LEARNING EVOLUTION AND THE NATURE OF SCIENCE USING EVOLUTIONARY COMPUTING AND ARTIFICIAL LIFE

ROBERT T. PENNOCK *Michigan State University*

ABSTRACT. Because evolution in natural systems happens so slowly, it is difficult to design inquiry-based labs where students can experiment and observe evolution in the way they can when studying other phenomena. New research in evolutionary computation and artificial life provides a solution to this problem. This paper describes a new A-Life software environment – Avida-ED – in which undergraduate students can test evolutionary hypotheses directly using digital organisms that evolve on their own through the very mechanisms that Darwin discovered.

APPRENDRE L'ÉVOLUTION ET LA NATURE DES SCIENCES AU MOYEN DU CALCUL ÉVOLUTIONNISTE ET DE LA VIE ARTIFICIELLE

RÉSUMÉ. Puisque l'évolution des systèmes naturels se produit lentement, il est difficile de concevoir des laboratoires fondés sur la recherche où les étudiants pourraient faire des expériences et observer l'évolution de la même façon qu'ils étudieraient d'autres phénomènes. De nouvelles recherches en calcul évolutionniste et en vie artificielle offrent une solution à ce problème. Ce travail décrit un nouvel environnement logiciel A-Life, Avida-ED, dans lequel les étudiants de premier cycle peuvent tester directement des hypothèses évolutionnistes à l'aide d'organismes numériques qui se développent par eux-mêmes, selon les mêmes mécanismes découverts par Darwin.

Introduction

Every biologist knows the celebrated geneticist Theodosius Dobzhansky's dictum that "Nothing in biology makes sense except in the light of evolution" (Dobzhansky, 1972). Evolution is the core explanatory principle in biology. The fundamental idea of "descent with modification" from common ancestors, as Darwin called it, accounts for not only the origin of species in a general sense, but for a whole range of specific biological phenomena – everything from the nested hierarchy of biological kinds to the homologous traits found among related organisms and the global patterns of geographical distribution of different species. And Darwin's law of natural selection, one of the most important mechanisms of descent with modification, accounts for phenomena such as how complex forms can arise by diversification from simple beginnings, how species can have highly specific adaptations to their environments and to each other, and how biological functions are shaped.

In addition to these and other important biological facts that are the findings of evolutionary research that Dobzhansky had in mind, I want to call attention to another critical set of issues that was assumed but not emphasized in his maxim, namely what it means to say that phenomena "make sense in light of" a scientific theory. This notion refers to some of the basic topics in the philosophy of science having to do with scientific explanation, confirmation, and other related issues involving the nature of science. Such issues are not unique to biology, but to appreciate the true force of Dobzhansky's dictum one needs to understand how it is that evolution is one of the best exemplars of the essence of scientific reasoning (Pennock, 2005).

This does not mean that it is impossible, say, for a biochemist to focus his or her research only on the immediate operations of some bio-molecular pathway without mentioning evolution. However, such proximate explanations, if myopically limited to that, not only miss the forest for the trees, but also miss the trees for the leaves. Evolutionary biology reveals the underlying order – the tree of life and the processes by which it develops – in what otherwise would be a jumble of unconnected phenomena.

National science standards in the United States properly emphasize the centrality of evolution as a major unifying theme in the science curriculum as well as the overarching importance of understanding the nature of science (National Academy of Sciences, 1998). There is also a significant trend in science education to get students involved in inquiry-based and active learning as a better way for them to learn scientific methods of inquiry (National Research Council, 2000; National Research Council, 2002; National Research Council, 2003). Yet every biology teacher knows how difficult it can be to teach these basic scientific principles, if only because the evolutionary process is difficult or impossible to demonstrate in the classroom. This paper aims to lay out a strategy that may help to meet this challenge and to introduce a new tool to help students learn about evolution and the nature of science by designing and running experiments using evolving computer organisms.

The challenge

We must begin by appreciating the degree of difficulty of the challenge that faces the biology teacher. Despite its critical importance in science, evolutionary theory continues to be misunderstood and even rejected by a majority of Americans. In a recent poll, a mere 29% said they thought that evolution was "completely accurate" or "mostly accurate." A whopping 71% said they thought evolution was "mostly not accurate," "completely not accurate," "not sure" or "might or might not be accurate, you can never know for sure" (People for the American Way Foundation, 2000). A college education improves understanding, but not as much as one would hope; in another poll, 32% of students answered "no" to the question "Do you think that the modern theory of evolution has a valid scientific foundation?" (Lord & Marino, 1993). Particularly disturbing is the finding that nearly 40% of high school biology teachers think "there are sufficient problems with the theory of evolution to cast doubts on its validity" (Eve & Dunn, 1990).

Some of this resistance must be attributed to the special circumstances in the United States, where the historical and continuing demographic influence of fundamentalist Christianity has bred a particular antipathy to evolution. Public acceptance of evolution is lower in the United States than any of the Western democracies. Indeed, it is lower than any surveyed country save Turkey, which must deal with its own extreme form of religious fundamentalism (Miller, Scott, & Okamoto, 2006). The politicization of evolution by creationists who lobby to get their religious "alternatives to evolution" introduced in the public schools is another ongoing obstacle to sound science education (Pennock, 1999; Pennock, 2003).

However, the challenge that biology teachers face goes beyond such hurdles. Even students who accept the validity of evolution in general turn out to have many specific misconceptions about it. For instance, students commonly think that the environment itself causes traits to change in an organism over time. They do not view genetic variation as important. They think that all individuals slowly change in their traits over time, rather than recognizing evolution as involving changes in populations of individuals with discrete traits (Alters & Nelson, 2002).

Besides these barriers, biology educators must also overcome practical difficulties. How can one demonstrate a ubiquitous but nearly invisible process that operates over unimaginable lengths of time and produces fantastic complexities but that students think of as no more than chance? Instructors have devised clever exercises to illustrate one or another element of evolutionary theory, but usually must fall back on the traditional lecture, explaining the evidence in words because it is so difficult to create lab experiences that allow students to explore the processes in a hands-on manner. Educational wisdom says that "Science should be taught as science is practiced at its best" (American Association for the Advancement of Science, 1990), but how can students make their own observations and perform their own experiments given the relatively glacial pace of evolution? Recent developments in the fields of evolutionary computation and artificial life have provided a possible opening.

Evolutionary computation and artificial life

Evolutionary computation and artificial life research are core research areas of what has become an exciting cross-fertilization between evolutionary biology and computer science and engineering. Computer scientists and engineers, inspired by the workings of evolution in nature, realized that they could apply the same powerful Darwinian mechanism in computers for practical purposes, such as for complex industrial design. For our purposes, artificial life is essentially a way to observe evolutionary design in action. This approach can be rigorously justified from a theoretical standpoint; as Daniel Dennett says, the evolutionary mechanism, properly understood, is "substrate neutral" (Dennett, 1995). What Darwin discovered is a universal principle that is not limited to its biological instantiation and can operate in virtually any medium.

This technology has recently progressed to the point that biologists can use it for their own research. Pioneering work of this sort was done by ecologist Tom Ray, whose artificial life platform *Tierra* allowed him to observe and study the evolution of a virtual ecology (Ray, 1991). Today, one of the most advanced artificial life systems is known as *Avida*, originally developed by theoretical physicist Christoph Adami and computer scientist Charles Ofria, and it has become the platform of choice for certain difficult questions in experimental evolution.

In both Tierra and Avida, the organisms are computer programs running on their own virtual hardware. The program that defines the genome of a digital organism is a sequence of commands in a simplified computer language. Neither system attempts to deal with the origin of life; both begin with a hand-coded program that simply has the ability to replicate. Nor do they model any particular biological organism; rather they model key elements that are common to all forms of life. To a first approximation, these organisms may be thought of as computer viruses, with the difference that they self-replicate, mutate, and adapt by natural selection to a computational environment. As Dennett has emphasized, "evolution will occur whenever and wherever three conditions are met: replication, variation (mutation), and differential fitness (competition)" (Dennett, 1995). And evolution is exactly what one observes – the original ancestor divides and mutates, creating divergent, novel lines of organisms as the generations pass.

The reason an artificial life system like Avida can be used as an experimental system is the way evolution is implemented: it is not just a simulation of the effects of evolution or of evolutionary patterns; rather, the core evolutionary mechanism of variation, inheritance, and natural selection is exactly instantiated (Pennock, 2007). For example, new variants can arise through random mutations in an organism's genome and then be inherited in the next generation if the organism successfully replicates. Natural selection occurs as organisms in a population compete with each other to survive and replicate. If variations arise that give an organism some competitive advantage, it will be naturally selected and will spread in the population.

Digital organisms compete for the energy needed to execute instructions. Energy in Avida occurs as discrete quanta measured in terms of ”single instruction processing” or SIPs. Each SIP suffices to execute one instruction. By executing instructions, a digital organism can express phenotypes that enable it to obtain more energy and copy its genome. In Avida, organisms can acquire energy in two mechanisms. First, each organism receives SIPs in proportion to its genome length. Second, an organism can obtain further SIPs by absorbing resources from the environment. Each resource is associated with one or another function that an organism must perform to absorb that resource. The functions are user-specified, but typically involve Boolean logic or arithmetic computations. These operations may be thought of as a kind of model metabolism; by performing these functions, digital organisms acquire the fuel needed for their replication.

In Avida we do not program what will happen, but simply set initial conditions and then observe the effects of the evolutionary processes. This is different from traditional evolution simulations used for research or education in that the populations of digital organisms are not constrained in how they adapt to solve problems. The underlying genetic language of an Avida organism is Turing complete, which means that they can theoretically solve any computational problem that is computable. Moreover, as in real biological systems, Avida never looks at *how* a task is accomplished when deciding if more SIPs should be awarded, only at the results. The specific methods that the digital organisms end up employing to solve problems are often novel, unexpected, and could even be said to be inspired. Because they are autonomous self-replicators, the digital organisms do not just appear to evolve; they actually do evolve in their digital environment.

The platform thus allows one to actually observe the evolutionary process at work, in as fine detail as one wishes. Avida has been used to study, among other things, hypotheses about phylogeny reconstruction (Hang, Ofria, Thomas & Torng, 2003), the evolution of complexity (Adami, Ofria, & Collier, 2000; Adami, 2003), the evolution of genome robustness (Lenski, Ofria, Collier, & Adami, 1999), epistasis and mutation (Wilke & Adami, 2001; Wilke & Adami, 2003), and the effects of high mutation rates (Wilke, Wang, Ofria, Lenski, & Adami, 2001), among dozens of published papers. A recent study published in *Nature* (Lenski, Ofria, Pennock, & Adami, 2003) used Avida to experimentally demonstrate with unprecedented precision how evolutionary mechanisms can produce novel complex features. This particular study had a happy side-benefit of demonstrating how evolution can produce a kind of complexity that creationists have said is impossible for natural processes, something they call “specified” or “irreducible” complexity which thus showed that their central criticism against evolution fails to get off the ground (Pennock, 2003).

Evolutionary computation and artificial life platforms now have the potential to become revolutionary new educational tools that can help undergraduate students – our future researchers and teachers – understand and appreciate not only the power of the evolutionary mechanisms to produce bio-complexity, but also the nature of scientific reasoning itself. Because of the relatively long generation times in natural systems, it is not feasible to observe evolutionary design directly, but it can occur on very short time scales in the digital environment of Avida. This makes it possible for the first time for students to run evolution experiments in a laboratory course. Students can explore, observe, and test evolutionary concepts in a computational environment, allowing them to gain hands-on experience on a topic that might otherwise seem quite abstract. With evolutionary methods, students can learn to manipulate complex systems and observe their emergent properties. Guided exercises built around such inquiry-based experiments can also help students learn about the nature of scientific evidence and reasoning and come to understand that evolution by natural selection not only has a valid scientific foundation, but also is exemplary as a well-confirmed, powerful scientific principle.

Advantages of Avida-ED

In response to the same kinds of needs and problems that we identified above, educators have begun to develop a variety of software simulations, such as *EVOLVE* (Soderberg & Price, 2003), *Genscope* <http://genscope.concord.org>, *EvoBeaker* <http://www.ecobeaker.com>, and *EvolutionLab* <http://biologylab.awlonline.com> to teach evolutionary principles in biology lab courses. Each package has particular strengths – some simulate changes in gene frequencies in a population illustrating Hardy-Weinberg Equilibrium, some simulate interrelationships of traits and environment in a particular natural system, such as evolving beak size, and so on. We did not aim to supplant these simulations, but to complement them with a tool – Avida-ED, our new education version of Avida – that has unique advantages. The main advantage has already been discussed, namely that Avida-ED is a realization of the evolutionary process rather than a simulation and so can function as a true experimental environment, but there are several other advantages worth mentioning briefly.

- Avida-ED is usable for *multi-disciplinary learning*. Not only can Avida-ED be tailored for use in different biology courses, from ecology to genetics to zoology, but also it functions to teach evolutionary principles to students in computer-science and engineering courses when evolutionary methods such as genetic algorithms and evolutionary design are used.
- The game-like virtual world of Avida-ED, with its competing digital organisms, is a *non-threatening approach* to learning the subject. Students now have experience with the technology of virtual computer worlds

and will find this approach familiar. Additionally, students who come with a fear or bias against learning about evolution in nature may find it less problematic to first learn about the process by observing it in digital organisms. Once they see the process work in the digital environment, it will be easier to understand how evolutionary design works in engineering applications, and from there it is a small step to understanding its operation in the real world.

- Even creationists have come to accept small micro-evolutionary changes within species, so the real challenge is to get students to understand the power of evolution to produce novel functional complexity. Avida–ED allows students to observe this directly by watching digital organisms evolve. The Eureka! experience comes in being able to see how the basic evolutionary mechanism of automatic natural selection of randomly varying replicators can produce novel, complex traits in these organisms. No other package can do this. Advanced students can even "dissect" an organism and see exactly how its evolved program works.
- Using digital organisms and the virtual environment of an artificial life environment like Avida will also *allow students to understand evolutionary principles at the proper broad level of generality*. The goal is for students to come to understand that the Darwinian mechanism is a causal principle of universal generality that is not limited to just the biological world.
- *A major advantage over all other platforms is that Avida began as and remains a real research tool.* As discussed above, biologists and computer scientists use Avida's digital environment to investigate significant and difficult scientific problems about the nature of evolutionary processes. Students, like these researchers, will be able to perform experiments and test hypotheses, knowing that they are using the very same environment.

From research tool to educational platform

Of course, an educational platform is necessarily different from a research tool, so there were special challenges to be overcome to turn Avida into a useable tool for the classroom. Although we began with the same evolutionary computation engine that runs the research version of Avida, we needed a graphical user interface that would help students grasp the evolutionary and scientific concepts without having to worry about the technical details of the implementation unless they wanted to. Avida-ED is aimed to reach undergraduates, taking into account their background, preparation, and experience, but advanced students will be able to explore in much greater depth. A basic design principle for us was that evolutionary computation would be used as a tool to teach biology, not the reverse – the goal is not for students to learn about Avida-ED, but rather for them to use Avida-ED to learn about evolution and the nature of science.

Among the evolutionary concepts that Avida-ED can be used to teach are those that are fundamental to biology, such as the distinction between phenotype and genotype, the idea of a genetic code, descent with modification, adaptation, and the mechanism that produces it, namely variation, inheritance, natural selection, and time (VIST). Avida-ED makes it easy to demonstrate, for instance, how the natural selection of random mutations in the genetic material can lead to the evolution of functional complexity. The platform also makes it easy for a teacher to guide students towards an understanding of important concepts involving the nature of science, such as the basic notion of empirical evidence, the relationship between observation and inference, levels of explanation, and the like. For example, our model exercises take advantage of the fact that Avida is a true experimental environment and are structured not as cookbook labs but rather as guided investigations that ask students to propose and find ways to test hypotheses about the question being considered. We encourage students to think about how to design an appropriate experiment, how to choose relevant controls, how to sample data, and in general how to confirm or disconfirm their hypothesis. These kinds of exercises help them see some of the characteristic features of evidential reasoning in science and so come to understand the ways in which scientific conclusions are justified.

Together with these content-based learning goals, various pedagogical principles governed our decisions about how the program should look and operate.

(I) ALLOW HANDS-ON LEARNING. One important goal for hands-on learning in a lab exercise is to recreate the scientific process of discovery. While there are circumstances in which it is appropriate for students to just be given information directly, if this is done exclusively then they are missing what is most important about science, namely, its methods. There is no substitute for doing an experiment and making a discovery oneself.

We wanted to emulate a real world lab experience by creating the perception that the Avida world is a physical system the user can manipulate. This called for an intuitive interface with familiar control conventions so that students could get started right away without necessarily reading an instruction manual. More importantly, it meant devising a set of visualization tools that would help them understand the underlying concepts.

In the current version of Avida-ED, we use the visual metaphor of a colony of bacteria in a Petri dish to represent the population of digital organisms. An evolutionary run is started with one or a few organisms, which then replicate and soon fill the dish. Users can watch natural selection occur as fitter organisms overwrite less fit ones. Any individual organism may be examined in a viewer that lets the user see a colourful representation of its circular genome of instructions and watch what happens as it executes.

They can observe random mutations occur in its code during replication which are a source of new variations. At any time an individual or even a whole population in a dish may be "frozen" and stored in a virtual freezer for later examination.

The dish itself serves as a model environment. Users can set up experiments using multiple plates with different environmental settings. Among some of the simple environmental variables the user can change are the size of the dish, the rate that mutations are caused in the replicating orgs, and whether replication occurs next to the parent cell or at a random location, as though in a well mixed medium.

For hands-on learning to succeed, the learner cannot be overwhelmed with too much information too quickly. To avoid this problem we resist bloating Avida-ED with specialized capabilities that a researcher might use, but which would needlessly complicate the software for the undergraduate users the educational version aims to serve. For example, we omit settings that allow a researcher to test in advance what effect a mutation will have on fitness and to revert unwanted kinds of mutations (e.g., ones that would be fatal) to change artificially the abundance of various types in the population. For some kinds of specialized experiments, this kind of control is essential but not for the kind of material an undergraduate course would cover. (Another major reason for omitting this kind of control is that such interventions depart from the way that mutations occur in natural systems, and we want students to be absolutely clear that the evolutionary process in Avida-ED works the same way it does in nature – neither the specific mutations nor the kind of mutations that can occur are "preprogrammed.") The platform could even be used now for an honors high school biology class, but we hope to build a simplified version later for more general high school use. Naturally, it is not possible to smooth out completely the initial learning curve, but as far as possible we designed the interface to make it simple to use and understand the most important functions and then to allow complexity to be explored when students are ready to dig deeper.

(II) CONNECT THE ABSTRACT TO THE CONCRETE. Evolution by natural selection is, like similar universal laws in physics, a very abstract principle that can be difficult to grasp. Students need to begin with concrete examples and then learn to generalize from there. A challenge, therefore, is to find ways to help them grasp the concepts starting with ideas that were more familiar. We also had to find ways to represent graphically the evolution that occurs in the internal digital world of the computer. It is similarly always important to be clear about which concepts are realized exactly and which are simulated or modeled analogically.

The idea of the "Petri dish" environment with evolving colonies of Avidians helps provide a concrete frame of reference and the digital organisms exactly realize the basic evolutionary mechanism (VIST), but it is not meant to be a literal model of all aspects of bacterial evolution. For instance, in this world mutation rates are not restricted to the range found in real bacterial populations, but may be set to anything from zero to one hundred percent.

Similarly, users may set up dishes that have different "nutrient" resources available that will give extra "energy" to Avidians that evolve the ability to process them. As mentioned, the energy for an Avidian is actually processing power, and the system is set up to give extra power to organisms whose genomes evolve the ability to perform various logic operations. The abstract notion is made concrete by letting the user start with different "logic sugars" on a dish that Avidians might evolve to use, in the same way they might grow bacterial colonies on dishes with different media substrates. This gives Avidians a kind of virtual metabolism but, again, it is not meant to model any specific metabolic system. Rather it helps illustrate the general notion of how evolution can produce highly complex functional traits when these provide a selective advantage in the environment.

It is important, however, to recognize that there is no reason that one must be limited to the bacterial metaphor and in future versions we will likely add alternative ways to visualize the underlying evolutionary processes. Instead of a colony of virtual microorganisms on a Petri dish that evolve "metabolic" logic functions, students might see Avidians that move about in a variegated world trying to capture prey or avoid predators, or that try to solve mazes or win simple games.

(III) ENCOURAGE BRAINS-ON LEARNING. Although active hands-on learning often leads to active thinking as well, one should explicitly encourage brains-on learning. Rather than explaining everything up front, we encourage students to discover some of the properties of the Avida world on their own in the same way one would want them to discover features of an organism or environment in any wet lab. For instance, we intentionally say very little at first about how the virtual metabolism works, allowing students to raise and investigate that question on their own as they move from exploring the phenotypic traits of Avidians to the genotypic properties that underlie them.

For the most part we recommend avoiding canned experiments where the user is simply following a set of instructions to produce a predictable result. A canned experiment can work well as an introductory exercise to familiarize students with basic features of the system, but thereafter we recommend that students participate in hypothesis formation and experiment design as this helps them begin to think like a scientist. Of course, it is known that pure discovery learning of such concepts is difficult for students (de Jong & van Joolingen, 1998), so the model exercises and other curricular materials we are developing along with the software aim to provide sufficient constraints and guidance while still being open-ended in a way that stimulates learners to think independently and to take the initiative.

Similarly, although it would be very easy to program an artificial life platform like Avida-ED to automatically take certain data and calculate particular results or even run some kinds of experiments, we believe one should be very selective about what the software does automatically for the user. One must be careful not to put up "helpful" buttons that inadvertently turn off the students' brains.

Indeed, it can occasionally even be worthwhile to slow down a process that the computer could do faster just to make sure that a student can clearly follow the steps. If students have designed a good experiment, they should know exactly what factors they manipulated and what they did not, and thus how the effects they observed provide a real test of their evolutionary hypothesis.

Connecting this back to the content learning goals, this will let them learn first-hand that scientists do not just "assume" their conclusions, but base them upon repeatable empirical evidence. Avida-ED provides an environment for them to confront directly, and hopefully correct, their misconceptions about the scientific status of evolutionary theory. They will be able to see for themselves how evolutionary hypotheses – including the difficult cases having to do with the evolution of bio-complexity – can be confirmed by empirical tests.

Future directions

Initial development and classroom testing of Avida-ED was done at the Lyman Briggs residential science college at Michigan State University and then expanded to other MSU courses and to test sites at other universities. The software will be released for free national distribution in 2007. The current version of Avida-ED is already a powerful learning tool, but more can be done to expand its capabilities.

Avida will continue to be developed as a research platform, and Avida-ED will likewise develop along with that core. For example, Avidians initially reproduced asexually only, but recently the capacity for them to reproduce sexually was implemented as part of experiments to test hypotheses about the evolution of sex, so we will soon incorporate that into the educational version as well. Plans are underway to implement localized resources in their virtual environment and to divide the environment in other ways as well, which will allow one to begin to test hypotheses about the relation of evolution and ecology. We will also implement "sensors" to allow Avidians to perceive some features of environment. We will allow them to mutually interact in more complicated ways and to communicate. Such features will eventually even allow investigation of the emergence of rudimentary intelligence. And while at this stage everything happens in the model world within the computer, we can envisage giving Avidians real bodies by linking the software to small tabletop robots, which would make the evolution of certain forms of complex behaviour even more tangible.

A formal classroom study to assess whether using Avida-ED helps students correct common misunderstandings about natural selection is now underway. However, informal evidence already suggests that using the tool helps students. In teaching courses on artificial life, we have seen that the experience of observing evolution in action with digital organisms often produced a feeling of wonderment in the students. Watching complex programs evolve from simple ancestors elicited from them the excited response that "Evolution works!" No matter how much instructors lecture about evolution, there is no substitute for the "Aha!" experience that happens when students witness a population adapt in a novel way that appears to be a creative or even inspired solution to a problem, but which they also saw was a natural result of the Darwinian process. Inquiry-based education with Avida-ED provides a way for students to unravel for themselves and understand the nature of science; they know that evolution works because they tested it themselves. That is the classroom experience that Avida-ED can help make happen.

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ROBERT T. PENNOCK is Professor in the Lyman Briggs College; the Department of Philosophy; the Department of Computer Science and Engineering; and the Interdisciplinary Graduate Program in Ecology, Evolutionary Biology, and Behaviour at Michigan State University. He is the author of *Tower of Babel: The evidence against the new creationism*, and he was called as an expert witness in the landmark U.S. federal court case of *Kitzmiller, et al. v. Dover Area School Board*, in which a policy enacted in a Pennsylvania school district promoting Intelligent Design was found to be unconstitutional. He is a Fellow of the American Association for the Advancement of Science and chairs the Education Committee of the Society for the Study of Evolution.

ROBERT T. PENNOCK est professeur à la Lyman Briggs College; aux départements de philosophie et d'informatique et de génie, en plus de participer au programme interdisciplinaire d'études supérieures en écologie, en biologie évolutionniste et en comportement à la Michigan State University. Il est l'auteur de *Tower of Babel: The evidence against the new creationism* et a été appelé à témoigner comme expert dans la cause Kitzmiller, et al. c. Dover Area School Board en cour fédérale américaine, qui a fait jurisprudence et dans laquelle une politique faisant la promotion de la création intelligente et promulguée dans un district scolaire de Pennsylvanie a été reconnue inconstitutionnelle. Il est membre de l'Association américaine pour l'avancement des sciences et dirige le comité en sciences de l'Education de la Société pour l'étude de l'évolution.