# Physics At the Turn of the 20th Century

(Paul Avery and Peter Hirschfeld, 2018)

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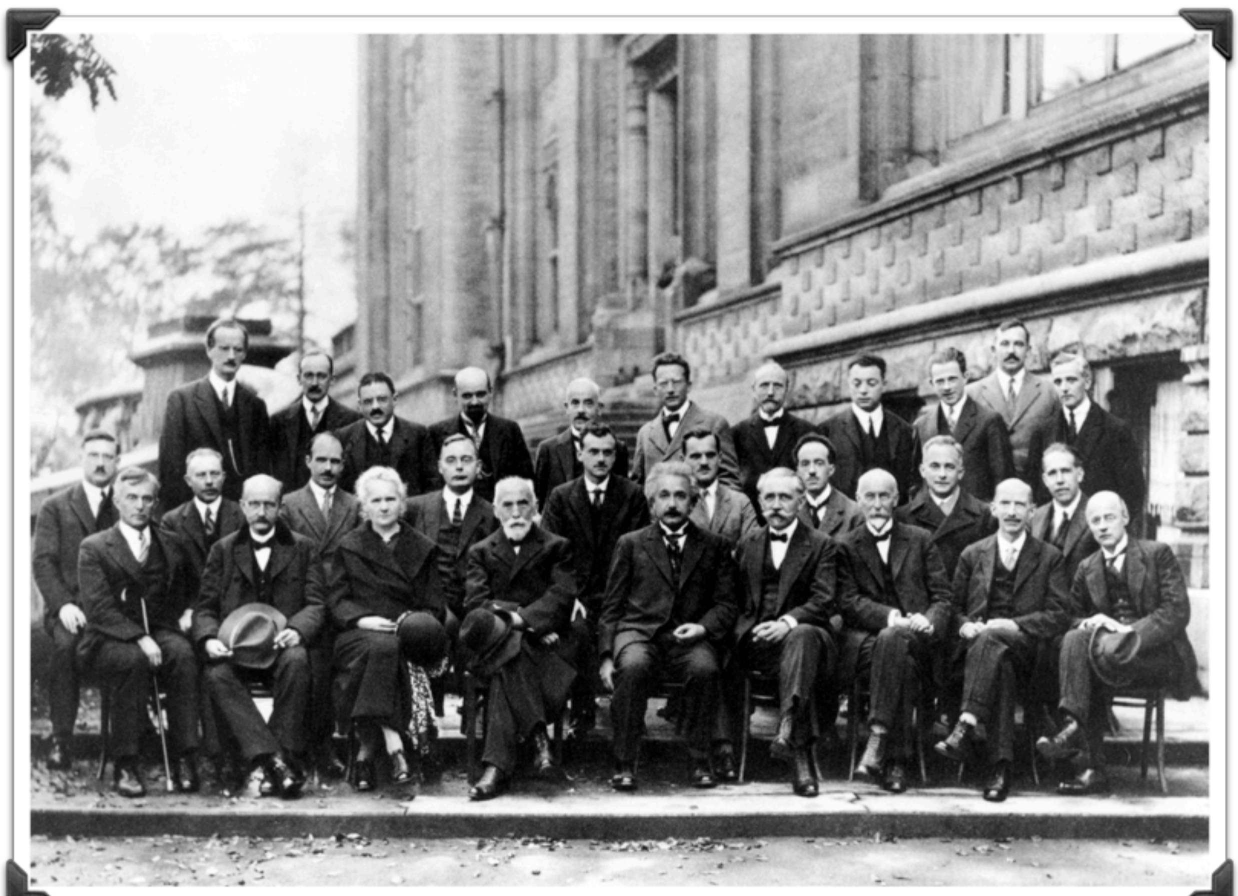

**Figure 1**: 1927 Solvay conference. 17 future Nobel Prize winners in this picture

# 1 Physics in 1900

At the turn of the 20th century, physics seems to be in excellent shape. Newton's mechanics and his law of gravitation proved successful in explaining the orbits of the moon and planets to angular resolutions < 1″ (1 degree = 3600″), as well as tidal phenomena. Recently developed theories of statistical and thermal physics had been used to understand a number of heat and gas phenomena. Sensitive experiments and theoretical advances understanding electric and magnetic phenomena culminated in Maxwell's brilliant theory of electromagnetism in the 1860s, and his prediction of electromagnetic waves was confirmed later by Hertz in the mid 1880s.

This situation led some physicists to believe that physics was reaching its endgame and that almost all major developments had already been made. As Albert Michelson (whose contributions to physics are enormous so he cannot be dismissed as a crank) famously said in 1894, during a dedication of University of Chicago's Ryerson Laboratory[1]:

> *While it is never safe to affirm that the future of Physical Science has no marvels in store even more astonishing than those of the past, it seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice. It is here that the science of measurement shows its importance — where quantitative work is more to be desired than qualitative work. An eminent physicist remarked that the future truths of physical science are to be looked for in the sixth place of decimals.*

While he and many other physicists expressed confidence in the state of physics around the turn of the 20th century, there were a number of unexplained problems, as discussed below.

# 2 Some Key Problems in Physics

## 2.1 Electrodynamics and the missing ether

One of the most successful theories of the 19th century was James Maxwell's unification in the 1860s of electric and magnetic phenomena into a single theory of "electromagnetism". The four "Maxwell's equations" beautifully explained previous experimental measurements and made the startling prediction of electromagnetic waves that could carry energy and momentum across space from one place to another, a prediction that was dramatically confirmed by the experiments of Heinrich Hertz from 1886 - 1889.

However, Hendrik Lorentz proved in 1890 that Maxwell's equations were not invariant under "Galilean transformations", which are ordinary transformations of position and velocity between moving reference frames or inertial frames. This strange mathematical behavior was not considered a major problem at the time because physicists assumed that E&M waves were transported by some medium (the "lumineferous ether" or "ether"), just like all known waves at the time. Like these waves (sound, water, spring, elastic cord, etc.), the velocity of E&M waves, $c = 1/\sqrt{\mu_0 \varepsilon_0} = 3\times10^5$ km/s, was interpreted as being relative to the frame in which the ether was at rest. This implies the existence of a special ether rest frame and a medium with the remarkable properties that it can transmit high velocity waves and yet offer no resistance to planets moving through it. But the 1887 Michelson-Morley experiment (and subsequent experiments after 1900) failed to detect the motion of the earth relative to the ether, a very disturbing result.

## 2.2 The mystery of the solar lifetime

To maintain life on earth the sun must have shining during its entire existence. So how old is the earth? Talmudic and other Biblical scholars such as Martin Luther made estimates based on Genesis and its chronologies to give a creation date of a few thousand years ago. The most famous exposition of this approach was the 1654 estimate of Bishop Ussher who derived the creation date as 4004 BCE or ~6000 years ago. This estimate was remarkably influential and accepted by many educated Europeans for about two centuries.

However, the Enlightenment and the use of scientific methods and observations brought rigorous attention to this problem from several disciplines. Mounting geologic data (strata, erosion rates, etc.) and paleontological evidence (dinosaurs!) through the 18th and 19th century made it clear that the earth was at least several hundred million and perhaps over a billion years old. Similarly, Darwin's theory of evolution (1859) required long periods for life forms to evolve, again requiring enormous spans of time, tens to hundreds of millions of years, though biologists could only make crude estimates of the times it took species to form.

So the sun was known to have been shining for an enormously long period. But what was the mechanism? Explanations of the sun's lifetime in terms of chemical reactions (we show later that this gives 20,000 – 50,000 years) or the release of gravitational binding energy of a shrinking sun (Kelvin estimated 10 – 20 million years) fell short by orders of magnitude (we know today that the earth is about 4.6 billion years old). As we shall see the energy emission mechanism is explained by nuclear reactions which are approximately 1 million times as energetic (~1 MeV/atom vs ~1 eV/atom) as chemical reactions. We will spend several lectures discussing nuclear processes and show their application to solar luminosity.

## 2.3 Strange behavior in emission and absorption of radiation

Discrete lines were discovered in the solar spectrum (Figure 2). Why was energy emission/absorption quantized when all theoretical models predicted continuous distributions of energy vs wavelength?

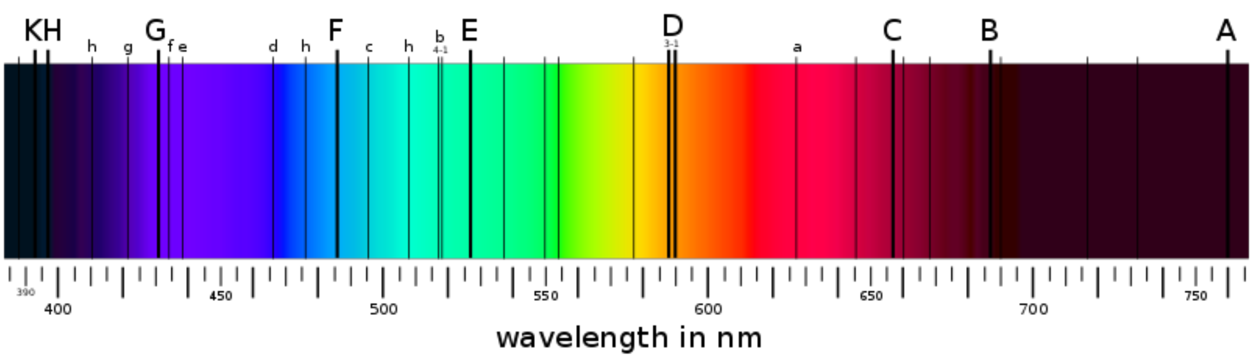


**Figure 2**: Absorption lines in the solar spectrum

In addition, theoretical predictions of $dP/df$ (power radiated per unit frequency) in black-body radiation gave infinite answers ("ultraviolet catastrophe") as $f \to \infty$, wildly contradicting experiment (Figure 3).

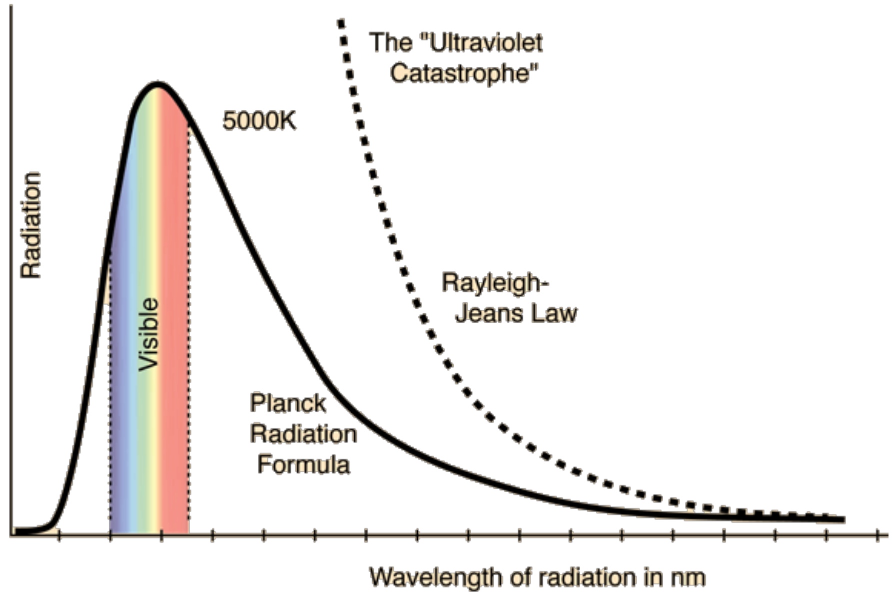


**Figure 3**: Intensity of radiation vs wavelength emitted from a blackbody at different temperatures. The dotted line shows the theoretical prediction from the Raleigh-Jeans theory, which agrees with experiment at long wavelengths but goes to infinity at shorter wavelengths (the "ultraviolet catastrophe").

Finally, details of the photoelectric effect (emission of electrons from a metal when light was shined on it) could not be explained.

### 2.4 Discrepancy in Mercury's orbit

For an isolated planet circling the sun, Newton's equations predict that the orbit is a stable ellipse. In actuality, the orbit is perturbed by the effect of other planets and the oblateness (flattening of a sphere from rotation) of the sun. The orbit in this case is not stationary but drifts in several well-defined ways. It was found by astronomers using centuries of accurate observations that Mercury's perihelion (point of closest approach to the sun) was advancing or "precessing" by 575″/century (see Figure 4). However, increasingly accurate predictions by astronomers indicated that perturbations from other planets could only account for 532″/century, leaving 43″/century unexplained.

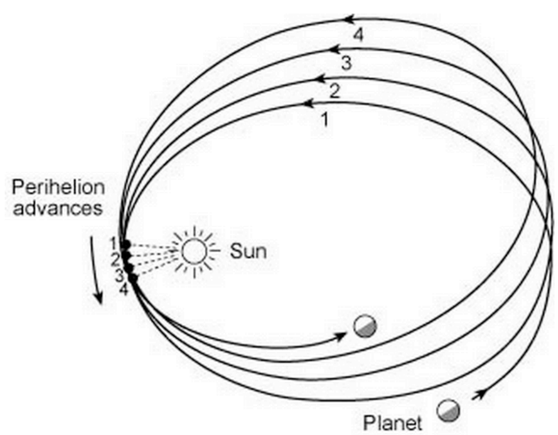


**Figure 4:** Perihelion advance (precession) for a planet revolving around the sun

## 3 Resolution: Modern Physics

The resolution of these questions involved multiple revolutions in our understanding of physics, starting around 1900. This course will explore these key ideas, including

- Special relativity
- Quantum mechanics
- Atomic and molecular physics
- Nuclear and particle physics
- Cosmology and general relativity

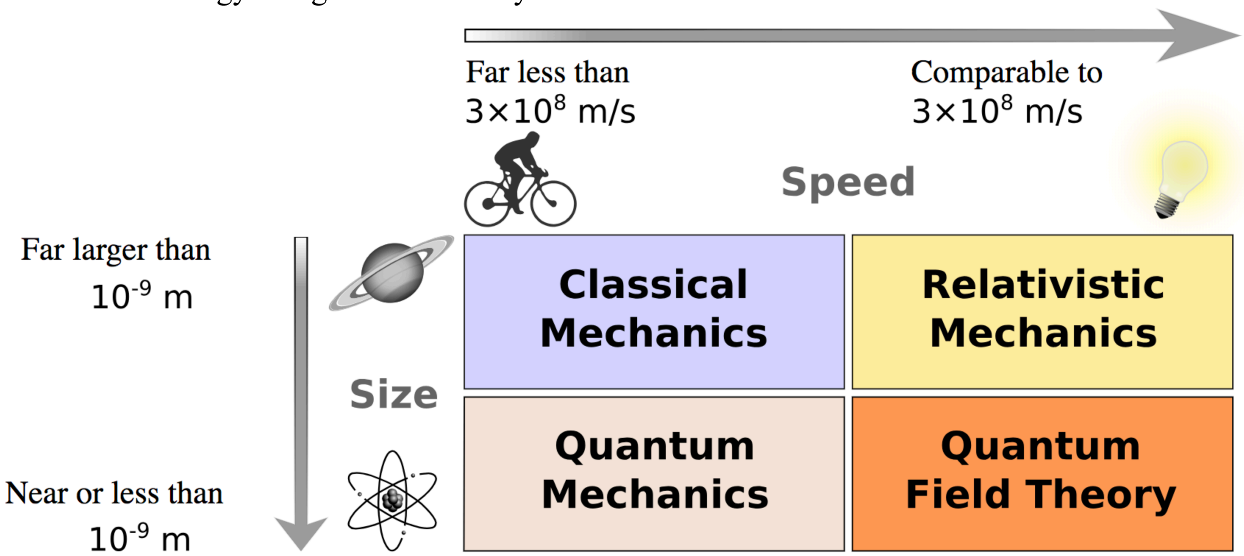


**Figure 5**: Modern physics theories at different size and velocity scales

## References

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[1] See https://www.quora.com/Which-19th-century-physicist-famously-said-that-all-that-remained-to-be-done-in-physics-was-compute-effects-to-another-decimal-place,
(This statement has been wrongly attributed to Lord Kelvin for decades.)