COMMENT / COMMENTAIRE

Darwin's legacy: why biology is not physics, or why evolution has not become a common sense[1]

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Abstract: Cosmology and evolution together have enabled us to look deep into the past and comprehend evolution—from the big bang to the cosmos, from molecules to humans. Here, I compare the nature of theories in biology and physics and ask why physical theories get accepted by the public without necessarily comprehending them but biological theories do not. Darwin's theory of natural selection, utterly simple in its premises but profound in its consequences, is not accepted widely. Organized religions, and creationists in particularly, have been the major critic of evolution, but not all opposition to evolution comes from organized religions. A great many people, between evolutionary biologists on one hand and creationists on the other, many academics included, who may not be logically opposed to evolution nevertheless do not accept it. This is because the process of and the evidence for evolution are invisible to a nonspecialist, or the theory may look too simple to explain complex traits to some, or because people compare evolution against God and find evolutionary explanations threatening to their beliefs. Considering how evolution affects our lives, including health and the environment to give just two examples, a basic course in evolution should become a required component of all our college and university educational systems.

Key words: cosmology, evolution, Darwinism, selection, gradual changes, human evolution, development.

Résumé : La cosmologie et l'évolution nous ont toutes deux permis de regarder dans le lointain passé et de comprendre l'évolution, du Big Bang au cosmos et des molécules aux humains. Dans cet article, l'auteur compare la nature des théories en biologie et en physique et demande pourquoi les théories physiques sont acceptées par le public sans qu'elles soient nécessairement comprises tandis que ce n'est pas le cas en biologie. La théorie de la sélection naturelle de Darwin, foncièrement simple dans ses prémisses mais aux conséquences profondes, n'est pas largement acceptée. Les religions organisées, et les créationnistes en particulier, comptent parmi les plus grands critiques de l'évolution bien que l'opposition à l'évolution ne vienne pas uniquement des religions organisées. Un grand nombre de gens, allant des biologistes spécialisés dans l'étude de l'évolution jusqu'aux créationnistes, incluant plusieurs universitaires, ne sont pas opposés logiquement à l'évolution mais ne l'acceptent pas néanmoins. Ceci découle du fait que le processus et les évidences de l'évolution sont invisibles aux non-spécialistes, ou encore qu'aux yeux de certains la théorie semble trop simple pour expliquer des caractères complexes, ou parce que des gens, en comparant l'évolution et Dieu, estiment que les explications fournies par l'évolution menacent leurs croyances. En considérant à quel point l'évolution affecte nos vies, tant en matière de santé que d'environnement pour ne donner que ces deux exemples, l'auteur conclut qu'un cours de base sur l'évolution devrait constituer une composante obligatoire au sein de tous les systèmes éducatifs collégiaux et universitaires.

Mots-clés : cosmologie, évolution, darwinisme, sélection, évolution graduelle, évolution humaine, développement.

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A confluence of centenaries in physics and biology have provided opportunities for thinking about the origin of life and the universe, about genes and genomes, and stars and galaxies—from the big bang to the cosmos, from molecules to humans. The year 2005 marked the 100th anniversary of Einstein's seminal papers that changed the way we think about space, time, matter, light, and energy. The year 2009 marked the 200th anniversary of Darwin's birthday and the 150th anniversary of his book *The Origin of Species* (Darwin 1859). The year 2009 was also the international year of As-

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tronomy, and 2010 marked the 65th anniversary of the publication of Erwin Schrödinger's *What is Life?* (Schrödinger 1945) in which he foresaw the informational repertoire of living cells and set the stage for the revolution in molecular biology. The year 2006 marked the 100th year of William Bateson's coining of the term Genetics. Bateson was on the path of discovering Mendel's Laws of Genetics, which remained unknown for 35 years until they were rediscovered in 1901. The year 2008 marked the 90th anniversary of Ronald Fisher's important paper on genetic correlations between organisms in which he provided the genetic basis of Darwin's theory of natural selection (Fisher 1918).

During a seminar delivered at Harvard in 1974, on the subject of measuring gene flow in Drosophila populations using fluorescence-marked fruit flies, Theodosius Dobzhansky remarked that under the microscope the flies shone like stars under the blue sky. Every time I see a microarray image of gene expression these days, Dobzhansky's remarks come to mind. In terms of how the sciences of genetics and cosmology have developed, there is indeed a similarity between genes and genomes (the subject matter of genetics) and stars and galaxies (the subject matter of astronomy). In both cases the science started with individual, isolated observations on genes and stars, respectively, and moved on, to large scale, comprehensive observations on genomics and astronomy, respectively. In both cases the science has moved from the study of samples to the study of the whole.

In this essay I first make some preliminary remarks about similarity between evolutionary biology and cosmology and then I treat the main question: why evolution has not become a common sense? I do not dwell on what evolution is (Mayr 2001) or on why evolution is true (Coyne 2009)—two of the most thoroughly dealt questions in response to challenges from the creationists. I argue that although evolution by means of natural selection is unassailable logically, it is not easy to understand mechanistically by the uninitiated. I also provide some criticism of how evolution is taught in schools and colleges. This essay is mainly intended for the general masses between evolutionary biologists on one hand and creationists on the other, i.e., noncreationist, humanists, social scientists, and others who are not logically opposed to evolution, and who are genuinely interested in serious dialogues between science and religion but do not have the background to understand the subtleties of evolution.

Evolutionary biology and cosmology

If Einstein's theory set the stage for the understanding of the physical universe, the science of genetics set us on the path to learning about ourselves—about the makeup of our biological universe. Starting from a humble beginning with Mendel's hypothetical factors (genes) to the sequencing of the human genome, the science of genetics has traveled from individuals to genomes, from stars to the galaxy by comparison, and has literally opened the universe of biological information and thus of the possibility of understanding the origin and evolution of life. Karl Popper (1963) characterized evolutionary biology as a historical science, but as disciplines engaged in learning about origins, both evolutionary biology and cosmology are historical sciences.

Winston Churchill remarked that "the longer you look back, the farther you can look forward". In both physics and biology, scientists are using the inverse of this dictum to look back in time and learn about the origins of the universe and life, respectively. In cosmology, the farther you can look into space, the longer you can see into the past. Physicists use the knowledge of stars and galaxies to learn about the origin and evolution of the universe just as molecular evolutionists use the knowledge of gene structures from organisms to learn about the origin and evolution of life. Evolutionists use DNA/protein sequence divergence and constant rates of evolution (genetic change) to trace back the biological diversity to the origin of life. When a gene evolves neutrally, such that changes in the gene do not affect the fitness of the organism, there is a constant relationship between the rate of genetic change and time (Kimura 1983). Therefore, the genetic divergence (D) between two species that have diverged for time t, $D = 2kt$, where k is the rate of genetic change per unit time. Thus comparing genetic divergence between distantly related species, the science of phylogenetics is able to map genetic divergence of organisms far back in evolutionary time. Astronomy uses red shift to measure distances of receding stars and galaxies through Hubble's law formula ($v = H_0D$; Hubble 1929) and relates them back to the origin—the Big bang.

As big ideas go, the theory of relativity and theory of evolution reign supreme: one deals with our understanding of the universe, the other of the biosphere. Einstein's theory opened the sky for us to see deep and allowed us to contemplate the origin and evolution of the universe; Darwin's theory allowed us to contemplate the origin and evolution of life including ourselves.

Theories in physics and biology, such as the theory of relativity and evolution, are not equally received—either by the scientific community or by the general public. One explanation is that the theory of relativity does not challenge our position in the universe but the theory of evolution does. More than that, physical theories of matter, space, and time can be harnessed technically for our benefit, which indirectly reinforces belief in their truth regardless of whether or not we comprehend them. Acceptance of ideas about evolution, on the other hand, has been controversial from the very beginning. Many remain uncomfortable with the idea of evolution and some, especially in the United States, continue to believe in special creation, especially of humans. The opposition to evolution from creationists is understandable, but they are not the only ones. A less appreciated fact is that a significant proportion of scientists, especially from the physical and medical sciences, also do not believe in evolution. This cannot be simply blamed on their lack of exposure to facts of evolution or for not having taken a course in evolution. Even among biologists it is not uncommon to find some successful scientists who may not, or one time did not, believe in evolution. The disagreement about evolution runs in different shades—from the origin of life to origin of humans, origin of consciousness and existence of a "soul".

The question naturally arises: why is it that after 150 years, Darwin's theory is still not widely accepted by the general public? The question is important as one cannot imagine a simpler theory with so profound consequences. The basic tenets of the theory are simple and clear. Evolution requires

that (*i*) there be phenotypic differences among individuals in different traits, (*ii*) that alternative forms of the phenotypes must have differences in their survival and reproduction (as a result of competition), and (*iii*) that the phenotypic differences between individuals must have a genetic basis, i.e., they must be transmissible from one generation to next. In addition, some random changes will occur from time to time as a result of population dynamics that may retard adaptation or even at times may produce new lines of innovation.

Any system, living or nonliving, that fulfills these three criteria would evolve and change over time. My favorite example is the evolution of cars. Cars have evolved and become better because car companies fulfill the three criteria for evolution to take place. Makes of cars are like a species and cars are like individuals within a species.

As far as the basic principles of evolution are concerned there is no difference between cars and humans. Car factories fulfill the three requirements that are needed for evolution to take place. First, there is phenotypic variation between different models to choose from just as we have differences among individuals within a species. These differences arise because of technical inventions, much like mutation, but also because of borrowing from other models much like recombination. Second, there are fitness differences between different models in the sense that they have different annual sale values. Fitness differential is imposed by the consumers because they like different models; different models sell differently in differently years. Third, there is "inheritance" of this fitness (i.e., sale values) in the sense that car workers copy and make more of those cars that sell the most in any given year. Car workers are equivalent to an organism's cellular machinery responsible for reproduction, and consumers are the agent of selection. Thus, like organisms, cars are born and they live, reproduce, and die, and over time different models go extinct as real species do. The problem with Darwin's evolution theory is that it is too simple—so simple that Thomas Huxley, a zoologist and a great supporter of Darwin, ruefully remarked "how extremely stupid not to have thought of that!" (Huxley 1900, p. 189).

There are limits to the parallel between biological and social evolutions. Some may feel that the making of cars unwittingly may support the theory of intelligent design. This is not true. We may choose to call our car workers inside the factory "intelligent", but, in nature's eyes, or to someone who does not know the inside of a factory, they are no more intelligent than the cellular machinery inside organisms. Both are required to do their job, failing which they will either be replaced with new and better workers or mutations or will go through a factory closure or become extinct. Factories do close and species do go extinct.

In one of his thought experiments Einstein imagined what it would be like to be sitting on the head of a light particle, a photon, and travel through space. To make the explanation simple to a nonspecialist, he went to the level of the physical mechanics of light and made us see that for such a traveler wherever he/she went, time would be the same. This is not to say that Einstein's theory is easy to understand, even for educated people. People may not comprehend it but they still believe it because it has been shown to work and explain phenomena not explained by other theories. Animal and plant breeders have produced spectacular varieties of breeds and cultivars and have shown how evolution can work and can produce diversity of life, but it is the lack of simple mechanistic explanations, linking short term, gradual changes to long term distinct outcomes, that makes evolution hard to understand even for educated people.

And yet evolution should be easy to understand. Evolution is a logical necessity that is bound to occur if you have things that reproduce with errors. Relativity is way more difficult. Relativity is not a logical necessity. Relativity needs a complex mathematical background and it makes precise predictions. So you can test it. Evolution is bound to be true, but it does not make the same kind of predictions.

Challenges to Darwinian evolution

There have been repeated scientific challenges to the theory of evolution in the past, and the nonbelievers of evolution cite them as support for their case. However, the scientific challenges to the theory of evolution were technical and of a very different kind.

The modern theory of evolution has enjoyed success by bringing together Mendelian genetics and Darwinian evolution; although the theory has faced many challenges from different corners, it has survived them all. These challenges have been of two kinds: those of scientific nature that question the adequacy of natural selection as sufficient explanation of change and those of general nature that question the truth of evolution on religious or other grounds.

Among the serious scientific challenges to the theory of evolution, the foremost has come from developmental biologists. Many developmental biologists felt Darwin's natural selection theory was inadequate to explain the diversity of developmental complexity observed among organisms. Yet 150 years after Darwin, although our notions about the fine details of mutation, gene regulation, and selection mechanisms may have changed, no new forces of evolution have been added to the important forces of evolution, i.e., mutation and selection. Many developmental biologists rightly see the complexity of development less of a problem to the theory of evolution and more of a challenge to their field to explain it by natural selection (Bonner 1988).

Other similar but more technical challenges have come in the form of non-Darwinian evolution from molecular biologists (King and Jukes 1969), neutral evolution from molecular population geneticists (Kimura 1968), and from punctuated evolution or "evolution by burst" (Eldredge and Gould 1972; Gould 1977). As these challenges have broadened our horizons and have enriched Darwinian evolution, especially in terms of the ever-unfolding dynamics of mutational and genomic variation (Lynch 2007), these were not challenges to the theory itself but only to the details of the evolutionary mechanics, i.e., about role of selection and rate of change.

Why evolution has not become a common sense

The opposition to evolution goes beyond religious fundamentalism and includes a great many people from educated sections of the population, including biologists, nonbiologists, and the lay public. This essay will focus on the lack of

belief in evolution in this latter group; opposition from religious fundamentalism has been covered in many places (Kitcher 1982; Futuyma 1983; Montagu 1984; Young 1985; Gould 1999; Dawkins 2006; Coyne 2009). There are several reasons why facts of evolution are not easily comprehensible by the general masses.

First, evolution is invisible to nonspecialists. A typical person is not exposed to the diversity of life and adaptations as very few of us are as well traveled as evolutionists like Charles Darwin, Alfred Russel Wallace, and Charles Lyell were in their time. Darwin and Wallace came up with the theory of evolution by natural selection from their observations on organisms in different habitats and from richness of species diversity and varied adaptations over space and climatic conditions. As an undergraduate student of biology in India, I did not believe there could be hundreds of species in a particular genus until I came to North America and saw that none of the plants and animals that I had seen in India were here. But travel can open our eyes only if we are willing to see.

As societies have grown we have surrounded ourselves, in our gardens, parks, schools, offices, road sides, and of course in the zoos, with contrasting varieties of plants and animals living side by side. This gives a false, exaggerated picture of the natural differences among organisms that makes evolutionary interpretation difficult if not impossible. In every day life we do not see the subtle phenotypic gradations among organisms, the type of variation that is the basis of evolution. Varieties of dogs and cats do not help because for the common person all dogs are dog. The situation is worse when it comes to understanding human evolution. There are simply no gradations of many human–primate differences. There seems to be no gradation of consciousness outside humans. And many would claim that only humans have a soul. Understanding is difficult without experience.

Second, there is misunderstanding about the role of mutation and selection. As it is true that most mutations are deleterious and get eliminated, the opponents of evolution go further and argue that as mutations are random, they cannot produce functional proteins, intricate cellular apparatus, and developmental complexity. They are either being ingenuous or simply do not understand that mutations alone do not produce evolutionary change and that although mutations are random, selection is not. Subject to constraint from population fluctuation (effect of drift), under natural selection you get what you expect; fitnesses do not lie.

The role of genetic mutations is misunderstood in another way. Contrary to the general perception generated by molecular biology and medical genetics, for most traits evolution does not occur on a gene-by-gene basis, good genes vs. bad genes, but by selection-driven small, incremental changes in the average phenotype of traits, often in many traits at a time, most of which are controlled by many genes (Wright 1978). Gene interaction and context are important in evolution (Lewontin 1974), and genes that interact favorably with other genes—Ernst Mayr's so called good mixers (Mayr 1963)—are favored in evolution.

A related misunderstanding among the opponents of evolution is how a protein evolves. They confuse between how a protein functions today and how it came to be that way over millions of years. They take the DNA or amino acid sequence of a protein and calculate the probability of them all coming together in that particular sequence and size by random mutation. It can be calculated as $(1/4)^n$ for DNA sequences and as $(1/20)^n$ for amino acids (frequency of nucleotides or amino acids raised to the power n, the size of the gene or protein). As expected this probability comes out to be as infinitesimally small and hence the argument that mutation alone cannot account for the evolution of protein functions. The adversaries of evolution fail to understand that proteins do not evolve by mutation alone nor start with a predetermined, final function. Both structure (sequence composition and gene size) and function evolve over time, step by step, by trial and error guided by natural selection. The unique sequences and the exact size of proteins seen today are not essential, as many mutational changes in their present sequence and size will leave their function unaffected. The present gene sequences are the combined results of mutation, selection, and historical accidents.

The power of natural selection remains badly unappreciated. The acceptance of evolution is limited by the perception that natural selection does not have the power to create complex organs like the vertebrate eye (but see, Dawkins 1996), or that it does not have the power to create new species but only trivial variation among populations within species. Darwin devoted two chapters of his book and much time trying to bring together the results of vast amounts of artificial selection experiments with crop plants and domestic animals to bear by analogy on the power of natural selection in evolution. The invisible hand of gradual evolution keeps ticking and over geological time produces immense diversity as a result of accumulated changes within and between taxa.

Third, there is a lack of appreciation for the sense of deep time, on the geological time scale. For the common public it is hard to appreciate the immensity of the geologic time and its importance in evolution. The polymath biologist J.B.S. Haldane, who did much work on the role of mutation and selection in evolution (Haldane 1966), pointed out that there has been enough time for selection to have acted and produced the diversity that we see in nature. If anything there has been more than enough time. Take any trait such as the height of our ancestor Lucy (*Australopithecus afarnensis*) whose fossils were discovered in Ethiopia in 1974. Lucy was only 3 ft. 8 in. (1 ft. = 0.3048 m) as compared with the height of modern humans, which varies between 5–6 ft. The difference between Lucy and modern human height of say 5 ft. 8 in. is only 24 in. This difference has evolved over 3.2 million years which comes out to be 0.00006 in. per generation, or 0.75 in. per 100 000 generation, assuming a generation time of 20 years in humans. The postulated average selection pressure (selection coefficient) required per generation is infinitely small that can be swamped by changes generated by chance (random genetic drift). Of course, it is rare that a trait evolves in a unidirectional manner for a long time. Often a trait evolves in combination with other traits. Therefore, a trait, such as height, can evolve back and forth as the selection pressure changes between lineages in response to environment. The power of small selection pressure, accumulated over time, was stressed by Darwin and later reinforced by Ronald Fisher in *The Genetical Theory of Natural Selection* (Fisher 1958). In Darwinian evolution it is not so much the inten-

sity of selection pressure but its perpetual operation that matters the most.

Fourth, a problem in accepting evolution is the role of environment. Environmental change is one-half of any story about evolution, but nothing is more misunderstood than the meaning of the environment (Lewontin 2000). The environment is often seen as something imprecise, impermanent, insignificant, oscillating back and forth, and going no where. Why not? In our life time we hardly notice any major directional change in the environment. And yet, in the final analysis, all evolution is a statement about the environment; all evolution is in response to changes in the environment. A gene is a piece of coded information, selectively maintained and accumulated over time in response to changes in the environment both biotic and abiotic.

Evolutionary changes appear directional because changes are slow and gradual. Evolution of a trait can go upward or downward but evolutionary change is perpetual, generation after generation, and it occurs by making use of genetic types (genotypes) that have survived up to that point. Evolution does not work by reassembling traits every generation and starting all over again. This leads to phylogenetic constraint, meaning that a change at an earlier stage in the lineage will affect further changes in that lineage. Evolution is blind; although its outcomes are not predetermined, it appears directional in the long term. People confuse apparent evolutionary directionality in traits with predetermination. People do not believe in evolution because they do not see that evolution is going anywhere in the short term—in their life time. However, recent careful selection experiments with bacteria and fishes have shown that evolution can occur amazingly fast (for details see chapter 5, Dawkins 2009). Extinction of species is becoming a reality now and this may also bring home the message of evolution.

An additional problem is that as biologists we have not done a good job of communicating the importance, the inevitability, and the ubiquity of evolution. A student once told me that she lost interest in evolution as it was thrown on her time and again from high school on, but no one ever helped her see the connection between the forces of evolutionary change and the evolution of complex phenotypes like the vertebrate eye.

Most students will never take more than one course on evolution. The problem of communicating mechanisms and dynamics of evolution is further complicated by the basic facts of population genetics. Consider the following theoretical results. (*i*) The rate of mutation is very low (10^{-6}, one mutation in a million copies of the gene) and each individual contains approximately one new mutation (one mutation per genome). (*ii*) Most mutations (over 99%) are deleterious and most of those surviving, the majority may be neutral, have no effect on fitness; all this is to say that beneficial mutations are rare. (*iii*) The probability that a new neutral mutation will go to fixation, i.e., will spread in the population and will replace the old copy of the gene is $1/2N$ and the time taken for a neutral mutation to go to fixation is $4N$ (where N is the population size). (*iv*) The probability that a beneficial mutation will go to fixation is $2s$ (where s is the amount of selective advantage over the old mutation), and it will take approximately the death of $30N$ individuals (30 times the population size) before the new beneficial allele will replace the old copy. The theory is solid, but all this is to say that with a small mutation rate (μ), large population sizes (N) and small selection coefficients (s), evolution is expected to be a slow process. Put it all together and present them to a student of evolution and you have the challenge of your lifetime to make them really understand how evolution works within the time frame of a 3 unit course. I do not think the fact that they do not believe has anything to do with these theoretical points; it comes from prior preconceptions and religious world view. After 30 years of teaching evolution I feel most students who take evolution courses may marvel the facts of evolution (fossils and all), they do not develop a true appreciation for the mechanisms of evolution, i.e., how evolution can be gradual and still produce profound change over time.

As biologists we must share some of the responsibility for the fact that evolution is not widely understood or accepted. During the 1940s scientists from various disciplines, such as population genetics, paleontology, and systematics, got together and forged an Evolutionary Synthesis taking into account all the known facts of evolution at that time. But check out any text book written following the Synthesis and you will find them full with principles of population genetics theory but lacking in biological details. The forces of evolution (mutation, selection, drift, and migration) are all explained there but what needs to be explained, evolutionary dynamics of complex phenotypes, is often missing. There is very little on the diversity of animal and plant breeding material that Darwin used in *The Origin of Species* to argue the case for evolution. There is virtually nothing on physiology, which constitutes the basic machinery of living organisms. And there is nothing on the developmental biology of complex traits, which Darwin found so challenging to explain.

The old text books on evolution had none of these. In these books, the story of evolution was presented more as a logical and reasoned argument sprinkled with examples for demonstrations than as a description of adaptive systems. There were no attempts made to appreciate the role of the small, incremental forces of selection in the evolution of complex phenotypes.

Modern text books have of course changed and improved, and the major facts of evolution (fossils, phylogeny, biodiversity, and developmental complexity) are presented before teaching the theory of population genetics as it should be. Serious interest in evolution can only come from learning about the facts of evolution, not from the theory of gene frequencies. Biologists like the late Stephen J. Gould nurtured a whole new generation of evolutionary biologists by writing about the facts of evolution for the general readership. Knowledge of evolution is required for a good understanding of all aspects of our life—from the functioning of our body and brain to our relationship with our fellow human beings and the environment around us.

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