Suggestions of case studies for seminars

(3 suggestions per module)

#1. Newton's mathematical force

1.1. Galileo's original studies on free fall

Galileo's studies on free fall were extremely influential for the establishment of a mathematical reasoning of nature, a characteristic trait of the so-called "scientific revolution". In this case you will get an insight into Galileo's original thoughts and representations, which were essentially geometric. His style of presenting arguments using *Dialogues* represents not only a scientific, but also a literary masterpiece. His studies on the pendulum provide excellent examples for reflecting on the role of idealizations in physics, as well as the interplay between theory and experiment.

A considerable amount of studies related to this episode can be easily found online. For an overview see, for example, N. M. Swerdlow "Galileo's Mechanics of Natural Motion and Projectiles" *Oxford Handbook of the History of Physics*: 25-55.

1.2. Huygens's centrifugal force and the pendulum

Building on Galileo's work, Huygens was able to obtain expressions for the *centrifugal* force, which were crucial for his studies on the pendulum and very important for Newton's innovative proposal of the *centripetal* force. Moreover, in *Horologium Oscillatorium* Huygens describes precisely the construction of a pendulum clock, which consists in a fascinating realization of the relationship between mathematics, physics and technology. This work/apparatus also helped changing our very notion of time.

Huygen's original work on the centrifugal force from 1659 can be found at https://www.princeton.edu/~hos/mike/texts/huygens/centriforce/huyforce.htm. An English translation of Huygen's *Horologium Oscillatorium* (1673) by Ian Bruce is at http://www.17centurymaths.com/contents/huygenscontents.html. For a good 2nd source see, J. G. Yoder, "Unrolling Time: Christian Huygens and the Mathematization of Nature", Cambridge University Press, 1989, 256 p.

1.3. The less known Newton: Alchemy and Theology

Isaac Newton is widely recognized as a model of rationality and the adjective "Newtonian" is almost synonym to exact, objective or rational. Thus, it will probably come as a surprise to you to get to know another Newton, a person who dedicated more than 20 years of research to Alchemy and spent more time with theology than with science. This episode will make you reflect on the complex relationship between science and religion.

Relevant literature can be looked up online. Two classical, although very extensive, studies are, J. E. McGuire and P. M. Rattansi, **"**Newton and the "Pipes of Pan"", *Notes and Records of the Royal Society of London*, Vol. 21, No. 2 and R.S. Westfall, "Newton and Christianity", in Cohen and Westfall, *Newton*, 357-70.

#2. Mechanics principles in the XVIII century

2.1. Different solutions of the Brachistochrone problem

The problem of finding the curve joining two points in a vertical plane along which a frictionless beam will descend in the least possible time was apparently first considered by Galileo in 1638. This problem was to serve as inspiration for the still-to-be-developed Calculus of Variations. In 1696 John Bernoulli challenged the mathematical world to solve it and received solutions from acknowledged mathematicians of the time, including Leibniz, Newton and (James) Bernoulli. In this episode you have the opportunity to contemplate the rich variety of methods and reasoning that lead to the same curve (cycloid) as solution.

A detailed analysis in presented in H. Goldstine, "A history of the calculus of variations: From the 17th through the 19th century" *Studies in the history of mathematics and physical sciences* (1980): 30-66.

2.2. The vibrating string controversy: interplay of physics and mathematics

In the mid-1700s a debate raged between Jean d'Alembert, Leonhard Euler, and Daniel Bernoulli concerning the proper solution to the classical wave equation. This controversy was partially solved by Lagrange and, more conclusively, by Fourier (50 years later) and it provides an interesting case study for the role of mathematics in the modeling of physical phenomena. Of particular note in this debate, was the meaning of boundary conditions.

G. Wheeler and W. Crummet (1987). The Vibrating String Controversy, *Am. J. Phys*. (1987), v55, n1, p33-37.

E. Garber (1999). "The Language of Physics. The Calculus and the Development of Theoretical Physics in Europe, 1750–1914". See Chapter 2.

2.3. Other extremal principles of classical mechanics: Gauss and Hertz

In this case you will have the chance to study other less known extremal principles of mechanics, namely Gauss's principle of least constraint and Hertz's principle of least curvature. Similarities and differences with the more well known d'Alembert's and Hamilton's principles are the focus.

For a conceptual introduction to the principle of least constraint see E. Mach (1893) "The science of mechanics; a critical and historical account of its development" p. 350-363. A thorough analysis of Hertz's reasoning in Mechanics is provided by J. Lützen (2005) "Mechanistic Images in Geometric Form: Heinrich Hertz's Principles of Mechanics".

#3. Fluid dynamics

3.1. Clairaut's figure de la terre

In 1743 Alexis Claude Clairaut published an influential work entitled "Theory of shape of the earth extracted from hydrostatic principles" which contributed not only to mechanics but also to the theory of partial differential equations. This episode will enable to you take a closer look into this beautiful work and to see some original manifestations of what we today call the "curl" of a vector field.

Moreover, you will get an impression of a very important problem of the time, namely the determination of the earth's shape.

A brief account of its main principles, together with a comparison with Euler's later formulation of fluid mechanics in terms of pressure fields, is provided by J. Casey "Clairaut's hydrostatics: A study in contrast" *AJP*: **60**, 549 (1992). For an extensive treatment of the history of the "shape of the earth" problem see J. Greenberg "The Problem of the Earth's Shape from Newton to Clairaut: The Rise of Mathematical Science in Eighteenth-Century Paris and the Fall of 'Normal' Science" Cambridge University Press (1995).

3.2. The challenge imposed by vortices

Understanding and predicting the formation of vortices in fluid motion has (and still does) posed a major challenge for theoreticians. In this episode you will take a look at the historical development of vortex theory, especially through the works of Helmholtz and Kirchhoff. You will be surprised by the interesting relationships between fluid dynamics, acoustics and electromagnetism.

O. Darrigol "Worlds of flow" Oxford University Press (2005), Chapter 4.

3.3. Drag and drift

The problem of "fluid resistance", i.e. the determination of the forces that a fluid exerts on a solid body emerged in it, has a fascinating history that leads into current theoretical challenges. The story of the main characters and theories are to be presented in this case study. The importance of technological applications (e.g. flying machines) for the development of these theories will be evident.

O. Darrigol "Worlds of flow" Oxford University Press (2005), Chapter 7.

#4. Wave theory of light

4.1. Newton's *Opticks*

Newton worked on optics throughout his career and his *Treatise of the Reflexions, Refractions, Inflexions and Colours of Light* (1704) dominated this science for over a century. In this seminar you will investigate of this influential work and see how the Newtonian framework explained several optical phenomena, including diffraction and interference. You will also note a somewhat different approach from the *Principia*, since here we see the experimentalist Newton at his best.

A great overview of this work is given by Shapiro, A. "Newton's Opticks", Chapter 6 of *Oxford Handbook of the History of Physics*.

4.2. Huygens *Traité de la lumière*

Christiaan Huygens is known to be one of the first defenders of the wave theory of light. What we know today as Huygens' principle actually shapes the whole mathematical formalism of the theory put forward by Fresnel. But how does this principle appear in the original? A brief look into Huygens's classic "Treatise on Light" will suffice to show how different it is from our understanding today.

The original *Traité de la lumière* is fairly readable and English translations are easily found in the web.

4.3. The discovery of polarization (Malus, Biot and selectionism)

Attempts to theorize optics are usually divided into two groups (wave vs. particle theorists). However, another important distinction is given by the incompatible notions of a *wave front* and an *isolatable ray*. These distinctions become evident in the theoretical attempts to explain polarization. This episode will focus on Malus's original investigations on polarization as well as Biot's theory to explain (chromatic) polarization.

An overview is found at J. Buchwald "Optics in the XIX century", *Oxford Handbook of the History of Physics,* 447-451. A more detailed account is given by J. Buchwald "The Rise of the Wave theory of Light", The University of Chicago Press (1989), Chapters 1-4.

#5. Thermal physics and thermodynamics

5.1. Caloric theories of heat

For quite some time, phenomena associated with heat were explained by assuming the existence of a self-repellent fluid (caloric) that flows from hotter bodies to colder bodies. Caloric was also thought of as a weightless gas that could pass in and out of pores in solids and liquids. In this seminar you have the opportunity to take a closer look at the original formulations of some of these theories (e.g. Lavoisier and Laplace) as well as the process that led to the abandonment of this way of conceptualizing heat.

R. Fox, (1971), "The Caloric Theory of Gases from Lavoisier to Regnault", Oxford University Press.

H. Chang "Thermal Physics and Thermodynamics", *Oxford Handbook of the History of Physics*, 482-495.

5.2. The proposal of an absolute temperature scale by Kelvin

William Thomson's (Lord Kelvin's) proposal of an absolute thermometric scale ranks among one of the most influential works in thermodynamics. The original work is quite accessible to the modern reader and depicts Kelvin's deep reasons for the need of such a scale.

It is worth reading the original "On an Absolute Thermometric Scale founded on Carnot's Theory of the Motive Power of Heat, and calculated from Regnault's Observations" (William Thomson, *Philosophical Magazine*, 1848). For a broad philosophical overview of this episode see H. Chang, "Inventing temperature: Measurement and Scientific Progress", Chapter 4.

5.3. History of the conservation of energy principle

Although the first time we encounter the principle of conservation of energy is usually in mechanics, it has its origin in thermodynamics. Several formulations of the same idea are found in the works of Joule, Mayer, Helmholtz, Colding among others. This has led Thomas Kuhn to coin this episode as an "example of simultaneous discovery". This interesting and multifaceted story will be investigated in this episode.

There is a considerable amount of literature on this topic. A classic is T. Kuhn, "Energy conservation as an example of simultaneous discovery," pp. 321-356 in Marshall Clagett, ed., *Critical Problems in the History of Science*. Madison: University of Wisconsin Press.

#6. Kinetic gas theory and statistical mechanics

6.1. Neglected pioneers: Herapath and Waterson

In this case study you will have the opportunity to get an insight into the works of two rather unknown characters in the history of science, although, according to Stephen Brush, they are the founders of modern kinetic gas theory. A sociological issue is also in play in this episode, due to the reasons given by the Royal Society for refusing Waterson's 1845 paper. Interestingly, both Herapath and Waterson were trying to explain gravity by impacts of particles.

http://www.math.umd.edu/~lvrmr/History/Neglected.html

John Herapath, *Mathematical Physics; or the Mathematical Principles of Natural Philosophy: with a Development of the Causes of Heat, Gaseous Elasticity, Gravitation, and Other Great Phenomena of Nature*, London 1847.

S. Brush, "John James Waterson and the kinetic theory of gases", *American Scientist*, Vol. 49, No. 2 (1961), pp. 202-214.

6.2. On the size of air molecules

How big is a molecule? At a first glance this may seem an unscientific question, but in 1865 Johann J. Loschmidt published a paper containing theoretical considerations and experimental data to show that the diameter of a N_2 molecule was 9.69×10^{-10} m. How did Loschmidt manage to make such a calculation?

www.loschmidt.cz/pdf/discovery.pdf

6.3. Gibbs's formulation of chemical thermodynamics

Gibbs's contributions for theoretical thermodynamics can be hardly overestimated, since they were responsible for transforming physical chemistry into a rigorous deductive science. Thermodynamic potentials (especially the chemical), phase diagrams and Gibbs free energy, are some among his numerous contributions to the field. Gibbs's achievements are even more impressive when one considers that he was intellectually isolated in the US. In this episode you can get an insight into his life and work.

J. Hertz, "Josiah Willard Gibbs and teaching thermodynamics of materials (history)". *Journal of Phase Equilibria*, 1992, Volume 13, Number 5, Page 450
http://link.springer.com/article/10.1007%2FBF02665759

L. P. Wheeler, *Josiah Willard Gibbs, The History of a Great Mind*, (Woodbridge, CT: Ox Bow Press, 1998 [1951])

#7. Shaping electromagnetism

7.1. Stephen Gray and the discovery of electrical conduction

One of the most important aspects of the whole science of electricity is the fact that there are two sets of bodies with very distinct properties, *insulators* and *conductors*. The discovery of these two types of bodies and their main properties came only very late in the history of electricity. Stephen Gray (1666-1736) made this great discovery in 1729, publishing a fundamental work on the subject in 1731. The fact that Gray was a dyer and made his main discoveries when he was between 63 and 70 years old may come as a surprise for you.

http://www.ifi.unicamp.br/~assis/Electricity.pdf (Appendix B)

7.2. Ampère's Electrodynamics

What is traditionally called Ampère's law in physics instruction is fundamentally different from Ampère's original reasoning. The main reason is that Ampère's theory was based on the proposal of a force between current elements, which was analogous to Newton's law of gravitation and is "action at a distance" like (i.e., in opposition to the notion of field). Ampère was not only a very skilled mathematician, but also an ingenious experimenter.

A comprehensive account of Ampère´s work is found at http://www.ifi.unicamp.br/~assis/Amperes-Electrodynamics.pdf. It is recommended to choose a particular topic/chapter for the seminar.

7.3. Electricity in the 17th and 18th centuries

The early history of electricity is rather intriguing for several reasons, including the non-mathematical character of its investigations and the use of electricity for entertainment. The deductive edifice we learn nowadays with Maxwell's equations has a long and turbulent history. A comprehensive study is found in John Heilbron's classic book "Electricity in the 17th and 18th centuries, a study of early modern physics". You will find it in REX and there are online versions available. Take a look at the table of contents and pick up a topic for the seminar. From electric fluids to animal electricity; there are many strange/interesting things to be learned in this historical development.

#8. Maxwell's analogies

8.1. Light is an electromagnetic wave

A classical demonstration in electromagnetism courses is extracting the wave equation from Maxwell's equations. Maxwell is widely recognized as being the first to propose that light is an electromagnetic wave. Is that really true? In this episode you have the opportunity to investigate this matter more deeply. You will learn about the Weber's force, the Weber-Kohlrausch experiment and how both Weber and Kirchhoff (independently) showed that an electromagnetic signal propagates at light velocity along a thin wire of negligible resistivity.

http://www.ifi.unicamp.br/~assis/Weber-Kohlrausch(2003).pdf

8.2. Weber’s Planetary Model of the Atom

A rather unknown planetary model of the atom was developed by Wilhelm Weber (1804-1891) in the second half of the XIXth century. It is based on Weber's electrodynamic force of 1846, which depends on the distance between the interacting charges, their relative velocity and their relative acceleration. This model makes remarkable predictions (e.g. electrons orbiting around a positive nucleus), gives reasons for the stability of the nucleus as well as an estimation of its size, all things that became accepted much later.

A detailed account of this episode is given by A. K. T. Assis, K. H. Wiederkehr and G. Wolfschmidt, "Weber’s Planetary Model of the Atom" (Tredition Science, Hamburg, 2011), 184 p.

8.3. Shaping electromagnetism’s formalism: Quaternions vs. Vectors

Maxwell wrote his *Treatise* (1873) using the mathematics of quaternions. After reading his work, Gibbs and Heaviside created, independently, the vector analysis we know today, arguing that it is a more suitable formalism to express relations between electromagnetic quantities. But the developers of quaternions were quite revolted with the “distortion” of their system, which led to a heated (and rather unfriendly) debate in the 1890’s.

The full account of the debate is given in Chapter 6 of M. Crowe (1967) “A History of Vector Analysis”, University of Notre Dame Press. Other chapters in the book can be read to get an overview of the system of quaternions.

#9. Paths to relativity

9.1. Miller’s alleged refutation of special relativity

From about 1920 to 1933 the US experimental physicist Dayton Miller performed a series of very accurate interferometer experiments of the Michelson type from which he inferred a non-zero ether drift. Although the result obviously contradicted Einstein’s theory of relativity, it did not succeed in challenging the theory’s validity. How can a theory be maintained if it is falsified by experiment? It took several decades until it was realized that Miller’s experiments did not, after all, contradict special relativity.

Relevant literature and sources can be looked up online. See, for example, K. Hentschel, "Einstein's attitude towards experiments: Testing relativity theory 1907-1927," *Studies in History and Philosophy of Science* **23** (1990): 593-624.

9.2. Fine-structure spectrum and relativity theory, ca. 1916-1926

When A. Sommerfeld in 1916 explained the fine structure of the hydrogen spectrum as a relativistic effect, due to the mass variation $m = m(v)$ of the revolving electron, it was presented as a confirmation of Einstein's relativity theory. But other physicists disagreed and in Germany the case evolved into a controversy fuelled by the period's political climate. Was the fine-structure explanation really a confirmation of special relativity? What is the present explanation of the fine structure?

A full account is given in H. Kragh, "The fine structure of hydrogen and the gross structure of the physics community, 1916-1926," *Historical Studies in the Physical Sciences* **15** (1985): 67-125.

9.3. Does special relativity preclude superluminal velocities?

In his 1905 paper, Einstein wrote that "Velocities greater than that of light have … no possibility of existence." But is this correct? In fact, special relativity does not preclude particles always moving faster than light, so-called tachyons. This was only recognized in 1923 by an unknown Russian physicist (and nobody cared). Four decades later, tachyons attracted much interest as possible real particles. There is no good history of the tachyon concept, but try to find out what you can and what the arguments in favour of the tachyon were in the 1960s.

You may start with the Wikipedia article on tachyons, and also consult P. Fröberg, "Historical background of the tachyon concept," *Archive for History of Exact Sciences* **48** (1994): 373-380. The best paper on the subject has never been published, but I have a copy of it (R. C. Corby, "Never at rest: Superluminal particles in the scientific imagination").

#10. Original formulations of quantum mechanics

10.1. The discovery of spin.

The electron's spin quantum number was introduced in the summer of 1925, at roughly the same time as the new QM emerged; but the discovery was spectroscopic and phenomenological, and it owed nothing to QM. Indeed, it was at first considered a problem for QM. How was spin discovered? How was the new concept received in the physics community? Was it anticipated (cp. Stern-Gerlach experiment, Pauli's exclusion principle)?

Secondary sources include S. Goudsmit, "It might as well be spin," *Physics Today* **29** (June, 1976): 40-43, and A. Pais, "George Uhlenbeck and the discovery of electron spin," *Physics Today* **42** (December, 1989): 34-40. See also D. Greenberger et al., *Compendium of Quantum Physics* (Springer, 2009; e-book, REX), article on spin.

10.2. What is ψ? Early interpretations of Schrödinger's wave function.

Schrödinger introduced his ψ–function in the spring of 1926, without knowing what it was. At first he thought of particles being made up of waves, then that ψψ* signified an electric charge density; but he was unable to construct stable localized wave packets mimicking electrons, and his view was criticized by Heisenberg, Lorentz and others. Only a few months later did Born come up with the now accepted probability interpretation of ψ.

F. Steiner, "Schrödinger's discovery of coherent states," *Physica* **151** (1988): 323-326. On Schrödinger's theory and its early reception, see e.g. J. Mehra, "Erwin Schrödinger and the rise of wave mechanics, III," *Foundations of Physics* **18** (1988): 107-184. See also Mehra's paper in 10.3.

10.3. Origin and meaning of Heisenberg's uncertainty principle.

Heisenberg introduced his famous uncertainty or indeterminacy principle in 1927. What is the essence of this principle, how does it relate to the equations of QM, and what were the roots of Heisenberg's insight? And, perhaps, how does it relate to Bohr's almost simultaneous complementarity principle? Is the uncertainty principle still valid?

Sources include M. Jammer, *The Conceptual Development of Quantum Mechanics* (McGraw-Hill, 1966), pp. 323-345, and J. Mehra, “Niels Bohr’s discussions with Albert Einstein, Werner Heisenberg, and Erwin Schrödinger: The origins of the principles of uncertainty and complementarity,” *Foundations of Physics* **17** (1987): 461-506.

#11. Discovery of antimatter

11.1. Why did Dirac initially identify the anti-electron with the proton?

In 1929 Dirac suggested that the new solutions to his electron wave equation were valid for protons, meaning anti-electron = proton. Only in 1931 did he suggest anti-electron = positron. What were the reasons for Dirac’s first proposal and why did he change his mind?

The question is considered in D. F. Moyer, “Evaluation of Dirac’s electron,” *American Journal of Physics* **49** (1981): 1055-1062, and H. Kragh, *Dirac: A Scientific Biography* (Cambridge University Press, 1990), pp. 87-104.

11.2. Antiprotons and negative protons

From a modern perspective a negative proton is the same as an antiproton, but the situation in the 1930s was more muddled. The antiproton was first discovered – or manufactured – in 1955 and since produced routinely in high-energy laboratories.

On the early history, see H. Kragh, “The negative proton: Its earliest history,” *American Journal of Physics* **57** (1989): 1034-1039. For the discovery, see L. Brown, M. Dresden, L. Hoddeson, *Pions to Quarks* (Cambridge University Press, 1989), pp. 273-298.

11.3. Positronium

What is “positronium” and why is this simplest system of particle-antiparticle considered interesting? The idea of an electron-positron composite has a curious origin as it was first proposed by an obscure and speculative Yugoslavian scientist. For some time positronium was considered pseudoscience rather than science, but in 1951 it was actually discovered.

See the brief account in H. Kragh, "From 'electrum' to positronium," *Journal of Chemical Education* **67** (1990): 196-197. See also http://physicsworld.com/cws/article/news/2003/may/28/positronium-puzzle-is-solved

#12. Modern cosmology

12.1. The first CMB prediction

The cosmic microwave background (CMB) was detected in 1964 and interpreted as a fossil of the big bang in 1965. But its existence was predicted from big-bang assumptions as early as 1948 by R. Alpher and R. Herman. How did Alpher & Herman (and also G. Gamow) come to their conclusion of a cosmic background radiation of intensity ca. $T = 5$ K? Why was their prediction ignored, only later to result in a Nobel Prize to the two physicists who first detected it, R. Wilson and A. Penzias?

R. Alpher and R. Herman, "Evolution of the universe," *Nature* **162** (1948): 774-775; "Remarks on the evolution of the expanding universe," *Physical Review* **75** (1949): 1089-1095. And see also V. Alpher, "Ralph A. Alpher, Robert C. Herman, and the cosmic microwave background radiation," *Physics in Perspective* **14** (2012): 300-334.

12.2. The essence of the steady-state theory

From 1948 to around 1965 the steady-state cosmological theory was a strong alternative to the relativistic evolution theories of the big-bang type. The theory assumed an infinite and eternally expanding universe of constant mass density. It led to several sharp predictions concerning the geometry of space, the distribution of galaxies, and the rate of matter creation. Although a clever and impressive theory, it turned out to be wrong and is today more or less forgotten.

A comprehensive account of the steady-state theory and its history can be found in H. Kragh, *Cosmology and Controversy* (Princeton University Press, 1996). See also Yu. Balashov, "Uniformitarianism in cosmology: background and philosophical implications of the steady-state theory," *Studies in History and Philosophy of Science* **25** (1994): 933-958.

12.3. The ups and downs of the cosmological constant

The cosmological constant Λ first appearing in Einstein's 1917 theory has a curious history. Today Λ is believed to be the source of dark energy and hence the major ingredient in the universe, but for a long time it was considered unwanted (i.e. = 0). The quantity has one root in general relativity cosmology and another in quantum theory. It still remains a mystery why Λ has the value it has observationally.

See the relevant parts of H. Kragh & J. Overduin, *The Weight of the Vacuum: A Scientific History of Dark Energy* (Springer, 2014), available online, REX. See also J. Earman, "Lambda: The constant that refuses to die," *Archive for History of Exact Sciences* **55** (2001): 189-220.