OPINION

THE EVOLUTION-CREATION WARS: WHY TEACHING MORE SCIENCE JUST IS NOT ENOUGH

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ABSTRACT. The creation-evolution "controversy" has been with us for more than a century. Here I argue that merely teaching more science will probably not improve the situation; we need to understand the controversy as part of a broader problem with public acceptance of pseudoscience, and respond by teaching how science works as a method. Critical thinking is difficult to teach, but educators can rely on increasing evidence from neurobiology about how the brain learns, or fails to.

LA DISCORDE ÉVOLUTION-CRÉATIONNISME :
POURQUOI UN ENSEIGNEMENT ACCRU DES SCIENCES NE SUFFIT PAS

RÉSUMÉ. La « controverse » création-évolution existe depuis plus d'un siècle. Je soutiens que le seul fait d'enseigner plus de sciences n'améliorera probablement pas la situation : nous devons appréhender la controverse comme faisant partie d'un problème plus vaste lié à la réception de la population vis-à-vis des pseudosciences et nous devons y répondre en enseignant le fonctionnement des sciences en tant que méthode. La pensée critique est difficile à enseigner, mais les éducateurs peuvent compter sur l'augmentation des preuves issues de la neurobiologie qui montrent comment le cerveau apprend ou échoue à apprendre.

The "controversy" that does not go away

The theory of evolution by natural selection (and other natural means) has been socially controversial ever since its elaboration by Darwin and Wallace (1858), and has gone through countless legal challenges, from the infamous Scopes "monkey" trial in Tennessee in 1925 to the recent decision against the teaching of Intelligent Design in Dover, PA (Caudill, 1997; Larson, 1997; Alters & Alters, 2001; Pigliucci, 2002; Forrest & Gross, 2004; Young & Edis, 2004; *Kitzmiller v. Dover Area School Board*, 2005).

Of course, there is no scientific controversy at all. One of my colleagues teaches the difference between a cultural and a scientific controversy in the following manner. He enters the classroom bringing a pitcher full of water with some ice floating in it. He then asks his college freshmen class what they think will happen once the ice melts. Apparently unaware of the basic physics principles at work in this demonstration, the majority of the students predict that the water will overflow the pitcher (it will not, because of the lower density of ice when compared to liquid water, which means that the melted water will actually occupy less volume overall). He then proceeds with the lecture ignoring the pitcher. At a suitable point, he refers back to the pitcher, where the ice has now melted and, predictably, there has been no spillover. "You see," he says to his students, "there was disagreement among you on what the outcome would be, but that does not mean that there is a scientific controversy here. It only means that most of you do not seem to understand some of the basic principles of physics."

The creation-evolution problem is more acute and difficult to overcome precisely because it is not a scientific controversy. Social controversies about science teaching have much deeper roots, and they cannot be solved simply by explaining to people what science tells us about the topic at hand. In the following, I will present my ideas, based on personal experience and research, about what may be useful to do in order to redirect our thinking about the evolution-creationism debate. I will argue, for example, that more science education is probably a good idea, though it ought to be of a different kind than what is largely practiced now. More importantly, I think it is urgent that we consider broader issues of education, critical thinking, and even the neuroscience of belief, if we are serious about making progress with regard to this seemingly thorny issue.

Teaching science: Facts or methods?

Let us begin with the obvious: the teaching of science. It seems to me that a major problem, reflected in most current textbooks and curricula at both college and pre-college levels, is that educators are pressured to "cover" a vast amount of material and end up with little or no time to teach students how science is actually done. This is a terrible mistake because it does two things that we should avoid at all costs: first, it conveys the message that science is as boring as reading the yellow pages (which it is, if one simply enumerates all the factoids that are contained in the typical textbook); second, it unfortunately reinforces the idea that science is all about results that are somehow – and without discussion of scientific methodology might as well be magically – generated by people who dress in white coats and engage in mysterious activities. Little appreciation for the process of science is developed, and with each generation, we are directly responsible for rearing and educating citizens who will have no idea, for example, why global warming might be a threat and, most importantly, how we know that it is (or is not).

Consider a simple fact: although the typical introductory textbook in biology for college students can be more than a thousand pages long, usually only a small fraction of these pages are devoted to some explanation of how all those facts were gathered and those conclusions reached. A typical trend in the wrong direction is exemplified by the way genetics is taught. Typically, teachers used to follow a historical sequence, starting with Mendel and his experiments on heredity, progressing through their rediscovery at the beginning of the twentieth century, to the demonstration of the chromosomal theory of inheritance, up to the first evidence that DNA is the carrier of genetic information, and then on to the identification of the structure of DNA and the elucidation of the genetic code. Molecular genetics and recombinant DNA techniques were placed toward the end because they were the latest developments of a logical, if nonlinear, sequence of discoveries.

However, everybody "knows" that history is boring, and besides, molecular biology has literally exploded during the past few decades. This has led many teachers and textbook authors to feel compelled to give "up-to-date" information about this rapidly expanding field, often skipping the historical sequence entirely, starting instead with the wonders of bacterial genetics. The result is that students are confronted with a bewildering array of complex facts that they cannot link to each other conceptually as they probably have no idea from where this information has come. For example, although every teacher of molecular biology knows what restriction enzymes are (because they are so useful in a variety of recombinant DNA techniques), I doubt that most of them realize how they were discovered or what their natural function actually is.

The point of teaching science in its historical context is not just that history is interesting in its own right. More importantly, it is the best way to explain how and why scientific discoveries are made, which turns science from a barrage of meaningless and boring facts into a vibrant enterprise of discovery and human realization. Fortunately, some university and high school teachers are beginning to recognize this and are changing their lesson plans accordingly. However, the overwhelming majority are still turning students off to science every year. Is it any wonder that scientific misconceptions and pseudoscientific ideas (including but not limited to creationist claims) are so common among high school and university students?

Perhaps even more unfortunately, the major response so far to the sorts of concerns I am discussing here has been a shift in emphasis from traditional classroom lectures to "hands-on" activities in which students manipulate objects and perform experiments. Moving away from lectures and getting students to actually do things is an excellent idea, but the way the hands-on approach is often implemented, especially at the pre-college level, may actually produce worse results than the traditional lecture approach. The problem with many hands-on experiences is that the brain stays turned off. I have sometimes seen secondary level students just wandering about and giggling at whatever happens to be under the microscope, with little understanding of what they are doing or why. The reason is that their teachers are often in no position to provide them with the conceptual background to derive the greatest benefit from these activities. This may be either because the teachers themselves have a hazy understanding of the subject matter, or because they are more preoccupied with "classroom management" (i.e., with keeping order and making sure nobody gets hurt).

Things are often only marginally better in college or university classes, where so-called "teaching assistants" who usually have little or no training in teaching, and who are working for very little pay while trying to finish their Ph.D. dissertations, are unprepared to teach or might not even care much about teaching (there are, of course, significant individual exceptions). Even when a post-secondary course has a lab component, it is usually largely decoupled from the lecture class, so in effect students are taking two independent courses in the same discipline with little understanding of how to connect the experiments to the necessary concepts. Worse yet, most of these exercises are "prepackaged" labs designed to obtain a predetermined outcome, which often enough does not occur because of the carelessness of both students and teaching assistants. The latter are then tempted to do the worst thing they could possibly do in teaching science: tell the students that they should have gotten result X instead, and to write up their reports as if they had. Is it a surprise, then, that the whole enterprise becomes meaningless and that most students think science is either too difficult for them to grasp or, worse, is actually done by cooking the results to come out according to *a priori* expectations (the perennial creationist paranoia).

There is another pernicious myth that lingers in universities around the world, and it is a major cause of some of the problems we are considering. This unfortunate misconception is what Sperber (2000) refers to as "the myth of the good researcher = good teacher." By and large, university professors are officially paid to teach, especially at public institutions. They are also expected to do research and to bring in as much grant money as possible, but the main reason taxpayers and parents subsidize professors' salaries is teaching. However, academics who wish to advance in their career at any research university realize very quickly that the real trick is to invest as little time as possible in teaching and to concentrate on research, publishing, and especially bringing in grants. Worse yet, this is becoming the trend even at primarily teaching universities, where the main mission is teaching but the road to promotion and tenure increasingly goes through publishing. The result is a split-personality role for the university professor, who has to serve two masters, one of which is (unofficially) much more powerful than the other.

The standard response of university administrators (and of many faculty as well) is to cite the "good researcher = good teacher" myth. The assumption (which is all it is) is that people who are good at doing research in a certain field will also be good as teachers in the general discipline in question. There is no empirical evidence to confirm this, and quite a bit of my own and my colleagues' anecdotal experience goes directly against it. Sure, there are a few exceptions of individuals who are both excellent teachers and excellent researchers, but that is what they are – exceptions. By and large, universities are filled with mediocre researchers and even more mediocre teachers. One observation that reveals this is that faculty who are good at their research (as measured by the number of their publications and the amount of money they bring in with grants) are shielded as much as possible from teaching! Some might not teach at all (even buying out their own teaching through grant money), while others confine themselves (happily) to teaching only graduate seminars, avoiding the most crucial of all courses from an educational standpoint: the introductory sequences. If these are supposed to be our best teachers, why not employ them where it is most crucial to have good teachers?

The reality, of course, is that human talents are varied and multifaceted, and they are not necessarily coupled in the way we would like them to be. One can be an excellent teacher and a canny researcher, but that is the least likely combination because the two activities require quite different skills which seldom develop in one individual. The fact that a researcher can think up elegant experiments at the frontier of molecular biology does not necessarily mean that he or she will succeed in effectively explaining meiosis to a class of college freshmen. Similarly, being capable of writing a good book for the general public does not mean you will produce superb grant proposals that will be regularly funded, and so on.

I am not here advocating the dismantling of the current university system, much less doing away with funding of scientific research in universities. What I am saying is that we know there is a problem and we also may know why. The real obstacle is that taking the obvious steps to improve the situation requires vision and courage – two qualities often sadly lacking in faculty, administrators, and politicians; the very people who have the power to change things.

If we broaden the horizon from academia to our culture at large, the view does not improve very much. Dawkins (1998) complained about the fashion of making science "fun, fun, fun," as if it were a comedy show. Indeed, educators are often expected to perform like stand-up comedians to make their subject matter entertaining. Similarly, Postman (1994) remarked that we live in a society in which a major goal seems to be to "amuse ourselves to death." The particular case of science teaching is just one example of a cultural trend that will take a great deal of effort to slow down, let alone to turn around. The point, of course, is not that science has to be boring, but that there is a difference between something being interesting and simply entertaining. Human beings need entertainment, even of the mindless kind, but we are reduced to little more than brutes if everything in our lives must be packaged as flashing lights and funny sound bites, as we have been conditioned to expect by television and other media.

In the United States, the major television networks are required by law to provide a certain amount of educational programming for children in exchange for being allowed to use the public airwaves for free (and to make a mountain of dollars in the process). One of the networks in question used as part of its share of "cultural" programming a famous cartoon series featuring humans and dinosaurs living at the same time in an idealized version of suburban America (a scenario that many creationists take as essentially true). Even American public television, considered a paragon of cultural value (and accordingly little watched or financially supported by the public), is airing programs that are, at most, of dubious value in their attempt to educate children. Many of these programs feature a bewildering array of characters that talk about a particular subject matter for maybe one or two minutes before jumping off to something completely different. Now, it is true that young children do not have the attention span and capacity to focus that we expect (and rarely obtain) from an adult or an older child. But the point of education is to help children develop those abilities, not to set the expectation that they will be always entertained by colorful characters who cannot stay on the same subject for longer than the span of a television commercial. It is no wonder that elementary (and higher) school teachers have to contend with a chronic inability of their students to pay attention during class time.

The "problem" with education is so multifaceted and daunting that it is not surprising that progress has been slow. The type of students attending our colleges is the result of a long chain of events that often begins with little emphasis on education at home (or with parents who for various reasons may be unable to provide the necessary jump start), and continues with years of exposure to teachers who are trained in how to teach (and not necessarily so well) but who rarely know much about the subject matter they are supposed to present. The problem is often compounded by peer pressure and cultural stereotypes that favor (and reward) nonintellectual activities. This means that we need to broaden our horizons to go beyond the specific question of evolution-creationism, and even beyond the complexities of science education.

Not just creationism, not just education

Creationism's rejection of well established science is not the only concern I am considering, although it has its own peculiarities that deserve special attention. A more general problem is the widespread lack of critical thinking skills among the public, and the fact that we often fail to teach critical thinking in schools and universities. As a result, not only do 58 percent of Americans believe that "God created human beings pretty much in their present form at one time within the last 10,000 years or so" (Goode, 2002), but large numbers of people believe in UFOs, alien abductions, astrology, haunted houses, telepathy, the ability to predict the future, and a host of other purported phenomena one would have thought ended up in the dustbin of history at the end of the Middle Ages.

Will more science education bring about the end of all these paranormal beliefs? The answer that I lean toward, as unsatisfying as it may sound, is yes, and also no. I do not think that more science education of the standard variety will make much difference. Indeed, it may even do harm. Let me explain: scientists and science educators often assume that a major reason so many people believe in pseudoscience is that they do not know enough science. However, although the latter is an accurate empirical observation (most people do not know much about science), it does not follow that scientific illiteracy is the cause of widespread belief in all sorts of paranormal phenomena. If lack of scientific knowledge is not the root cause, then more science education will not necessarily solve, or even ameliorate, the problem.

In fact, the connection between education (science education in particular) and belief in paranormal phenomena or explanations is an empirical matter, and it has been investigated as such. The results are not very supportive of the standard view of the problem, at least not entirely. A survey by the Pew Research Center for the People and the Press (as cited by Goode, 2002) found that belief in heaven as a real (physical) place does diminish according to increasing levels of education from 92 percent among people with less than a high school education to 73 percent among people with a postgraduate education. But three out of four people with a college-level education in the US still believe in the physical existence of Heaven! The same trend applies to other measures of belief: Hell is considered an actual place by 80 percent of the respondents in the first category and by 56 percent in the second. If one is less educated, one is 20 to 30 percent more likely to believe in angels, but the most astounding fact is that 22 percent of college-educated people in the United States think that "people on this earth are sometimes possessed by the devil"! That equals one in every four or five of the most educated people in the most prosperous country in the world – one that is proud of possessing many of the best universities on the planet.

There is more. Although an inverse relationship does obviously exist between the level of education and the beliefs mentioned here (a finding mitigated by the fact that even many of the most educated people still hold on to such beliefs), notice that the Pew survey addressed beliefs with a strong religious component. What about beliefs in paranormal phenomena that are not based on a religious mythology? Anecdotal evidence suggests that religious fundamentalists tend actually to disbelieve paranormal phenomena that are not part of their religious doctrine, such as alien abductions or astrology. But this lack of belief in these aspects of the paranormal is hardly a result of critical thinking, it is simply the denial of things not mentioned or expressly condemned in the Bible.

Quantitative evidence is available: a Gallup poll (as cited by Goode, 2002) reported that the highest level of belief in UFOs visiting Earth is found among people with a college education (51 percent), a figure that is only slightly less for respondents who had not graduated from high school (48 percent). Similarly, a study by the Princeton Survey Research Associates (as cited by Goode, 2002) that asked about belief in the paranormal and supernatural found that high school dropouts responded more positively by only a very slim margin over more educated respondents (43 versus 39 percent). Several other polls have produced similar results, which amount to an inconsistent pattern of alleged correlation between education and some kinds of paranormal beliefs.

Research on various sorts of non-scientific beliefs seems to point to two important conclusions that science educators should keep in mind. First, there is a difference between religious-based and non-religious-based beliefs: the former appear to be inversely related to the degree of education; the latter do not. This means factors other than just the general degree of education are at play. Second, even when education makes a difference, it leaves a staggering number of people believing all sorts of ideas not supported by science. Why? Before delving into this question from the perspective of what we know about how the brain works, let me report and briefly discuss two more sets of data, which I obtained while surveying classes at the University of Tennessee in Knoxville.

I used to teach a course on science and pseudoscience which was offered to honors students, which are most definitely not a random subset of the student population at the university. These were among the best and brightest students on campus. They also came from disparate backgrounds with fewer than half of those I interviewed pursuing a science major. I asked them to respond to questions aimed at evaluating their general knowledge of science as it is assessed among aspiring high school teachers. These were questions about matters of fact, not principles of science or critical thinking. Not surprisingly, science majors knew (slightly) more science than non-science majors did. I then asked them to rate their belief in a series of paranormal phenomena, from voodoo to astrology, from water dowsing to haunted houses, and so on. The results (Figure 1) indicate no significant difference between genders, but, astoundingly and contrary to expectations, the science majors held more strongly to paranormal beliefs than the non-science students!

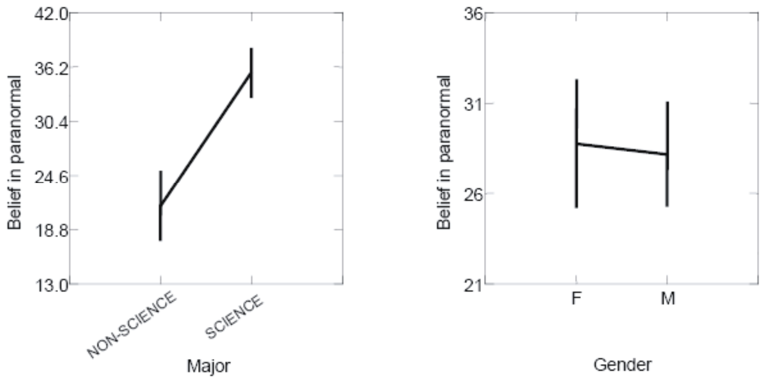

FIGURE 1. Results of a survey conducted by the author on the belief in a host of paranormal phenomena by honors students at the University of Tennessee. The diagram on the left shows that – surprisingly – science majors actually show more belief in the paranormal than non-science (mostly philosophy) majors. The diagram on the right demonstrates that in this sample there was no relationship between belief in the paranormal and gender. Brackets indicate standard errors.

In a broader follow-up study (Johnson and Pigliucci, 2004), we compared in-depth knowledge and belief of groups of science and non-science majors in the following categories: knowledge of science facts (e.g., what is the dominant source of energy on earth, the nature of photons, the relationship between earth-sun distance and seasons, etc.); knowledge of the conceptual foundations of science (e.g., the nature of theories, the role of experiments, the use of theoretical entities, etc.); and belief in a series of paranormal phenomena (e.g., healing power of magnets, telepathy, Loch Ness monster, etc.). The results were rather disturbing. Once again there were significant differences between science and non-science majors in their degree of factual knowledge of science (with science majors having more), and no gender differences. However, there were essentially no differences (only one out of ten comparisons being statistically significant) between majors in students' understanding of the conceptual foundations of science (Table 1). Moreover, there were no measurable differences between science majors and non-science majors in their degree of acceptance of a series of pseudoscientific claims. It seems that there is little evidence for the ideas that better knowledge of science facts leads to better understanding of the nature of science, or to a lower degree of belief in the paranormal.

Variable	R-squared	Major (1 d.f)	Gender (1 d.f.)	Major-by-Gender (1)	Error (142 d.f.)
Science Facts	24.7%	**0.8419** **(0.0001)**	0.0019 (0.7570)	0.0326 (0.2026)	0.0199
Science Concepts	1.4%	0.0315 (0.3090)	0.0146 (0.4878)	0.0001 (0.9474)	0.0302
Pseudoscience Belief	1.0%	0.1840 (0.4713)	0.4450 (0.2631)	0.0011 (0.9552)	0.3526

TABLE 1. Analyses of variance of the relationship between major, gender, and major-by-gender interaction on the one hand, and overall students' scores in science facts, science concepts, and pseudoscience belief. R^2 indicates the amount of variance explained by the model; numbers in parentheses in the top row indicate degrees of freedom; inside the table are the p-value corresponding to each test; boldface indicates statistically significant effects.

I do not wish to claim too much on the basis of a couple of surveys of a small sample at a particular university, but it was interesting to follow up with a few questions to the students in order to generate causal hypotheses to be tested with additional research. The most revealing thing was that most of the non-science students in the first survey (those with a lower belief in the paranormal) were in fact philosophy or psychology majors, who actually take courses on the scientific method and on critical thinking. In contrast, science majors are seldom exposed to that sort of course, and spend most of their initial scientific education in large classrooms where a professor whom they can barely see from across a large lecture hall inundates them with a flood of disconnected facts that they are supposed to remember in order to pass the test. Could it be that it is not just the amount of education (scientific or not) that matters, but the way in which that education is administered?

How the brain actually works, and why it matters to education

In considering matters of education, it seems strange that most of us educators do not know much about how the brain learns, or – perhaps more importantly – refuses to learn. This is obviously a huge topic, which by necessity I will have to treat very superficially here. However, the suggested readings will provide fascinating introductions to this literature. The main point is that the brain is a crucial piece of our biological machinery, and yet we seem to care little about learning how it works or how to improve its functionality. This is like having an expensive car and replacing its tires, polishing the chrome, and making sure all the fluids are there, but completely ignoring the engine – not a good recipe for a long and happy ownership.

This lack of application of our knowledge about the brain to everyday life is especially astounding in the world of education (with a few exceptions of teachers or schools that are taking the first tentative steps toward making practical use of neurobiological research). It would seem that teachers and college professors should be mandated to take a course in how to help their students make the best of this wonderfully intricate organ that has been so crucial to human evolution and to our very identity as a species of primates. Books like Jensen's (1998) *Teaching with the Brain in Mind* and Brasford, Brown, and Cocking's (1999) *How People Learn: Brain, mind, experience, and school*, are full of specific recommendations for teachers and students on how to use their brains. However, what I would like to discuss here are a few major characteristics of the functionality of the brain which help explain why simply lecturing to people will not solve the problem.

Perhaps the most astounding piece of evidence comes from experiments on split-brain patients (i.e., individuals with no connection between the two hemispheres of their brain) conducted by Gazzaniga (1998) and his collaborators. Neurobiological research on individuals with split brains has shown quite clearly that what we perceive as a unified self is really made of at least two distinct and largely independent components – one overseen by the right hemisphere, the other by the left hemisphere of the brain. The two hemispheres are normally connected by the *corpus callosum*, which contains millions of neuronal bridges between the two sides. When the *corpus callosum* is severed (surgically or by accident), the two hemispheres function independently of each other, to the point that they can cause completely contradictory behaviours in an individual.

Experiments on split-brain patients show that the left hemisphere is dominant, meaning that it is in charge of unifying the different inputs from both hemispheres into one coherent narrative. The interesting thing is that we can show experimentally that this narrative is woven *a posteriori*, as an explanation for what the individual has perceived or done. In a now classic example, a patient with a severed *corpus callosum* was shown a picture and then asked to pick a complementary picture from a given series. The experimenter could direct questions separately to each of the two hemispheres because the left one controls the right side of the body and the corresponding visual field, while the right one controls the left side of the body and visual field. The patient gave answers by hand gestures, because the right hemisphere does not have access to spoken language. The right hemisphere was asked to pick out a picture that would go with that of a house covered with snow; logically enough, the patient picked a shovel. The left hemisphere was asked to pick out a picture that would go with a chicken leg; equally logically, the patient picked a chicken head.

Here is the interesting bit: when the left hemisphere (which is in charge of language) was verbally asked why the subject picked a chicken head and a shovel (notice that it was unaware of the house with the snow, because of the disconnection between the two hemispheres), the patient answered that he needed a shovel to clean up the excrement from the chicken! In other words, lacking complete information about the shovel (available only to the right hemisphere), the left hemisphere – our much-vaunted rational self – made up a story after the fact, the only characteristic of which was that it fit the available information, however awkwardly.

I think this sort of finding has profound implications for the teaching of evolution and for science education in general. Our brain is constructed in such a way that it comes up with an explanation (a story) for the world around it. How good an explanation the left hemisphere will create depends on how good the input is from the surrounding world: the better the information provided, the better the model that the brain will create. Think of the brain as a virtual-reality device that literally creates not only your perception, but your understanding of the world. If the input is faulty, the device will construct something nonetheless. But as the data become more and more faulty, the model produced will bear less and less resemblance to reality.

Neurobiologist V. S. Ramachandran (1998) has suggested, in his delightful *Phantoms in the Brain*, that one's views on the world or on a particular topic depend on a balance between the respective inputs of the two hemispheres. The right one plays the part of the devil's advocate, always feeding information that may at times be in dissonance with the currently held model. The left hemisphere filters this information in one of three ways: (1) it uses the information to reinforce the currently held model; (2) if the information does not quite fit the prevailing model, it can alter it slightly to accommodate it; or (3) it can temporarily just ignore any information that does not fit. Ramachandran suggests that when we change our mind about something, the reason is that the amount of information that does not fit has exceeded a certain threshold (which is probably variable within the human population) and has caused the left hemisphere to change its story in a radical fashion. Whether you are gullible, reasonably open-minded, or a die-hard skeptic may depend on the exact constitution of your *corpus callosum* and the way your left hemisphere handles cognitive dissonance!

During years of involvement with the creationism-evolution social controversy, I have spoken with many people who, because of their upbringing, were initially hostile to evolutionary ideas and eventually overcame their ideological biases. It is important to find out how they did it, because that insight provides us with crucial clues as to what works and what does not. One thing that does not work is the "I will explain it to you once, and you should be convinced" approach employed by many scientists when they teach.

(I call this the "rationalistic fallacy.") Repetition, and especially repetition by different sources in different formats, seems to be the key. For some people I know, the road to critical thinking started after they read a book or an article by scientists like Carl Sagan, watched a television special, attended a debate or a lecture, or simply had conversations with friends or family.

Here, too, psychological research can help. Altmeyer and Hunsberger (1997) report that "conversions" regarding matter of faith work very differently when they go from skepticism to belief than from belief to skepticism. In the first case, typically (although, of course, not always), the change of mind is triggered by a strong emotion, often associated with a traumatic event (like the loss of a close relative, especially in an unexpected or untimely manner). In the second case, however, the process is very slow, and it often takes years of learning and coming to terms with the meaning of what one is trading off by abandoning a particular faith-based conception.

Since the process of change is long, the people who are responsible for this change rarely get feedback from those they have affected. Education may sometimes seem like a thankless, even wasted, effort, but it is not. It is just that the physiology of our brains is such that the results take a long time and often require a tortuous trajectory. Education, as Aristotle pointed out, is a work in progress that lasts a lifetime.

What to do

I will now reflect over all I have said so far and offer a few concrete suggestions that every reader can take home and use. This is obviously not going to be a series of magic bullets, but if the educational community will start adopting the recommendations I describe here on a consistent basis, change could be apparent within the next generation. Some universities and schools are moving in these directions already, and occasionally individual faculty take the initiative where there is no institution-wide effort yet in place. For those who are interested, there is help. For example, the report of the Boyer Commission on Educating Undergraduates in the Research University (http://naples.cc.sunysb.edu/Pres/boyer.nsf/) is an excellent starting point.

To make progress in the creation/evolution controversy, and more generally in science education, I think the following steps are essential:

Scientists must come down from the ivory tower! It is high time for scientists to take seriously their role in their communities and give more back to them. This is not only for practical reasons (like the constant and very real threat to funding of certain areas of scientific research), but simply because it is the decent thing to do. Scientists who do not give back to the community in some tangible way should start thinking of themselves as social parasites – perhaps not of the worst sort, but parasites nonetheless. As much as it seems to some of us that our particular field of research on aspect X of organism Y is so fundamentally important that of course we should be paid for life to carry it out, this is simply not so.

Conducting our research is a privilege that we enjoy because we serve the community. Our contributions take four forms: (1) the (remote) possibility that something we do will better the condition of humankind; (2) the fact that we are adding bricks to the edifice of knowledge (though such bricks often build uninteresting dead ends, or simply lay on the ground with no use whatsoever); (3) the teaching we do for graduate and especially undergraduate students; and (4) whatever contact we have with the community (so-called "outreach"). Clearly, the last two are the most immediate contributions a scientist can make to society, and they are also those that receive respectively the lowest and no priority at all because of the way our system of rewards is constructed. We are not currently awarded tenure because of how much community work we do or how good we are as teachers. However, we are the ones who set the criteria and standards for promotion and tenure, so we are the ones to blame (together with shortsighted administrators, but that goes without saying).

There are plenty of things scientists can do. We can contact our local elementary, middle, and high schools or the university outreach program and volunteer to give occasional lectures, or better, provide demonstrations or facilitate discussions among students and community members. We can write both letters and occasional guest editorials to the local newspaper. We can engage in public debates on important issues (not just creationism, but the environment, ethical problems in science, the use of biotechnology, and so on – the possibilities are endless). Scientists with a particular talent for it can write articles for national magazines or work on an occasional book for the general public. It would not be necessary for a few people to do as much as a Carl Sagan, Stephen Gould, or Richard Dawkins if more colleagues would bother writing for the public at least once in a while.

Hiring practices in universities must be changed. We should acknowledge the aforementioned myth of "good researcher = good teacher," and we should act accordingly. Let us hire researchers to do research, teachers to do teaching, and hybrids for their strengths (e.g., there are excellent science educators who also research in the field of pedagogy). This means changing the current mentality in both faculty and administrators of colleges and universities, which is not something that is likely to happen easily. But I really do not see any reason for perpetuating the horrors of the current system, with its abysmal rate of failure in producing thinking, well-informed citizens, which, let us not forget, is the chief goal of education.

Another good model is currently represented by Richard Dawkins at Oxford University. He chairs a (privately funded) position in the "public understanding of science." What a concept! Imagine somebody being paid in a university for the sole purpose of explaining to the public what that university is doing. Ideally, every major department in every university should have a position dedicated to the public understanding of X, where X can be any discipline that is actually the object of research in that department – from biology to physics, from philosophy to language, from law to psychology. It really would not cost much. It could probably be financed by special fund drives to which the public and several educational foundations are likely to be highly responsive, and it would pay enormously both in terms of public relations and – more importantly – in educational impact.

There must be mandatory continuing education for teachers. A teacher is really supposed to be a lifelong learner, but this ideal is seldom realized in practice. One of the major obstacles to achieving effective teaching of evolution in high schools, for example, is simply the fact that most of the teachers have never been trained in the discipline and do not have regular channels through which to update their knowledge of the subject matter. One of the experimental programs I started when I was at the University of Tennessee consists of bringing together faculty from biology, anthropology, and education to address this problem. The result has been a yearly workshop for teachers on how to teach evolution and deal with the surrounding issues. This workshop has gradually crystallized into a university course called "Evolution and Society," which is open to pre-service teachers, current teachers for continuing education credit, and students from other disciplines who are interested in the topic.

Training in teaching must be provided to university faculty and graduate assistants. As I have already mentioned, not only is it simply not true that a good researcher is also necessarily a good teacher, but unfortunately, faculty and teaching assistants rarely get any training at all in teaching! The assumption is that, because we are professionals with the requisite expertise in our disciplines, we will be able to communicate what we know (or what we are learning) to an audience of undergraduates. How difficult could it be, right? Well, it is extremely difficult, and it is about time that universities start setting up support centers for faculty to learn the basics of classroom and laboratory teaching according to the most up-to-date research in pedagogy. The same universities should require intensive training of their teaching assistants and make sure that they have more than a passing knowledge of the subject matter they are supposed to help the students understand. This is important; nothing less than the scientific literacy of the next generation and continuing public financial support for science are at stake.

Schools and universities should institute truly interdisciplinary courses and curricula. This has been done to some extent, of course, yet in many cases it is something that is true on paper but not in the reality of the classroom.

Often interdisciplinarity simply means putting together two faculty from different departments who will split the teaching load of a course, with little coordination and no overarching vision.

Administrations tend to be favorable in principle toward interdisciplinary courses. In practice, however, they often revert to their bean-counting activities that penalize faculty who wish to create new courses or truly engage in co-teaching experiences, failing to provide incentives and requiring rigid accounting systems of the number of "contact hours" actually spent by faculty members with the class.

Interdisciplinary courses are often easy to envision and are generally not too difficult to implement. As far as the creation/evolution controversy is concerned, courses integrating philosophy of science and evolutionary biology come to mind, or multi-science courses on origins (of the universe, of the solar system, of life), or courses blending the history of scientific ideas with the current state of research in a given field. For example, the State University of New York (SUNY) at Binghamton offers a university-wide interdisciplinary program on evolution (http://bingweb.binghamton.edu/~evos/).

The textbooks must be rewritten. The problem with most textbooks, both at the college level and earlier, is not that they carry the sort of factual mistakes that so often upset creationists and make them cry "conspiracy" (although such mistakes should be corrected, of course), but that they tend to teach the sciences in a manner similar to a sequential reading of the yellow pages. A lot of facts are followed by a lot of other facts, which are followed by more facts and so on, with little if any attempt to put the major ideas in the foreground, to explain how they were discovered or constructed, or how they are connected. Most importantly, we need textbooks that clearly and extensively convey the message that science is a vibrant enterprise, very much alive, with a rich past of triumphs and mistakes, and hopefully a bright future of more discoveries and better understanding of nature. Let us remember that curiosity is innate in human beings and that most children are spontaneously drawn to ask questions about nature during their early school years. How is it that we succeed so systematically and almost completely in smothering that Promethean fire?

The lecture format should be greatly deemphasized. Lectures do have a place, but largely not in the classroom. Lectures can be highly efficient ways to convey a large amount of information in a small period of time. This is excellent when one is talking at professional meetings, or giving invited seminars to specialists, or when one is forced to present material for the general public to a very large audience (in the latter case, more for entertainment purposes than anything else). These are situations in which the listeners want to be there and are receptive to what the speaker is saying. That is hardly the situation in most classrooms, either in college or before.

Preferable to lectures are all sorts of classroom situations in which students can exercise active learning – that is, where they can actually participate in their own learning process. Think about the difference between simply watching a play on TV and helping to put it together for a community theater, or even better, actually performing in it. Which way do you think students will learn more about the play?

Pedagogical research has repeatedly shown what should be common sense (e.g., Sundberg, Dini, & Li, 1994; Miller, Wozniac, Rust, Miller, & Slezak, 1996; Marbach-Ad and Sokolove 2000): more active and multi-modal ways of learning produce better and longer-lasting results. Small discussion groups are ideal forums for brainstorming and active learning, but of course they are expensive because they require a much better faculty/student ratio than targeted by most large universities. Unfortunately, the currently widespread alternative is to provide the illusion of education at what is still a very stiff price, at least in the United States.

"Canned" hands-on activities stipulating predetermined outcomes must be replaced with open-ended inquiry exercises. Science is not about following the instructions found in a manual in order to obtain pre-ordained results (if one is lucky and has followed the directions conscientiously). Science is an activity of open-ended inquiry. This does not have to be very complicated or high-tech. The point is to make students understand that sound reasoning and empirical evidence can help solve problems and find answers to questions. It does not matter what the question is. As I mentioned already, the classic type of laboratory exercises is a terrible model of how science works – one that leaves students bored or, worse, suspicious of the methods employed to reach obviously predetermined conclusions. Several schools and universities have experimented with open-ended inquiry alternatives (which of course are more demanding of the teacher), and they have shown that a little effort goes a long way toward reaping large rewards for both students and faculty.

More emphasis should be placed on the how of science, rather than merely on the what. I have touched already on this issue, but I think the point needs to be stressed: it is not important merely to teach kids what exactly science has found on this or that subject. It is much more crucial to make them appreciate how and why it was done. I am not suggesting we do away with content altogether, of course. For one thing, one needs to know facts in order to study how scientists arrive at certain conclusions. Furthermore, we still need people who are knowledgeable in all fields, which requires learning factual content. But more crucially, people must also develop a habit of scientific thinking. The details of the sub-cellular structures or of the classification systems of plants will soon be forgotten after the course, and at any rate this knowledge is available in reference books and articles. The ability to approach problems in terms of rational thinking and empirical evidence, however – once developed – stays with students for life and can be applied to everything, from buying a car to making a career decision (it is a "portable skill" in pedagogical parlance).

We must teach critical thinking to all students. The term critical thinking is now a rather fashionable buzzword, the importance of which is in danger of being lost in the rush to jump onto the next educational bandwagon. It is actually rather amusing that we need to teach courses in critical thinking because one would think that that is what education is all about. Ironically, while critical-thinking textbooks are proliferating, most are not terribly engaging. Nevertheless, good books on critical thinking do exist, and it is high time that at least one course of this type became mandatory for every college student, no matter what the discipline. Are there any educators who can seriously claim that students would be better off without knowledge of the basic kinds of reasoning and accompanying fallacies?

Students' writing and communication skills must be improved. It is astounding to me how many college-level students essentially do not know how to write and are barely capable of expressing themselves orally on complex subjects. Both oratorical and writing skills come with intense practice that should be started very early (much earlier than college) and continually required.

Again, research in pedagogy weighs heavily here: the best way to learn something is to have to communicate it to others. If you do not know how to explain it, you do not understand it. The best way to learn something is to do it or to prepare a lecture or write a book about it. One of the chief motivations for me to teach and to write is that it is the surest way to really understand subjects in which I am interested. Everybody should try it at least occasionally. Surely it will not hurt if we have a citizenry that is more articulate and proficient in clear writing.

The use of information technology must engage the student's brain, not bypass it. There has been a concerted push to computerize classrooms and to put courses online. This push will certainly continue in the near future, in part because of its novelty and in part because it is much cheaper to put computers in all classrooms than to actually train teachers to do what they need to do or to reduce the size of those classrooms so that real learning can occur.

Nevertheless, I am certainly not advocating that we discount the role of modern technology in education (after all, I am writing this essay on a laptop computer, not with pen and paper). What I am saying is that we need to use new technologies, like everything else, with our brains switched on. To repackage a traditional, boring, and ineffective lecture into a snazzy computer presentation will not alter the fact that the material is presented in a boring and ineffective way. As students become more used to computer projection technology, they are going to be as little impressed by an electronic slide as they were by the old-fashioned slides or overhead transparencies, and rightly so. However, there are plenty of positive applications of computer technology for classroom use, ranging from online interactive exercises to the exchange of electronic drafts of papers with the instructor, to simulation environments to help students understand complex quantitative concepts and how they might play out in realistic situations. These are good uses of the new technologies, but technology for technology's sake is a travesty, not effective education.

Similar considerations apply to online courses. Again, the potential is high in the sense of being able to reach students who might not otherwise have the opportunity to attend a "brick and mortar" school or university, or to augment the classroom experience offered by traditional courses with ongoing discussion boards, test samples, and additional resources linked via Web pages. The danger is that many university administrators are looking at online courses as a cheap and "efficient" (financially, not educationally) way to solve the problem of ever-increasing enrollment in introductory courses. With Web-based courses, there is no physical limit to the number of students who can be "served," except, of course, that unless one also deploys a platoon of faculty with time to engage in online interactions with the users, the pedagogical effectiveness of these enterprises soon plummets to a negligible level.

Teachers should use controversial subject matter as a stimulus to thinking, not shy away from them. A school board in Kentucky a few years ago stated that certain subject matters (such as evolution, sexual education, and AIDS) should be kept out of the classroom because they are too "upsetting" to the students. On the contrary, I think that if students do not move a bit out of their comfort zone at least once a week, they are not receiving a good education. Education is about challenging one's ideas and opening them up to scrutiny. A student's ideas may or may not withstand such scrutiny, but either way the student will benefit from the challenge.

In the specific case of the creation/evolution issue, I take a position different from that of most of my colleagues. I think teachers should be encouraged to use the social debate as a springboard to teach not only evolution, but science as a process. I am not talking about teaching creationism in the classroom; that would be not only unconstitutional in the US, but also simply wrong from a pedagogical standpoint. What I am suggesting is that creationist rhetoric might be turned into material for critical-thinking exercises in the classroom. Teachers can direct the students to creationist Web sites, books, and articles and compare them to those of scientific organizations and journals. Teachers would need to guide students through this type of activity toward an understanding of how science works and why creationism is pseudoscience. The students might actually get excited about this more proactive approach, and those who reject evolution may be less likely to feel shut out of the learning experience.

There are many hazards with this strategy, beginning with the fact that science teachers, who are trained in science, are not generally sufficiently prepared to deal with objections based on religious beliefs. This is a broader problem of teacher education that goes well beyond the evolution/creation controversy. If people do not understand the issues surrounding a particular discipline, then they probably should not be certified as teachers in that discipline.

Another problem is presented by the potential resistance of parents and administrators. This is why I suggest that teachers should be encouraged, when possible, to present the social controversy in a scientifically sound manner, but certainly not required to do so. This would be possible only given an environment of constructive relationships among teachers, parents, and administrators. Once again, however, this is a broader issue that affects education in general.

Finally, there is also – unfortunately – the very real concern that many science teachers are creationists themselves. This seems to me to fall into the same category of teachers' training mentioned above. We must require that teachers know the subject matter they are to present, and that they intend to teach science according to currently accepted knowledge. This is not a matter of respecting individual teachers' religious beliefs: if you believe that the earth is 10,000 years old, then you really do not understand, at a deep level, geology, physics, and biology. Consequently, you simply should not be teaching science. It is up to university-level teaching programs, as well as to the people setting hiring procedures, to make sure that unqualified individuals are not responsible for teaching our children.

Again, let me stress that this approach of "teaching the controversy" is not a way to yield to creationists demands nor is it catering to their calls to "teach the controversy" as a ploy to have their religious beliefs presented as alternative scientific theories. On the contrary, it is a broader take that can be used to engage students in active learning on a variety of topics, from evolution to global warming, from stem cell research to the use of alternative energy sources. Of course this would require bold moves within the education community, but if we are to change education, we have to take risks and try new things. Taking such risks is part and parcel of the job.

Academics should organize community days. Finally, I think it is of paramount importance that university departments start a series of "community days" during which they enlist their faculty and graduate students in an open house for the public so that people can appreciate what goes on inside the ivory towers of academia. These events are actually organized by some science and humanities departments at a few universities, but they should become as much a regular feature of the post-secondary experience as homecoming days and football games.

My own experience, first at the University of Tennessee and now at SUNY-Stony Brook, has been with what we call Darwin Day. Darwin Day is a day of learning about evolutionary biology and the nature of science that I helped start in 1997 after the Tennessee legislature once again attempted to pass a bill curtailing the teaching of evolution in public schools. Normally celebrated on or around February 12, Darwin's birthday, this event includes a panoply of activities, ranging from an information booth where graduate students and faculty distribute literature and answer questions, to a series of videos followed by moderated discussions, from a book display to a keynote lecture by a biologist, an historian, a philosopher, or a civil liberties activist. By now hundreds of schools in the United States, Canada, and Europe are organizing Darwin Days to improve the public's understanding of science.

Darwin Day, "Socrates Day," "Geology Week," or whatever else a university may wish to organize, actually requires very little effort from only a few people in a department and, once again, results in a significant impact not only on the image of a university (something one can successfully sell to administrators), but more importantly on how people feel about education in their community. Universities that try this approach will not regret it.

Improving the quality of education requires energy, money, ideas, and enthusiasm, and it might not always pay off in the immediate future. This means that only people with enough foresight and endurance are likely to attempt it. But the results do follow, and they last much longer than those generated by simplistic slogans and sound bites. Humanity has already paid an incalculable price for the ignorance of its ranks. Kurt Vonnegut (1990) once wrote that "it is embarrassing to be human." It is up to educators to do their best to at least ameliorate that embarrassment for generations to come.

REFERENCES

Altemeyer, B., & Hunsberger, B. (1997). *Amazing conversions: Why some turn to faith and others abandon religion*. Amherst, NY: Prometheus.

Alters, B. J., & Alters, S. M. (2001). *Defending evolution: A guide to the creation/evolution controversy.* Mississauga, ON: Jones and Bartlett.

Brasford, J. D., Brown, A. L, & Cocking, R. R. (1999). *How people learn: Brain, mind, experience, and school*. National Academy Press, Washington, DC.

Caudill, E. (1997). *Darwinian myths*. Knoxville, TN: University of Tennessee Press.

Darwin, C., & Wallace, A. R. (1858). Laws which affect the production of varieties, races, and species. Communication to the Linnean Society.

Dawkins, R. (1998). *Unweaving the rainbow: Science, delusion and the appetite for wonder.* Boston: Houghton Mifflin.

Forrest, B., & Gross, P. R. (2004). *Creationism's Trojan horse: The wedge of intelligent design*. Oxford: Oxford University Press.

Gazzaniga, M. S. (1998). *The mind's past*. Berkeley, CA: University of California Press.

Goode, E. (2002). Education, scientific knowledge, and belief in the paranormal. *Skeptical Inquirer*, 26(1):24–27.

Jensen, E. (1998). *Teaching with the brain in mind*. Alexandria, VA: Association for Supervision and Curriculum Development.

Johnson, M., & Pigliucci, M. (2004). Is knowledge of science associated with higher skepticism of pseudoscientific claims? *The American Biology Teacher*, 66, 536-548.

Kitzmiller v. Dover Area School District. 400 F Supp 2nd 707 (MD Pa 2005).

Larson, E. J. (1997). *Summer for the gods: The Scopes trial and America's continuing debate over science and religion*. New York: Basic Books.

Marbach-Ad, G., & Sokolove, P. G. (2000). Can undergraduate biology students learn to ask higher level questions? *Journal of Research in Science Teaching, 37,* 854-870.

Miller, R. L., Wozniak, W. J., Rust, M. R., Miller, B. R., & Slezak, J. (1996). Counterattitudinal advocacy as a means of enhancing instructional effectiveness: How to teach students what they do not want to know. *Teaching of Psychology, 23,* 215-219.

Pigliucci, M. (2002). *Denying evolution: Creationism, scientism and the nature of science*. Sunderland, MA: Sinauer.

Postman, N. (1994). *Amusing ourselves to death*. Ashland OR: Blackstone.

Ramachandran, V. S., & Blakeslee, W. (1998). *Phantoms in the brain: Probing the mysteries of the human mind*. New York: William Morrow.

Sperber, M. (2000). *Beer and circus: How big-time college sports is crippling undergraduate education*. New York: Henry Holt.

Sundberg, M. D., Dini, M. L., & Li, E. (1994). Decreasing course content improves student comprehension of science and attitudes towards science in freshman biology. *Journal of Research in Science Teaching, 31,* 679-693.

Vonnegut, K. (1990). *Hocus pocus*. New York: Putnam's.

Young, M., & Edis, T. (2004). *Why intelligent design fails: A scientific critique of the new creationism*. New Brunswick, NJ: Rutgers University Press.

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