Goals, Models Frameworks and the Scientific Method

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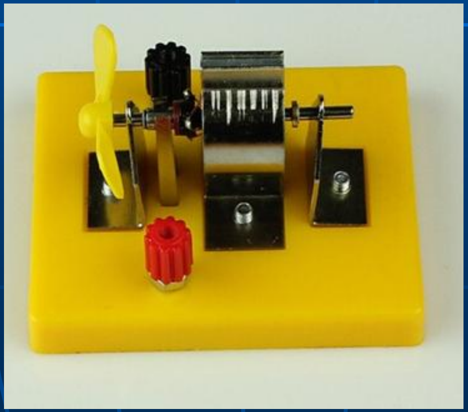


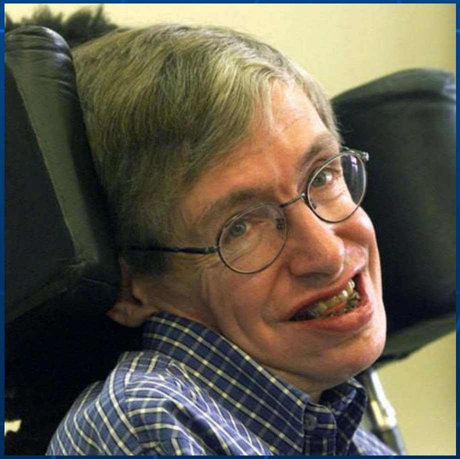
What is valid science?

When should we consider something claimed as science to be valid?

Most scientists say they believe in the "primacy of empiricism".

Many of us swear by "testability" and "falsifiability".

"Most physicists would consider themselves logical positivists, if only they knew what that meant."



Alarms have been raised…

In recent years, there have been concerns that the integrity of physics is in danger.

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Scientific method: Defend the integrity of physics

George Ellis & Joe Silk

16 December 2014

Attempts to exempt speculative theories of the Universe from experimental verification undermine science, argue George Ellis and Joe Silk.

Should we worry?

The confusing word “theory”

- We talk of “falsifiability” or “testability” of a theory.
- But the word “theory” is used with widely different meanings:
  - *quantum theory*
  - *density functional theory*
  - *Fermi liquid theory*
  - *BCS theory*
  - *big bang theory*
  - *theory of elasticity*
  - *gauge theory*

The confusing word “theory”

- I will try to reformulate the discussion using these three words:

Goal

Model

Framework

- These words too are subject to some confusions!
- For example, sometimes the same words may describe either a framework or a model.

Goal

- A goal is something one would like to understand or create.
- Some popular goals in physics:
  - *Superconductivity*
  - *Nano-mechanics*
  - *Quantum gravity*
  - *Active matter*
  - *Quark-gluon plasma*
  - *Photonics*
  - *Quantum computing*

Goal

- Typically a goal has both experimental and theoretical sides, e.g. quark-gluon plasma.
- However at a given time, some are driven more by experiment, e.g. photonics.
- Others are driven more by theory, e.g. quantum gravity, as we will see shortly.

Model

- A model is a concrete theoretical description – typically inspired by experiments – to achieve a specific goal. Some examples:

Model	Goal
Nuclear shell model	*Energy spectra of nuclei*
Fermi liquid theory	*Metals at low temperatures*
Yukawa model	*Strong interactions between nucleons*
Dual resonance model	*Hadron scattering*

Model

- Sometimes a model is summarised (and named after) a particularly famous equation or law, for example:

Model	Goal
Navier-Stokes equation	*Motion of viscous fluids*
Van der Waals law	*Intermolecular forces*
Newton’s law of gravity	*Gravitational forces*
Dirac equation	*Motion of relativistic electrons*

Framework

- A framework is a way of formulating and studying classes of systems.
- Frameworks are different from models or goals. As their name suggests, they are only structures.
- Examples of frameworks:
    - *Classical Mechanics*
    - *Quantum Mechanics*
    - *Statistical Mechanics*

Framework

- Frameworks can sometimes overlap with models.
- For example, Quantum Field Theory is a very general framework to describe fundamental particles and forces.
- But the first known quantum field theory was Quantum Electrodynamics – a model to describe electrons and photons.
- In this case the framework and the model were developed together.

Framework

- Along with frameworks it is appropriate to include mechanisms and effects:
  - Meissner effect
  - Zeeman effect
  - Mossbauer effect
  - confinement mechanism
  - phase transitions
  - asymptotic freedom
  - even symmetries, like conformal invariance
- These also have wide applicability and are not limited to any single physical system.

Testability/Falsifiability

- Now we can highlight more clearly the question of testability and falsifiability.
  - Goals are not falsifiable. They are valid or not, depending on your point of view.
  - Models are falsifiable, but in fact almost all models in physics have been falsified.
  - Frameworks are not falsifiable. They are only useful or not useful in varying degrees.
- The issues of testability and falsifiability should be considered in the light of these observations.
- In particular, falsifiability hardly deserves its “cult” status.

Testability/Falsifiability

- Why did we say that most models are falsified?

Model	Goal
Nuclear shell model	*Doesn't explain multipole moments.*
Fermi liquid theory	*Doesn't explain non-Fermi liquids*
Yukawa model	*Doesn't provide accurate scattering amplitudes*

- "Models work only when they work."

Testability/Falsifiability

- Even after working well enough to get Nobel prizes, they <u>still</u> fail.

Nuclear collective model	*Nobel 1975*	**X**
BCS theory of superconductivity	*Nobel 1972*	**X**
Standard model of particle physics	*Nobel 1979*	**X**

- But it is more polite (and more appropriate) to say that they are “valuable but incomplete”.

Testability/Falsifiability

- Next let's consider a framework: Classical Mechanics.
- Is it useful?
  - Yes, civil engineers use it to build bridges and buildings.
- It is testable/falsifiable?
  - It's perfectly good for bridges and buildings, and partially successful for satellites, but fails totally to explain the hydrogen atom or semiconductors. Thus we can only consider it useful or useless to varying degrees.

- Frameworks/mechanisms possess a high degree of universality.

Higgs mechanism (=dual Meissner effect)	*Nobel 2013*
Critical phenomena/ Renormalisation group	*Nobel 1982*
Spontaneous symmetry breaking	*Nobel 2008*

- Each of these has had a crucial impact on the two opposite poles of physics: (i) elementary particles, (ii) condensed matter.

Quantum Field and Strings

- In the light of the previous discussion, let us examine the current status of Quantum Field Theory (QFT) and String Theory.
- In our language, QFT is a framework, but it was developed in order to create a model of electromagnetism.
- The model, Quantum Electrodynamics, is extremely successful (indeed, to my knowledge it has not been falsified!).
- And the framework is even more successful.

Quantum Field and Strings

- For a long time it was thought that within the QFT framework one could not find a model for the strong nuclear interaction.
- Other frameworks ("S-matrix theory", "Bootstrap" etc) were proposed for this interaction. They were useful, but not very useful.
- Meanwhile the QFT framework was revived with the Quantum Chromodynamics model of strong interactions. This has been a spectacular success.

Quantum Field and Strings

- Today QFT is the best framework we have for understanding three fundamental interactions: electromagnetic, weak and strong.
- Within it, the Standard Model is an excellent model and there is truly no rival.
- It will need to be “tweaked” as we get new experimental data, but this is fine.
- Thus, to a remarkable extent the goal of understanding elementary particles and their interactions has been/is being achieved.

Quantum Field and Strings

- But there is a fourth force in nature: gravity.
- It is by far the most familiar force.
- Experimentally we have no evidence so far that it obeys quantum mechanics.
- But it would be contradictory for one force in nature to be classical and the other three, quantum.
- Thus, understanding quantum gravity is a valid goal.

Quantum Field and Strings

- A natural approach is to try and place gravity in the same framework as the other forces, namely QFT.
- This works very well as long as we do not allow extraordinarily high energies.
- However, in QFT, interactions are mediated by virtual particles.
- In lowest-order processes these virtual particles have fixed energies, but in higher-order processes the virtual particles have arbitrarily large energies.

Quantum Field and Strings

- A broad consensus is that the framework of QFT is inadequate to describe quantum gravity at high energies.
- This is very parallel to the fact that the framework of Classical Mechanics was inadequate to describe atomic processes.
- In both situations, one has to find a new framework that extends the old one but renders it valid in a new regime.

Quantum Field and Strings

- For Classical Mechanics, the new framework was Quantum Mechanics.
- For QFT, the new framework is proposed to be String Theory.
- In fact String Theory is not such a radical change from QFT as Quantum Mechanics was from Classical Mechanics!
- All we need to know about String Theory for the purposes of this talk is that at lowest order it reduces to a QFT (General Relativity), and at higher orders it is consistent.

What good is String Theory?

- A framework must be judged by its usefulness.
- String Theory was at first thought to be extraordinarily useful – not only would it describe quantum gravity, it would also unify it with the other forces.
- In fact we can make unified string models, but we have no experiments to help us select one from the others.

What good is String Theory?

- Hence the focus is on understanding universal features of quantum gravity from String Theory.
- In the absence of experiment, internal consistency of the answers is a very good guide to correctness.
- The entire theory of Black Holes has undergone a revolution of understanding in the last 20 years.
- Conceptual questions such as “Do black holes violate quantum mechanics” have been decisively settled.

What good is String Theory?

- And, as with all successful frameworks, there are now many applications of String Theory to other branches of physics:
  - Quantum phase transitions in superconductors
  - Quantum information
  - Fluid dynamics
  - Cosmological inflation
  - Chaos
- Each of these applications has a goal distinct from quantum gravity, but is addressed by a model within the String framework.

Thank you!