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Dr. Thomas Young—Natural philosopher

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This year marks the 200th anniversary of Thomas Young's presentation of his pivotal essay on cohesion in fluids in which, among other important insights into capillarity, he stated in qualitative terms the concept of the Contact Angle. This, together with the Young/Laplace Equation (relating the surface tension to the pressure and radius of curvature) have formed the foundations of Capillarity theory and practice.

It is interesting and timely to review briefly the life and achievements of this remarkable man who formally trained as a medical practitioner. A child prodigy brought up in the classics, with a command of numerous ancient and existing languages, he was a rare spirit driven to understand all physical phenomena about him; a polymath in an age of scientific enlightenment, he left an indelible mark in the humanities, sciences and technologies—in linguistics, egyptology, optics, the strength of materials, bridge and road construction, among many other fields.

What interests us particularly today is that he always returned to the intriguing question of how particles are associated and held together to form the various states of matter. He invoked a model of matter being held together by short range attractive and repulsive forces acting between particles and gave plausible explanations of phenomena such as rigidity, elasticity and rupture, and what interests us in particular for this Meeting, because of his involvement in the hydrodynamics of blood flowing through capillary vessels, he made astonishing insights into basic Capillarity.

1. Introduction: Thomas Young the polymath

This meeting on a theme of Capillarity falls on the 200th anniversary of Thomas Young's presentation of his historic essay to the Royal Society, in which he anticipated many of the fundamental principles of capillarity. It is fitting and timely to take a fresh biographical glance at the life and works of a scholar who has left his name and a powerful impression in this and other fields of knowledge.

It is surprising to learn that, had this meeting concerned other subjects—such as medicine, civil engineering, the decipherment of codes or even classical poetry—the name of Thomas Young would not have been out of place. In looking into his life and achievements, this is the over-riding impression—Thomas Young, original mind, fertile intellect and true polymath. Living in an age of enlightenment, all knowledge and philosophy was his natural domain. It was also an age impelled by the industrial revolution and (perhaps reflecting his puritan background), he also concerned himself with practical social matters and in the skilled trades and in applied research. Hence it is astonishing to learn of the wide gamut and depth of his research and teaching in the sciences, arts and humanities: on the hydrodynamics of blood flow; on acoustics; optics; statics; mechanics; theory of tides; bridge construction; and more exotically, on Greek poetry, Coptic and other eastern languages and on the decipherment of Egyptian hieroglyphics (where he anticipated some of the work of the great Champollion).

Hence we shall touch upon the way of life, the works and attitudes of those times some 200 years ago when Capillarity, the subject in which we are all engaged today was given a firm scientific foundation by Young and his contemporary, Laplace as well as other scholars, including Gauss.

Young's essay of 1804 [1] is mainly concerned with capillarity theory and practice. Curiously, it was entitled "Cohesion in Fluids". This paper was not the outcome of a life dedicated to this unique field, but a singular outburst on a subject matter that probably came to his attention through his professional work in medicine and in particular the dynamics of blood flow in capillary vessels. In the same manner, we draw attention to the numerous other studies he made and which he presented as a set of some 60 lectures for the Royal Institution in London, where he was retained as a Professor: "A Course of Lectures on Natural Philosophy and the Mechanical Arts"—considered as an intellectual mine of originality and inspiration, which contains the bulk of his output and discoveries. Sweeping across a wide field on countless subjects, ranging from carpentry to the fundamental structure of matter, each subject was treated with the same respect and in depth. These were the times of a true universality of learning where natural Philosophers recognised no boundaries in human knowledge and in his case, no distinction in value between utilitarian matters and abstract philosophical and scientific matters.

2. The example of "Young's Modulus"

We are reminded that most students in the physical sciences are introduced to the name of Young through the important parameter on the strength of materials, the "Young's Modulus". This demonstrates well the breadth of Young's interests.

In this time of the Industrial Revolution, the use of iron and steel was proliferating in all sorts of civil structures and machinery and not forgetting in the engines of war. Clearly the rupture strength of steel was of paramount importance. This was treated in one of Young's lectures, "Passive Strength and Friction", wherein he considered the engineering properties of solids—such as extension, compression, flexure and fracture in terms of (remarkable for his times), the arrangements and movements of the basic units of matter. As a tool for architects and engineers of his day, Young defined a quantity, the "passive strength" or elasticity of a material. He then proceeded to describe the familiar stress-strain relationship in a metal as follows:

"*The simplest way in which a body can be broken is by tearing it asunder. The cohesive force continues to be increased as long as the tenacity of the substance allows the particles to be separated from each other without a permanent alteration of form; when this has been produced, the same force, if its action continued, is generally capable of causing a total solution of continuity; and sometimes a separation takes place without any previous alteration of this kind that can be observed*" (brittle fracture).

Here he is dealing with the fundamentals of elasticity and rupture in crystalline solids, anticipating modern theoretical understanding such as crystal plane slip, gliding and work hardening which have been subsequently understood largely through the introduction of Dislocation Theory. Note how, in his own words, he anticipates modern notions of ductility and even creep in crystalline materials:

"*The more capable a body is of permanent alteration of form, the more ductile it is said to be—pure gold, silver, annealed iron. Wood admits of little permanent change of form, except in the green state—even stone will become permanently bent in the course of years*".

3. Historical background of Young's work

It is interesting and helpful to digress a little at this point to consider the general historical circumstances in which Young lived and worked. Europe, already experiencing a wider industrial revolution and colonial rivalry now found itself in a state of momentous social upheaval and revolutionary wars. It was also ironically a brilliant period of intellectual enquiry—we recall that Napoleon in his military venture into Egypt and the Middle East took with him many scholars—engineers, mathematicians, astronomers. In addition to a wide-spread urge to change the political structure of society, there existed a universal urge to discover new knowledge.

Yet during this period of strife, there was, surprisingly, a considerable amount of communication among scholars throughout Europe. In spite of official expectations on scientists to work on technological aspects of warfare - such as explosives, metallurgy and artillery—in general they continued their involvement in their special scientific interests. During the lull in the wars, we learn of fraternal visits between Young, Arago and Gay-Lussac in order to discuss each other's work. Young was elected as a foreign member of the Institut de France; Volta was another. The world of science was in considerable ferment and the fraternity of science was eager to learn of new discoveries and to exchange ideas. Inevitably, there arose vexing antagonisms in matters such as priority of discovery, a phenomenon unfortunately better known today.

In this connection, we mention for the record that Young's "Essay on the Cohesion of Fluids" in which his main discoveries in Capillarity were announced, was read to the Royal Society of London on the 20th of December 1804 and published in 1805 in the Philosophical Transactions of the Society. Very soon after, in 1806, Laplace read his Memoir "Théorie de l'Action Capillaire" to the Institut de France and it was published the following year, 1807, as a Supplement to the 10th Volume of his momentous "Mécanique Celeste" [2] Starting from an entirely different position and applying rigorous analytical techniques, Laplace arrived at capillarity formulations identical to those of Young, very probably without knowledge of the work of Young. This led to bitter friction between the two with accusations of plagiarism, although Laplace later wrote in recognition of the priority of Young's discoveries.

4. A note on Young's style and personality

Young's essay on the cohesion of fluids established his views that capillarity phenomena were the result of the "cohesive attraction of the superficial particles" which result in a uniform tension of the surface. It is a concisely written exercise in logic, totally descriptive with not a single mathematical or other symbol. It is an intense and difficult paper to understand and to discover the nuggets of truth buried in it. In this connection, his main biographer, Peacock [3], states: "The investigations which it contains are amongst the most original and important he made to physical science; but being conducted without the aid of figures or symbolical reasoning, are extremely obscure." Without doubt, this was one of the main reasons for the difficult confrontation with Laplace whose publication the following year with its elegant analytical presentation was quickly appreciated by his contemporaries.

Furthemore, Young was not a popular lecturer; as with his writings, his style and delivery was very compact, the thought flowed quickly and he did not allow for members of his audience with less intellectual proficiency. He did not pander to the gallery. The presentation of his landmark course of lectures on Natural Philosophy was all but a dismal failure—to quote again Peacock, "If indeed, these lectures were delivered nearly in the form in which they are printed, they must have been generally unintelligible, even to the prepared persons in spite of the many important discoveries they contained".

As a point of interest, we note that Young was often compared and contrasted with Humphrey Davy, a fellow professor at the Royal Institution and an outstanding and popular lecturer. Young suddenly and unexpectedly resigned from his post, claiming that he wished to devote more time to his medical practice. In fact, he was forced out by new circumstances. The Institution was developing a new image, a style of fashionable science, in which science was being used as a sort of popular entertainment. This was a far cry from the original reason for founding the Institution by Count Rumford, namely, "to bring together the Natural Philosophers and those engaged in arts and manufactures in order to improve industrial and domestic efficiency"—an aim which science policy makers today would consider admirable. The Managers of the Institution were now turning it into a respectable centre for polite upper class society and for the subscribing nouveau riche industrialists, who came with their ladies to be titillated by light hearted lectures such as the hilarious effects of "laughing gas".

Young stood out as a scholar with strong moral principles. He could not support the prostitution of science for the amusement of the shallow rich classes. He stood out boldly for his views and the truth as he saw it, in the great tradition of Socrates. At one stage he dared to criticise the corpuscular theory of light associated with the name of Newton, at that time a revered figure. Young's wave theory of light was heavily ridiculed mainly because he questioned accepted dogma. In spite of his personal sensitivities, Young is for our times a model of scientific integrity and courage.

5. Young, Laplace and capillarity

Although we focus here on Young because of the anniversary aspect of his work on capillarity, in order to do justice to this theme we should consider the almost simultaneous discoveries of two brilliant minds, Young and Laplace: one a polymath who adorned with originality every subject he touched, the latter a mathematical astronomer who made epochal studies on the structure of the universe and the birth of planets. Both turned to capillarity theory for different reasons and from different positions and both arrived at similar conclusions.

Young assumed an elementary model of matter as a system of particles that are impenetrable to one another. How these particles congregated and cohered to form the various states of matter, gaseous, liquid or solid became for him an over-riding interest. Earlier, he had postulated the hypothesis of a dense, lumeniferous "ether" that encapsulated all bodies, but by the time of his Essay of 1804, his ideas had moved sharply to a consideration of the effects of interactive short range forces. Perhaps his fundamental contribution to the understanding of capillarity was his belief that the contractile tendency of free surfaces was related to forces which act over atomic distances, that is to the same forces which determine cohesion in matter.

6. The equation of Young and Laplace

Arguably the most important law in capillarity theory and practice is that which relates the pressure difference across a curved interface to the surface tension and the curvature. It has enabled the understanding of meniscus effects and numerous interfacial capillarity phenomena. Furthemore, most of the techniques for measuring surface tension in fluids are based on this relation. Because of the fundamental importance of this law and because it was discovered independently and at about the same time by Young and by Laplace, it has to be in the best scientific spirit to call this relation, in common with other authors in the surface sciences, The Equation of Young and Laplace.

We note that the concept of a fluid surface adopting a curved shape in response to a pressure difference is of considerable antiquity and it was well appreciated by those who came before Young. For those interested, Adam [4] in his well known book on surface chemistry provides a simple geometrical derivation of the equation for a surface having two radii of curvature, in the well known form:

$$\Delta P = \gamma \left(\frac{1}{R_1} + \frac{1}{R_2} \right)$$

where ΔP is the pressure difference across the interface, γ the surface tension, and R_1 and R_2 the principle radii of curvature. Which for the surface of a sphere, becomes

$$\Delta P = \frac{2\gamma}{R}$$

In his Essay, Young introduces the essence of this equation in a conceptual form, without the aid of figures or symbols, as follows:

"It is well known, and it results immediately from the composition of forces, that where a line is equally distended, the force that it exerts, in a direction perpendicular to its own is directly as to its curvature; and the same is true of a surface of simple curvature; but where the curvature is double, each curvature has its appropriate effect, and the joint force must be as the sum of the curvatures in any two perpendicular directions".

In the Essay and in a later extensive Memoir [5], Young related the form and tension of the surface to the binding strengths between particles. For this he introduced two short range forces which operate simultaneously—a Repulsive force which varies inversely with distance between particles and a Cohesive force, assumed to be constant in magnitude but operating over a very short distance. Through the joint action of these two forces which effectively determine the state of binding between particles, he explained many well known capillarity phenomena such as the height of ascent of fluids in capillary tubes. In addition he was able to demonstrate the above fundamental concept of capillarity—how on any point on the curved part of the surface, the action of the Repulsive and Attractive forces would give rise to a resultant force directed to the concave part of the surface, which would be greater with increasing curvature.

As noted earlier, the Memoir of Laplace on Capillarity appeared soon after that of Young. The model of Laplace consisted of an incompressible fluid and between the constituent particles, he assumed the existence of a force of attraction over a short range, the force being "sensible at insensible distances" to use his description. From this assumption and with his clear exposition and analytical skills, Laplace developed the general differential equation for the surface of a fluid from which he deduced the basic capillarity laws.

Although Young and Laplace discovered essentially the same basic relations, we must be aware of the sharp differences of opinions between them and in particular Young's extreme sensitivity in feeling that his work had been ignored. In one of the arguments, Young asserted that since Laplace recognised no other molecular forces than those which are attractive, an impossible situation had been created. Thus in his Memoir of 1809 [5], Young states:

" M. La Place seems to rest the most material part of his claim to originality in the deduction of all the phenomena of capillary action from the simple consideration of molecular attraction. To us, it does not appear that the fundamental principle, from which he sets out, is at all a necessary consequence of the established properties of matter."

It was not until 1890 that the misunderstandings between the two were clarified in Rayleigh's paper [6] on "The Theory of Surface Forces". This brought to light the full value and originality of Young's work, which was somewhat concealed by the obscurity of his presentation. Rayleigh made clear scientific judgements and came to the rescue of Laplace in connection with Young's accusations regarding the absence of repulsive forces, stating that "it would appear at first as if the attractive forces were left to do the impossible feat of balancing themselves". However, Rayleigh pointed out that Laplace had introduced in his theory a pressure term, which is really the representative of the Repulsive Force, adding, "all that we need to take into account is then covered by the ordinary idea of pressure—it presents to the mind a good picture of capillary phenomena".

In effect, in the Laplacian model of matter as a continuous, incompressible mass, the parts are assumed to attract one another resulting in an internal pressure, called by Rayleigh the "Intrinsic Pressure". This pressure is a measure of the cohesive strength of the substance. In the case of a solid, Rayleigh argues reasonably that this corresponds to the rupture strength. Thus in this manner, as in Young's model, a fundamental connection is made between the forces of molecular cohesion (the molecular binding energy) and the forces giving rise to a uniform surface tension.

7. The contact angle: The equation of Young and Dupré.

It is typical of Young's scientific methodology that he first throws out a fundamental statement, seemingly based on intuition or "common sense", then proceeds to demonstrate this with well known phenomena and finally attempts to prove it in terms of the basic properties of matter. This is exactly the manner in which he introduces the concept for which he is probably best known in Capillarity theory and practice, the law of the Contact Angle. Quoting from the Essay of 1804:

"*But it is necessary to premise one observation, which appears to be new, and which is equally consistent with theory and experiment; that is, for each combination of a solid and a fluid, there is an appropriate angle of contact between the surfaces of the fluid, exposed to the air, and to the solid.*"

At a later stage, Young treated this problem in the simple familiar manner, as an equilibrium between three forces (Fig. 1)—the two surface tensions and the interfacial tension resolved parallel to the solid surface, giving the simple relation

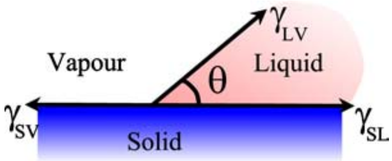

Figure 1 Three phase equilibrium of interfacial tensions.

$$\gamma_{SV} = \gamma_{SL} + \gamma_{LV}\cos\theta$$

It is interesting to note here that Young had no difficulty with the notion of a surface tension at an interface between a solid and a liquid, something which troubled Rayleigh. In turn he applied the concept of interfacial energy introduced earlier by Gauss. In this connection, he states, "This principle, applied to a hypothetical displacement in which the point of meeting travels along the wall, leads with rigour to the required result." Adamson [7] in his book gives an elegant derivation of the Contact Angle law by considering small displacements in surface and interfacial energies in the manner of Rayleigh. (He shows also that this derivation remains rigorous regardless of the macroscopic geometry of the surface.)

We should be aware of the several important shortcomings in the practical application of the Contact Angle Law as shown above. Among these:

(a) Possible effects of the micro-topology of the solid substrate: for this, there have been empirical treatments which introduce a corrective term, the "roughness factor",

(b) Again, the equation assumes an idealised value of the surface tension for the solid substrate appropriate to a perfectly clean surface: in practice, nearly all substrates except that of gold have an adsorbed layer of the vapour phase, which changes substantially the surface tension of the solid. Where known, of course this should be used.

(c) But probably the most questionable feature of the application of the Law is that a vertical component of surface tension, $\gamma_{LV}\sin\theta$ is ignored. In most cases this may be justified, but there are combinations of substances where it is suspected that the shape of the three phase boundary could be affected because of the highly stressed zone of contact. This matter should be studied further.

Young was clearly the first to formulate the Contact Angle Law. In passing, it is worth bearing in mind that Laplace made a similar derivation without recourse to concepts of surface energy or surface tension, using procedures that even Rayleigh found difficult to follow.

However, at a later point in time, we become aware of the remarkable efforts of Dupré who in 1869 introduced the very useful term, the Work of Adhesion, defined as the difference in interfacial energy between adhering and separated phases. From the basic contact angle law, he arrived at the simple and practical relation:

$$W_{SLV} = \gamma_{LV}(1 + \cos\theta)$$

In this form, it has had wide application in many fields of surface chemistry.

It is for this reason and also in common with many scientific authors, we call the Contact Angle Relation the Equation of Young and Dupré—this gives credit to Young's discovery and also due recognition to Dupré for his huge efforts in the practical application of the concept.

References

1. T. YOUNG, *Phil. Trans. Roy. Soc.* **95** (1805) 65.
2. P. S. DE LAPLACE, "Sur l'Action Capillaire," Supplement to Book 10, "Traité de Mécanique Célèste," Coureier, Paris, 1806.
3. G. PEACOCK, "Life of Thomas Young" (John Murray, Albermarle St, London, 1855).
4. N. K. ADAM, "The Physics and Chemistry of Surfaces" (Oxford University Press, Oxford, 1938).
5. T. YOUNG, "Cohesion", in "Miscellaneous Works of Dr Thomas Young," edited by G. Peacock and J. Leitch (John Murray, London, 1856).
6. J. W. S. LORD RAYLEIGH, *Collected Papers* **3** (1890) 397.
7. A. ADAMSON, "Physical Chemistry of Surfaces" (Interscience Publishers, John Wiley, NY, 1967).
8. A. DUPRÉ, "Théorie Mécanique de la Chaleur," Paris, 1869.

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