Plenary Lecture

NAME, NUMBER AND UNIT

G. F. Hewitt

Imperial College, London, England

11th International Heat Transfer Conference

Kyongju, Korea, 23 – 28 August 1998

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by

G. F. Hewitt
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INTRODUCTION AND BACKGROUND

It has been something of a tradition that the Opening Address at the International Heat Transfer Conferences is on a topic of general interest, not specifically reflecting the Assembly President's personal research. In considering the options for my own Address, I decided to talk about *people* rather than *science and technology*, my theme is people within their framework of scientific endeavour. Let us start with a well known equation:

$$Nu = 0.023 Re^{0.8} Pr^{1/3} \qquad (1)$$

which is generally known as the Dittus-Boelter equation (though the original equation differs somewhat from this!). Equation 1 already finishes us with three of the *dramatis personae* of this lecture, namely Nusselt (Nu), Reynolds (Re) and Prandtl (Pr). In fact, my interest in the subject of this lecture has arisen from a chance remark made to me by Tom Davies of the University of Exeter during a conversation at the 1997 UK National Heat Transfer Conference. We were talking about Reynolds and Tom Davies told me that he had visited the tomb of Reynolds in the town of Watchet in Somerset. Shortly afterwards I was in Somerset and also visited the tomb which bears the inscription:

"SACRED TO THE MEMORY
OF OSBORNE REYNOLDS
BORN AUG 23RD 1842, DIED FEB 21ST 1912

ALSO ANNE CHARLOTTE HIS WIFE
BORN DEC. 11TH 1859, DIED MAY 27TH 1942

AND OSBORNE REYNOLDS, BORN APRIL 29TH 1917
KILLED IN ACTION, FRANCE, MAY 27TH 1940

ALSO RICHARD HENRY REYNOLDS, BORN JUNE 16TH 1940
DIED OF WOUNDS, ITALY, APRIL 2ND, 1944"

Presumably, the second Osborne Reynolds and Richard Henry Reynolds were the grandson of their famous predecessor. I could not help reflecting that the tomb of a man whose name is spoken many thousands of times every day did deserve a little less obscurity. Watchet is a small port town on the Bristol estuary, at the end of narrow road; a place that time seems to have passed by. This developed in me a desire to know more about Reynolds and about his fellow-occupants of Equation 1.

Looking more closely at Equation 1, we can discover the remaining members of the *dramatis personae.* The dimensionless groups in Equation 1. Are defined as $Nu = \alpha D/\lambda$, $Re = VD\rho/\eta$ and $Pr = c_p\eta/\lambda$ where α is the heat transfer coefficient ($W/(m^2.K)$), D the tube diameter (m) and λ the thermal conductivity of the fluid (W/(m.K)), V the fluid velocity (m/s), ρ the fluid density (kg/m^3), η the fluid viscosity ($N.s/m^2$) and c_p the specific heat capacity (J/(kg.K)). We can thus see that the other famous inhabitants of Equation 1 reside in the *units,* namely Newton (N), Joule (J), Watt (W) and Kelvin (K).

In what follows, we will discuss all of the seven great men whose names are hidden in Equation 1, starting with Nusselt and going full circle to Reynolds.

WILHELM NUSSELT (1882-1957)

Wilhelm Nusselt (Fig. 1) was born at Nurnberg, Germany on November 25th 1882. He studied at the Technical Universities of Berlin-Charlottenburg and Munich, graduating in Munich in 1904.

Figure 1: Wilhelm Nusselt ((1882-1957)

He carried on to work for his doctorate at Munich, being granted this in 1907 based on work on the conductivity of insulating materials. Following this, he was an assistant to Mollier in Dresden in 1907-1909 before entering one of his most productive periods at the University of Karlsruhe. He became a Professor at Karlsruhe in 1920 then moved to a chair at the Technical University of Munich in 1925, a post he occupied until his retirement in 1952. Nusselt died on September 1st 1957 in Munich.

Although Nusselt continued to do excellent work throughout his whole career, his most famous achievements occurred whilst he was still in his early thirties. In 1915 he published his paper "The Basic Laws of Heat Transfer" (Gesund. Ing. Vol. 38, pp 447-482, 490-496, 1915) which proposed the basic dimensionless groups for modelling of heat transfer, including what later became known as the Nusselt Number. In 1916, he published his famous work: "Film Condensation of Steam" (Zeit. VDI. Vol. 60, pp 541-546, 569-575, 1916) in which he derived for the first time the basic equations of film condensation. It is noteworthy that these equations still form part of the curriculum of most engineering courses and, perhaps surprisingly, are almost universally applied in the design of condensation systems. I say "surprisingly" since real systems are very much more complex than the ones envisaged in the original theory; the equations fit reasonably well because of a number of self-compensating factors. Nusselt also studied a wide range of other problems including the combustion of pulverised coal, laminar entrance region heat transfer and the analogy between heat and mass transfer in evaporation.

LUDWIG PRANDTL (1875-1953)

Prandtl (see Fig. 2) was born at Friesing, Bavaria on February 4th 1875, qualifying in Munich in

Figure2: Ludwig Prandtl (1875-1953)

1900 with a thesis on elastic stability. He became Professor of Applied Mechanics at Gottingen in 1904 at the astonishingly young age of 29 and retained this position until his death on August 15th 1953. Prandtl could rightfully claim to be the founder of modern thermodynamics and aerodynamics. His discovery of the boundary layer (1904) led to an understanding of skin friction and drag with obvious application to the reduction of drag on airplane wings. He developed a theory (1918-1919) for wings of finite span. His other many interests included supersonic flow and turbulence and he was a pioneer in the development of wind tunnels for modelling experiments in aerodynamics.

ISAAC NEWTON (1642-1727)

Now we come to the first of our inhabitants of Equation 1, whose name resides in a *unit* rather than in a *number*. Newton (see Fig. 3) was born on Christmas Day, 1642 at Woolsthorp Manor,

Figure 3: Isaac Newton (1642-1727)

Lincolnshire. After attending the King's School at Grantham starting in 1654, he went on to do a B.A. degree at Cambridge in 1665. In 1665, Cambridge University was closed for a year because of the Great Plague and Newton returned to Woolsthorp Manor House; this was a year of contemplation and astonishing discovery, the so-called *anna mirabilis* in which Newton developed the "method of fluxions" (calculus), the theory of light, and, most importantly, began his work on gravitation.

Newton became the Lucasian Professor of Mathematics in 1669, was elected a Fellow of the Royal Society in 1672, becoming President in 1703. In later life, Newton became Warden of the Royal Mint in 1695, holding this lucrative post until his death on March 20th 1727. Figure 3 shows a picture of Newton in his later years.

It is difficult to revisit the life of Newton without a sense of awe. His discoveries in optics would, in themselves, given him immortality. He discovered that white light was composed of rays of different colour which, when passed through a prism, were bent out of their paths at different angles (Fig. 4). This is why the lenses used in telescopes in Newton's day always produced blurred images with coloured fringes. This problem can, of course, be overcome by using two lenses of different materials but Newton never succeeded in making a true achromatic lens for telescopes; he got round the problem by inventing the reflecting telescope (Fig. 5). However, Newton's most important contribution lay in his development of the laws of motion and the related laws of gravitation. Near the earth's surface, a weight falls 4.9m in 1 second and the basis of Newton's hypothesis for lunar and planetary motion was that the gravitational force was proportion to $1/r^2$, where r is the distance from the attracting body. The moon was known to be at a distance from the earth of sixty times the earth's radius. Thus, the moon would "fall" towards the earth by a distance 4.9/3600 = 0.00136m in a second. The "fall" could also be calculated from the radius of the lunar orbit which was known as a multiple of the earth's radius.

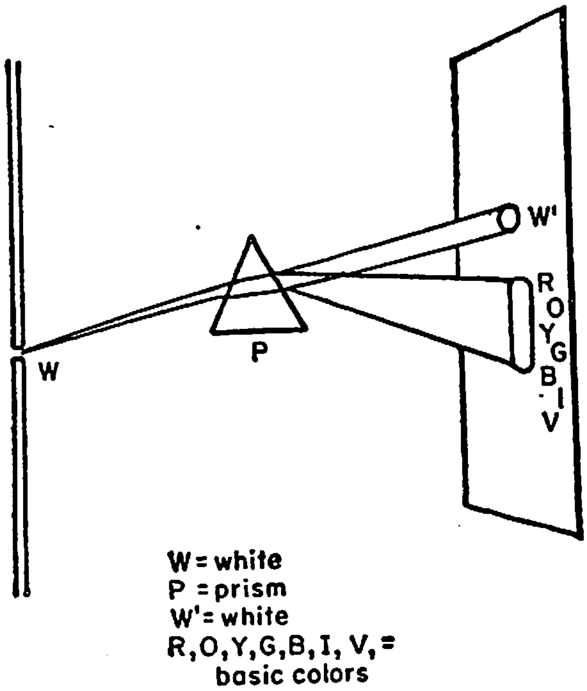


Figure 4: *Newton's experiment on refraction of light by a prism*

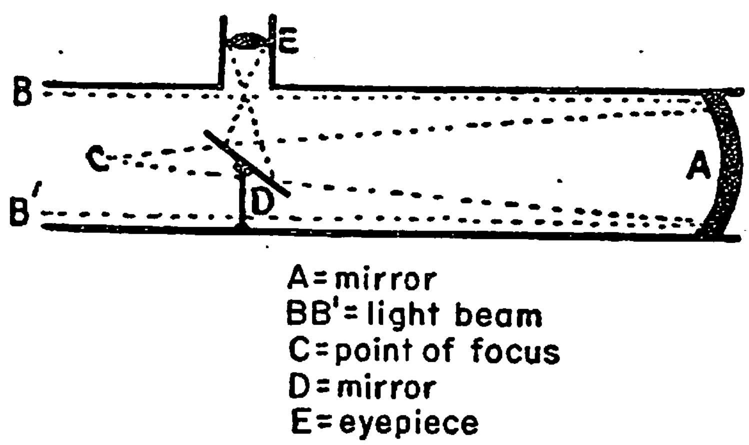


Figure 5: *Newton's reflecting telescope*

Unfortunately, at the time Newton made the original calculation, the radius of the earth was believed to be 5530km and Newton calculated the fall of the moon in one second to be 0.00118; this was too far outside the value predicted on the basis of gravitation to satisfy Newton and he set the calculations on one side. However, six years later, a new estimate of the radius of the earth (6370km) was made and the theory now agreed precisely! However, it was only at the prompting of Edmund Halley that Newton was persuaded to publish the results of his findings; his first publications in the area of optics were controversial at the time and Newton, in a letter to the secretary of the Royal Society, said: "I see a man must either resolve to put out nothing new, or to become a slave to defend it". Nor did he seek fame, refusing to publish his solutions of certain problems with the words: " I see not what there is desirable in public esteem were I able to acquire and maintain it. It would perhaps increase my acquaintance, the thing which I chiefly study to decline". In these days of excessive communication by e-mail, one can certainly sympathise with this point of view !

The publication of *Philosophiae Naturalis Principia Mathematica* (embodying the laws of motion and gravity) in 1686 represents perhaps the most significant contribution ever to the scientific literature. The theory of gravity was triumphantly successful. Notable in the successes were:

(1) An explanation for differences in the periods of pendulums between Paris and at the equator. Newton suggested that this was due to small deviations of the shape of the earth from spherical form. That the earth was, in fact, a flattened spheroid was confirmed by a French Academy expedition in 1735.

(2) Comets have large elliptical paths, influenced in complex ways by the planets in the solar system. By studying historical records, Edmund Halley realised that comets reappeared regularly and predicted the return of the comet named after him (Halley's Comet) on the basis of the theory of gravity in1747/1758. A French convert to the theory of gravity (Alexis-Claude Clairaut) aided by a Hortense Lepaute (a sort of human computer who worked at the Paris Observatory) predicted the return more accurately by taking account of more interactions. His calculation indicated a period March/May 1759. It duly arrived, reaching perihelion on the 14th March 1759 !

(3) Working independently, J. C. Adams in England and U. J. J. Leverrier in France started calculations aimed at demonstrating that irregularities in the motion of the planet Uranus were due to the presence of another planet (subsequently named Neptune). On completion of the calculations, Leverrier sent his results to J G Galle of the Berlin Observatory, who trained his telescope at the predicted position and discovered the planet !

The law of gravitation can be expressed in the form:

$$F = G\frac{m\,m'}{r^2} \qquad (2)$$

Where F is the force between two masses m and m' at a distance r apart. The gravitational constant G (whose value is $6.670 \times 10^{-11} M.m^2/kg^2$) could not initially be determined since the mass of the earth was unknown. However, both the validity of the inverse square law and the value of G was measured in elegant experiments by Cavendish using a torsion balance.

Whewell (quoted by Harvey-Gibson) sums up the achievements of Newton in developing the theory of gravity as follows:

> *"The great Newtonian induction of universal gravitation is indisputably and incomparably the greatest scientific discovery ever made, whether we look at the advance which it involved, the extent of the truth disclosed, or the fundamental and satisfactory nature of this truth."*

Alexander Pope's epitaph on Newton's tomb in Westminster Abbey in London says a similar thing more poetically:

Nature and Nature's Laws lay hid in Night
God said, Let Newton be! and all was Light

JAMES PRESCOTT JOULE (1818-1889)

Joule (Fig.6) was born in Salford near Manchester on December 24th 1818. He was the son of a

Figure 6: James Prescott Joule (1818-1889)

wealthy brewer and himself had ample means (except towards the end of his life when he was saved by a pension granted by Queen Victoria). Thus, he was able to pursue his scientific interests independent of the framework of a university system (though he had good contacts with Reynolds and other scientists through the Manchester Literary Philosophical Society). He did not have formal education; rather, he was tutored by resident tutors including the father of chemistry, John Dalton, in 1834-37. In 1838 he started his first laboratory in his father's house and always maintained a private laboratory until his death on October 11th 1889 in Sale near Manchester.

Joule's obsessive interest throughout his life was in the *Mechanical Equivalent of Heat*. To understand this obsession, one has to appreciate the context in which he worked. When he started his experiments, heat was considered to be a substance (*caloric*). Power could be generated from caloric by passing it from a higher to a lower temperature. The analogy was with a waterwheel where water at a high level drove the wheel whilst passing to the lower level. This process did not result in the destruction of the water and it was believed that the same thing applied to the mysterious substance *caloric*. The alternative theory was that heat was related to the vibration of atoms within a substance (the *dynamical theory of heat*). The caloric theory was in the ascendancy at the time Joule began his experiment and was supported by many eminent people including Laplace and Clapeyron. It seems amazing that the caloric theory still had it's adherents even towards the end of the 19th century, and, indeed, I myself have been accused of being such an adherent; Professor Edwin Le Fevre accused me of being such when I had carelessly used the term *specific heat* rather than *specific heat capacity* in a handbook article which he had reviewed!

Joule carried out an exacting series of experiments converting electricity firm voltaic cells, electricity from magneto-electric sources, mechanical energy from paddle wheels and mechanical energy from the flow of water in tubes and waterfalls into heat. His final value for the mechanical equivalent of heat was 772ft-pounds per Btu (the best value nowadays would be around 778ft-pounds).

Joules paddle wheel experiment is illustrated in Figure 7.

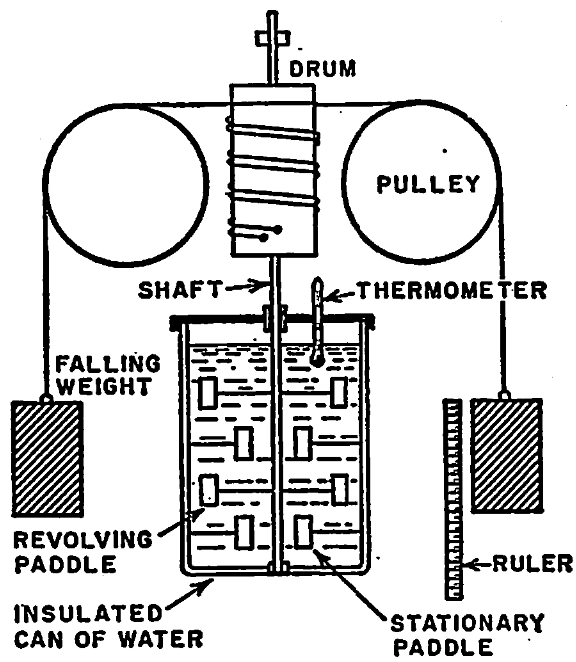


Figure 7:Joule's paddle wheel experiment for the determination of the mechanical equivalent of heat.

Many of Joule's experiments had temperature changes as low as 0.5^{0}C and, to achieve the accuracy he needed, temperature measurements to ±0.003^{0}C were required. Such accurate measurements could only be achieved by enormous attention to detail and were received sceptically by his contemporaries. William Thompson quotes:

> *"His boldness in making such large conclusions from such very small observational effects is almost as noteworthy and admirable as his skill in extorting accuracy from them. I remember distinctly at the Royal Society, I think it was Graham or Miller saying simply he did not believe Joule because he had nothing but hundredths of a degree to prove his case by".*

I think that the main conclusion I draw from looking again at Joule's life is that patience and persistence in obtaining accurate experiments can ultimately influence enormously the way we look at things! The principle of conservation of energy is now such a natural part of our view of nature that it seems extraordinary that this principle was not accepted before the work of Joule which was, after all, relatively recent!

JAMES WATT (1736- 1819)

James Watt (Figure 8) was born at Greenock (near Glasgow) on January 19th 1736. He never had any formal education. He started an apprenticeship as a scientific instrument maker in London in

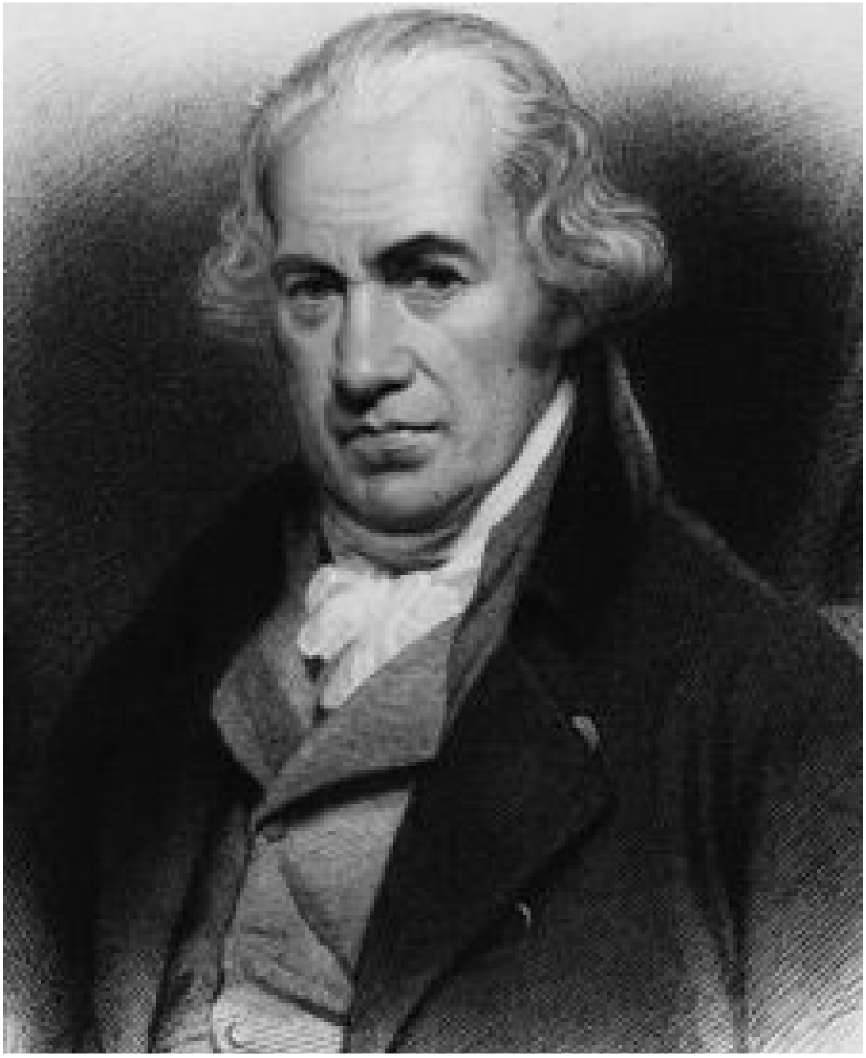


Figure 8: James Watt (1736-1819)

1755, but left after one year. With the help of friends in Glasgow, he set up a workroom at the University of Glasgow where he became friends with Professor Joseph Black who interacted closely with him in a variety of projects.

James Watt's story is an extraordinary one in that he became a folk hero in Britain and elsewhere for something he did not actually do, namely invent the steam engine. In the popular imagination, we have the picture of James Watt as a child looking at the way in which the lid of the kettle rose when the water boiled and converting this into the idea of the steam engine. In fact, the steam engine already existed, the most advanced form being the Newcomen engine which came into operation in 1712 and continued to be developed for a further sixty years. In 1769, there were 99 engines of this form in the north of England, their main purpose being to extract water from mines. The principle of the Newcomen engine is illustrated in Figure 9.

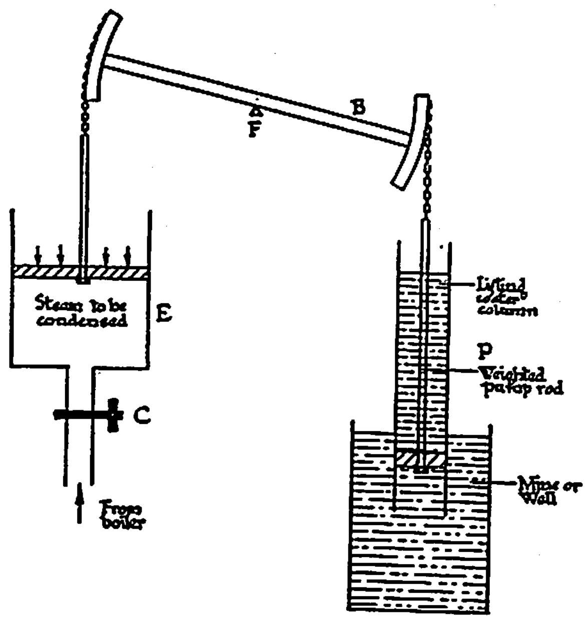


Figure 9. The principle of the Newcomen atmospheric engine.

The cylinder is fed with steam from the boiler and valve C closed. Water is then sprayed either onto or into the cylinder, condensing the stream inside. This causes the rocking arm to move, lifting water up as shown. The whole process is then repeated and even the earliest engines were able to achieve a stroke rate of 10 per minute or more, delivering water to great heights relative to the bottom of the mines. James Watt entered the steam engine arena when asked to repair Glasgow University's model of a Newcomen engine in 1764. He realised that the engine would be more efficient if the steam were condensed in a separate condenser and not in the cylinder (this avoided repeated cooling and heating of the cylinder wall materials with consequent loss of efficiency) and that the steam itself could be used to actuate the piston rather than atmospheric air. After a period of development (foreshadowing the present day method of development of new products using small scale models etc.), James Watt eventually patented the condensing engine in 1769. He was lucky to form a partnership with Matthew Boulton (the son of a Birmingham engineer) and the famous company of Boulton and Watt came into being, producing the first really successful single-acting engine in 1774. The development work continued, an important feature of this being the evolution of a system for cutting off the steam supply to the cylinder, the steam already in the cylinder continuing to expand to drive the piston for the remaining part of the stroke. This lead to the development of the double acting condensing engine and the extent of the progress in this development work can be judged by comparing Figures 10 and 11 which show respectively the single acting condensing engine and the double acting engine , in the latter case with a rotary action.

The development of the steam engine did, of course, contribute greatly to the industrialisation of England and elsewhere and James Watt had an important role in this development. Thus, though he certainly did not invent the steam engine, he can be remembered as a pioneer who combined an insight into the physical processes occurring in steam engines with an aptitude for mechanical design and development. In short, he was the epitome of the best in the engineering approach.

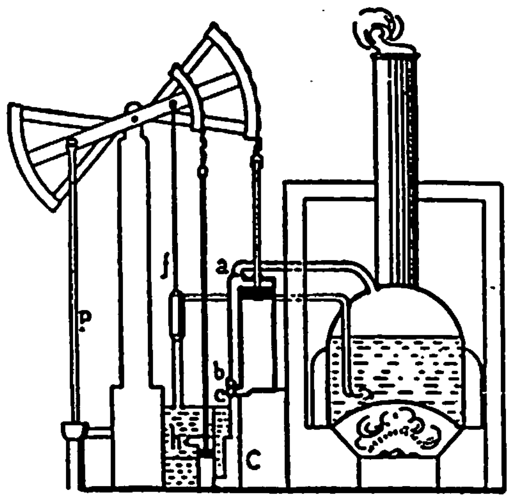


Figure 10. *Watt's single acting condensing engine*

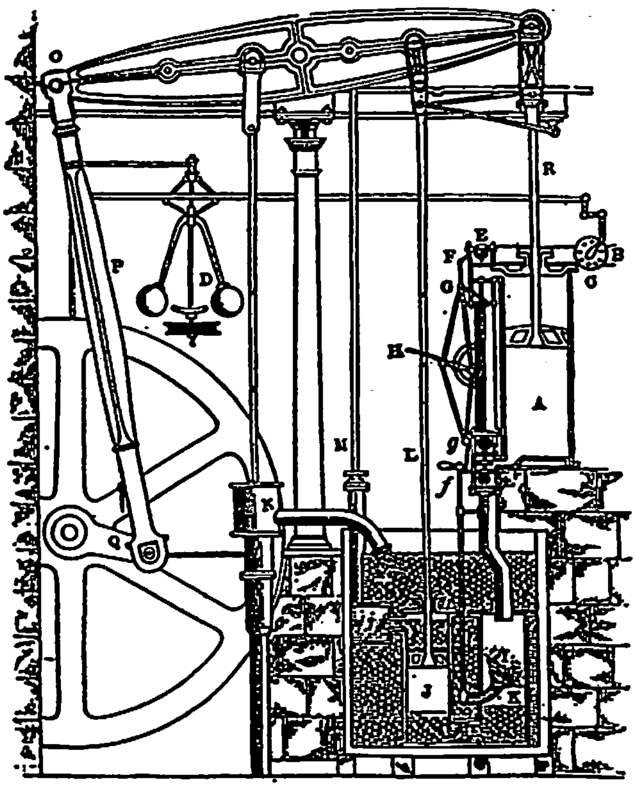


Figure11. *Watt's double acting condensing engine*

LORD KELVIN (WILLIAM THOMPSON) (1824-1907)

William Thompson was born on June 26th 1824 in Belfast, Ireland. In 1841, he entered Cambridge University to study advanced mathematics. After spending a year with Regnault in Paris in 1845, he went to Glasgow University in 1846 to become Professor of Natural Philosophy. He held this chair for 53 years. He was created Sir William Thompson in 1866 and became Lord Kelvin in 1892. He died on December 17th 1907.

Lord Kelvin made numerous contributions in thermodynamics, hydrodynamics, field theory etc. However, he was also involved in many developments which met widespread application and also made him a relatively wealthy man. These practical developments included improvements in telegraphy; he was deeply involved in the successful linking up of the Atlantic telegraph in 1866 and developed the siphon recorder, which recorded telegraphic signals on moving paper. Lord Kelvin was also involved in navigation, developing the magnetic compass and sounding apparatus.

In the context of his habitation of Equation 1, Lord Kelvin must be remembered for his definition of the Absolute Temperature Scale, his work on this subject being published in 1848. It should remembered that his work on this subject (like that of Carnot) was done within the framework of the caloric theory of heat. A degree in the absolute temperature scale is defined as *" the amount that a unit of caloric had to fall in order to produce a unit of work"*. However, in a footnote in this paper, Kelvin mentions the work of Joule which was just then beginning to emerge, saying that this was inconsistent with the idea of the permanent existence of caloric (heat). Strongly influenced by the work of Joule, Kelvin then became a strong adherent to the interpretation of heat as molecular motion and his papers on this subject ("On the Dynamical Theory of Heat", published 1851-55) lead to the development of the Second Law of Thermodynamics.

OSBORNE REYNOLDS (1842-1912)
Now we come full circle to complete our description of the inhabitants of Equation 1, back to

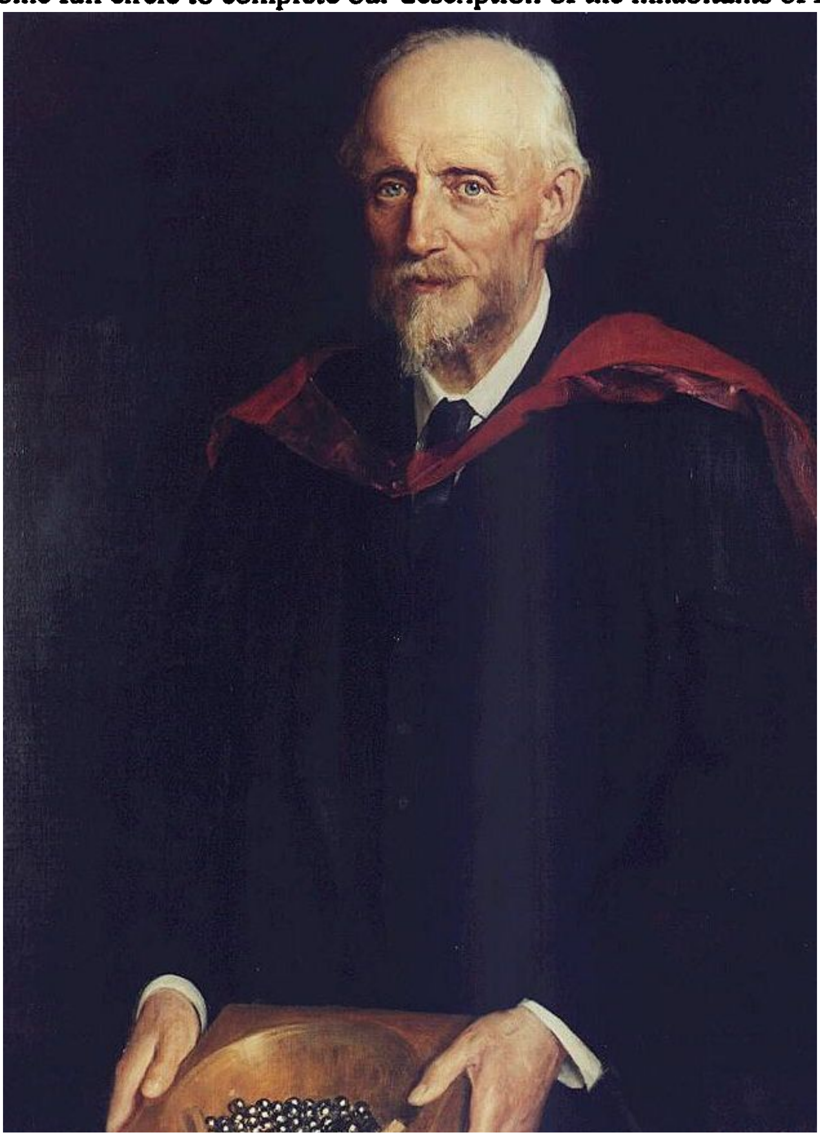


Figure 12. Osborne Reynolds (1842-1912)

where it all started with Osborne Reynolds. Reynolds (Figure 12) was born on the 23rd August 1842 in Belfast, Ireland and was educated at Queens College, Cambridge from 1863-1867. In 1868, he was appointed to the new Chair of Engineering at Owens College, Manchester (later the University of Manchester). He held this chair until his retirement in 1905, when he moved to Watchet in Somerset, dying there on the 21st February 1912.

Reynolds is, of course, best known for his work on turbulence but, during his career, he worked on many other subjects including thermal transpiration of gases through capillary tubes, cavitation (where he made the first demonstration of the effect), critical flow in orifices, determination of the mechanical equivalent of heat using a steam engine, improvements in pumps and turbines, modelling methods for rivers and estuaries and dilatancy and the theory of the universe. His classical experiment on the onset of turbulence is illustrated in Figure 13. And Figure 14. shows the results. The appearance of turbulence was described as follows:

> *".. all at once, the colour band appeared to expand and mix with the water (b). On viewing the tube by the light of an electric spark, the mass of colour resolved itself into a mass of more or less distinct curls, showing eddies".*

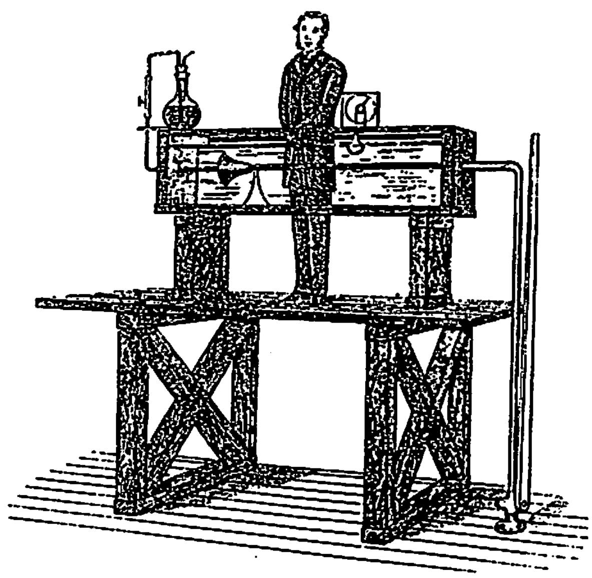


Figure 13. Reynolds experiment on turbulence

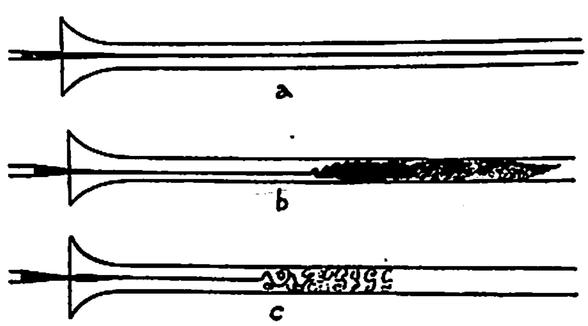
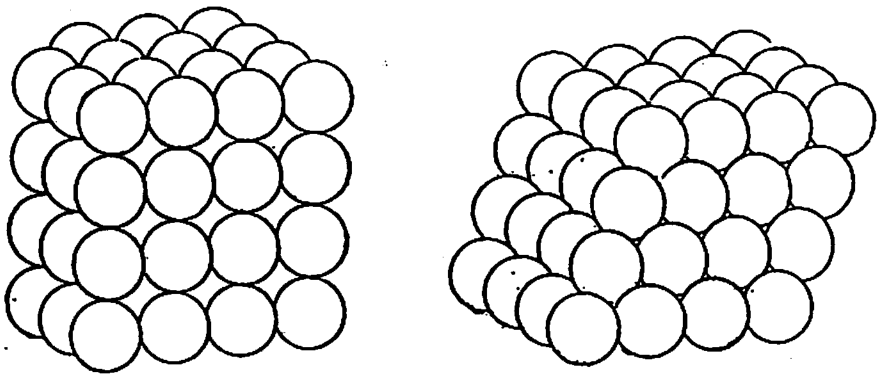


Figure 14. Results from Reynolds experiment

It was interesting to note that with the smooth entrance conditions used by Reynolds in his original experiment, the critical values of Reynolds number were in the range 11,800 to 14,300. This represents what is now known as the *higher critical Reynolds number*. Later, Reynolds showed that if the fluid entering the tube is disturbed then the critical Reynolds number is around it's well known value of 2000 (the *lower critical Reynolds number*). Reynolds was a distinguished mathematician in addition to being an experimentalist and was able to develop the theory of turbulence based on averaging, leading to the well-known "Reynolds stresses".

A curious episode in Reynolds' life occurred towards the end of his career and arose from his interest in *dilatancy*. His favourite illustration of the principle is shown in Figure 15.



(*a*) (*b*)

Figure 15. Illustration of Dilatancy

A pile of spheres in cubical form occupies a volume which is √2 times that of a close packed form. An intriguing illustration of the effect of dilatancy is given when one walks on the beach near to the sea's edge. Around one's footprint, and perhaps counter - intuitively, the sand becomes dry rather than wet. This is due to a change in the pore structure leading to transport of water into the compressed region, with drying out of the surrounding region.

Again, in considering this final work of Reynolds, one has to remember the context of the Victorian scientific scene. There was great concern about explaining the long-distance transmission of light. If light was in the form of waves, there must surely be a medium (the *ether*) through which the light was transmitted. Gravity must also be a property of the ether. In Maxwell's theory of electromagnetic waves, it was not necessary to postulate such a medium and the concept of "action at a distance" was born. Furthermore, the idea of transmission of *photons* as small elements of energy was more intellectually satisfying in explaining the way that light moves through the universe. However, Reynolds (like many other Victorian scientists) felt the need to specify a medium through which transmission of light and gravity could be achieved. Reynolds *magnum opus* on this subject was submitted for publication in 1902, near to the end of his scientific career. The referees of the Royal Society were critical of his paper ("on the Sub-mechanics of the Universe ") and there was a view perhaps his mind was beginning to fail! Finally, the article was published by Cambridge University Press, copies being distributed to the Royal Society in the same way as the *Philosophical Transactions.*

If, indeed, Reynolds mind was beginning to fail, then this view has to be reconciled with the curiously quantitative nature of the predictions which Reynolds made. He suggested that the universe consisted of a granular medium whose pressure was 1.172×10^8 Bar. The diameter of the grains of the medium was 5.534×10^{-20}m and the grains had a mean relative velocity of 0.677m/s. The mean free path of the grains was calculated as 8.612×10^{-26}m. Reynolds postulated that matter (as we know it) is simply the gaps between the grains in this granular medium. On the basis of this medium, he was able to explain gravity and the transmission of light and the subject had clearly occupied him for several decades before the publication of this paper. Professor George Shires has pointed out to me that the size of the grains postulated by

Reynolds was of the same order as the "strings" in modern string theory; perhaps it is time that the theoretical physics community looked again at this paper!

CONCLUSION

I can think of no better way of concluding this journey to meet the inhabitants of Equation 1 than quoting from two of the principal inhabitants, namely Reynolds and Newton. In his Introductory Address to the 1868-69 Academic Session, regarding the need for engineers:

> *"there is a very general impression at the present time that engineers have had their day, and that unless some great discovery is made which shall cause railways to be superseded and the speed of the locomotive to be surpassed, little remains to be done by the engineers. Though another mile of railway should never be made, there will still be room for all the engineering skill the country can find."*

This is surely just as true today as it was in 1868 despite the enormous range of further advances which have taken place since then.

My final quotation is from Newton:

> *"I know not what the world will think of my labours but to myself it seems that I have been but a child playing on the seashore; now finding some pebble rather more polished, and now some shell rather more agreeably variegated than another, while the immense ocean of Truth extended itself unexplored before me."*

Sometimes, with all the pressures of academic life, we forget how lucky we are to play on that same seashore, driven by curiosity about the shore and the ocean before us. I read a referees report recently criticising a proposal for a research project as being *curiosity driven!* A common feature of all the inhabitants of Equation 1., and the basis for their success, has been this same curiosity. Long may it continue!

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My friend and colleague Professor George Shires had for a number of years intended to write a book about the people who are commemorated in dimensionless groups. This book was to be entitled *Name and Number* and George Shires has kindly allowed me to use this title (with the addition of *unit)* for the title of this present lecture. The source of both titles is, of course, the identification of a soldier, being the only information which could be passed on by a soldier on being captured. I must also thank George Shires for passing on to me material which he had collected for his book which I have found invaluable in preparing this lecture. I would also like to place on record my admiration for the marvellous resources of the Science Museum Library in London