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From Bones to Biotechnology: 60 Years of New Biology in the Old World

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The first 40 years of this century, until the outbreak of the second World War, were a period of steady progress in our understanding of living systems. No particular field of biology could be said to dominate this period. The major hypotheses of the 19th century were tested and in some cases confirmed and integrated into other fields of science. Biology was represented by zoologists who studied animals, botanists who studied plants, physiologists who, if they were not zoologists, studied human-related animal systems, geneticists who worked mainly with fungi, cereal plants or the fruit fly *Drosophila*, and biochemists who were the pioneers of investigation into the molecular events that characterised living systems. All branches of biological science were academic subjects that were open ended and challenging. There were some clear, and mostly formidable, medical objectives, such as understanding cancer or dealing with pathogenic microbes and amongst the geneticists there was an ongoing commitment to selective breeding in the service of agriculture, but for the most part the biological sciences were just intrinsically interesting. They were also rewarding in the sense that they provided countless opportunities to generate distinct building blocks of knowledge upon which the names of individual young scientists could be carved, and that is important when it comes to matters of drive and motivation in scientific research.

Biologists of the 1930s were, with the exception of the biochemists, grouped according to the classification of living organisms. Even the geneticists were for the most part either botanists, microbiologists or zoologists. After 1945, the grouping started to be driven by technology and research. Stronger links were forged between medicine, science and technology and the urge to be identified with modern trends and dissociate from 19th century academic traditions brought the introduction of new breeds, like cell-, developmental-, molecular-, marine- and neuro- biologists.

The significance of all this in relation to an overview of the history of biology in Europe is that it represents a process of expansion, diversification, evolution and speciation within the field. The driving forces and facilitating factors behind this process are not hard to identify or define. They can be summarised in just two words, technology and environment.

Europe emerged quite quickly from the trauma of the 1939-45 war. Scientists were back at their benches almost immediately. Technology had progressed and machines were being developed or adapted for the purpose of measuring things and expressing science by numbers. Questions and hypotheses became smaller and more circumscribed such that they could be tested more quickly and objectively. An investigator might prefer to be identified as a person who examined animal cells with an electron microscope - a cell biologist -rather than as zoologist with, for example, an interest in the growth of eggs in insect ovaries, even though both descriptions were entirely appropriate. Accordingly, a whole range of new "job descriptions" emerged, leading to a present day scenario in which European universities offer over 50 different first degree titles in the biological sciences. The trends in the early post-war years were influenced by other factors too. The expansion of technology made science more expensive and it also made it improbable that one person could accomplish a useful research objective without the help of one or more technological experts. Science by numbers meant working as a team, publishing as a team, and sharing success.

Perhaps one of the most important human trends over the past 50 years relates to our attitude towards animals, plants and our environment. In the immediate post-war years animals were regarded by the vast majority of European adults as pets, game, pests or food. Some were appreciated for their beauty but most people were contentedly unaware of the animals in their surroundings. Plants commanded a little more respect and interest, perhaps because in wartime many of us learned, through necessity, how to cultivate them for food and took pleasure in constructing pretty and productive gardens around our homes. The environment really did not exist in 1945. Few species were known to be endangered. The major oil products had yet to be developed. Oil consumption itself was relatively low. There were few automobiles, no pesticides and no herbicides. Such exploitation of forests as had taken place in the previous 200 years in both Europe and North America seemed to be under control and commercially sustainable. The construction industry was in its infancy, even if it was to expand at a truly phenomenal rate in years to come. Perhaps most significantly, there was no television. Mass media impact in defence or glorification of the natural world was impossible. Environmental issues either were not there or they were too immediately unimpressive to capture people’s imagination or sympathy. It took the deaths of over 3000 people following the famous London "smog" of December 1952 to begin to convince us that we might actually be doing things that adversely affected the quality of our own lives. Television changed all that by bringing the natural world right into the living room and by making news out of environmental catastrophes. For many the air was unimportant until the London smog, and there was no life in the sea until the fully laden oil tanker Torrey Canyon was shipwrecked off the south west of England in 1967. Environmental science and all its related fields suddenly became respectable and the living world became more precious and exciting.

Progress, development and discovery in biology 1945- 2004.

A detailed account of progress and development in biology over the past 50 years would be long and of limited usefulness. Some of the major events and accomplishments up to 1972 have been neatly covered by Glass (1979) [1], and a more comprehensive historical treatment of eight principal areas of late 20th Century Biology was published in the 1992 Pergamon Encyclopedia of Higher Education (see Macgregor 1992).[1]

In the present context, three matters are considered to be of special importance: technology, molecular biology and ecology. Nearly all the major new techniques that have been developed for biological science since 1945 have been aimed at improving the resolution and understanding of living systems at the molecular level. Chromatography was developed in 1944 and allowed the separation of amino acids, the building blocks of proteins, on paper, such that proteins could be analysed and compared. Electrophoresis

[1] B.Glass, ‘Milestones and rates of growth in the development of biology.’ *Quarterly Rev. Biol.* 54 (1979), 31- 53; H.C: Macgregor. (ed.) ‘Biological Sciences’. in B.R.Clark and G. Neave (eds.). *The Encyclopedia of Higher Education* 4 (Pergamon, Oxford, 1992), 2181 -2270.

followed, then centrifugation and ultra-centrifugation: all designed to separate and purify the molecules of living organisms so that they could then be examined and the significance of their variation from organism to organism, from cell to cell and from time to time within cells and organisms, could be evaluated and understood. Electron microscopy was developed in the 1950s and readily available to biologists for the examination of living organisms at the macromolecular level by the early 1960s. Radioisotopes were employed as tracers to follow molecules through cells and tissues and, most importantly, to determine the behaviour of macromolecules that seemed to be specially important in inheritance and development.

All of the core technologies for molecular biology were in place by 1953, which was when one of the greatest discoveries of the 20th Century in biological science was synthesized. The structure of DNA and its significance in relation to inheritance, evolution and development became clear. Never before and never since has there been an advance in biology that was so swift and so instantly enormous in its impact.

Since the discovery of DNA, biologists have come to understand how information contained in DNA is transferred and expressed in living cells. They have learned how this expression is controlled, how DNA itself replicates and passes on information to generation after generation of cells and organisms according to specific rules that are implicit in the nature of the molecule itself and they have learned how DNA changes and the extent to which such changes can affect normality in living organisms.

There is absolutely no field of biological science that has been untouched by the progress in our understanding of the molecular biology of DNA. The study of the immune system is a good example. Until 1976 most of the effort in immunology went into understanding the shape of antibodies and the specificity of antigen/antibody interaction. In the early 1970s the three dimensional structure of immunoglobulin was solved[2], and this was the essential step for an understanding of the basis of antibody diversity .After that, there follows a comp1ex history of investigation and experimentation, leading to the publications of nearly 1000 papers a year over the past 15 years, into the genes, the DNA sequences, that are concerned with antibody specificity. It is probably fair to say that there is now little that is not known about the genes of the immune system and the information transfer processes that regulate antibody production. That is not, of course, the end of the story. The greatest challenge, the cell biology of the immune system, remains, involving complex cellular interactions, information transfer between cells, transformations of cells, changes in cellular behaviour - all of it happening with lightening speed amidst huge numbers of cells charging around in the almost endless system of blood vessels and lymphatics that keeps the vertebrate body in good living condition.

A major technological advance came in the late 1960s when enzymes that were able to cut DNA at highly specific sites were discovered in some micro-organisms; they were called restriction enzymes. There were other enzymes, ligating enzymes, that could attach pieces of DNA to the broken ends produced by restriction enzymes. There were quite simple techniques that had been around for many years for injecting foreign DNA into bacteria or integrating it into the DNA of viruses. Quite suddenly, in the course of just a few years, all the tools were on the bench for genetic engineering. Specific pieces of DNA, specific genes, could be isolated, trimmed with restriction enzymes in a controlled manner and then joined with other pieces of DNA or ligated into special places in whole genetic systems of living organisms. Quite suddenly all kinds of scenarios, hitherto confined to the pages of

[2] D.R: Davies, E-A- Padlan,. and D.M. Segal, 'Three dimensional structure of immunog1obulins'. *Ann. Rev. Biochem.* 44 (1975) , 639 -667

science fiction, became absolutely possible. Genetic manipulation had arrived. In so far as the entire workings of a living cell are controlled by its genes it was then possible to change the orders and compositions of genes in ways that would have predictable consequences for the cells. It is in this sense that molecular biology and techniques of genetic manipulation have come to dominate almost every branch of biology.

The history of cancer since the second world war is of special interest. In 1940 cancer was a sure killer. There was no cure and there was little hope for cancer sufferers. Twenty five years earlier Theodore Boveri (1862-1915) had suggested that cancer was associated with changes in chromosomes[3], and between 1940 and 1950 scientists in Europe became convinced that cancer was associated with changes in cells that involved their nucleic acids.[4] . Then, following the discovery of the "Philadelphia chromosome"[5], came a general realization that the transformations that produced the cells of malignant tumours were primarily caused by lesions in the chromosomal DNA brought about by environmental factors, radiation, toxic chemicals, free radicals and so on. Molecular biology suddenly zoomed in on cancer and only a few years later most of the general cellular characteristics of malignant tumour cells were known and DNA became the prime target for future research. In the early 1980s oncogenes were discovered. By 1990 more than 50 good correlations had been recognised between specific tumour types and specific chromosome lesions and by far the greater part of the world effort in search of a better understanding of the biology of cancer was sharply focussed on the DNA, the genes and the expression of genes in cancer cells. Today, after all that effort, people are still dying of cancer but at least we now know more or 1ess exactly what we are up against. There is still no "cure" but there is such a depth of understanding that the misfortune of cancer can be much more successfully regulated, managed and prevented.

It would be misleading to suggest that the molecular biology is only to do with DNA. Watson and Crick may have announced their discovery of the "secret of life" in 1953 – and this was little less than would be expected of two remarkably intelligent and inspired young scientists working in the highly select environment of Cambridge University - but theirs' was just one of the secrets. Fifteen years before them, another young scientist. also working in Cambridge University, explained how green plants, using only water and carbon dioxide (CO_2) utilize the energy from sunlight to synthesize carbohydrates[6]. Since then, the molecular biology of photosynthesis has progressed step by step to the point at which we now understand the transfer of energy among the light-harvesting pigments in plant cells, the molecular arrangement at the reaction centres and the events that characterize the primary photochemical reaction and bring about the conversion of the energy of the photon to a form of chemically-based energy that is usable by a living cell. The molecular biology of energy systems, which includes everything to do with movement and growth as well as the original capture of the sun's energy by green plants, shares two important characteristics with the molecular biology of DNA but differs from it in one very interesting respect. Both are areas of activity that seek to understand and explain the key events in living systems. In both, the biological objects of study are chosen to provide the simplest model systems for experimental analysis with a profound and well justified faith in the unity of life. The difference between them is with respect to the instruments and procedures that are applied. The molecular biology of energy has relied almost entirely on pre-existing tools that have been developed in the physical sciences and modified for

[3] T. Boveri, *Zur Frage der Entstehung maligner Tumoren.*(Jena, 1914)

[4] T. Caspersson, *Cell Growth and Cell Function* (Norton, Chapman & Hall, New York, 1950); J. Brachet, *Biochemical Cytology* (Academic Press, New York, 1957)

[5] J. D. Rowley, J.D. 'The Philadelphia chromosome translocation: a paradigm for understanding leukaemia', *Cancer* 65, (1990), 2178- 2184.

[6] R. Hill, R. 'Oxygen evolution by isolated chloroplasts.' *Nature* 139 (1937), 881-2

application to biological problems. In the early days, the same could be said of DNA and associated matters. For the past 30 years, however, molecular genetics has become technologically more and more simple. The expensive ultracentrifuges, radio-isotope detection systems and transmission electron microscopes that filled the laboratories of the 60s, giving them an air of awesome high technology and a noise level that seemed to rival that of a busy international airport, have gone. The tools of the 21st Century are either whole micro-organisms or have been forged by biologists out of selected components of living systems. In some senses, the molecular biology of DNA and the information transfer processes of cells has reverted to using some of the most primitive approaches known to humankind: we investigate things by taking them apart using a blunt instrument in the expectation that in the course of our investigations we will discover some potentially sharper tools that will enable us to do the job more quickly and more carefully the next time round. This is the story of restriction enzymes, of vectors, of recombinant organisms and all the galaxy of "natural" implements that are employed in today's molecular biology labs.

Most of this complicated laboratory-based biology is beyond the understanding of the average citizen. The impact is at the level of curing illness and maintaining supplies of good quality food, together with all the commercial and industrial aspects of medicine and agriculture.

The other side of biology is the study and measurement of the interactions between living organisms with each other and with their environment. We call it Ecology. Throughout the first half of the twentieth century, ecology was a relatively low technology and low-cost science mainly focussed in the United States on succession in plant communities and in Europe on statistical description of community types. The emphasis in animal ecology was on the causes of population fluctuations and species interactions in the wild. The ecology of the 50s and before was perceptive and speculative. What else could it be? The ecosystems under study were immensely complicated and, what is more, they were immensely variable, so statistical data analysis was of paramount importance. In this regard, we should remember that there were no computers to speak of until the early '70s and, of course, few people today could possibly imagine the plight of a serious ecologist who has no computer!

Several important developments influenced ecologists after 1970. Computing and statistical techniques allowed them to design experiments, to undertake more extensive sampling programmes, to analyse their data more quickly and more searchingly and to construct testable models. Most of these modern approaches are described by Charles Krebs in his 1989 book on Ecological Methodology[7] which must surely rank as one of the most important texts of the 20th Century in this particular branch of science. Ecology, like all other branches of biology was helped by technological developments in other kinds of science. Gas-liquid chromatography with electron capture amplification permitted the detection and measurement of toxic chemicals, such as the residues of pesticides. Radio-isotopic tracers facilitated the tracking of chemicals through ecosystems and measurements of the flow of elements through nutrient cycles. More recently, the use of photography from aircraft and from orbiting space satellites, coupled with sophisticated computer modelling and analysis, has proved to be immensely valuable in the study of mapping and classification of vegetation communities and of global changes that relate to human activity and intervention.

Inevitably, of course, DNA technology has penetrated into ecological science. There was a time, in the 1950s and '60s when such a marriage would have been regarded as

[7] C.J. Krebs, *Ecological Methodology* (Harper and Row, New York, 1989).

improbable, to say the least. At that time, ecologists and molecular biologists simply did not talk to one another. One wore Wellington boots, the other wore a white coat. They were, to all intents and purposes, different species and it seemed inconceivable that hybridization between them could ever produce fertile offspring. Then it was shown that different species could be identified by certain quite easily detectable properties of their DNA and that by examining these properties, taxonomic relationships and species divergence times could be determined with remarkable degrees of resolution and precision. Ecologists took note. This was something they had wanted to do for along time. DNA technology crept in, the initial trend being fostered by molecular biologists who actually needed to know more about the rates at which different classes of DNA sequence were changing in nature, and others who were curious about the relationships between genes and speciation. Then, quite suddenly, mini-satellite DNA was discovered and DNA fingerprinting was invented[8].

The average non-biologist needs to pause and think for a moment before realising what DNA fingerprinting means to an ecologist. Ecology is all about interactions between individuals and species. We all know about interactions between human beings. We see them every moment of every day in our own personal worlds, in our newspapers and on our television screens. It is, if we care to think about such simple matters, easy to follow human interactions. People have different faces and our perception is trained to distinguish between them on the basis of the minutest details. Families present few problems: we can usually distinguish fathers, mothers, brothers sisters and so on. But what about interactions between individuals in populations of bees or rabbits or starlings. How can we possibly examine family relationships between birds, for example, when to our eyes, all the males look exactly alike and it is even hard to distinguish young from old. DNA fingerprinting has solved all that. It's not as straightforward as direct visual identification, but it is just as unequivocal and it has transformed accelerated an important section of ecology.

There is now not much that we do not know about life. We can manipulate organisms of all kinds at a level that was science fiction in the 1950s. We understand nearly all the major aspects of living systems. There are still major problems with animal development but they are mostly well defined, and there is no doubt that we will solve them in due course. We can control most of the diseases and afflictions of the human species. We may never find a "cure" for cancer but it represents real progress to be able to say that we have given up looking for one; modern strategies are more informed, more reasonable and much more promising. We have it within our grasp to eliminate aging and establish virtual immortality, although that kind of thing is, of course, strictly limited or prevented by socio-economic or political factors. The greatest problem for the human species today is how to keep pace with evolution and with our own man-made forces of planetary destruction. Microbes, HIV , cancer and the major parasitic diseases of the tropics represent the evolution and diversification of cells and organisms at speeds that often outstrip both our immune defence systems and our scientific ingenuity. For members of future generations who care to stand back and examine true historical perspective, the second half of the 20th century must undoubtedly stand out as the time it took for us to discover how living systems work. Some will probably say, "Why ever did it take them so long”? A hundred years ago, E. B Wilson (1856-1939) concluded his book on The Cell in Development and Inheritance by saying "The study of the cell has, on the whole, seemed to widen rather than to narrow the enormous gap that separates even the lowest forms of life from the inorganic world"[9] .Sixty years later, Jean Brachet, one of the most advanced and experienced cell biologists of his time concluded in 1957 his book on Biochemical

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[8] A.I.V. Jeffreys, D. Wilson, and S. L. Thein, ‘Hypervariable "mini satellite" regions in human DNA’. *Nature* 314 (1985), 67 -73.

[9] E.B. Wilson, *The Cell in Development and Inheritance.* (Macmillan, London and New

Cytology with the words "The more we delve into these problems (he was referring to the basic concept of a living system), the more life remains a mystery"[10]. Today, there is not much mystery left, which is perhaps just as well, because the practical problems relating to human survival and quality of life on earth today are formidable and a comprehensive understanding of living systems is fundamental to our success in meeting them.

The Human Genome Project

The Human Genome Project was a 15 year research programme spanning most of last two decades of the 20th Century. It cost around 200 million dollars a year which, although seemingly a very large sum of money was defended as being less than 1% of the total research budget of the United States National Insititute of Health. The project was acclaimed as the first internationally co-ordinated effort in the history of biological research. Although most of the funds and investigators were provided by the United States, the European involvement , particularly that of France and the United Kingdom, was significant. European laboratories already had experience of large scale collaborative genome research from their work on the yeast genome and in the early 1990s French scientists were leading in gene mapping technologies.

The aim was to determine the complete sequence of nucleotides that make up the DNA of one complete set of 23 human chromosomes. DNA is a very long string of 4 nucleotides given the letters A, C, T and G in varying order.

ATTCGCTAGCTAAGTCGAGTCCATGCATC

The longest human chromosome has 300 million nucleotides. To give a sense of dimension, if we were to type out the entire arrangement of A, C, T and G on the longest human chromosome using the same type size and format as in the diagram above, the row of letters would extend for 400 miles to the right or left of the page. The Human Genome Project set out to determine the precise sequence of A, T, C and G that makes up this enormous string, as well as that in the 22 other strings (chromosomes) that make up the human chromosome set. It was a massive task that required the bringing together of a wide range of highly sophisticated technologies and expertise on an unprecedented scale.

The project was justified as a means of discovering how DNA sequences determine an organism's phenotypic characteristics and how they control its development. It was also assumed that in the course of sequencing the human genome, genes would be discovered that govern a variety of human diseases and this would lead to the development of new strategies for diagnosis, prevention, therapy and cure.

As of 2005, the pay-off from investment in this project is already noticeable. Molecular prognostics and diagnostics – the sciences of predicting and diagnosing human disease by examining DNA are developing fast. The human genome project has spawned technologies that are now being applied to mapping the genomes of a whole range of commercially important organisms, plant and animal, and it has provided molecular tools for tackling all kinds of questions and problems across the entire spectrum of living organisms. The claims of some of the early proponents of the project back in the early 1990s were shockingly bold, doubtless intended to encourage financial backing, but it's

York, 1896)

[10] J Brachet. Final remarks. *Biochemical Cytology* (Academic Press, New York, 1957) Pages 464 – 466.

beginning to look as if they were not entirely unjustified.

Something like the Human Genome Project had to be done. Technologies were there, looking for problems. Questions were there looking for answers. At the end of the 1980s, Biology was in danger of stalling if a new level of investigation could not be initiated. DNA seemed like the answer, of course, and the kind of money that was needed could only ever be won if the DNA was human.

An excellent account of the project was published in 1994, edited by Necia Grant Cooper, the Editor of Los Alamos Science, a periodical of the Los Alamos National Laboratory in [11]the USA (Cooper 1994).

The role of the university

Since this article is intended to be targeted mainly on biological sciences in the universities of western Europe during the post-war years of 1945 -2005, it seems appropriate to inquire about the role of European universities and the part they have played in pushing back the frontiers of biology.

In the Author's view, the business of a university is to transfer existing knowledge and to develop new and more effective transfer processes, to generate new knowledge through analysis and discovery and to develop potential for future enhancement of knowledge. The marketable products of a university are therefore units of new knowledge and units of personal ability. In common parlance they are called "research" and "graduates". The two are closely linked to the needs of the community. Knowledge and ingenuity must outpace the inexorable expansion of world human activity, and future generations of men and women must be equipped to cope with a faster and more complex environment than that of their ancestors. It is altogether imperative that the "manufacture" of these two products continues apace.

All the universities in Europe have clearly had a role in generating graduates. It is doubtful that any would have survived for long if they had formally withdrawn from this task. Undoubtedly, national policies with regard to undergraduate training are varied, but in general, a student can obtain a training in some aspect of the biological sciences at virtually any university in Europe. Some universities attract more highly qualified undergraduates than others and some offer better facilities and opportunities for learning. It is, of course, inappropriate to cite specific examples in this regard. In general, the production of undergraduates is neither a good nor an objective way of assessing the contribution made by universities to the advancement of the biology. Research is a much better yardstick and, since it is reported in small measurable bits that we call "scientific papers", it is entirely possible to assess and compare by simply counting papers.

Table 1 shows the extent of growth in scientific literature overall since the l7th Century and the growth in biomedical literature during the past 100 years.

[11] Necia Grant Cooper (editor). *The Human Genome Project – Deciphering the Blueprint of Heredity.* (University Science Books, Mill Valley, California, USA. 1994)

Table 1
Scientific literature and biomedical literature published in Western Europe[a]

Year	No. of science journals	No. of biomedical articles
1670	4	
1800	90	
1879		20,000
1900	10,000	
1979		250,000
1991	70,000	400,000

[a] Personal Communication from Dr. A.P.Swan, Senior Managing Editor, Current Awareness in Biological Sciences, Pergamon Press. 1991.

Is Europe a significant contributor to biological research in terms of publications in learned journals? According to the author's personal research on the geographical locations of authors of articles published in 1991. Western Europe, the U.K. and Eire together represent the second largest source of publications in biological sciences, next to the United States and Canada. Eastern Europe and the former USSR, represented only 4% of published work in 1991 although that proportion has certainly increased in recent years.

How much of this work is generated by universities? Table 2 shows this author's analysis of 1991 publications in 11 different areas of modern biology in relation to the kinds of institution in which the research was carried out. Data for Eastern and Western Europe are presented separately. Western Europe in this instance includes the U .K. and Eire. The most interesting aspects of this dataset are that, at the time of the survey, just 43% of Western European science came from universities, whereas in Eastern Europe and the former USSR the corresponding figure was 86%.

These data, of course, reflect a massive commitment of universities to scientific research and a correspondingly massive investment of funds into this form of activity. The level of this commitment presents both universities and government with some cause for concern,

The problem, if indeed there is one, has its roots in the universities understanding of their role in society. Fifty years ago the situation was entirely clear. The functions of a university were to educate young people, to promote and maintain scholarship amongst those who were responsible for conducting the education process, and to provide an environment within which particularly able scholars could apply their brains with the concentration and intensity needed to advance the frontiers of knowledge. It was an elitist sector of society but a highly respected one.

Today the scenario has changed. In the first place more young, and not so young, people want educating, and the task of teaching them is now exceedingly hard work and only rewarding to those few teachers who have the skills to do it properly. Secondly, existing knowledge in all fields is more diverse, more complex and much more abundant than it was 50 years ago, so that promoting and maintaining scholarship is, like teaching, an exceedingly demanding and potentially overwhelming process. But perhaps the greatest change of all concerns the relations between universities, government and industry .In recent years, Government has invested money, taxpayers' money, in universities. For a time the universities enjoyed their nations' confidence and were deemed to be too deeply respectable and trustworthy to be held accountable for the deployment of their resources. Then several things happened. Science and technology became very expensive, and

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industry turned to universities for help. These events were to set in motion a cycle of change that would have far reaching effects in and beyond our educational systems. Universities had to be held accountable to their governments. Their business had to be inspected, their policies criticised, their methods evaluated and their expenditure justified – justified to the people, whose television sets provided the evidence upon which they could exercise judgement in casting their votes. Universities had, overnight, become industries with shareholders. At the same time their relations with real industry were expanding. The private sector was less willing to commit capital and manpower costs to advanced research and development programmes, so they turned to universities for help. Universities were quick to respond. This was a new dimension and a lucrative one too for the impecunious but enterprising academic who was tired of teaching badly and having to account for every penny spent on his/her favourite research programme. So universities and industry became mutually dependent upon one another. Education and the promotion of scholarship had to be replaced by training, contract and consultancy. Research was expensive and so had to be accurately targeted. Finance was foremost in the minds of management. Management learned from its new-found industrial partners and, in effect, converted the laboratory, the library and the lecture theatre into factory workshops occupied by employees and manufacturing materials.

There remain a few old-timers who deplore these trends and yearn for a return to old traditional values and practices. The changes, however, have not all been misguided, even though the happier consequences have often emerged by luck rather then through good judgement! There were times when the industrial influence seemed likely to stifle scientific progress by overfocussing on applied research that might generate profit. There were cries of anguish when university departments were closed, merged or starved out of existence by overzealous government. There were serious misgivings when universities in the U.K. tried to bribe their senior academics to quit the system: the most astonishing aspect of that policy was the discovery that many of our ablest men and women actually wanted to quit and were only too glad to accept the bribes of the premature retirement compensation schemes, much to the detriment of a system that was actually looking for ways of conserving talent and off loading "deadwood". The system, however, is emerging from 30 years of change looking healthier, more streamlined, more efficient and very much better equipped to operate at the pace that is needed in modern times. Industrial support is widespread and substantial. An appropriate level of high quality fundamental research is flourishing amidst the hubbub of applied projects, objectives are clear, universities are retaining public respect and very little of real substance has been lost along the way. Indeed it could be argued that changes of the kinds that we have seen in European universities over the past 30 years were absolutely inevitable. Real scientific progress at a rate that would have satisfied the demands of modern society simply would not have been possible within the framework of the traditional university system of the '50s and 60s

Undoubtedly the most significant factor affecting policies relating to university biological science has been the spiralling costs of research. Some remarkable and highly significant data on this subject were published in 1979 by Professor Bentley Glass[12]. According to him the number of scientific research publications in biology has doubled every 15 years since 1750. The enormous proliferation in scientific literature, mentioned earlier in this article, reached a total of nearly half a million publications a year in 1993. Glass also examined the rate of increase in "breakthroughs" or "milestones of achievement" in the biological sciences and he found that this rate, although still exponential, is far slower than the rates of increase in publications, the cost of science or number of scientists. Accordingly, although the rate at which new major achievements are recorded is still increasing, the ratio of normal or "ordinary" scientific papers to major breakthrough

[12] B Glass, 'Milestones' (see note 1)

reports is also increasing dramatically. Glass observed that it took more and more effort to produce appreciable gain. Therefore more and more money and resources must be allocated in order to maintain our progress. Glass took a pessimistic view of these circumstances and anticipated that we would have to develop science in the next century on the basis of non-expanding scientific manpower and a fixed, non-increasing, proportion of gross national product. He also anticipated that in the relatively near future, a few hundred years hence, scientific knowledge of Nature will be so complete that there will only be a scattering of inconsequential matters to explore. A different view – and one held by the author - is that we are really only at the end of the beginning of biological science and that future progress can and indeed must be sustained by our own efficiency and technical ingenuity .One thing is absolutely certain, however: in the year 2100 we will not be communicating scientific progress in the form of a million articles a year written on 20 tonnes of paper.

The Biology undergraduate

Recruitment of undergraduates into the biological sciences in the '50s was based on the same basic set of aspirations that operate today. Three very different categories of person present themselves at the desks of admissions tutors in universities throughout the world. First, and most commonly, there are those who come in by default. They find the arts and social sciences subjective and intellectually unappealing. They cannot or will not come to grips with the concepts of mathematics and natural philosophy, so they opt for Biology. Then there are those who fail to make the grades for medicine or veterinary science and for whom Biology is a second best, offering the chance of a modest return on the investment of effort that went into competing for medicine or vet school. Thirdly there are the few who are already biologists with enough experience to know that they want to continue as biologists for the rest of their lives. No other subject in the entire compass of learning has been more haphazard in its recruitment of talent.

What has been on offer for young would-be biologists in our universities? Here, once again, we see an intricate interplay between the development of technology, the expansion of knowledge, the ability of a young person to cope with advancing science and, most important of all, the resources of the science educator. The transition has been an extremely interesting one and it may well signify an ominous trend towards the loss, decay and fossilization of vast tracts of knowledge and experience devalued and neglected beneath the logarithmic curve of modem technology. Breakthroughs that seem to impinge directly on the day to day life of politicians and their voters make good headlines. Almost invariably, the technology of modern discovery , with its young, immaculate, white coated operators in clean, colour-coded, and usually very expensive laboratories is a powerful attractant for the young and impressionable. The old knowledge gathers dust in the basement. University undergraduate biology in the 50s was an almost comprehensive reconstruction of developments since the beginnings of scientific discovery. It was possible to teach and learn within the space of 3 or 4 years almost all there was to know about plants, animals and microbes. Fifty years on, three years is scarcely enough to establish a foundation in modem biotechnology, and only just enough to implant the principles of some branches of modern biology that were mere twigs in the 1950s. The trends are unmeasureable. There are no data, except for those that would show a precipitous decline in the world bank of deep knowledge in areas like animal comparative anatomy, plant diversity, adaptive radiation, growth and form. There are now very few persons in the world who could teach in these areas, still fewer who could do it effectively, and probably even fewer who would wish to learn. But let there be no mistake. Biology of this kind is of absolute value. It represents the catalogue of life, and without it, all the magnificent technological progress of the past 50 years would, of course, be impotent.

Universities, as never before, should perhaps be considering more carefully the relative merits of adopting specific policies for the conservation of knowledge as opposed to operating a free market economy in their recruitment of undergraduates.

New recruits into the biological sciences are undoubtedly better equipped for their advanced training than ever before. So too is the educational system that is committed to teaching them. The freshman undergraduate of the 50s and 60s probably knew more about animals and plants than his counterpart in the 21st century, but he was generally weak in the mathematical and physical sciences, naive in scientific logic, unaccustomed to the experimental approach and hopelessly terrified of data. The educational technology of these times was simple and old fashioned. It consisted of the blackboard, the textbook and a library stacked with weighty journals full of articles written in unconventional styles of individual authors, such that the science could often only be truly evaluated by those who actually knew something of the author's personality and background. Conference proceedings, symposia volumes, subject reviews, were scarce. The abstracting journals of the 50s were, of course, of immense value, but they were difficult and slow to use. The idea of the monthly review journal, promoting science for the citizen or the undergraduate, although pioneered by *Scientific American* (initially *The Peoples' Journal & Scientific American Monthly*) which was launched on August 28th 1845, remained undeveloped until November 1956 when *The New Scientist* was first published.

Without doubt, *The New Scientist* represented an important milestone for the advance of science in Europe. The editors proclaimed that their aims were to make an "intensive effort to stimulate nation-wide interest in scientific and technological development", to "capture the imagination of young people who have latent scientific aptitudes, but are uncertain about a choice of career and to appeal to all those men and women who are interested in scientific discovery and in its industrial, commercial and social consequences"[13]. They also made life much easier for teachers by making them more aware of current science and providing them with something other than dry textbooks or learned journals to supplement their classroom activities.

It has to be remembered that those same teachers presented information in lectures and in the teaching laboratory, and they recommended books. They had no video and no computers. Visual aids in the form of projection slides were expensive to make and of unrewarding quality. Overhead projectors arrived in the late 60s. Photocopiers were definitely not available for undergraduate use and such reprographic equipment as did exist could only be exploited with the aid of a secretary or clerical assistant.

The principal source of advanced undergraduate learning right through to the mid 60s was the single author book. Some remain as classics and are still widely recommended and read today. All were written by leading scientists and scholars. By the most modem of standards, the best of them were absolutely magnificent productions of timeless value.

E. B. Wilson's *The Cell in Development and Heredity* was first published in 1896,[14] followed by several new editions right through until 1924. The 1896 edition was reprinted as a facsimile in 1966 and the 1924 edition was last reprinted in 1955. The book was 370 pages long in its first edition and 1232 pages in its last (1924) edition and even today, 110 years after its first publication, it serves as a major source of information on natural variation at the cellular level.

Michael White's *Animal Cytology and Evolution*, first published in 1945, with second and

[13] Editorial. New Scientist, vol.1, number 1, page 5 (1956)
[14] see note 9

third editions in 1954 and 1973, also remains a classic, a fund of timelessly valuable information on chromosomes and the evolution of genetic systems [15].

Goldschmidt's *Theoretical Genetics*, 563 pages of facts and ideas based on a lifetime of involvement with the genetics of the fruit fly *Drosophila* , represents the kind of book that no author would ever consider writing today; yet in its time it was one of the most important pieces of literature in its field [16].

Bullock and Horridge, *Structure and Function in the Nervous Systems of Invertebrates* in 2 volumes and 1715 pages has to be mentioned as one of the very last truly monumental, beautifully produced and illustrated classics of modern zoology[17].

Today, such is the pace of progress in all fields of biology that, for everyone above the first grade of university undergraduate biology, the textbook has been replaced by review journals such as *Current Biology, BioEssays* , the *Recent Advances* series and a host of other quarterly or monthly publications that specialize in helping scientists, teachers and students to keep abreast in the trendiest areas of modern biology. These kinds of publications have their shortcomings, of course, but they do seem to be appropriate for scientists whose entire efforts are necessarily concentrated into sharply defined and fast moving areas of biological science. And, of course, all this has changed dramatically since the birth of the Internet, the impact of which will be discussed later.

Some say that Biology is a practical subject and that it can only be taught effectively in the field and the laboratory. That view was rarely contradicted when universities were richly funded, teachers were in plentiful supply, technology was simple, animals and plants were exploitable and computers didn't exist. Then technology expanded and became expensive, universities had less cash to spare, teachers were encouraged to spend more time on research, animals and plants became endangered and computers became available for modelling and data processing on an unprecedented scale. The 1950s graduate commanded a broad field of simple science and possessed a wide range of practical transferable skills. They were generalists and as such they stood a good chance of survival and success on their own. The graduate of the 21st Century is a product of a system that generates specialists who have actually learned more science than would ever have been thought possible in earlier times, but whose real expertise is confined to highly specific areas. Just as in nature, specialists succeed by being members of a community made up of individuals with complementary skills.

Universities across the world have adjusted their philosophies and practices accordingly. The most important advance was recognition of the unity of biology, the inevitability of specialization in the face of a vastly expanding volume of science and the importance of providing enough early experience in all aspects of modern biology to allow young persons to choose the specialization that best suited their individual personalities. The pattern of training changed from the steady progression through one major field of biology, occupying 3 or 4 years, to one year broad based introductory courses, followed by short modular courses in specific areas, capped by one or two years of intensive study right through to the very frontiers of a highly specific area of modern science. Emphasis was on the production of graduate technologists. The trend began in the early 60s, reached its climax in the mid 80s and then, curiously, reversed quite suddenly in the 90s. The reasons

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15 M.J.D. White, *Animal Cytology and Evolution. (*Cambridge University Press, 1973)

16 R. B: Goldschimidt, *Theoretical Genetics.* (University of California Press, Berkeley and Los Angeles, 1955)

17 T.H: Bullock and G. A: Horridge, *Structure and function of the nervous system of invertebrates*.(Freeman, San Francisco and London, 1965).

for the reversal were quite simple and have already featured earlier in this article. Technology is expensive. Progress in biological science is struggling to remain cost effective. Biology retains its identity as a science of living organisms, and all that is happening is that the organism is proving to be more intrinsically interesting and rewarding than the technologies we adapted for investigating it.

The Internet

The Internet has had an impact on the entire fabric of university life of unprecedented magnitude. Its effects have been swift and dramatic. The main areas of change have been the accessing and publishing of scientific information, methods of teaching, and the conduct of undergraduate study.

Until just 10 years ago, European scientists in universities or research institutes accessed published work by using abstracting services that scanned and classified all publications across the entire field of biomedical science. Having identified items of particular interest, the scientist would then go to a library, pull journals off shelves and read the relevant articles. As the Internet became established, publishers started selling on-line versions of their journals as well as the printed versions, so that teachers and researchers could consult recent publications from the computer in their office or laboratory. The practice became more widespread as publishers added more and more archival material to their websites. Now, in 2005, the past 10 years or more of published material in most reputable scientific journals can be accessed on-line. For a few journals, the older archives of science and medicine cannot, for the moment, be accessed on-line and can still only be seen by going to a library and systematically pouring over stacks of dusty journals: a situation that is sure to change eventually.

Information access is moving outside the library walls. For example, see http://informationr.net/ir/9-4/paper187.html (*Library usage patterns in the electronic information environment*), which presents an analysis of how library usage is changing as a result of the advent of networked electronic services in the medical field. In this study, it was shown that remote users outnumbered in-house users of electronic information at 5 major medical libraries. Medical library users, and especially faculty, staff, and fellows, found that virtually all of their information needs could now be addressed from outside the library. The trend is happening in other disciplines, including the biological sciences, as more and more networked electronic resources become available.

For many users, the term "library" is now just a word on an authentication or link page. The only thing tying them to the library is that access to content is currently purchased by and controlled by a library. That tie will but cut if open access to all scientific literature becomes the norm. This doesn't mean that libraries necessarily will become irrelevant. It just means that they won't look like they do today and paper journals and perhaps also books, will disappear entirely.

To this author, whose involvement in teaching and research has spanned the past half century, the most remarkable change brought about by the Internet has been in speed of communication. Recently published scientific literature can be accessed in minutes from home, office or laboratory. Messages, data and images can be instantly transmitted and exchanged worldwide. Whereas in the 1960s a scientist might write a dozen letters and make a few phone calls to colleagues each week, in 2005 a hundred e-mails a week would be regarded as conservative. This easy and cheap high-speed communication has proved in many instances to be an enemy of diplomacy, careful planning, decisiveness and acceptance of responsibility. But society is adapting quickly. James Cook, the great navigator and explorer of the 18th century wrote a letter to his wife from Capetown in 1772. She was overjoyed to receive it in London 6 months later. Then came radio, then the telephone, then communications satellites and now the Internet and that is undoubtedly not the end of the story. The 21st century needs the Internet, just as 20th Century needed the automobile! Who's to say if they were good or bad?

Teaching by computer is now commonplace in European universities. Teachers provide students with suggested strategies for on-line information. Access to models, graphics and video recordings replace laboratory and field-work. E-mail communication between students and teachers is encouraged. Essays and projects are written and submitted on-line. Feed-back to students is by e-mail. Self-assessment tests and even examinations are conducted by e-mail. The average science undergraduate may spend up to 90% of his/her formal learning and private study time in front of a computer. Just where this trend is leading is impossible to tell. The quality of the teaching material currently available on the Internet is highly variable but it is improving, as are the means for accessing the most appropriate and the best material for the job in hand. Putting modern science in a true historical perspective remains difficult without going to a library and reading the printed page - a facility that fewer and fewer universities are able to provide. Opportunities for hands-on practical experience of science is all but disappearing because it's so much cheaper and simpler to use the Internet. In Biology, the Internet is proving to be a timely and welcome facility, since laws relating to health and safety and the use of animals, dead or alive, in teaching have strangled traditional approaches to laboratory and fieldwork.

Universities, Graduates and Employment

The western European environment for teaching and research in universities remains to this day a product of history and happenstance in states that have, for the most part, allowed their higher education systems to evolve in response to national rather than international trends and politics. The sudden and enormous expansion of student numbers (80.000 to 175.000) in Spain between 1961 and 1968 is a case in point.

Student qualifications are about the same in all western European countries. The time taken to reach first degree status seems to be broadly related to the "density" of students on university campuses. In general, the larger the institution and the less money allocated by government per year per student, the longer it takes for an individual to reach first degree level. In this regard, the British system, with its small campuses, low staff/student ratios and relatively generous government support has always succeeded in producing reasonably good quality first graduates after an average of just 90 weeks of on-campus training. Other systems that are based on very large campuses with high staff/student ratios take longer to bring their undergraduates up to the same academic standard.

A major concern related to the widespread increase in student numbers has been ensuring that they find employment that will utilize their talents. Approximately 25-45% of biological science graduates become professional biologists or biology teachers. The remainder are recruited into all manner of occupations that tend to exploit transferable persona! skills rather than specific biological knowledge[18] .

A higher degree, Ph.D., has always been essential for a career in research. In the 1960s. during the first phase of the great expansion of European universities, those who wished to be researchers were happy to follow their Ph.D. training with short term contracts as postdoctoral fellows or research assistants in confidence that they would eventually be able

[18] S. Green, Biological science graduates - employment prospects and flexibility. *Biologist* 36 (1989), 209-13.

to secure a permanent post in a university .The expansion phase ended in the late '70s. There was a drop in recruitment of academics. Researchers were forced to hop from one short term contract to another and. if they did not find a secure foothold in academia by the time they reached their mid 30s, they moved away from biology into industry or management

The mid 1970s saw a decided shift in attitudes towards careers for biologists. Up to 1975 most undergraduates in biology expected to find employment as professional biologists of one kind or another. Between 1975 and 1980 there was something of a crisis during which it was said that unemployment was rising amongst biology graduates. Jobs were scarce and the outlook seemed generally bleak. Of course, it was nothing of the sort. It took some coldly objective surveys to prove in the early 1980s that most biology graduates were finding employment appropriate to their qualifications within one year of graduating. Of the
remainder, the majority were occupied with further training or parenthood and less than 2% were convincingly and involuntarily unemployed[19]. But the early 1980s did see a decided shift in attitudes amongst both prospective biology graduates and employers. Employers came to recognise that biologists can cope with large amounts of information in a systematic way. Biologists have a much broader scientific training than most other scientists, simply because biology cannot be studied in isolation from the physical sciences. Biologists have to know about statistics and computing. They often have to work in groups and are accustomed to responsibility for their own part of a project and to working with other people. Above all, living organisms are exceedingly complex and designing experiments to study them usually involves a wide range of variables, analysis of complex datasets and skillfu1 interpretation. A background of this kind is an excellent training for management. A 1987 survey by David Hind at Newcastle Polytechnic showed that 38% of advertisements for new graduate recruits in industry made explicit reference to personal transferable skills[20].

Apart from the undoubted lure of the United States, European graduates have until recently opted to stay at home. Exchange between European countries has been largely confined to the leading universities and research establishments and has involved the very best of research-orientated graduates. Language and culture have doubtless been strongly influential in this regard. The situation is at last changing and the winds of change are being quite vigorously fanned by the government commitment to funding of co-operative research between western European universities and institutions and by a widespread tendency for big industry to become multinational and to operate above the somewhat trivial level of language and cultural barriers.

The outlook

Several matters have already been mentioned that will influence the history of biology over the next 50-100 years. Cost effectiveness in relation to technology and the rate of discovery is bound to be a significant force. As to the goals and objectives of future years, whatever we say today wll probably only serve to remind us in years to come of how bad we are at predicting the future. The subject was addressed with characteristic wisdom and skill by Professor John Postgate in his 1990 article *'Biology Forty Years On'* [20]. Quotation of the main points in his article would seem to be appropriate to quote in this context.

> " Humanity is certain to reach the nine billion mark. All these people will engender a demand for food, energy and industrial resources on a scale greatly exceeding

[19] R. W. Pethen and P. Calow, 'Zoology graduates of 1980 - where are they now?' *Biologist* 35 (1988), 126 - 128

[20] Green, 'Biological science graduates' (note 18)

anything mankind, or the planet, has yet experienced. Both teaching and research will be on an emergency footing compared with today, compelled to cope with local, international and global exigencies of overpopulation. The public may accept that scientists are necessary, like parking meter attendants, but it is unlikely that they will ever again be seen as the harbingers of Utopia. We are in a no-win situation from which we cannot escape: technological advances which serve to ameliorate the lot of the world's deprived billions only augment the drastic impact this burgeoning species is having on its own ecosystem. Population control is the only ultimate means of containing our ecological impact and universal literacy is the only way to spread common sense about research and its applications. Biologists will have no acceptable solution to offer for the economic problems in developed countries resulting from a retirement age of 50 and a mean life expectancy of 100".

The author, Professor Postgate, is probably right in most respects, but two observations seem worth making in postscript. First, it is fortunate that most men and women die well before they reach 100. It limits their span of practical involvement in the future of the world to something less than 50 years. Human nature is such that an average individual does not care much about the future of the world beyond the next 100 years. After that, it's a matter for future generations to sort out. Second, it might be said that, provided we accept the inevitability of total domination of the planet and its entire subservience to the needs of humankind, then our track record for successful management of our environment is not entirely unpromising.

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