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The Modernity of Ibn al-Haytham (965–1039)

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Abstract

Ibn al-Haytham (Alhazen) is considered the initiator of modern optics and the scientific method. The latter is based (1) on reciprocal relation between experiment/observation and theory (expressed here in mathematical language) and (2) on primacy of the verdict of the experiment.

Starting from four propositions based on experiment, Ibn al-Haytham develops geometrical optics, like Euclid, who develops geometry from five axioms.

Publication of his experimental/observational data is accompanied by that of description of different steps of measurements as well as of measuring instruments in order to allow verification of results by others. It opens the way of doing modern physics, resumed five or six centuries later in Europe.

Ibn al-Haytham deals with perception of images by the eye and with vision by the brain. This allows him to establish an objective conception of the world, treating the observed object as independent of the observing subject. The eye thus acquires its scientific status: that of first detector. Moreover, Ibn al-Haytham practices methodical doubt by subjecting not only the writings of the ancients but also his own prejudices to ruthless criticism.

Today, while priority to verdict of practice is in many respects challenged — in particular in cosmology —, contemporaneity of Ibn al-Haytham is more evident than ever.

Introduction

Ibn al-Haytham, known in Western Europe as Alhazen, was born in Basra (Iraq) in 965 and died in Cairo (Egypt) in 1039.[2] There he wrote several books on various subjects (astronomy, medicine, mathematics, physics, psychology, scientific method, etc.). He is above all a physicist. From Claude Ptolemy (~90–168) to Nicolas Copernicus (1473–1543), Ibn al-Haytham is the major figure of physics.

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2 Bradley Steffens, *Ibn al-Haytham, First Scientist*, Morgan Reynolds, 2007.

Between 1015 and 1021, he wrote his major work, *Book of Optics* [in Arabic *Kitab al-Manazir*, in Latin *De Aspectibus* or *Opticae Thesaurus: Alhazeni Arabis*][3]. This book had an important influence on the development of optics and physics in general because it radically transformed the knowledge of light and vision and introduced the scientific method. It was not until the two treaties in optics, of Johannes Kepler (1571–1630) that a real advance was made in this field.

"His work on optics, which includes a theory of vision and a theory of light, is considered by many to be his most important contribution, setting the scene for developments well into the seventeenth century. His contributions to geometry and number theory go well beyond the archimedean tradition. And by promoting the use of experiments in scientific research, al-Haytham played an important part in setting the scene for modern science." (Roshdi Rashed)

It is from the point of view of a 20th-21st century physicist that I will speak to you about Ibn al-Haytham and not as a historian, because that is not my job. Historians such as Roshdi Rashed[4] have done important researches on this subject in the last half-century[5].

I was interested in Ibn al-Haytham for several reasons. Two of them here. First, there is the underestimation in Europe and the United States of the profoundly original contribution of the Arab world to physics between the 8th and 13th centuries. This is the case, for example, of Steven Weinberg's otherwise excellent book *To Explain the World: The Discovery of Modern Science* (2015). Next, in this 21st century, the scientific method, initiated by Ibn al-Haytham, is challenged by various brilliant theorists specialized in superstrings, cosmology or speculating on the existence of a multiverse. Arguing that it would not be possible to experimentally verify the validity of their speculative theories, they come to conclude that the logical coherence of their theories will suffice.

Optics

Historically, optics appeared as early as Antiquity, then was developed by Muslim scholars. Ibn al-Haytham is considered the father of modern optics. Latin translation of part of his work, Book of Optics, had a great influence on scientists in the West, particularly on Kepler.

The geometrical optics introduced by Ibn al-Haytham developed on the basis of simple observations and is based on four propositions:

— rectilinear propagation in a transparent (homogeneous and isotropic) medium;

— reverse return principle, which expresses the reciprocity of the light path between transmission and reception;

— the law of reflection of light;

— the law of refraction of light [attributed to Snell and Descartes].

Geometrical optics makes it possible to find almost all the results concerning mirrors, lenses, optical instruments, etc. Problem solving is done using geometric constructions (straight lines representing light rays, angle calculations). Geometrical optics works well as long as polarisation or interference

[3] *The Optics of Ibn al-Haytham, Books I – III*, On Direct Vision, translated with Introduction and Commentary by A. I. Sabra (ed), 1989 https://monoskop.org/images/f/ff/The_Optics_of_Ibn_al-Haytham_Books_I-III_On_Direct_Vision_Sabra_1989.pdf. For a short review of the *Book of Optics*, Jim Al-Khalili, *Nature*, Vol. 518, 164–165 (2015), https://static1.squarespace.com/static/57bf33a137c58162d95139aa/t/5827008c20099e6175572b9c/1478951057856/nature.pdf. See appendix I.

[4] Roshdi Rashed, "A Polymath in the 10th century", *Science* 297(5582) (2002):773, http://d2ufo47lrtsv5s.cloudfront.net/content/sci/297/5582/773.full.pdf.

[5] Ibn al-Haytham, http://www.newworldencyclopedia.org/entry/Ibn_al-Haytham.

phenomena are not modelled and no dimension of the system is comparable or less than the wavelength of the light used.

Ibn al-Haytham, by multiple experiments, shows that light — a ray of light — propagates in transparent media in a rectilinear manner. He counters other conceptions such as a diffuse propagation of it.

“How does light travel through transparent bodies? Light passes through transparent media in a straight line only (…). We have explained this exhaustively in our *Book of Optics*. But let us now mention something to prove it convincingly: the fact that light travels in a straight line is clearly observed when light enters a dark room through holes. … the light path will be clearly observable thanks to the dust suspended in the air.”

According to Rashed Roshdi, “in his conception of optics the smallest grain of light, as [ibn al-Haytham] calls it, retains only properties that can be evaluated by geometry and verified by experience, it loses all perceptible characteristics except energy.”[6]

Note that the discovery of the law of refraction,

$$\sin \theta_1 / \sin \theta_2 = \text{constant}$$

with θ_1 and θ_2 the angle of incidence and the angle of refraction respectively, attributed to Snell and Descartes living in the 17th century, was actually made by Ibn Sahl (940–1000) in 983, as shown in 1990 by Rashed Roshdi. More than 600 years before Snell and Descartes. However Ibn al-Haytham knew the law of refraction in approximate form (θ_1 / θ_2 = constant) only.

A characteristic of modern physics is that theoretical formulation in different fields is based on principles and laws that can be formulated so compactly that they can be printed on a T-shirt : geometric optics (Ibn al-Haytham), mechanics (Newton), gravitation (Newton and Einstein), thermodynamics, quantum mechanics, standard models of fundamental interactions, etc.

While Euclid bases his geometry on five axioms to logically deduce multiple theorems, Ibn al-Haytham, on the basis of four propositions, derives multiple results from geometrical optics which he tests experimentally. It was a novelty in the natural sciences. Chemistry or biology relied on too few experimental facts at the time to achieve such a level of logical coherence reflecting reality.

Among his many contributions, he was the first to explain why the sun and moon seem larger when they are near the horizon; he established that moonlight comes from the sun; he understood that the phenomenon of dawn and dusk (light at sunrise and sunset without seeing the sun) is due to a phenomenon of refraction in the atmosphere, etc.

To Ibn al-Haytham applies what Hans Bethe (Nobel Prize in Physics 1967) told me 50 years ago: “In research, it is not enough to have sufficient intellectual qualities, you must also have the intelligence to choose a subject, an area where you can make an important contribution, taking into account your own limitations.” One thousand year ago, geometrical optics was such a field, unlike for example, Ptolemy’s world model[7].

Eye

[6] Roshdi Rashed, “The Celestial Kinematics of Ibn al-Haytham”, *Arabic Sciences and Philosophy*, Cambridge University Press, Vol. 17, 7–55.

[7] See appendix II.

By multiple experiments, with *camera obscura* (darkened chamber) in particular, Ibn al-Haytham showed that:

— "Sight does not perceived any visible object unless there exists in the object some light which the object possesses of itself or which radiates upon it from another object".

— Light rays emanate in all directions from each point on surface of all illuminated objects.

— Light rays intersect with each other without interference.

Ibn al-Haytham proves the theory of intromission according to which light enters the eye. It proves that all objects reflect light in all directions, but it is when a ray collides with the eye that we see the object reflecting the ray. Thus the eye can perceive the shape, the color, the transparency as well as the movement of the object. He also proved that indeed each of the two eyes captures an image even if only one is seen. He contradicted Ptolemy on the fact that the eye would emit light. According to him, if the eye was designed that way we could see at night. He understood that sunlight was scattered by objects and then entered the eye.

"Straight lines [exist between] the surface of the eye [and] every point on the surface of an object. An experimental study of this fact can easily be carried out with the help of rulers and tubes. If a part of the opening is closed, only that part of the object which is on a straight line between the eye and the body observed will be masked, the straightness being verified by the straightness of the ruler and the tube. It results from this experiment, with an evidence that dispels doubt, that the eye does not perceive as visible any object located in the same situation, this perception can only be realized by the reflection of light and by following straight lines that can be extended by imagination between the surface of the object and the surface of the eye. The view does not perceive any object unless there is some light from the object, either the object itself is bright or it is illuminated by the radiant light of another object."

"Illuminated objects emit light in all directions from the light impact on their surface. When the eye is facing an illuminated object, it is located on the light path that starts from the object. And as the property of light is to affect the sight and as the characteristic of the eye is to be sensitive to light then the sight is exerted thanks to the light which leaves the object and reaches the eye."

Ibn al-Haytham indicated vision occurs in the brain not in the eyes. Eyes are detectors, brain is an interpreter of reality. Scientific method is necessary to get a faithful picture of reality and not an illusory picture.

The scientific method

Ibn al-Haytham introduces his method of research into the introduction to his Book of Optics as follows:

"We should distinguish the properties of particulars, and gather by induction what pertains to the eye and what is found in the manner of sensation to be uniform, unchanging, manifest and not subject to doubt. After which we should ascend in our enquiry and reasoning, gradually and orderly, criticizing premises and exercising caution in regard to conclusions our aim in all that we make is subject to inspection and review, not to follow prejudice, and to take care in all that we judge and criticize that we seek the truth and not be swayed by opinion"

He formulated a theory about judgment and recognition of objects. He notices that we only recognize objects we know, and that the image of an object persists some time after we close our eyes. Recognition is based on memory and is not just a feeling, because we do not immediately recognize objects that are unknown to us.

Ibn al-Haytham, in developing his theory of optics, founded his realistic, materialistic, objective vision of the world. It practically distinguishes the propagation of light from the vision process. The eye is thus the prototype of the detector whose existence is independent of the observed object.

Ibn al-Haytham is the first to use scientific method systematically[8]:

(1) Start from existing observations and theoretical elements with a critical attitude.

(2) Define the project and formulate a hypothesis.

(3) Testing the hypothesis through controlled experimentation and analysis of results.

(4) Interpret them and draw conclusions (confirming, improving or changing the existing theory).

(5) Publication of results.

(6) Publication of description of different steps of measurements and of measurement instruments in order to allow verification of results by others.

Methodical doubt

Ibn al-Haytham practices methodical doubt by subjecting not only the writings of the ancients but also his own prejudices to ruthless criticism. Three examples:

I. “The seeker after truth is not one who studies the writings of the ancients and, following his natural disposition, puts his trust in them, but rather the one who suspects his faith in them and questions what he gathers from them, the one who submits to argument and demonstration and not the sayings of human beings whose nature is fraught with all kinds of imperfection and deficiency. Thus the duty of the man who investigates the writings of scientists, if learning the truth is his goal, is to make himself an enemy of all that he reads, and, applying his mind to the core and margins of of its content, attack it from every side. he should also suspect himself as he performs his critical examination of it, so that he may avoid falling into either prejudice or leniency.”

II. “The search for truth is arduous, the road that leads to it is full of pitfalls. To find the truth, one must set aside one’s opinions and not trust the writings of the elders. You must question them and submit each of their assertions to your critical spirit. Rely only on logic and experimentation, never on the affirmation of one another, for every human being is subject to all sorts of imperfections; in our quest for truth, we must also question our own theories, with regard to each of our research to avoid succumbing to prejudice and intellectual laziness. Do so and the truth will be revealed to you.”

III. Here is how Ibn al-Haytham responds in a scathing way to an anonymous contradictor who opposes his scientific conceptions : “From the statements made by the noble Sheikh, it is clear that he believes in Ptolemy’s words in everything he says, without relying on a demonstration or calling on a proof, but by pure imitation; that is how experts in the prophetic tradition have faith in Prophets, may the blessing of God be upon them. But it is not the way that mathematicians have

[8] Bradley Steffens, *op. cit.* (note 2).

faith in specialists in the demonstrative sciences. And I have taken note that it gives him [i.e. the Sheikh] pain that I have contradicted Ptolemy, and that he finds it distasteful; his statements suggest that error is foreign to Ptolemy. Now there are many errors in Ptolemy, in many passages of his books. If he wishes me to specify them and point them out, I shall do so."

The modernity of Ibn al-Haytham

As British-Iraqi physicist Jim Al-Khalili writes:

"In unpicking Ibn al-Haytham's contributions to science we find that his greatness is thus not so much a consequence of any single revolutionary discovery, such as Newton's inverse square law of gravity or Einstein's theory of relativity, or even al-Khwarizmi's algebra. Rather, it is the way he taught us how to 'do' science. I would therefore argue that he has a stronger claim to the title of 'father of the scientific method' than either Francis Bacon or Descartes. Ultimately what Ibn al-Haytham did was to turn experimentation from a general practice of investigation into the standard means of proof of scientific theories. We have no evidence to suggest that Ibn al-Haytham was not a devout Muslim[9], but his rational mind meant that he would accept nothing about the world that could not be verified experimentally. He always trusted and relied upon his observational skills and powers of deduction, for he believed that through logic and induction one can reduce all phenomena in nature to mathematical axioms and laws. In this way, he is every bit a modern physicist."

"Ibn-al-Haytham (Alhazen, 965–1039 C.E.) was one of the greatest physicists of all time. He made experimental contributions of the highest order in optics. He enunciated that a ray of light, in passing through a medium, takes the path which is the easier and 'quicker'. In this he was anticipating Fermat's Principle of Least Time by many centuries. He enunciated the law of inertia, later to become Newton's first law of motion. Part V of Roger Bacon's *Opus Majus* is practically an annotation to Ibn al-Haytham's *Optics*." (Abdus Salam [Nobel Prize in Physics 1979])[10].

Ibn al-Haytham's continuators in his geometrical approach for the theorizing of physics are, for example: (1) Isaac Newton who wrote his *Principia Mathematica* and his *Optics*, mostly, in geometrical language. He hardly used the differential and integral calculus he had just invented, probably to make his works more accessible to the physicists of his time. (2) Richard Feynman with his wonderful little book: *QED: The Strange Theory of Light and Matter*[11]. There, in its second chapter "Photons: particles of light", Feynman extends Ibn al-Haytham's geometric method to quantum physics, demonstrating the laws of light reflection and refraction in the quantum framework. A masterpiece. (3) Albert Einstein, in the kinematics of special relativity, especially in his demonstration of the relativity of simultaneity. Isn't it precisely on this point that Einstein surpasses Lorentz and Poincaré?

Ibn al-Haytham's modernity appears when his positions are compared to those of his European and American successors, six hundred years to a thousand years later.

1. Nature is written in mathematical language. "Philosophy [nature] is written in that great book which ever is before our eyes — I mean the universe — but we cannot understand it if we do not first learn the language and grasp the symbols in which it is written. The book is written in

[9] See appendix III.
[10] C. H. Lai, (ed.). *Ideals and Realities: Selected Essays of Abdus Salam*, World Scientific, 1987.
[11] Richard Feynman, *QED: The Strange Theory of Light and Matter*, 1985 https://www.scribd.com/document/358478820/QED-the-Strange-Theory-of-Light-and-Matter-PDF.

mathematical language, and the symbols are triangles, circles and other geometrical figures, without whose help it is impossible to comprehend a single word of it; without which one wanders in vain through a dark labyrinth." (Galileo.)

2. "To explain all nature is too difficult a task for any one man or even for any one age. 'Tis much better to do a little with certainty, & leave the rest for others that come after you, than to explain all things by conjecture without making sure of any thing."[12] (Isaac Newton 1704.)

3. "I think I know why these [Newton's] laws took the form they did. It is very simply, because to a very good approximation the world really does obey Newton's laws."

"So the world acts on us like a teaching machine, reinforcing our good ideas with moments of satisfaction. After centuries we learn what kinds of understanding are possible, and how to find them."[13] (Steven Weinberg, Nobel Prize in Physics 1979.)

4. "The ancient contrast between celestial Light and earthy Matter has been transcended in modern physics. There's only one thing, and it's more like the traditional idea of light than the traditional idea of matter"[14] (Frank Wilczek, 2004 Nobel Prize in Physics.)

5. There is a crisis in a part of physics [superstrings, cosmology, multivers,…] today. And this is not without consequence on the way to approach the reality in the whole of the society. This crisis lies in the questioning of the scientific method based (1) on the dialectic between experience and theory and (2) on the primacy of the verdict of experience. As German physicist Sabine Hossenfelder put it: "An increasing number of physicists, (…) have become strongly convinced of the viability of theories that have no empirical confirmation. This trend is most pronounced in the quest for a theory of quantum gravity — notably string theory — and in cosmology where theories for the early universe give rise to a multiverse. Why (…) do scientists trust theories that have not been experimentally tested? Worse, in some cases, these theories cannot even been tested in principle. Is this still science?"[15]

6. "Science works because, after hypotheses and reasoning, after intuitions and visions, after equations and calculations, we can check whether we have done well or not: the theory gives predictions about things we have not yet observed, and we can check whether these are correct or not. This is the power of science, that which grounds its reliability and allows us to trust in it with confidence : we can check whether a theory is right or wrong. This is what distinguishes science from other kinds of thinking, where deciding who is right and who is wrong is usually a much thornier question, sometimes even devoid of meaning." (Carlo Rovelli.)

7. To the question, why did he not receive the Nobel Prize for his work on Black Holes (black hole evaporation or Hawking radiation), Stephen Hawking (1942–2018), replied:

"The Nobel is given only for theoretical work that has been confirmed by observation. It is very, very difficult to observe the things I have worked on."

Here it is clearly stated that observation/experiment is the determining authority for judging whether a theory is correct, however attractive it may be.

8. In 1934, Albert Einstein wrote[16]:

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12 Statement from unpublished notes for the Preface to *Opticks* (1704).

13 Steven Weinberg, *To Explain the World: The Discovery of Modern Science*, Harper Perenial, 2016.

14 http://www.lightnessofbeingbook.com/inside_Why.html. See appendix IV.

15 https://www.forbes.com/sites/startswithabang/2015/12/10/why-trust-a-theory-physicists-and-philosophers-debate-the-scientific-method/#6f82034e1476. And more on: http://backreaction.blogspot.be/2018/05/dear-dr-b-should-i-study-string-theory.html . In contradistinction, see appendix V.

“[Ancient Greece] for the first time created the intellectual miracle of a logical system, the assertions of which followed one from another with such rigor that not one of the demonstrated propositions admitted of the slightest doubt - Euclid's geometry. This marvellous accomplishment of reason gave to the human spirit the confidence it needed for its future achievements. The man who was not enthralled in youth by this work was not born to be a scientific theorist. But yet the time was not ripe for a science that could comprehend reality, was not ripe until a second elementary truth had been realized, which only became the common property of philosophers after Kepler and Galileo. Pure logical thinking can give us no knowledge whatsoever of the world of experience; all knowledge about reality begins with experience and terminates in it. Conclusions obtained by purely rational processes are, so far as Reality is concerned, entirely empty. It was because he recognized this, and especially because he impressed it upon the scientific world that Galileo became the father of modern physics and in fact of the whole of modern natural science.”

In 1934, research on importance of the great Arab scientists of the 11th century was rare. Today, we are clearly invited to replace the names of Galileo and Kepler by the one of Ibn al-Haytham who lived six centuries before them!

9. "What is science to-day?"[17]

Science extends and enriches our lives, expands our imagination and liberates us from the bonds of ignorance and superstition. The American Physical Society affirms the precepts of modern science that are responsible for its success.

Science is the systematic enterprise of gathering knowledge about the universe and organizing and condensing that knowledge into testable laws and theories.

The success and credibility of science are anchored in the willingness of scientists to:

1. Expose their ideas and results to independent testing and replication by others. This requires the open exchange of data, procedures and materials.
2. Abandon or modify previously accepted conclusions when confronted with more complete or reliable experimental or observational evidence.

Adherence to these principles provides a mechanism for self-correction that is the foundation of the credibility of science.

Conclusion

In my opinion, the greatest originality and the most important scientific contribution to the contemporary world, from the Arab culture of the 8th to the 13th century was the introduction of the scientific method whose most illustrious representative is Ibn al-Haytham.

“The creation of Physics is the shared heritage of all mankind. East and West, North and South have equally participated in it. The creation of Physics is the shared heritage of all mankind.” (Abdus Salam)

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16 Albert Einstein, “On the Method of Theoretical Physics”, *Philosophy of Science*, Vol. 1, No. 2, (Apr., 1934), pp. 163-169 https://www.stmarys-ca.edu/sites/default/files/attachments/files/On_The_Method_of_Theoretical_Physics.pdf.

17 Adopted by APS Council on November 14, 1999, https://www.aps.org/policy/statements/99_6.cfm.

Appendices

I. *The Book of Optics*, by Ibn al-Haytham is divided in seven parts, seven Books:

Book I deals with al-Haytham's theories on light, colors, and vision.

Book II is where al-Haytham presents his theory of visual perception.

Book III and Book VI present al-Haytham's ideas on the errors in visual perception with Book VI focusing on errors related to reflection.

Book IV and Book V provide experimental evidence for al-Haytham's theories on reflection.

Book VII deals with the concept of refraction.

II. "Ibn al-Haytham's work in astronomy is (…) remarkable. For instance, one of his texts, *The Model of Motions of Each of the Seven Planets*, (…) outlined a new theory of planetary motion far in advance of anything Ptolemy had written. Modern historians of science now regard it as a monumental achievement and at the cutting edge of science at the time. We must not forget that lbn al-Haytham still believed in a geocentric model of the universe, but what he wanted above all was to 'mathematize' astronomy as he had done with optics. He wanted to be able to describe the observed motion of the planets in terms of pure geometry and was not particularly interested in the physical mechanism or reason behind their motion. Nor was he interested in the way the planets move in an absolute sense, but only as they are seen to move from the vantage point of the observer on earth. This 'phenomenological' approach is therefore independent of any notion of the earth going round the sun or the sun going round the earth; it was a theory of planetary dynamics from the earth's frame of reference. To help with this, he introduced a new concept what he called 'required time': the time needed for a planet to trace an arc in the sky. But he treated time in a way that a modern theoretical physicist would recognize, as a parameter in his mathematics; in fact, as a purely geometrical quantity."[18]

Ibn al-Haytham wrote a scathing critique of the physical reality of Ptolemy's astronomical system, noting the absurdity of relating actual physical motions to imaginary mathematical points, lines, and circles: "Ptolemy assumed an arrangement (*hay'a*) that cannot exist, and the fact that this arrangement produces in his imagination the motions that belong to the planets does not free him from the error he committed in his assumed arrangement, for the existing motions of the planets cannot be the result of an arrangement that is impossible to exist…. [F]or a man to imagine a circle in the heavens, and to imagine the planet moving in it does not bring about the planet's motion."

III. Scientific research and religion. Ibn al-Haytham: "I have constantly sought knowledge and truth, and it has become my conviction that, in order to have access to God's bliss and closeness, there is no better way than to seek truth and knowledge."

IV. The contemporary language of physics is that of optics. "Few observations are so common as light can be created from non-light, say by a flashlight or aborted and annihilated, say by a black cat. But translated into the langage of photons, this means that the quantum theory of Maxwell's equations is a theory of the creation and destruction of particles (photons). Indeed, the electromagnetic field appears, in Dirac's [electromagnetic field] theory, primarily as an agent of creation and destruction. The particles — photons — we observe result from the action of this field, which is the primary object. Photons come and go, but the field abides. The full force of this development seems to have escaped Dirac, and all his contemporaries, for some time, perhaps

[18] Jim Al-Khalili, *Pathfinders: The Golden Age of Arabic Science*, Allen Lane, 2010, Penguin 2016.

precisely because of the apparent specialness (dichotomy between light and matter!) of light. But it is a general construction, which can be applied to the object that appears in Dirac's equation — the electron field — as well."

This indicates the meaning of quantum field theory : "Both particles and light are epiphenomena, surface manifestations of the deeper and abiding realities, quantum fields. These fields fill all of space, and in this sense they are continuous. But the excitations they create, whether we recognize them as particles of matter or as particles of light, are discrete."[19]

In short, "the way that modern quantum field theory works is that you have a field, which has values everywhere throughout space and time. Particles are therefore considered to be fundamental disturbances or fluctuations of the quantum field. They kind of pop out, they undergo collisions, and we make measurements on them."[20]

V. "We have seen **how modern cosmology is faced with big questions which touch the very foundations of physics**. What is this form of matter which interacts only with gravity and apparently with nothing else? Why is the expansion of the universe accelerating? What caused the universe to undergo a period of rapid expansion soon after the Big Bang? These questions, motivated by cosmological observations, lead to questions about fundamental physics. Are there forces and interactions besides the four we know of, that is, gravity, electromagnetism, and the strong and weak nuclear forces? Are there particles beyond the Standard Model? What determines the value of the fundamental constants of nature? What is the real structure of spacetime? Are there extra dimensions? Science needs data, so each of these questions must be addressed through careful experiment.

The challenge of modern experimental physics is to probe nature at extreme distances and energies, well outside the capabilities of the instruments that were available to Einstein. It has certainly come a long way, as shown by the detection of gravitational waves in 2015, a feat which was thought to be impossible by many of Einstein's contemporaries.

General Relativity is not the final theory of gravity, for there is no such thing. As General Relativity turns 100, we would do well to celebrate it with a healthy does of scientific scepticism. Long live General Relativity, and a big welcome to its eventual replacement, whether in our lifetime or not."[21]

VI. The cornerstone of the interaction light-matter is the **fine structure constant α**. Its determination is a triumph of the deep inter-relation between experiment and theory:

$$\alpha\ (\text{Cs-133}) = 1/137.035999046(27)$$ [22]

and

$$\alpha(a_e) = 1/137.035999149(33)$$ [23]

[19] Frank Wilczek, "The Dirac Equation", in Graham Farmelo (ed.), *It Must be Beautiful: Great Equations of Modern Science*, Granta Books, 2002.

[20] Jim Baggott, https://fivebooks.com/best-books/physics-jim-baggott.

[21] Ivan Debono and George F. Smoot [Nobel Prize in Physis 2006], "General Relativity and Cosmology: Unsolved Questions and Future Directions", https://arxiv.org/abs/1609.09781.

[22] Richard H. Parker, Chenghui Yu, Weicheng Zhong, Brian Estey, and Holger Müller, *Science*, 360, 6385, pp. 191–195, published 13 Apr 2018, http://science.sciencemag.org/content/360/6385/191.

[23] Tatsumi Aoyama, Toichiro Kinoshita, and Makiko Nio, *Phys. Rev.* D 97, 036001, published 8 February 2018, https://journals.aps.org/prd/pdf/10.1103/PhysRevD.97.03600.