01. Introduction

Big Questions:

- What is science?
- How does it differ (if at all) from technology?
- How does it differ from other ways of describing the world?
- What is/should be its relation to society?

These are Important Questions!

- evolution *vs*. intelligent design
- science policy and science education
- science literacy and the democratic process
- technological progress: world hunger, standards of living, *etc*.

What distinguishes science from poetry, art, literature, religion, politics, etc.?

- "Objective", true description of the world? Predictive success?

> *Pessimistic Meta-Induction*:
>
> Since all scientific theories in the past have been wrong, all current and future scientific theories must and will also be wrong!

- Technological progress?

⇒

$\Rightarrow$

- Is this progress?

$$\textit{progress} \overset{?}{=} \textit{faster, stronger, sturdier, etc.}$$

$$\textit{progress} \overset{?}{=} \textit{more stylish, intricate gizmos (fancy forks)}$$

$$\textit{progress} \overset{?}{=} \textit{higher standard of living}$$

$$\textit{progress} \overset{?}{=} \textit{more "accurate" description of phenomenon}$$

Example: Progress in physics

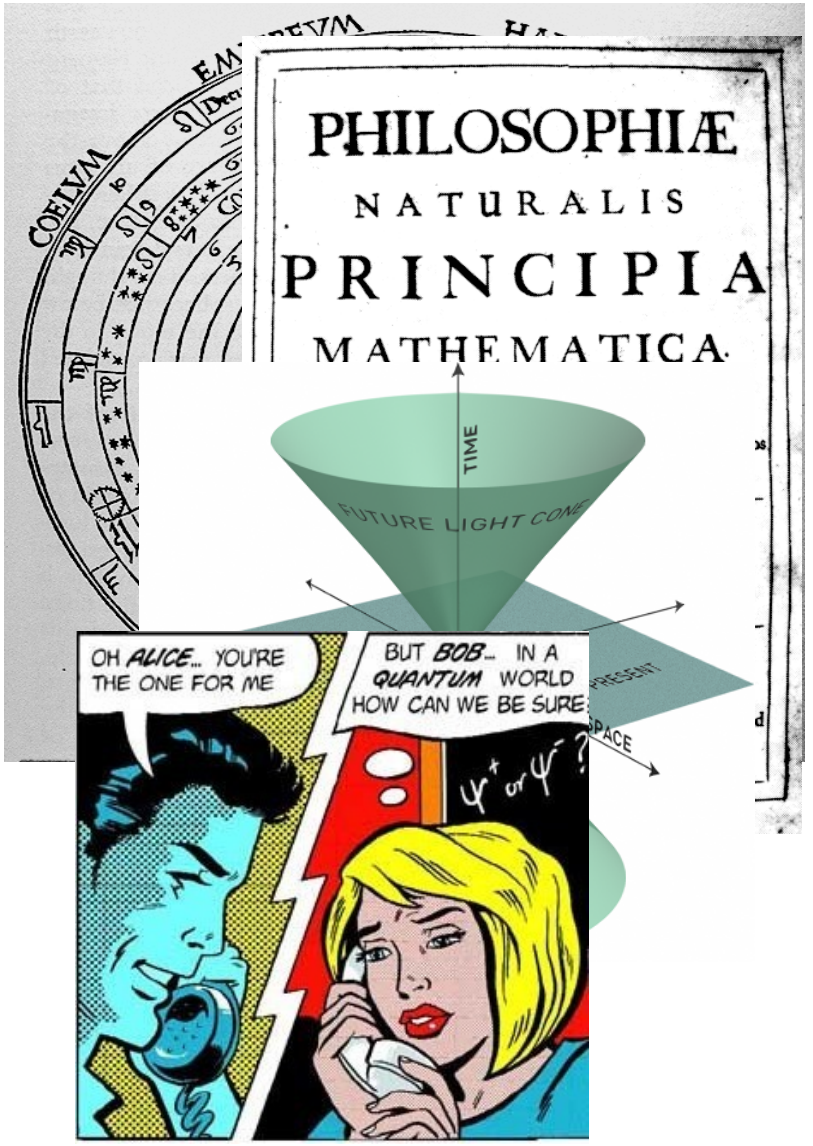
Consistent, unifying account of the world?

- Aristotle (~500 B.C.).
  - celestial physics
  - terrestrial physics

  } *inconsistent!*

- Newton (1687). Newtonian physics unifies terrestrial and celestial realms.

- Einstien (1905, 1916). Relativistic physics.



- Planck, Bohr, Heisenberg, Dirac, *et al*. (1900-1925). Quantum physics.

- 21st century physics:
  - general relativity = current best theory of spacetime
  - quantum field theories = current best theories of matter

  } *inconsistent!*

What does the world consist of?

- Empedocles (~500 BC). Two forces of nature = "love" & "strife".

- Democritus (~400 B.C.). Matter consists of atoms.

- The Standard Model (1980's). Atomistic matter interacting *via* four forces.

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

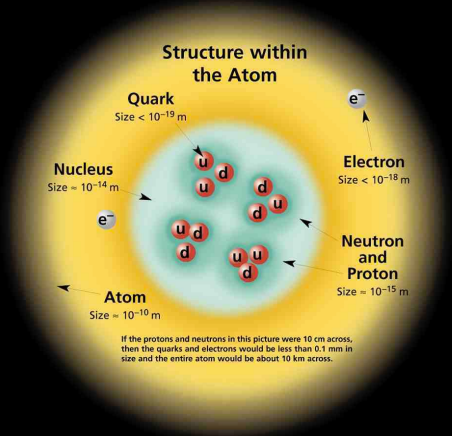
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and **W** and **Z** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons
One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
There are about 120 types of baryons.

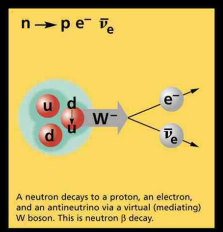
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

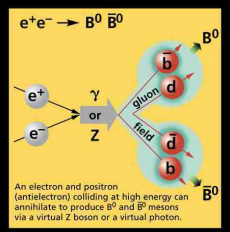
Mesons $q\bar{q}$
Mesons are bosonic hadrons.
There are about 140 types of mesons.

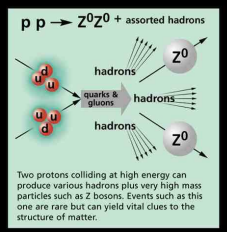
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.







The Particle Adventure
Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
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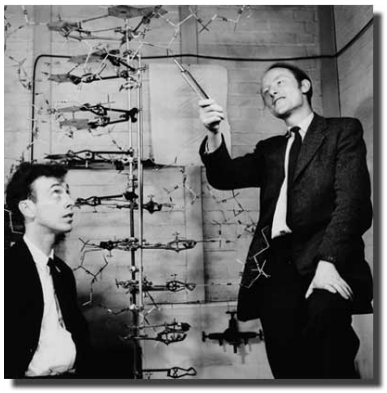
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

Example: Progress in biology

- Structure of DNA molecule: Watson & Crick (1953).
- Genetically modified organisms (GMO's).
- Drug research and development.
- Average human lifespan of ~80 in 2020, compared with ~40 in 1700's.
- *But*: Why are these signs of progress?
  Who's progress?



21st century NYC?

A monk living on a mountaintop?

2. Three Attempts to Distinguish Science from Other Fields

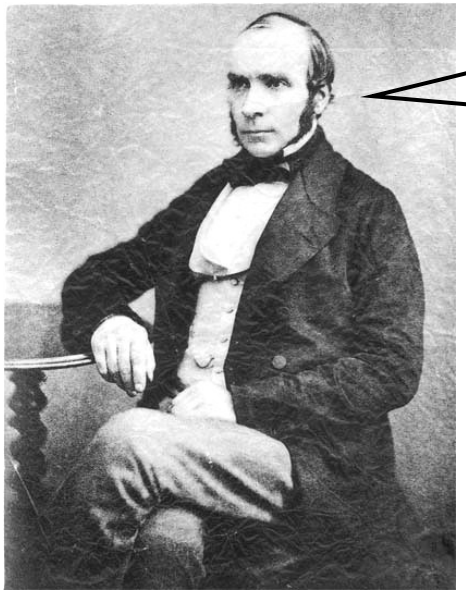
(a) The Role of Empiricism

> *Claim*: Science, as opposed to other fields, is based soley on empiricism.

Empiricism: The only source of knowledge about the world is experience.

Ex: *1854 cholera outbreak in London.*

- John Snow maps outbreak to single public water pump in Soho.
- Pump handle is removed and outbreak goes away!

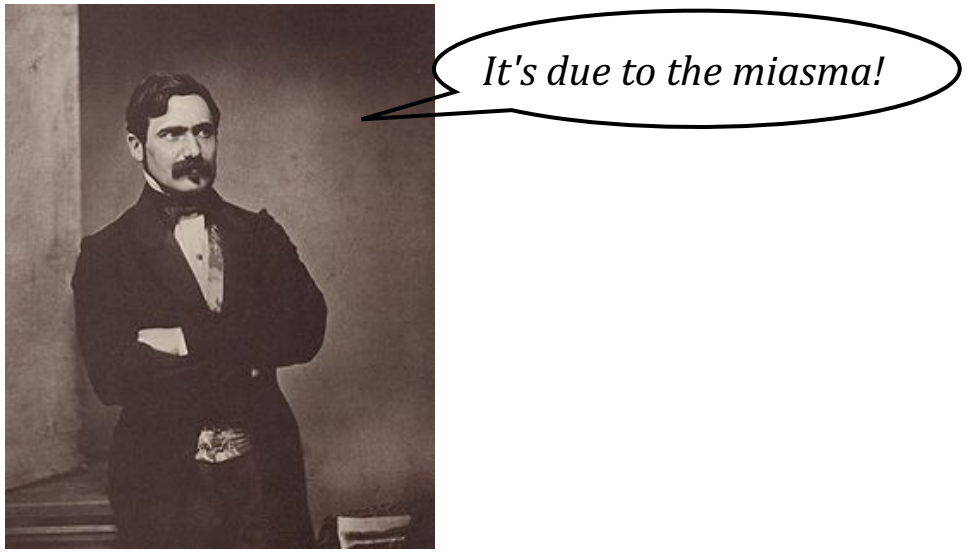


There's something in the water!

John Snow
(1813-1858)

But: Can such examples support the empiricist's claim?

- Max von Pettenkofer disputes Snow's claim that cholera is due to an imperceptible bacterium.
- Pettenkofer drinks water laced with alledged bacterium *with no effects!*
- An empiricist should conclude that cholera is *not* due to bacterium...



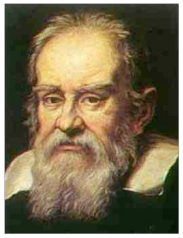
Max von Pettenkofer
(1818-1901)

So: A *simple*, naive form of empiricism may be inadequate as a way to distinguish science from other fields

(b) The Role of Mathematics

Claim: Success of science due to its use of mathematics in describing the world.

"Nature is written in the language of mathematics and its characters are triangles, circles and other *geometrical* figures."



Galileo Galilei
(1564-1642)

Ex. 1. Maxwell Equations: govern electromagnetic phenomena.

$$\vec{\nabla} \cdot \vec{E} = 4\pi\rho \qquad \vec{\nabla} \times \vec{E} = \frac{1}{c}\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \vec{\nabla} \times \vec{B} = \frac{1}{c}\frac{\partial \vec{E}}{\partial t} + \frac{4\pi \vec{J}}{c}$$

$\vec{E}$ = electric field
$\vec{B}$ = magnetic field
ρ = charge density
$\vec{J} = \rho\vec{v}$ = current density

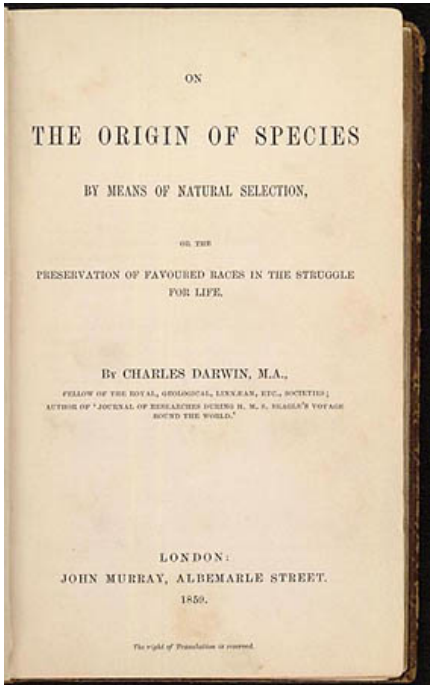
Ex. 2. Einstein Equations: govern gravitational phenomena.

$$R_{\mu\nu} - \tfrac{1}{2}R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

curvature of spacetime — *metric of spacetime* — *Newtonian gravitational constant* — *mass/density*

But! Physics may be special in its use of mathematical representations.

- What about biology? No equations in *Origin of Species*.
- Chemistry? $H_2 + O \rightarrow H_2O$
- Psychology?
- Sociology?


ON

THE ORIGIN OF SPECIES

BY MEANS OF NATURAL SELECTION,

OR THE

PRESERVATION OF FAVOURED RACES IN THE STRUGGLE FOR LIFE.

By CHARLES DARWIN, M.A.,

FELLOW OF THE ROYAL, GEOLOGICAL, LINNEAN, ETC., SOCIETIES;
AUTHOR OF 'JOURNAL OF RESEARCHES DURING H. M. S. BEAGLE'S VOYAGE ROUND THE WORLD.'

LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1859.

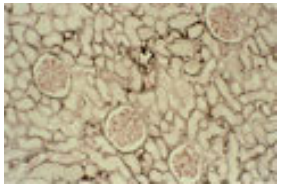
Reductionist Response: There is one unique mathematical description that all physical phenomena in principle fall under.

Organizations

Sociology

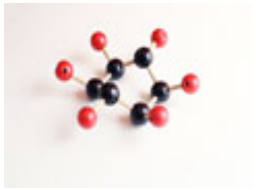
Individuals

Psychology



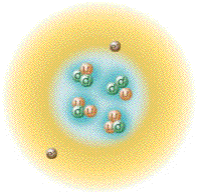
Organs/cells

Medicine, Cellular Biology



Molecules

Chemistry, Molecular Biology

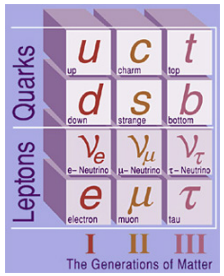


Atoms

Atomic Physics

Protons, Neutrons

Nuclear Physics



Leptons, Quarks

Particle Physics

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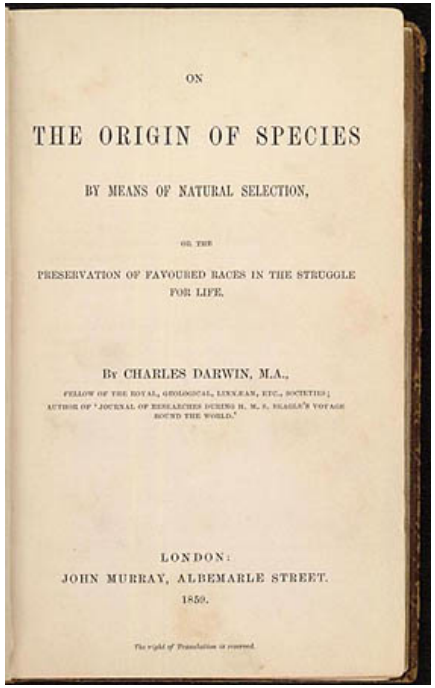
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Reductionist Response: There is one unique mathematical description that all physical phenomena in principle fall under.

Is reductionism feasible?

- mental states
- condensed matter physics and emergent phenomena.

(c) The Role of Social Organizations

Claim: What makes science different from other fields, and especially successful, is its unique social structure.

Sociological Characteristics of Science

- cooperation
- competition
- peer review
- status
- trust
- citations
- pedigree

Strong Claim: These are why science is successful, and not because it is more accurate in its methods of investigation and description.

Weaker Claim: Social organization makes scientific communities uniquely responsive to experience (as opposed to artistic communities, political parties, *etc*).