CONCEPTS OF 'ULTRA-DIMENSIONS' AND 'THERMODYNAMICS' FOR YOUNG CELL BIOLOGISTS

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Cells are visible mostly through the help of optical microscope and their organelles usually are seen through the electron microscope. Various organelles of cells, though small in size, perform vital functions. All the food we consume is synthesised by tiny chloroplasts of the green plants and used up by still tinier mitochondria in the cell. The magnanimity of the tasks performed is inversely proportional to the size of the 'performer.' A young, high school cell biologist may know about the structures and functions of the various cell organelles, but he is hardly able to develop an appreciation of the diversity of the size-range on ultra-dimensional scale and the intricacies of the reactions on such minute sites.

Further, the cellular processes, at least many of them, have been resolved in terms of chemical reactions which obey the same physico-chemical principles as applicable to *in vitro* systems. Therefore, a clear understanding of these principles becomes prerequisite of the teaching of the essentials of cell biology.

In the present article an attempt has been made to show the way to teachers and students as to how to absorb and assimilate these 'so called' hard concepts.

THE ULTRA-DIMENSIONS

The Scales

We talk of larger organisms in terms of metres (m) the small ones or their body parts in terms of centimetres (cm) and those still smaller but visible through unaided eyes or a dissecting scope in terms of millimetres (mm). These units are all comparatively larger and within the range of the resolution of human eyes. But with the exception of certain giant cells of algae, etc., other cells as well as their parts fall under much lower range of the measuring units thus requiring some mental training for actual visualisations. These ultra or micro-dimensions recur very frequently in cell biological literature. It is not just enough to know that a micron (µ) is 10^{-3} mm and an angstrom (Å) unit is 10^{-7} mm. The mind must be able to carry out a mental abstraction from the sub-visible dimensions to visible units and realise the need and utility of finer resolutions and magnifications. The earlier is this achieved by the learner the more effective it would be in assimilating the concepts and principles of cell biology. There may be several ways in which this could be accomplished. Indeed, each learner would develop his own mental process to achieve this visualisation, but a few approaches are suggested here which would particularly aid an average learner. One way could be to discuss and work out such problems as how long a metre scale would look if it were reduced one thousand times, and then again, to one thousand times. The process may be repeated till one reaches the value of an Å or a nanometre (nm). Similarly, an exercise may be carried out as to how much two dots as close 1 Å must be magnified so that they are seen clearly apart through unaided eyes. At this stage the resolving power of the human eyes may be given as about 1/5 mm. It is possible that some learners already possess this sense of reduction-magnification, if already trained in mathematics. If so, one could do the following exercise straightaway on the basis of his earlier knowledge of the names of cell components and the ability to draw histograms. The following set of data or a similar set may be tried out as a classroom activity:

Cell diameter	100 μ
Nuclear diameter	15 μ
Chloroplast length	5 μ
Mitochondrial diameter	2 μ
Lysosome	1 μ
Cell wall width	2 μ
Plasmalemma width	100 Å

While doing this exercise, the dimensional proportions involved would come rather lucidly to the learner's mind and he will soon start pondering about the subcellular structures and phenomena. One can well imagine what sort of problems will be encountered, amusements and thrills derived, if one tried to carry this exercise further to drawing a scaler sketch of a typical cell after learning more about the cell organelles.

Magnification and Resolution

As already evident, the organisms and their organelles are observed at three levels of resolution which are: a fraction of mm, micron and Å corresponding to the resolving power of the human eyes, the optical microscope, and the electron microscope. With each of the three tools, of course, exists not one definite value but a range. The word resolution and magnification are often erroneously understood and used. Small objects, just visible through unaided eyes, can be photographically enlarged several hundred times. But shall we see any details comparable to what could be seen under an optical microscope? If that were possible, microscopes could have been done away with as tools of observation. Therefore, the utility of the microscope lies in its property to resolve two close-by points apart from each other and in this the optical microscopes are about 100 times better than our eyes. The magnifying power of the instrument functions simply to bring the points already resolved to the level of the resolving power of the eyes. Therefore, the magnifying power of the optical microscope is of the order of a few hundred times only. The wave-length of light and the properties of glass lenses do not permit much betterment of the resolving power of the light microscope.

The resolving and magnifying powers of the electron microscopes are based on similar considerations. The best resolutions available in the electron microscope are of the order of a few Å units and the magnification in these works to bring the resolved points on a photo-graphic plate to more than the limit of the resolving power of the eyes, i.e. of the order of few hundred thousands.

Energy and Cellular Processes

Why Thermodynamics in Biology?

No one can logically question that for every 'work' to be done certain amount of 'energy' must be spent. "I neither have time nor energy to waste". is a commonly encountered expression among the educated people. The biologists know that the energy-work relation applies not only to machines but also to man and other organisms. For instance, man performs 'work' through his limbs and the muscles inside, the muscles derive energy ultimately from the food consumed by the man. The foods are made of definite chemical molecules and are broken down into other molecules, thus releasing their energy which our muscles use. It naturally follows that the bio-energetics must be conceptualised at the molecular level. The thing to realise at this stage is that basically the apparent expenditure of energy has molecular basis, that energy exchanges do take place during the process of chemical reactions and that no system, physical or biological, is 100 per cent efficient in the sense that all the energy released in a reaction is available to do work, and further, that a part of it always becomes unavailable for doing work (Entropy).

Just as the ultra-dimensions should be clearly visualised for the study of cell biology, simple mental images must also be built to understand the total energy (Enthalpy), energy available to do the work (Free Energy) and the third thermodynamic quantity (Entropy) which is not available for doing work. For a biology teacher these terms and concepts may appear new but the need to understand the energy transfer processes not only in the cells but also in the biosphere necessitates a bit of effort made in this direction. It is made quite explicit here that in introducing these terms and concepts it has been kept in mind that no prior knowledge of physics or chemistry is required but those having some background would not only find it easier to comprehend but will be able to relate better their previous understanding to its applications in cells.

For the present level of the subject matter, the theoretical discussions, mathematical derivations, and numerical calculations will be avoided. It is only being attempted to help the learner to perceive these thermodynamic quantities as would aid them in visualising the energy transfers, directions of reactions and the irreversibility of the biological processes in the light of these definite physico-chemical principles as being applicable to biological systems.

Total Energy

As the life processes are now seen as an integrated sum of physico-chemical reactions, we can say that a number of reactions that occur in the protoplasm are made of components like:

$A + B = C + D$

where A and B are reactants and C and D are the products of the reaction. As already mentioned, each molecule has its own built-in energy. Hence, when any two molecules react to form any product or products, some energy transfer is definitely involved. If the reactants and products of the above reaction could be taken in isolation and physically burnt to obtain a certain number of calories, for each side of the equation we shall get the total energy content (Enthalpy) for either side of substances. Let us say that (A + B) gives us X calories and (C + D) gives us Y calories upon combustion, in this way. Then ΔH (delta H or change in enthalpy or the heat of reaction, all synonyms) will equal Y – X calories, $\Delta H = Y - X$ cal.

Free Energy

As will be seen in our later discussion of entropy, ΔH is not necessarily (ideally never) the indicator for the direction of a particular reaction. In every reaction, a component of it becomes unutilizable to do 'work'. Therefore, the remainder of the energy released in a reaction that is actually available to perform work is termed 'free energy'. It is easy to imagine free energy with the analogy of the potential energy of a body kept at a height from the ground. The potential energy of such a body depends upon its vertical distance from the ground. The stretch of a spiral spring or the voltage of electricity may be other analogies. Although the free energy (F) of a molecule depends on its constitution it is not measurable except, in terms of ΔF, or change in free energy in course of a reaction or a process. So, for our example, A + B = C + D; ΔF is also a measurable quantity. If the ΔF (i.e. Freact – F prod.) is a negative quantity the reaction will move spontaneously to the right and useful energy will be available for the performance of work 'by' the system. Such a reaction is known as exergonic reaction. For the reaction to proceed in the reverse direction (endergonic reaction) energy must be supplied from outside, i.e., work must be done 'on' the system.

Entropy

But as pointed out, not all such energy transfers are one hundred per cent efficient and for each reaction, a fraction of it becomes unavailable for doing work. The lost energy is due to the intra-atomic movement of electrons, intra-molecular movements of atoms; and intermolecular movements with relation to each other. It follows that the faster the movements the greater will be the unavailable energy.

Entropy is a measurable quantity though difficult to imagine. Besides, in contrast to enthalpy and free energy, it is not an energy form. It becomes an energy form only if multiplied by T (absolute temperature).

or, E (unavailable) = T S

The following example will help us visualise this quantity better. For any well-ordered system or structure, the entropy is the minimum. The row-wise arrangement of desks in the classroom means less entropy than the same classroom completely disorganised by the unruly behaviour of children. Someone has to put in extra work to bring back order to such a disorderly system. If a few of these desks are broken down then a carpenter has to do further work first to reassemble them before the desks could be put in rows again. It would thus mean that larger the number of possible arrangements of the components of the classroom the greater would be the entropy. Further, if some of the desks are damaged to such an extent that even any repair becomes impossible, i.e. if the damage is irreversible, then the increase in entropy is further enhanced. Therefore, increase in entropy is not only associated with *disorderliness* but also with *irreversibility*, increasing in each condition.

The Relationship between H, E, and S

Being already aware of these three parameters we can sum up their interrelations as follows:

$$H = F + T\ \Delta S$$

and $$F = H - T\ \Delta S$$

Entropy and Life

Entropy can also be seen as a philosophical concept not just for the physico-chemical reactions or life processes but any range of socio-economic or political events since order and disorder are common phenomena all around. In the case of socio-economic and political phenomena, the role of administration is to reduce entropy. The living organisms and life processes are often characterized as giving rise to 'negative entropy'. This is by virtue of their being highly regular and orderly. When large number of amino acids join at random to form a protein molecule of highly ordered nature the system is actually proceeding from larger number of possible assortments to a definite sequence. Here the thought or negative entropy comes into picture. The protein synthesis in cells is the 'key' to biological organisation and function. Similarly, when smaller molecules like water and carbon dioxide give rise to orderly organic molecules, the work must be done on the system, free energy provided and the entropy reduced. The energy of the sun, through photosynthesis, makes it all possible.

The arrow of life moves in one direction, i.e., the direction of time, it is irreversible and the loss of life means increase in entropy.