Teaching and learning about EVOLUTION: Part 1

George Branch has been teaching evolution at university level for many years and is aware of the controversy surrounding teaching the subject at schools.

No topic in biology is more controversial than evolution; and no topic is so fundamental to understanding biology. In the view of Kenneth Miller (2007): 'In the minds of many, evolution remains a dangerous idea. For biology educators, it is a source of never-ending strife'. My own view is very different, for I have taught evolution to university students for 40 years with a sense of joy and awe: more than any other subject, it engages students with critical thinking, compels analysis of evidence and forces contemplation of the bigger issues of life. In this year, the 200th anniversary of Charles Darwin's birth, school teachers in South Africa have been challenged with the introduction of evolution as a formal part of the biology curriculum. And a challenge it is indeed: many teachers have not formally been trained in the subject, are pondering what approach to take, and fear the controversy it may engender. For me, it has been an exhilarating experience meeting and running workshops with teachers, to see the subject through the fresh eyes of teachers at the coalface.

In teaching evolution, I believe there are five components that must be covered:

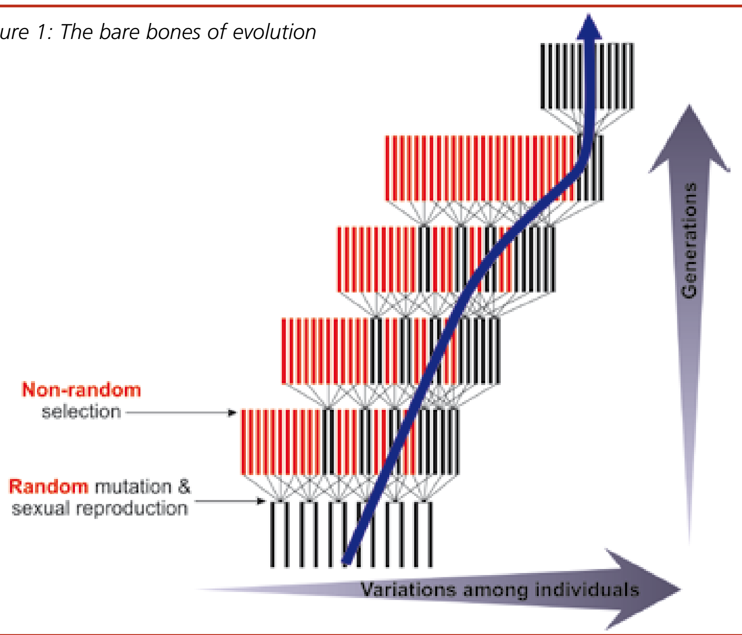
1. Understanding the basics of what Charles Darwin's ideas entail.
2. Testing the concept of evolution and the mechanism proposed by Darwin.
3. Appreciating how science is continually advancing, adding new ideas.
4. Grasping the relevance of evolution in our modern-day world.
5. Exploring the controversies and testing alternative views against the evidence.

In this article, I cover the first two and the last two aspects, leaving for a follow-up article the controversies and how I believe they should be handled.

A summary of Charles Darwin's theory

Theory	Evidence then	Evidence now
More individuals are born than survive to reproduce	Then	
Variety exists among individuals of a species	Then	
'Fitter' individuals are more likely to reproduce = 'survival of the fittest': Natural selection eliminates less well-adapted individuals		Now
If characteristics are inherited, species slowly evolve = adapatation, or 'micro-evolution' eventually even giving rise to new species = speciation, or 'macro-evolution'		Now

Figure 1: The bare bones of evolution



The basics of Charles Darwin's ideas

Many people before Charles Darwin believed in the *concept* of evolution – that species change over time and adapt to the environment – but Darwin's great contribution was developing a plausible *mechanism* for how it takes place. I find it useful to distinguish the two, because while there is universal agreement among biologists that evolution is a process that has and is taking place, there are still today many refinements to Darwin's ideas about the mechanisms that are being added. Darwin's ideas about the mechanism can be summarised in the four simple statements in the table on the left.

Read these carefully. It's hard to disagree with any of them. When Darwin was alive he had hard evidence of the first two. We now have strong evidence for all four. The ideas are deceptively simple but enormously powerful in providing a natural mechanism for how and why species change over time. In the short term, they explain change within species as they adapt to the environment – which some prefer to call 'micro-evolution'. But there is no reason why the process should not lead to the development of populations so different from the parent species that they can become separate species. This is speciation, called 'macro-evolution' by some, although I personally avoid the term because of ambiguities about what it means and because the processes leading to speciation are not necessarily different in kind from adaptation within the species.

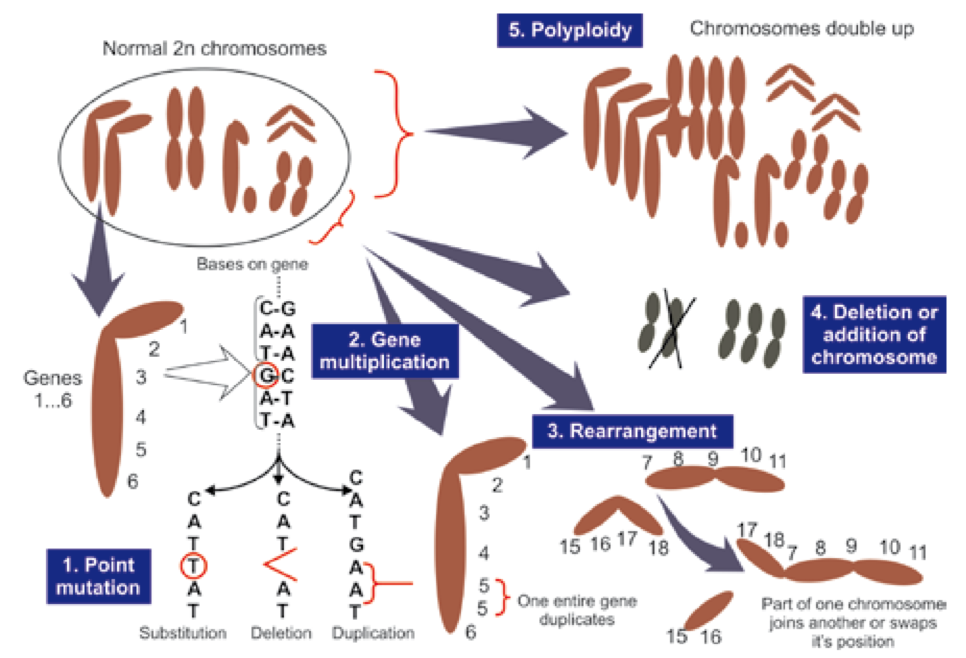
Figure 1 shows the process over time (generations), and I often tell my students that if they understand this figure they have grasped the essentials of Darwin's ideas.

At the bottom of the figure are lines representing 12 individuals – in male-female pairs – that vary in some characteristic (perhaps ranging from slow-moving on the left to fast-moving on the right, for example). These parents produce a range of offspring, which also vary among themselves, partly because they may contain some 'new' mutations and partly because they share their parents' characteristics. Natural selection 'prunes out' individuals – say those that are slow-moving – leaving the next generation with mainly fast-moving individuals. The process is repeated over generations, progressively changing the nature of the species. Note that whereas the formation of mutations is a random process (new mutations may by chance be good, bad or indifferent for the chances of survival of the individual offspring), natural selection is clearly not random, so the overall process of evolution is not random either.

In addition to natural selection (the action of environmental factors in selecting for particular varieties), Darwin also wrote extensively about sexual selection – how the characteristics of individuals of one sex may make them more attractive to the opposite sex (like the long tails of male widow birds or peacocks), or better able to compete with members of their own sex when seeking mates (like the antlers of male deer). As one of my first-year students memorably commented in an exam: 'It's the horniest male that wins…'

Darwin's greatest difficulty was a lack of understanding about inheritance. Gregor Mendel did publish his ideas in Darwin's lifetime, but Darwin failed to grasp their significance. Research has since unearthed multiple ways in which genetic variations can come about (Figure 2).

Figure 2: Different types of mutations.



Most familiar are point mutations, which change one individual base within a gene (by substitution of a new base, deletion or multiplication of the base), sometimes altering the amino acids in the resultant protein. Genes may duplicate themselves or swap their positions within chromosomes. Whole chromosomes may be deleted or duplicated, and even the entire chromosomal compliment can multiply in a process called polyploidy. All these genetic changes can alter the nature of the individual.

Two of these genetic changes are particularly interesting. When a gene is duplicated, one may continue its original function while the other is free to mutate and can lead to the formation of a 'new' gene with a completely different function. It seems that many of our own genes arose this way, including those involved in the complex sequence of reactions that takes place when our blood clots.

At first sight, polyploidy just looks like a doubling up of the chromosomal complement without the generation of anything 'new' in the genotype. But in reality the process seems immensely important in the creation of new species – particularly new species of plants. There is strong genetic evidence that large proportions of 'new' plant species are formed by a combination of hybridisation between different species and a doubling up of chromosomes. This seemingly unlikely combination of events forms offspring that have a unique genetic composition and cannot mate with either of their parental species, effectively 'instantly' becoming a new species. If we doubt the importance of this, ponder the fact that bread wheat – one of the most important food sources today – arose by two separate events of hybridisation-induced polyploidy.

Such modern developments in genetics throw light on how inherited genetic changes allow species to adapt and even how new species come into being – about which Darwin could only guess, despite the title of his book *The Origin of Species*.

Testing Darwin's ideas

In science, ideas are of no value unless they are testable (falsifiable). In Darwin's day it was easy to test the first two of his ideas. Variety is evident in all species; and it is easy to calculate what would happen if all individuals that are born were to survive to reproduce. For example, flies can achieve 17 generations in a year: if 30 females mated and all the offspring subdivided and bred unchecked for the 17 generations, there would be 12.9 million million million million flies produced (equivalent to a layer 2 km deep over the whole world). Mercifully, there aren't: so we can safely assume Darwin was right.

As a classroom exercise it is possible to explore family trees to demonstrate the principles of variety among individuals, survival-to-reproduction, and inheritance of family characteristics. I normally take a whole lecture to get students to discuss among themselves what lines of evidence they could seek to test Darwin's ideas – and the concept of evolution as a whole. As a prompt, one can ask: 'If evolution occurs, then …'. This leads to all sorts of evidence that can be sought in the natural world, which should exist if evolution takes place.

For example, 'If evolution occurs as Darwin proposed, then … not all individuals that are born should survive to reproduce.' That much is so ▷▷

Figure 3: The bottlenosed dolphin has vestigial remnants of all three elements of the pelvic girdle – mementoes of ancestors that possessed the hind limbs that have been lost in whales and dolphins.

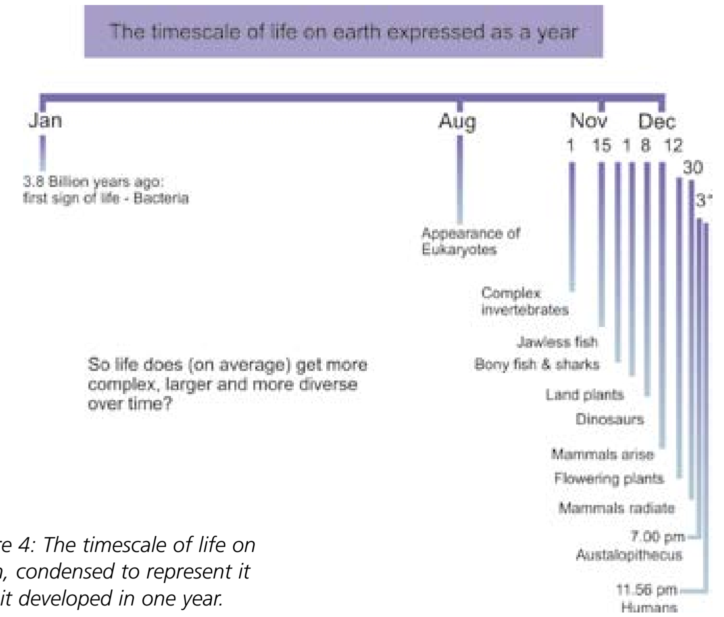


Figure 4: The timescale of life on Earth, condensed to represent it as if it developed in one year.

obvious as to be almost self-evident.

Over the years, my students have come up with 14 different, and largely independent, lines of evidence that can be used. Space doesn't permit examination of all of them, but they included expected trends in the fossil record, modern changes in the nature of species ('evolution in action'), the existence of intermediates between species (and between major groups of organisms such as reptiles and mammals), population studies on survival, genetic causes of variety, embryology, comparative morphology, comparative genetics, biogeography (patterns and explanations for where species live), taxonomy (classification of species), geology and dating of the Earth.

There are examples of modern-day 'evolution in action' in all textbooks. The change of peppered moths from populations dominated from pale forms to those dominated by dark (melanic) forms is a classic because it was one of the first to be recorded. But there are now hundreds of cases. Challenge students to come up with cases drawn from their own knowledge. Examples are development of drug resistance in the tuberculosis bacterium; the formidable adaptation of HIV to drugs; evolution in insects of resistance to insecticides; and human incidence of sickle-cell anaemia in areas with high malarial infection.

Let me dwell on two of my favourite tests of the phenomenon of evolution.

First, the existence of vestigial (or rudimentary) organs is to me one of the most convincing pieces of evidence that evolution is a fact. Consider a species of fish that lives solely in total darkness in caves and has rudimentary, stunted, non-functional eyes that cannot detect light. Why possess such a useless structure? If this species was created as it now is, and did not evolve from an ancestral species, 'blind' eyes are hard to explain. Personally, I would find it hard to accept that God would create species like that. If, on the other hand, the blind cave fish arose from a sighted ancestor that lived in sunlit waters, then possession of eyes would not only be understandable but expected. Also to be expected would be the loss of sight and the progressive degeneration of eyes in pitch-dark caves where eyes would not only be useless but a waste of energy. Natural selection would favour individuals that developed mutations eliminating the eye. Similarly, one could ask 'Why does a dolphin have the rudiments of a pelvic girdle buried in its hindquarters, when it has no hind limbs?' (see Figure 3).

Second, the fossil record also provides opportunities to test evolution. At least five things would be predicted of the fossil record if evolution occurs. Over time, there should be: (1) increasing complexity; (2) greater diversity; (3) overall increase in size; (4) more species that are similar to modern life; and (5) existence of intermediate forms. Indeed, the relative appearances of different major groups of animals and plants do reflect an increase in complexity, diversity and size, and there are many examples of intermediate stages, between – for example – fish and amphibians, dinosaurs and birds, and reptiles and mammals. Our own Karoo is world-famous for the 'mammal-like reptiles' that are bridges between reptiles and mammals. Figure 4 provides some perspective.

If we imagine the time-course of life on Earth being condensed into one year, three things always strike me. First, life – in the form of single-celled prokaryote Bacteria or Archaea – seemingly appeared on Earth around 3.8 billion years ago, relatively soon after the creation of Earth itself, which is dated at about 4.7 billion years ago. Second, for a very long period of time, there was only single-celled life, and then relatively modern-looking multicellular life abruptly burst on the scene. Third, our own human species is a real

Johnny-come-lately, emerging at 11.56 pm on the last day of this hypothetical year-of-life. I am always awed and humbled by this latter fact: by the immensity of events that preceded us, and by the awful responsibility we carry as the only sentient being both capable of destroying Earth's ecosystems and of contemplating means of avoiding that.

In short, *all* lines of evidence that have been used as tests uphold the idea that evolution does occur, and that Darwin's fundamental ideas about the mechanism are correct.

Appreciate how science is ever on the advance, adding new ideas

Darwin may have been vindicated by multiple lines of evidence, but his ideas were, nevertheless, far from complete: many other mechanisms have since been added to complement his visionary views. By far the most important have been in the field of genetics, which has generated an understanding of inheritance and an independent means of testing evolutionary ideas. After Darwin's insights – regarded as the 'first wave of understanding', genetics constituted a 'second wave'. But I would like to concentrate here on what some call the 'third wave', which is the revolutionary field of 'evo-devo' dealing with the evolution of embryological development. The miracle of embryology, in which a single-celled egg is transformed through organised stages into an adult stage with all its parts functioning in the correct time and place has taught us much about how evolution operates. More importantly, it has opened a new understanding of how quite minor genetic changes can bring about major changes in body form.

'Evo-devo' has revealed the presence of 'master-switch' or 'hox' genes that control by promotion or inhibition the expression of a cascade of other genes responsible for the assembly of the developing embryo. Every cell in the embryo has the full complement of genes. But it is the expression of particular genes in particular cells at particular times and places that regulates the development of the body. Imagine, for example, the development of an insect's body. In the head of the developing embryo, a hox gene is expressed that 'turns on' other genes controlling eye development. Further back in the body other hox genes may repress eyes but initiate limb formation. In the abdomen, both eyes and limbs may be inhibited (Figure 5).

Figure 5: In different parts of the insect body, 'master-switch' (hox) genes are activated (or switched off), controlling other genes that produce particular structures in different parts of the body. Here, the hypothetical action of three hox genes is illustrated for an insect body.

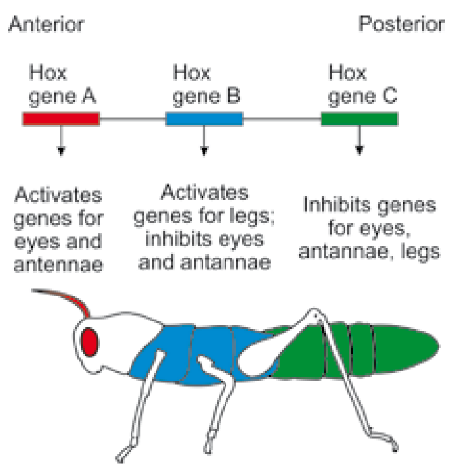


Figure 6: Neoteny in 'glow-worms': the premature development of sexuality and suppression of later stages, generating a grub-like adult that is fully mature – shown here with one of the snails on which glow-worms feed.

There are several extraordinary things about hox genes. First, they are exceptionally constant across major groups of organisms. For example, the hox gene regulating eye development (named 'Pax-6') is virtually the same in humans, molluscs, fish, birds, flatworms, bristle-worms and flies. Even although the eyes that are produced may differ radically in these very different animals, the 'master-switch' genes are nearly identical. Second, and as a consequence of this, the 'eye' hox gene can be extracted from, say, a mouse, and used to initiate development of a fly's eye in a fly. Third, if hox genes are experimentally activated in a 'wrong' part of the body, they will induce the 'wrong' body parts there: an eye can be formed on the abdomen, or a leg on the head.

In short, hox genes are in charge of controlling the embryological development of the body, initiating or inhibiting particular body parts in particular places and in the correct sequence. There are two enormous implications for the process of evolution that arise from this. First, the deep similarity of hox genes among a wide range of species implies that these genes have been shared over hundreds of millions of years of ancestral history. Second, very minor change in the activity, timing or place of expression ▹▹

Examples of the application of evolutionary principles in the modern world

1. Resolving legal issues – DNA fingerprinting
2. Tracing evolutionary origins of diseases and developing treatments
3. Genetic modification of organisms – e.g. generation of insulin by bacteria
4. Selective breeding of plants and animals
5. Warfare – biological pathogens and mutation-inducing chemicals
6. Resistance of insect pests to insecticides
7. Eugenics – countering genetic deficiencies
8. Justifying antisocial behaviour because of genetic predisposition
9. Genocide or racialism justified by supposed evolutionary superiority

of a hox gene can have a profound influence on the structure of an organism. It becomes, for example, easy to understand how a creature such as a centipede with its myriad of legs, might have become transformed into an insect that has only three pairs of legs. But we do not have to settle for a hypothetical case such as this: there are modern-day examples of creatures that have become radically modified by a change in the sequence of the expression of hox genes. One case is the 'glow-worm', which is actually the female of a beetle, in which the expression of wings has been suppressed by inactivation of the gene responsible for wing formation, and the premature activation of genes responsible for sexual maturity. The result is a creature that is not at all 'beetle-like', but resembles a grub that never develops its adult beetle features and becomes sexually active at a premature stage – a process called neoteny (Figure 6).

So as science has advanced, new ideas have been added to Darwin's core ideas, reinforcing, strengthening and expanding them.

Grasping the relevance of evolution

When first confronted with the idea of evolution, students and pupils often express excitement about the concept but regard it as abstract and distant from their everyday lives. Nothing could be further from the truth, and communicating this and getting young minds to appreciate the applications of evolution is an important part of education.

This can be used as a participative part of a course on evolution, in which scholars offer their own examples, research them, and present them. Their thoughts can be stimulated by asking them to work in pairs to come up with one positive and one negative application of evolutionary principles. Above is a list that resulted from one class of scholars, with positive outcomes being shown in green and negative ones in red.

In a world where HIV is mutating at a ferocious rate and thwarting efforts to find a vaccine or an effective drug, where we have the capacity to alter our own genetic composition but feel nervous of the moral implications, where we can genetically modify bacteria to produce life-saving insulin but balk at altering food crops, there is not only abundant evidence of the relevance of evolution, but plenty of scope for discussion – as evidenced by the fact that several topics ended up being a mix of green and red – neither all good or all bad.

Conclusions

1. The *process* of evolution is an established fact. It has been exhaustively tested against multiple lines of evidence and upheld. Species do evolve.
2. Darwin's ideas on the *mechanism* are equally well supported, but are clearly incomplete and have since been supplemented and supported, particularly by genetic and developmental research.
3. Science doesn't have answers to all questions, even in the material realm, but mysteries are a challenge for science, not a weakness … the fact that research in the field of Evolutionary Biology is so active shows we have much to learn; but the base on which we build is still founded on Darwin's central ideas.

There is still much material for debate. Is it right or wrong to screen unborn babies for genetic defects? What actions should be permissible if we do so? How can we as human beings be almost unanimous in supporting the use of 'genetic fingerprinting' to determine with certainty the guilt or innocence of people charged with crimes – and yet be resistant to accepting the concept of evolution without which this process would be impossible? In the next edition of *Quest* we will return to topics such as these – and the bigger question of how teachers might handle evolution and religion – in a second part to my pair of articles on 'Teaching Evolution'. □

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He has spent decades teaching undergraduate and postgraduate zoology students, inspiring generations of young scientists and offering a balanced approach to the science of evolution.

Suggested reading

Carroll S. *Endless Forms Most Beautiful: The New Science of Evo Devo and the Making of the Animal Kingdom*. New York: WW Norton, 2005. (An exciting and lucid account of the genetic control of embryology and its evolutionary implications.)

Dawkins R. *The Ancestor's Tale: A Pilgrimage to the Dawn of Life*. London: Weidenfeld & Nicolson, 2005. (A brilliantly written account of life, starting with humans and tracing backwards through their ancestors, with multiple insights into the evolutionary process.)

Hoagland M, Dodson B. *The Way Life Works*. South Africa: Ebury Press, Random House, 1995. (A superbly illustrated introduction to evolution and biology in general, written for the younger mind, but a delight for 'oldies' as well. Brilliant material for teachers.)

Millar, K. *Finding Darwin's God*. New York: Harper Perennial, 2007. (A great introduction to the controversies, written by a deeply religious person who is a molecular biologist and an authority on evolution.)