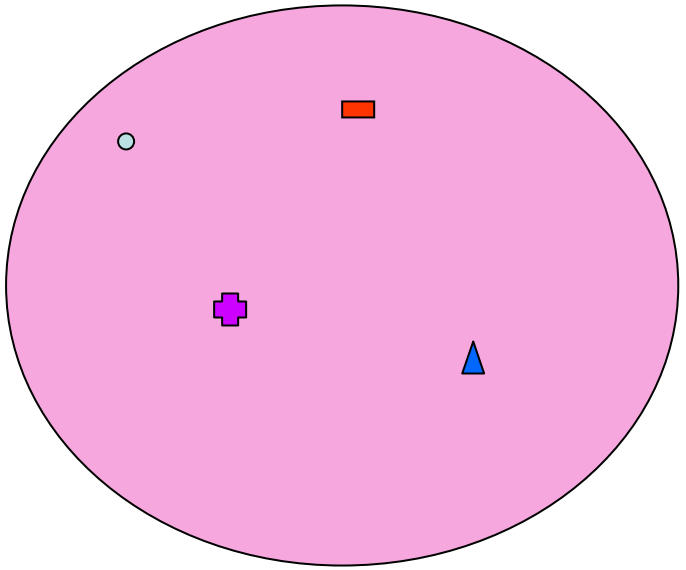
Metabolism without replication: self/mutually catalyzing chemicals

Replication without metabolism: phage, virus

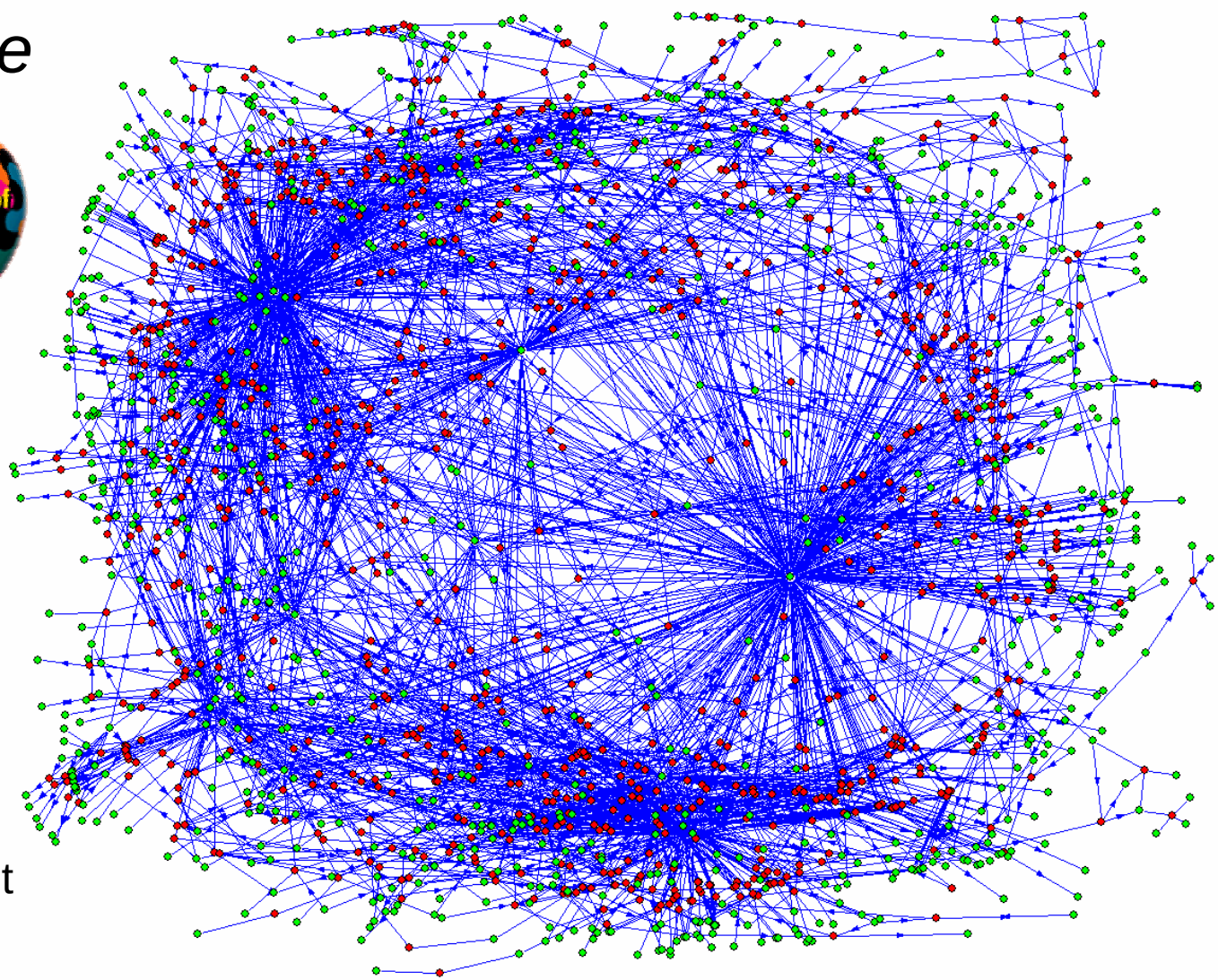
Oparin/Dyson: The double origin hypothesis

Cells → Enzymes →→→Genes

1. Life started as a garbage bag of simple organic molecules
2. Protein creatures emerged first that ran a primitive metabolic cycle with many variations
3. Nucleic acid creatures emerged later, perhaps from within the protein creatures, and hijacked the metabolic apparatus
4. Darwinian evolution: refinement through natural selection



Full metabolic network of *S. cerevisiae*



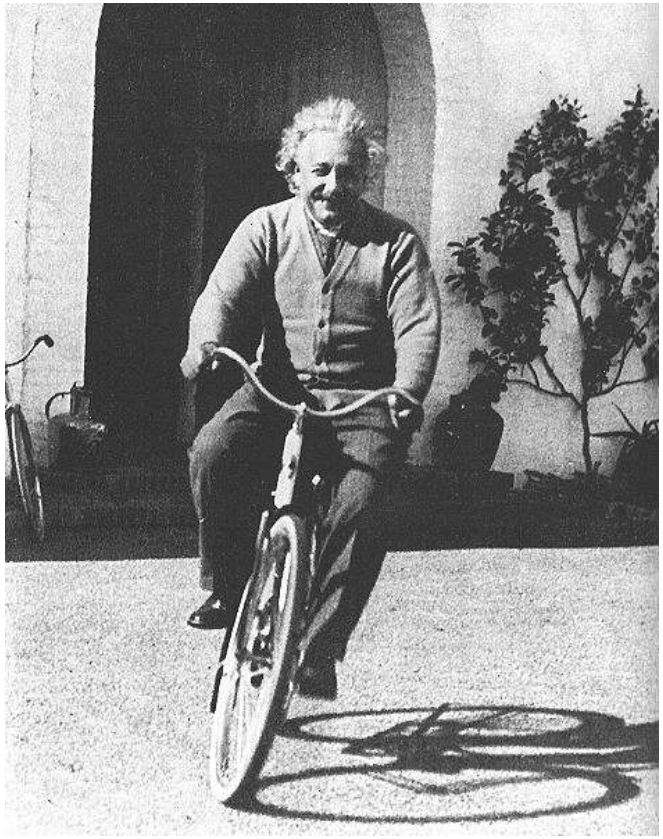
Complexity

- 980 reactions involving 981 compounds catalyzed by 449 different enzymes
- 1163 yeast ORFs with EC assignment

Lesson #3

Life succeeds through parasitism

Orgies: Watch out for Mecha!



I want to know God's thoughts; the rest are details

References

1. Erwin Schrödinger: *What is life*
2. Freeman Dyson: *Origins of life*
3. Anthony Zee: *Fearful symmetry*
4. Brian Greene: *The Elegant Universe*
5. Stuart A. Kauffman: *The Origins of Order*
6. http://www.physics2005.org/
7. http://www.nobel.se