Institute of Physics

Life physics: Physics in 21st century biomedicine

This briefing note has been produced for journalists from a seminar and discussion on Life Physics held at the Institute of Physics on Tuesday 19 October 1999.

The past few decades have brought exciting new developments and potential from the biological sciences. However, the physical sciences – and physics in particular – remain the bedrock of our understanding of the natural world, the development of techniques and the source of applications for wealth creation.

Responding to a concern that inadequate attention was being paid to retaining the strengths of our physical sciences research, the Institute of Physics has initiated a programme to draw out examples of the exciting new areas of research in physics and their application. This takes the form of a series of Vision Papers and seminars. To date, these have covered High Intensity Lasers, Physics in Finance, Exotic Nuclear Beams, Quantum Information, and Life Physics.

New research detailing the workings of tiny structures in animal ears may eventually lead to a nanotechnological solution for human hearing loss. The work, carried out at the Institut Curie in Paris, was described during an erudite double-act at the Institute of Physics, in which Professor Wilson Poon of the University of Edinburgh explained why physicists will increasingly be indispensable to biology. Dr Tom Duke of the University of Cambridge then expanded on the ways in which physicists are finding out how our bodies work.

The physics of hearing

The hearing research centres on the role of molecular motors, which have for a long time been thought to play an active role in hearing. These motors are proteins that work together in large ensembles as machines that form the cell's workforce and which burn a chemical fuel called ATP to generate force and movement within the cell. In non-mammalian animals, they power hair cells which detect sounds; and it is the precise physical mechanism of this energy system which the Institut Curie group has been trying to describe. Although mammals have evolved different and better hearing mechanisms than non-mammals, physicists believe that both systems work in fundamentally the same way. Their conviction is bolstered by evidence that people with genetic conditions in which molecular motors are missing, are deaf. The physicists hope that a better understanding of these mechanisms in animals might one day be applied to humans, and that exquisitely precise mechanical repairs may be able to be carried out to restore hearing in deaf people.

Physics skills

The skills physicists bring to this and other biological problems are ones that point to the need for greater collaboration between the two disciplines. The President of the US National Academy of Sciences, Bruce Alberts, asserted this recently in an article about viewing the cell as a collection of protein machines. "We generally find that our most talented graduate students [in biology] lack the background in the physical sciences that they are likely to need to decipher the detailed chemistry of protein machines", he wrote. "A deep understanding of the key constraints on the system, as well as an ability to use new developments in chemistry and physics as appropriate tools, will often be vital to success."

Physics experiments have yielded insights into the way motor proteins work. A typical example is a molecule called kinesin, that can run along a long polymeric molecule in one direction like a train along a track, carrying a cargo of other proteins from one place in the cell to another. Kinesin burns ATP in order to move. The way these molecules work together can be demonstrated in vitro by isolating them from cells and staining them fluorescently. Their movement can then be tracked across a microscope slide, enabling physicists to quantify what force the molecules are producing and how fast they can push their load.

Quantification – measurement – is one of the distinctive features of physics. The drive to measure ends up with the development of new measurement techniques, such as optical tweezers. These are a clever way of using a focused laser beam to grab hold of small things, pull them and measure forces. It can be used to measure the forces exerted when the molecular motor works: in the myosin molecule, for example, which powers muscle. Biologists recently solved the structure of the myosin head, and found a portion of it that looks like a lever that might rotate as an arm to produce a movement. Using optical tweezers, biophysicists have obtained more direct evidence of what is going on. They have been able to measure the individual force-generating events in the molecule – the kicks it gives. In another experiment, they have used fluorescent technology to see individual chemical reactions taking place in the myosin head. The molecule flashes on and off as the reactions take place. This allows the physicist to test the hypothesis that movement of the head corresponds with the chemical reactions.

Understanding complex systems

Physicists also understand that more is not just more, but different. They are trained to deal with systems containing many interacting entities. When systems with lots of entities are changed by external conditions, completely new properties emerge. Biology is full of examples. Proteins are long-chain molecules that only work as proteins when they are folded into a particular shape. The brain is made up of millions of connected neurones; but the properties of the brain cannot be read off from a single neurone. Population ecology cannot be deduced from the study of one animal.

More is different in muscle too. Physicists are skilled at making quantitative models, and these show what happens in the working of a whole muscle. Their investigation of the way that many myosin molecules work together provides an interpretation of data from classic experiments which measured the speed of contraction of muscle as a function of the load it supports. When the load is small, the muscle is moved by the action of each myosin molecule, which acts like a rower, rowing along a filament. Each molecule rows in its own time, but the combined effect is to push a filament along. Models suggest that the system works efficiently, with the gearing equivalent of automatic transmission: with greater load, it automatically puts more motors on to hold that load. Computer simulations also predict that if the load is really great, the myosin molecules will all row together like a crew in a boat race. This prediction can then be tested in another experiment; and the to-and-fro between theory and experiment allows a more accurate picture to emerge.

Physicists also like simple models. A cow may be modelled as a sphere if you want to know how much more hide you need for double its weight. If, however, you want to know what limits the size of quadrupeds, the answer is that the neck is the limit! – and therefore the simplest model that will do is two spheres, one for the body and one for the head, joined by a line representing the neck. Similarly, a cell membrane can sometimes be modelled as an elastic sheet with just two constants to characterise how supple it is in two different directions. This is a perfectly adequate model to make progress on some questions in soft condensed matter physics.

Molecular motors

Simple models help physicists to generalise. Almost the entire biological literature asks how particular molecular motors work: how they move a muscle, or translocate DNA to copy the genetic code. But there are general questions that can be asked about molecular motors. When any molecular motor is dropped into water, the water molecules push the motor molecules at random and cause them to jiggle about in so-called Brownian motion. Yet they move in one direction only. Why? Physicists have answered this with a simple model of the movement. A very small molecule in water is constantly being hit by water molecules and is being moved around. In the presence of a polymer, it will feel a potential which can be represented as a mountain. The system then looks like a chain of mountains, shaped so that the molecules are more likely to jiggle over a peak to the right than to the left. This is a Brownian ratchet – a very simple way of representing a system that will move. Physicists have used the ratchet in conjunction with a silicon device to separate out DNA molecules by size. The molecules will hop over different numbers of peaks depending on how large they are. This sort of separating device is needed in genetics, when biologists are taking the chromosomes out of cells, cutting them up and separating out the DNA they want. A Brownian ratchet is much more convenient and faster than the techniques currently used.

Just as many interacting molecules can go through an instability and a phase transition from gas to liquid or liquid to crystal, so coupled motors can also undergo a dynamical instability and a dynamic transition from one state to another: from a still state to one that goes either backwards or forwards, or from a quiescent state to an oscillatory one. There are many motor protein systems in which oscillatory states occur in biology, and one is in sperm. The tail consists of a cylinder of filaments, with molecular motors in between them. Physics-type experiments show that the motor proteins are able to produce a force which buckles the flagellum and produces motion. In a simple model, the cylindrical structure can be reduced to just two filaments with the motors between them. When there is some instability that makes the motors produce an oscillatory force, a wave will propagate along the filaments; and if this simple system is put in water it will swim! This shows that the basic physics of swimming flagella may be extremely simple.

With their particular skills of measuring, building simple models, asking general questions, dealing with many interacting entities – as well as bringing their own perspective to problems – Professor Poon and Dr Duke concluded that physicists will play a central role in life sciences in years to come.

Information and links

The two speakers at the Institute's seminar were:

Professor Wilson Poon
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Further Reading:

Fear of Physics, Lawrence Krauss, Vintage Science, London (1996).

The Machinery of Life, David S Goodsell, Springer-Verlag, New York (1997).

The Impact of Physics on Biology and Medicine, Harold Varmus, Physics World, September 1999, p. 27.

Single Molecules Feel the Force, Manfred Radmacher Physics World, September 1999, p. 33.

Molecular Rotary Motors, Robert H. Fillingame, Science, November 26, 1999, p. 1687.

Can physics deliver another biological revolution? Nature editorial, January 14, 1999, p. 89.

US universities create bridges between physics and biology. Laura Garwin, Nature, January 7, 1999, p. 3.

For further information on the Institute's initiatives to raise the profile of physics research please contact:

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The Engineering and Physical Sciences Research Council has recently initiated a programme in the life sciences. The contact details are:

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