Development of Physical Science up to the 20^{th} Century

1. Prehistoric origins: The origins of the practices and techniques that were essential for the emergence of science and which, after extensive development, came to define the nature of science, especially physical science, begin in the dim recesses of prehistoric time. The pre-civilization, hunter gatherer groups and tribes developed the skills of careful observation and accurate counting and the retention of the important data in memory. These abilities were needed to reliably distinguish edible berries and other vegetation from toxic ones, to reliably track and skillfully hunt the game that were accessible to humans and to know ahead of time when and where to look for different varieties of edible plants and animals. With the discovery of agriculture and herding a great increase in the level of organization and record keeping and long term time keeping was needed. Allocating quantities of seed or sprouts to areas of land, or sizes of herds to grazing areas and anticipating the best times for planting and harvesting and calving and slaughter and the best methods and times for storage of what, for the first time, was surplus food; all of these activities of growing and more stable communities, as well as the increased barter trade between such communities, drove the continuing evolution of techniques for *remembering the past, keeping track of the present and anticipating the future*.

2. Early civilizations: We surmise these practices must have developed, not only from the evidence left at temporary and semi-stable sites of hunter-gatherer and agrarian groups, but also from the facts that with the appearance of the earliest civilizations, during the fourth and third millenia BCE, the practices and techniques are already highly developed. Written language for record keeping, practical arithmetic and practical geometry for accounting and measuring goods and land and construction and practical astronomy for keeping time are all in evidence. Indeed, there is already present elite, priestly groups within the civilizations that study arithmetic, geometry and astronomy for their presumed spiritual significance and further development. The investing of the practical techniques with spiritual significance is understandable on two counts. On one hand the apparent dichotomy between the turbulent, dangerous, life giving and taking Earth and the stable, reliable, cyclic and cycle laden sky, both literally awesome to early humans as they remain today, constitute natural abodes for the multiple deities of early religious belief. On the other hand the seemingly magical utility, without accompanying deep understanding, of the techniques of arithmetic, geometry and astronomy, which enable humans to quantitatively 'grasp' the Earth, the heavens and time, make those techniques into ‘gifts of the gods’ and deserving of spiritual reverance.

3. First explosion of theory: From this spiritual reverance there gradually evolves the theoretical reverance or deep interest for the sake of the technique alone. This transition is mainly driven as arithmetic and geometry and astronomy come to be seen as the domains in which humans can achieve levels of precision in thought that are unattainable in any other endeavor. While the beginnings of this attitude can be seen in the earliest civilizations, it appears with comparatively explosive development during the first millenium BCE with geometry and astronomy enjoying extensive development in Hellenic civilization while algebra (a generalization of arithmetic) and cosmological speculation was developing in India, the introduction of the zero concept being a singularly important event.

4. The Arabic preservation: The first millennium CE is widely characterized by political instability and the disintegration of societal institutions within the former and aging centers of civilization. Accordingly, we see mostly a conservative retrenchment in learning generally and in mathematics and science particularly. The principle exception to this being the preservation, translation and advancement efforts of the Islamic civilization originating in what is now the Arabian peninsula. This culture eventually extended from portions of western Asia across North Africa and southern Europe to Spain and flourished for a thousand years. The Arabs preserved much of the mathematics and science of the first millennium BCE and made their own contributions in medicine, optics and math. The transmission of this heritage to Europe (frequently under violent circumstances) helped to both stimulate and drive the Renaissance, which in turn led to the Scientific Revolution of the 17th Century.

5. Copernicus and Gilbert: The first major contribution to the revolution in physical science occurred in the 16th Cent., 1543 to be exact. This is the publication date of Nicolai Copernicus' (1473-1543) demonstration that the astronomical data from ancient times to his own could be more simply and more accurately represented in a model of the Universe that placed the Sun at the center and the Earth and other planets in orbit around the Sun as well as giving the Earth a daily rotation about its own North-South axis. The previous, Ptolemaic, system, with the Earth, motionless at the center, had been accepted throughout Western civilization, such as it was, for over a thousand years. Consequently, the Copernican system, initially, was widely regarded as absurd if taken literally, and was best accepted as merely an improved calculational tool. A literal interpretation was also objectionable for seeming to demote humanity and the Earth from center stage in the Universe; God's creation.

The rest of the truly major contributions occurred in the 17th Cent., beginning, in 1600, with the publication of William Gilbert's (1540-1603) study of magnets and discovery that the Earth behaves like a giant magnet, with poles aligned roughly near and under the geographic North and South poles[1]. This was an early indication that quantitatively precise science could pertain to terrestrial matters and not only to the heavens and astronomy.

6. Kepler and Galileo: The first half of the 17th Cent. saw the publications of Johannes Kepler (1571-1630) and Galileo Galilei (1564-1642). Kepler was a German mathematician and astronomer who, accepting Copernicus' main ideas literally and acquiring access to the new data of Tycho Brahe, data of unprecedented accuracy, was finally able to find an astronomical model which, in a simple manner, could do justice to the accurate data. To do this he had to break with the traditional, technical restriction of using only circles upon circles with offsets to describe the data[2]; a restriction that characterized both the Ptolemaic and Coperican systems. Kepler found the planets to move on ellipses, rather than circles, with the details of the motion governed by three simple rules. The demotion of circles as the only appropriate elements of astronomical models because of their 'perfection' amounted to a troubling but greatly freeing move of the scientific imagination from ancient traditions.

The Italian, Galileo, being the first scientist to turn the telescope, a recent invention, on the sky, discovered many features of astronomical bodies (the craters of the Moon, the sattelites of Jupter, the phases of Venus and Sunspots) that convinced him and others that the Copernican system (and its Keplerian modification) should be interpreted literally and not just as a mathematical tool. His other great work was to apply quantitative analysis to the experimental study of the motion of falling bodies and projectiles near the Earth's surface. This led to his introduction of a precise concept of acceleration and the discovery that, if air resistance is small enough, the vertical component of projectile motion always has the same constant acceleration while the horizontal component has no acceleration. These achievements, by one person, of (1), discovering genuinely unknown features of the presumably fixed and unchanging heavens (except for cycles) by technologically enhancing human observational powers and (2), discovering mathematically precise rules governing common terrestrial phenomena, thereby undermining, if not destroying, the long standing presumption of the perfection of the heavens against the corruption of the Earth, as well as his superb writing skills and his battle with the Church over his astronomical writings, have led to Gallileo being often judged the father of modern science.

7. The Age of Newton: By the late 17th Cent. many figures have taken up the pursuit of scientific discovery. But towering over all is the figure of Isaac Newton (1642-1727), born in England the year Gallileo died. Newton greatly enlarged the understanding of optics and the properties of light that had previously been achieved by Kepler, Gallileo and Descartes, inventing the reflecting telescope in the process. He furthermore pulled together the dynamical work of Kepler, Gallileo and only slightly lesser figures such as Huyghens and Hook to show that their work fit within a universal dynamical scheme governed by his famous 'three laws of motion' (**A1**) and a dynamical world held together by Newton's universal law of gravity.[3] He also discovered, contemporaneously with the German philosopher, Gottfried W. Liebniz, a whole new branch of mathematics (Calculus) that was essential for solving the bulk of the problems involving rates of change and raised by Newton's scheme. The totality of his discoveries and theories in physical science, astounding even to those of his contemporaries who did not agree with all of them and to all scientists to this day, were published in his later years in two masterpieces, "Phiosophia Naturalis Principia Mathematica", in 1687 (called today simply Newton's Principia) and "Opticks", in 1704. The most important disagreement for later developments was from Huyghens who examined and embraced the notion that light was a wave phenomena while Newton believed light to be a stream of particles[4] (**A2**). Nevertheless, with Newton's work physical science reached a level of unity and maturity from which hundreds of research programs were spawned that stretched through the next two centuries.

8. Consolidation in the 18th century: The 18th century is frequently referred to as "the age of reason" and the developments in the arts and sciences of the renaissance and the 17th century had, indeed, led to a growth in the confidence of Europeans, - i.e., the minority of comfortable, well off, educated, Europeans, - that by the exercise of reason humans could come to understand almost any aspect of the world, existence or life. Accordingly, physical science enjoyed an almost systematic and comprehensive elaboration and development of the scheme of ideas that Newton had presented in the "Principia" and the "Optics".[5] Newton's concepts and ideas were made clearer and more precise and were applied to an ever growing variety of circumstances. The dominant character of this approach was to regard all physical systems as consisting of numberless minute pieces of matter (particles), each moving under the influence of the totality of forces they all exert on one another in accordance with Newton's three laws of motion. The entire motion of such a system through time was completely determined by the positions and velocities of all the participating particles at any one time.[6]

Most of the contributors to this development were French, men of real genius such as Bernoulli, D'Alembert and Lagrange. But the dominant contributor was the German, Euler. The principles governing the motion of rigid bodies, elastic bodies and fluids were established in such a manner that one no longer had to bring genius to the table to master the subjects.[7] Because of the successes of these efforts, physical scientists began to think that the particular form of the theories and pictures of the world that emerged were the only forms that should ever be accepted as constituting real understanding and acceptable explanations. In other words the success of the new ideas led to their elevation to the level of dogma![8]

9. The 19th century: While all this was going on in the field that came to be called rational mechanics, other fields of phenomena such as heat and electricity and magnetism and novel aspects of light were being studied in the expectation that, eventually, they also would be included in the Newtonian, mechanical world view. But in the 19th century, when these less developed fields would enjoy their maturation and theoretical formulation, they would stretch the boundaries of the mechanical world view and, eventually, bring about its downfall.

a. Electricity and Magnetism: At first, through the work of Coulomb, Gauss and others, the forces associated with electric charges and magnetic poles seemed destined to be understood as similar to Newtonian gravity in acting instantaneously over large distances, the main novelty lying in their displaying repulsion as well as attraction. Eventually, however, the discoveries of Oersted and Ampere of the mutual influence of electric currents (moving charges) and magnetic forces, followed by Faraday's discovery (among many others) of the generation of electric forces due to changing magnetic forces (electromagnetic induction), led to the idea that the electric and magnetic forces distributed through space had a dynamical life of their own. Maxwell's mathematically precise formulation of these tentative ideas led to the gradual recognition of the Electromagnetic field as an entirely new kind of physical entity or system distributed continuously throughout all of space and time.

b. Light as Waves: The establishment, by Young and Fresnel, of light as a wave propagation (by displaying interference and diffraction phenomena (**A3**)) rather than a stream of particles, as the 19th century began, initiated the almost century long search for a mechanical model of the material medium that was doing the waving. It had to permeate interstellar space in order to carry starlight to us; it had to be very stiff in order for light to travel so fast and yet it, apparently, did not offer resistance to the motion of the planets through it.[9] The persistent failure of the many models that were tried eventually led to the recognition of light, also, as a new kind of physical entity, not grounded in matter.[10]

Maxwell's theory suggested that it was, in fact, the same kind of new entity as the electromagnetic field. Light was just an instance of propagating waves of the field with frequencies to which our eyes were sensitive.

c. Heat, Energy and Statistics: The remaining major development of physics in the 19th century occurred in the study of heat and thermal phenomena. Early on the studies of Fourier, on the conduction of heat through matter, and Carnot on the use of heat flow to generate mechanical work indicated an element of irreversibility; the impossibility of ever completely reversing a process involving heat flow. Somewhat later the recognition by Mayer, Thompson, Helmholtz and others that heat was not a conserved substance, but just a form of energy which spontaneously flowed from regions of high temperature to regions of low temperature and that the total amount of energy involved in any process was conserved, led to the attempt to interpret thermal phenomena in purely mechanical and/or electromagnetic terms. But, strictly speaking, pure mechanical and/or electromagnetic processes are all exactly reversible.[11] If, at any given time, one reversed the velocities of all the pieces of matter, the particles, and reversed the magnetic field everywhere in space, while leaving the positions of the particles and the electric field everywhere in space unchanged, the entire mechanical-electromagnetic system would then exactly run through its previous evolution in reverse. No matter that it would be impossible to actually pull off all the required reversals.[12] IF you could, THEN the reverse evolution would occur! Consequently, if one could understand thermal phenomena in mechanico-electromagnetic terms (and it gradually emerged that one could) then the irreversible aspects - the irreversible laws of thermal phenomena, such as the prohibition against a net decrease of disorder (entropy) during thermal processes within a closed system - had to be understood as statistical laws- laws that were overwhelmingly likely to hold but which could, extremely rarely, fail to hold. In this way statistical and probabilistic considerations came to acquire a fundamental position in the analysis of complex systems, another unnerving development to many scientists, but a harbinger of 'worse' things to come in the next century![13]

d. The Classical World Picture: So, as the end of the 19th century approached, the physical picture of existence that was accepted had the world consisting of matter (either continuously distributed or composed of infinitely divisible pieces or, possibly, composed of indivisible atoms) which was the source of gravitational attraction at a distance and, if electrically charged, was also the source of electromagnetic fields which, themselves, evolved in space and time and exerted forces on charged particles in ways that depended on where they were and how they moved. At the level of the individual atoms, if there were such things, the atoms were so numerous and their motions so complex and chaotic that only statistical and probabilistic modes of analysis could yield advances and a deep understanding of all thermal phenomena could only be had in such terms.

The basic properties of matter were mass, charge, position, velocity, acceleration, momentum, energy, angular momentum, the forces that acted on matter and the work that they did. The basic properties of the electromagnetic field were the electric and magnetic field magnitudes and directions at every point of space and every moment of time, their rates of change with time and the densities with which energy and momentum and angular momentum were distributed through the fields. All these properties had definite values at all times and if and when the values changed, they changed continuously, i.e., not by jumps, as time progressed.[14] The probabilities of thermal phenomena also had definite values at all times and changed continuously with time. All changes were in accordance with precise laws and the precise values of all the basic properties at any one time determined the values of those properties at any other time. Such was the picture.

Footnotes

(1) Current understanding: Earth has a core that is a solid, mostly iron ball surrounded by a region of molten iron that both rotates with the Earth and flows on its own. Because it's iron and because it flows, it generates a magnetic field which is very beneficial to us. Some of the other planets of our system have magnetic fields, but not all. Our Sun and essentially all stars have magnetic fields. All these fields are not rigidly fixed but are dynamic and change with time. The Earth's magnetic field may, presently, be entering a period of reversal.

(2) The ancient Greeks tended to allow esthetic values to constrain their science in ways that we no longer regard as appropriate. In particular, believing that the circle was the most 'pefect' geometric figure, they regarded an account or explanation of the motion of heavenly bodies as satisfactory only if it employed nothing but circles. For the stars and the Sun, this worked very well, but for the moon and the planets then known, the restriction to circles was difficult. Ptolemy accepted the restriction, but had to use systems of circles moving on circles and with off center placements of the circles in order to account for the data possessed at the time. With the passage of centuries the astronomical model deviated more and more from the data. Copernicus simplified the model by placing the Sun at rest (near but not quite in) the center and the Earth in orbit. But he still accepted the ancient restriction to circles and so also had to use off center circles moving on off center circles. Not until Kepler worked with the much more precise data of Tycho Brahe did anyone finally have the courage to abandon circles in favor of other closed curves which fit the data better. This elevation of the importance of data against aesthetic and traditional motives for selecting theories became a permanent feature of all subsequent science.

Kepler didn't know why the planetary orbits were elliptical. He simply recognized, after endless agonizing over trying numerous models to fit the data, that ellipses worked much better than anything else. It was Newton who showed that his theory of gravitational attraction of the planets by the Sun would explain the elliptical orbits of the planets.

(3)Newtonian gravity explained the elliptical Keplerian orbits, but with that explanation Newton and his contemporaries already knew that the ellipses, themselves, were not exact, but simply a very good first approximation. The exact orbits, influenced by all the gravitational pulls from all the planets and all the moons of all the planets, would deviate slightly from perfect ellipses, but in ways too complicated to calculate at that time.

(4) Newton thought light must be a stream of particles because light casts such sharp shadows whereas people knew that sound waves and water waves bend around corners and obstacles. He also thought streaming particles moving through a void was easier to understand for light coming from distant stars. An interstellar medium supporting waves would interfere with planetary motion around the Sun. Huyghens thought that light was a wave because beams of light can cross each other without scattering. Following DesCartes, he believed all space was filled with a medium of agitated particles. Ultimately Newton's influence prevailed and light was regarded as a stream of particles

until the end of the 18th cent. Then Thomas Young and Augustin Fresnel demonstrated interference and diffraction phenomena which are natural consequences of waves. The wave theory prevailed throughout the 19th cent. Then, in the very early 20th cent., Planck and Einstein argued that high frequency light had distinctly particle like features. Ever since we have understood light to have a dual personality, so to speak. It is both wave-like and particle-like, an instance of wave-particle duality.

(5) Newton, clearly, was an amazing person, but, unfortunately, not a very likeable person. He was very quarrelsome and very jealous of his competitors in science. He lived to a ripe old age and his increasingly rigid authority over British science gave continental Europe the opportunity to outpace British science during the 18th cent. Still, many have argued that his powers of creative imagination and analytical concentration have never been exceeded by any other scientist.

(6) The solar system is usually regarded as a prime example. Even parts of the solar system (Sun, Earth and Moon) are pretty good examples. In other words, if we know the locations and velocities of the Sun, the Earth and the Moon at any one time, then Newton's laws of motion and his theory of the gravitational forces between them will pretty accurately determine just where the Sun, Earth and Moon will be at any later time and where they must have been at any earlier time. The accuracy will slowly diminish with increasing duration of the time intervals because we have ignored the gravity from the other planets and their satellites. If we include them, the accuracy persists longer, but the calculation of the future positions becomes much more complicated. Another example is the determination of the future motion and positions of a swinging pendulum due to Earth's gravity and air resistance. If the position and velocity of the pendulum is specified at any one time, then the later positions and velocities are determined and calculable.

(7) This is important! The vast majority of practicing scientists and engineers, certainly including yours truly, neither possess nor require genius for their work. They are, at best, well educated and, perhaps, a little clever and, most important, fascinated by their work. They are all dependent on the small number of geniuses and the growing armies of merely clever minions who have preceded them.

(8) This is always at risk of occurring! It actually occurs to varying degrees in different specialties at different times. The dogma of Newtonianism became so intense and long lasting precisely because Newton's ideas applied so broadly and worked so well for so long. Today the various branches of science mostly progress so rapidly that deep seated, long lasting dogmas hardly have a chance to arise. But some slower moving sciences, like paleontology and geology, can still harbor them. Think of the long battle over Plate Tectonics.

(9) This passage is more technically dense than usual with terms like 'interference' and 'diffraction' and 'material medium'. I wont try to explain them here, but will draw an analogy with sound. We recognize sound as a wave phenomena where the molecules of the air vibrate back and forth as a sound wave passes by. The people who argued that light was also a wave phenomena had to explain what stuff was vibrating back and forth

for a light wave that came from the Sun. The stuff would have to fill the space between Earth and the Sun. Wouldn't that stuff provide resistance to erode the Earth's motion around the Sun? The light wave theorists had a hard time answering such questions.

(10) This was difficult for many to accept. But it appears, more and more all the time, that not only is light just as legitimate a physical entity as matter, but that matter only *appears* more 'real' than light. In essence matter and light seem to be two forms of energy, with matter being a more concentrated form.

(11) This was important and, for many, troubling because it meant that our distinction between the past and the future is something that could not be found in the laws that seemed to govern the motion of mechanical - electromagnetic systems. By reversing all velocities and magnetic fields at one instant of time, any such system would then evolve as if the former past had become the future. It makes our future - past distinction seem only psychological rather than physically real.

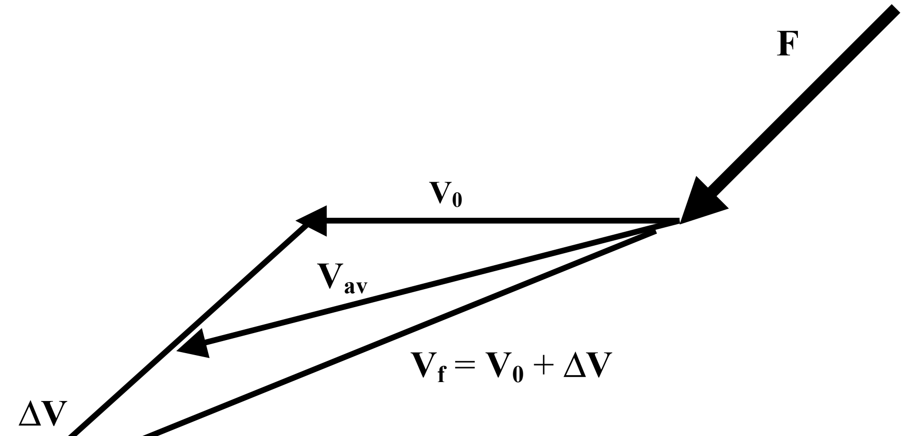
(12) Once physical laws are discovered, many scientists systematically study them to try to discern all their general properties. Reversibility was recognized in this way.

(13) For many scientists this meant that thermal 'laws' weren't really laws! More precisely, while the laws of mechanics and electromagnetism were seen to be precise and exact, the laws of thermodynamics involving heat and temperature came to be understood as merely VERY likely and referring to averages. While the difference is very great as a matter of principle, in practice the thermodynamic laws hold VERY nearly as precisely as the mechanical and electromagnetic laws. They are certainly every bit as important and the difference enabled the laws of thermodynamics to not be reversible and to capture some aspect of the human distinction between past and future. Nevertheless, there still exists a residual controversy over the degree, if any, to which the irreversibility of thermal-statistical laws reflect an element of subjectivity and human psychology in physical science.

(14) With some exceptions, most of the examples that we call laws of nature are statements about the manner in which changes occur. Newton's laws tell us how the velocities of material particles change due to the forces that act on them. The electromagnetic laws (Maxwell's equations) tell us how the electric and magnetic fields change due to the charges and currents that produce them. The thermodynamic laws tell us how the forms of energy, including heat, change into one another due to temperature differences and forces doing work. Fortunately, even when a lot of things are changing, not everything is changing. The total energy stays the same. So does the total momentum and the total electric charge, etc. But accounting for some of the changes when and while they are going on is among the most important things that laws of nature enable us to do.

(**a**) $\mathbf{F}_{AB} = - \mathbf{F}_{BA}$

(**b**)

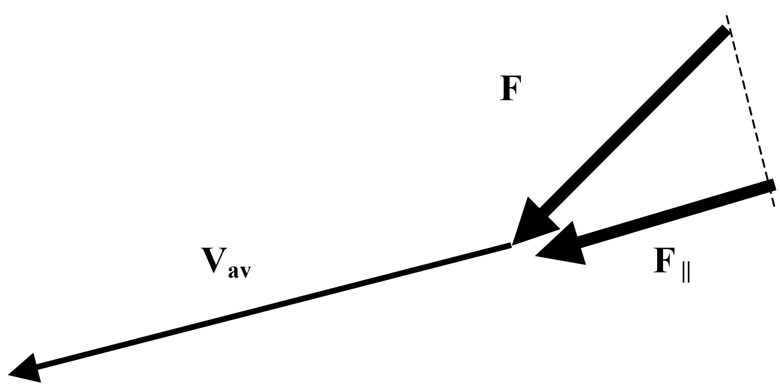


$\mathbf{V_f} = \mathbf{V_0} + \Delta\mathbf{V}$

$\mathbf{V_{av}} = (1/2)(\,\mathbf{V_f} + \mathbf{V_0}\,)$

$M\,\Delta\mathbf{V} = \mathbf{F}_{\mathbf{res}}\,\Delta t$ or $M\,(\,\Delta\mathbf{V}/\,\Delta t\,) = \mathbf{F}_{\mathbf{res}}$

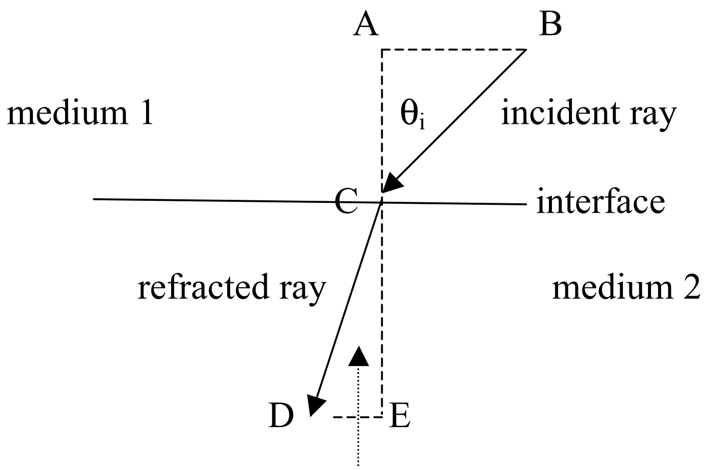
(**c**)



$W = \pm\ |\,\mathbf{F}_{||}\,|\,|\,\mathbf{V_{av}}\,|\,\Delta\, t$

$W_{tot} = \Delta\, K$

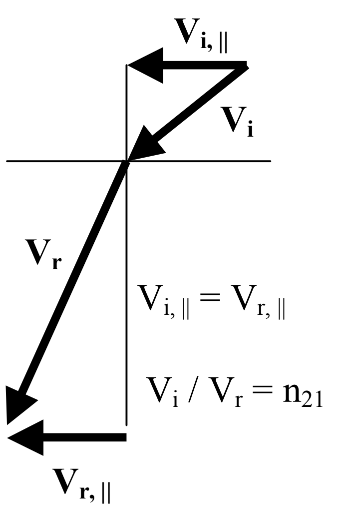
A1: The basic principles of the mechanics of material particles and systems composed of them: (**a**) Newton's third law, the action – reaction principle, (**b**) Newton's second (and first) law(s), resultant force changes velocity at a rate inversely proportional to mass, (**c**) the definition of work done by a force on a material body and the work –energy theorem relating the total work done to the change in kinetic energy.

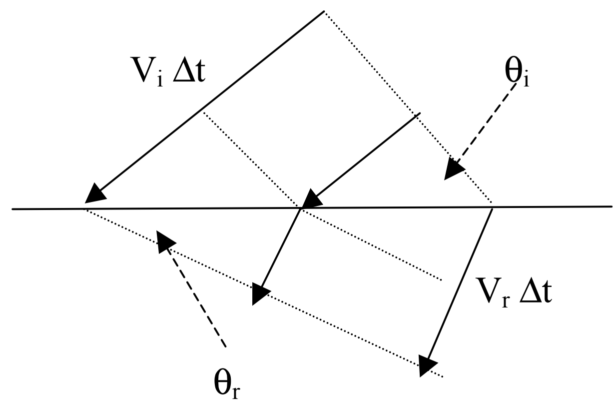


(**a**)

$\underline{AB} / \underline{BC} = \sin \theta_i$ θ_r $\underline{DE} / \underline{DC} = \sin \theta_r$

The law of sines: $\sin \theta_r / \sin \theta_I = \text{constant} = n_{21}$



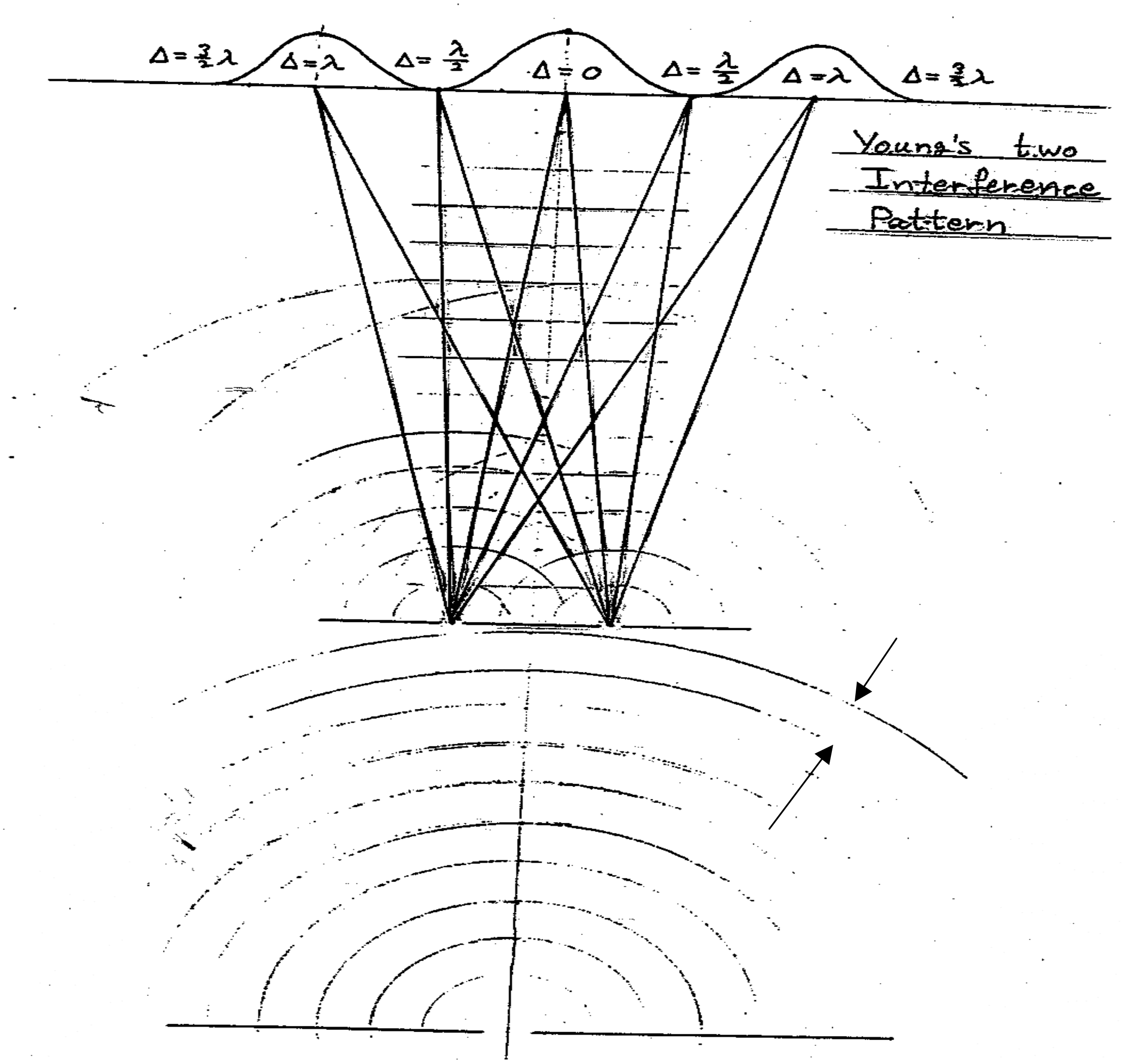


(**b**)

$V_i \Delta t / \sin \theta_i = V_r \Delta t / \sin \theta_r$

$V_i / V_r = n_{21}$ $V_r / V_i = n_{21}$

A2: The refraction of light passing from some ‘medium 1’ to some ‘medium 2’: (**a**) the observed law of sines discovered by Descartes and Snell, (**b**) (left) Newton’s particle theory account of refraction, (right) Huyghens wave theory account of refraction.



$$\lambda f = c$$

A3: Young's double slit interference experiment demonstrating the wave nature of light. Path lengths from the two slits differing by an odd number of half wavelengths give destructive interference. Path lengths differing by an even number of half wavelengths give constructive interference.