Chapter 8
Evolution Is a Model, Why Not Teach It That Way?

Paul Horwitz

Introduction: The Model

Evolution is not an intuitive idea. At first blush, in fact, it seems ridiculous to suppose that the wondrous interdependency and exquisite adaptations of living creatures could have evolved by natural causes without conscious planning. Not only is the concept counterintuitive, but the evidence for it is mostly indirect and cannot be appreciated without prior knowledge of seemingly unrelated sciences. And of course in some circles, particularly in the United States, the theory of evolution is in conflict with firmly held religious convictions (Scott, 2004; Sinatra & Nadelson, 2010; Verhey, 2005). No wonder evolution is so hard to teach!

On the bright side, the process of evolution by natural selection is ideally suited to teaching via computer simulations, which can transcend space and time constraints to model processes that take place on scales from molecules to ecosystems and over times ranging from milliseconds to billions of years (Horwitz, 2010; Ottino-Loffler, Rand, & Wilensky, 2007; Rosca, O'Dwyer, Lord, & Horwitz, 2010; Wilenski & Novak, 2010). A very simple model, in fact, can demonstrate how evolution occurs. Here's an example—imagine a highly simplified model of a plant that needs only one thing to grow: light. But it is not enough to have any old amount of light; our plant is very picky. In too much or too little light, it will wither and die, but if it gets just the right amount, it will flower and produce seeds. When winter comes, our plant will die, but if it has made seeds they will germinate, and come spring they will produce other plants, which will produce more seeds, and so on. So if the conditions are just right, even though the original plant has died, our model will support a *population* of plants that can live forever as long as the light level doesn't change.

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In fact, if we're not careful, this model will *blow up*! If each plant produces multiple seeds that in turn grow into viable plants that produce their own seeds, there will be more plants in each succeeding generation, and the number of plants will grow without limit. If, on average, each plant produces fewer than one viable seed, the opposite will happen: The plants will all die off. The model is *unstable*: Unless we can somehow contrive to make the birthrate exactly equal the death rate, our model plants will either grow without limit or go extinct. If we do succeed in exactly balancing the two rates, the population will remain exactly the same. Boring—and not at all what you would expect in nature! What's wrong?

The problem is that our model is too simple; in mathematicians' terms, it is *linear*, meaning that there is nothing in it that sets the scale for how many plants can be supported at once. We need to add to our model the concept of the finite *carrying capacity* of the environment. We can accomplish this by adding the feature that the plants they compete for scarce resources and when they are overcrowded they become sickly and produce fewer seeds. This kind of thing is called a *negative feedback loop*, and it's very common in nature, so we're well within our rights to add it to our model.

With this addition, we've got a model that is stable, in the sense that there will be different numbers of plants each year, but they will never exceed a certain number, nor will they go extinct. So far, so good, but what does this have to do with evolution? Evolution depends on three things: inheritance, variation, and fitness. Our model incorporates the first of these; it's time to add the next two.

Imagine that our model plants come in different varieties, distinguished by the size of their leaves. Some plants have big, bushy leaves with lots of surface area for photosynthesis, so they need very little light. Other plants have small, skinny leaves, and they need a lot of light to survive. Still other plants are in between these two extremes: They have medium-sized leaves and are adapted to moderate amounts of light. For simplicity, let's label these different varieties of plant numerically according to size of their leaves: Level 1 plants have very small leaves so they need a lot of light, level 10 plants have big leaves and need very little light, and the other levels are in between. Figure 8.1 shows what these plants might look like.

Now here comes the tricky part: In our model, all the plants depicted in Fig. 8.1 are *different varieties of the same species of plant*. What exactly does that mean? We know that offspring don't always look exactly like their parents; even the littermates of purebred dogs show some variation. So let's add this important feature of the real world into our model by setting up a rule that says that when a plant produces seeds, *the offspring sometimes are shifted in level by one unit*. A level 5 plant, for instance, will mostly produce level 5 offspring, but every once in a while, *by accident*, it will make a level 4 or a level 6 plant. In the presence of a uniform environment suited to level 5 plants, most of the offspring of our plant will do just fine; they will germinate, grow into adult plants, and produce seeds of their own. The occasional level 4 and level 6 seeds, however, will be at a disadvantage. They will grow up withered, and they won't produce a flower, so they will produce no seeds and have no offspring. So after a while, each generation will

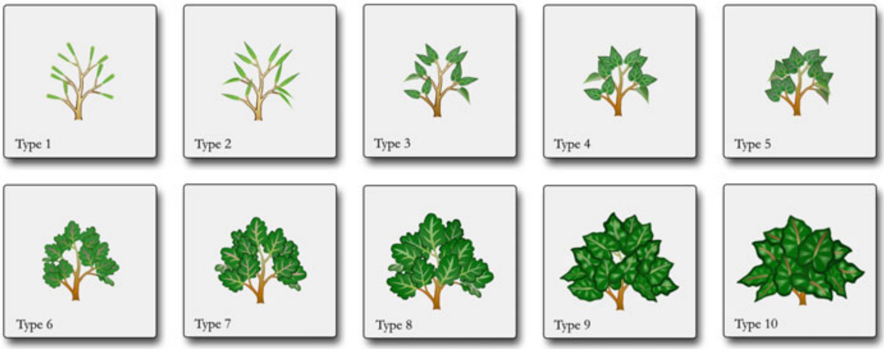

Fig. 8.1 Ten types of plant in the model. Plants with thin leaves are adapted to abundant light; plants with bushier leaves are adapted to shade. All plants are varieties of the same species

consist mostly of level 5 plants, with the occasional, infertile, level 4 or 6 plants randomly mixed in.

Now our model has inheritance, variation, and fitness: the three things that are essential for natural selection to take place. To get evolution, we need to add one little thing: change. Environments are not eternal. A grassy plain that gets plenty of sunshine may over time become a forest of tall trees. When that happens in nature, the original plants that were adapted to lots of sunshine will give way to other kinds more adapted to shady conditions. Our model will do the same thing, *if the change is gradual enough*.

Here's a mental exercise for you. Imagine that we add to our computer model a slider with a range of 1–10 that controls the amount of light available to our plants. You can think of it as a simple way to control the growth of those trees, except that you can do it in seconds instead of having to wait for decades, and we can make the trees grow shorter as well as taller. If we set the slider to 5, which corresponds to a forest of medium-tall trees, we will reproduce the situation described above: a hardy, healthy population of level 5 plants with a few 4s and 6s appearing in each generation. What do you think will happen if we abruptly move the slider to 10, suddenly increasing the light level (the real-world equivalent might be clear cutting that forest)?

The answer, of course, is that all the plants will die because none of them is adapted to live in such a high-light environment. In evolutionary terms, our plants will go *extinct*. Is there any way to avoid this dire fate? What if we were to move the slider just a bit so that the light level changes from 5 to 6? Now the level 5 plants, which are the vast majority of the plant population, can no longer survive; neither can the small minority of level 4 plants. But the level 6 plants, and remember there will be a few in every generation, will thrive in the new environment—all the more so since there will be no other plants around to hog those scarce resources! So even though there may be very few level 6 plants at first, each one will flower and drop seeds, and in just a few generations, their numbers will grow to reach the carrying capacity of the environment, and we will be right back where we started, but with level 6 plants that look subtly different from the level 5 plants we started with. Simple, isn't it?

And of course it doesn't stop there. If we change the environment to light level 7, the same thing will happen: The small minority of level 7 plants that are always present in the level 6 population will form the basis for a whole new population of level 7 plants, adapted to the new environment. And this goes on through levels 8, 9, and 10. In this way, by changing the light level gradually enough, we can make our model plant population grow from its original level 5 to level 10, which looks quite different. And of course we could have performed the same transformation in the opposite direction, gradually reducing the light level and eventually producing a population of level 1 plants. With this simple model, which includes inheritance, variation, and fitness, our different varieties of plants are capable of keeping pace with changes in the environment, evolving into one another (and back again!) as long as the changes are gradual enough to allow the variant plants to take hold and prosper each time the environment changes.

Note that our ability to create and run such a model says nothing at all about whether evolution actually happens in nature! After all, we created all those different levels of plants, specifically designed to be able to live and reproduce in different light conditions, before we even ran the model! So the level 5 plants evolved, yes, but they evolved into something that was in the model to begin with. The model I have described doesn't *prove* evolution by natural selection—no model could do that!—it simply *illustrates and explains* it. And that, with support from the National Science Foundation, is what we set out to do in a recent project called.

Evolution Readiness[2]

The goal of the project is to introduce students in the fourth grade—10-year-olds—in the United States to the concept of evolution by natural selection. Working with school systems in three states, Massachusetts, Missouri, and Texas, we have been presenting students with computer-based learning activities that incorporate models of plants and animals similar to the one described above. The activities present themselves to students in the form of educational video games, in the sense that they have a definite goal and provide context-sensitive scaffolding in the form of helpful hints and congratulatory messages when the goal state is attained. Many of the activities offer a *back story* in the form of real-world examples associated with the students' explorations of the model. All these activities keep track of everything the students do, including their answers to embedded questions, and report back to the teachers and to the research team. In addition, the teachers were requested to fill out a brief survey at the end of each lesson, with comments on their students' reaction to the activities. Some of these comments are included in the descriptions below.

Description of the Learning Activities

Plant Activities

The Virtual Greenhouse

The goal of this activity is to teach the students that plants with different types of leaves are adapted to different amounts of light. The students are given three different types of seeds and are challenged to determine by experiment in which of five virtual flower boxes—differing in the amount of light they receive—each of three types of seeds grows best. They may keep track of their data by taking snapshots of each experiment and saving them in an online laboratory notebook that is incorporated into the program. The activity also introduces a bar graph that shows how many plants of each type have produced flowers, indicating that they are healthy and their environment is optimal for them. This activity is depicted in Fig. 8.2.

The Virtual Field

In this activity, students plant seeds in a field with a gradient of illumination. Plants at the top of the field receive less light than those at the bottom. (Note that the direction of the gradient is reversed from that in the flower box arrangement of the virtual greenhouse activity above, so that students do not confuse location with the critical environmental factor: light.) As in the flower box environment, plants with big leaves can only live where the light is least, whereas those with the smallest leaves must be planted in the part of the field that receives the most light if they are to survive, produce a flower, and drop seeds. The students discover this by experimenting with the same three seeds as before. If they plant their seeds in the wrong place, the plants will wither or die and fail to produce seeds. This activity also introduces the plant life cycle. *Winter* arrives at regular intervals, and all the plants in the field die and disappear. Their seeds, if any, survive the winter and grow into plants the following spring. This feature of the model is pedagogically important because it reinforces the point that the evolutionary changes the students observe take place over many generations and affect the population of plants rather than individuals. Initially, all the *offspring* plants are identical to the *parent* plant—no new types appear, and after many generations, the field is populated by three distinct rows of plants, corresponding to the three types of seeds the student was able to plant. This situation is depicted in Fig. 8.3. The activity ends with a *zoomed-in* simulation of a single plant that produces exactly six seeds—two of which grow into plants that are slightly different from those of the parent plant. These *mutant* plants wilt and do not produce seeds in the environment into which they were born, but the student can pick them up and move them to a slightly different environment where they will do well.

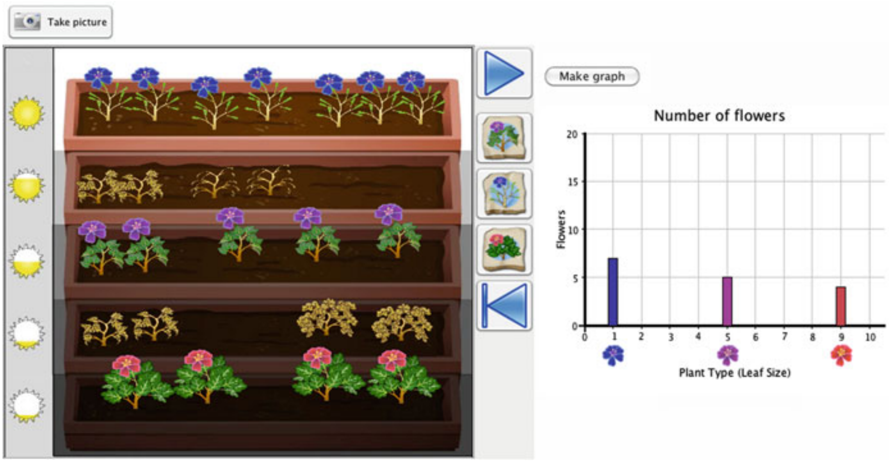

Fig. 8.2 The virtual greenhouse. The bars are color coded to match the colors of the flowers

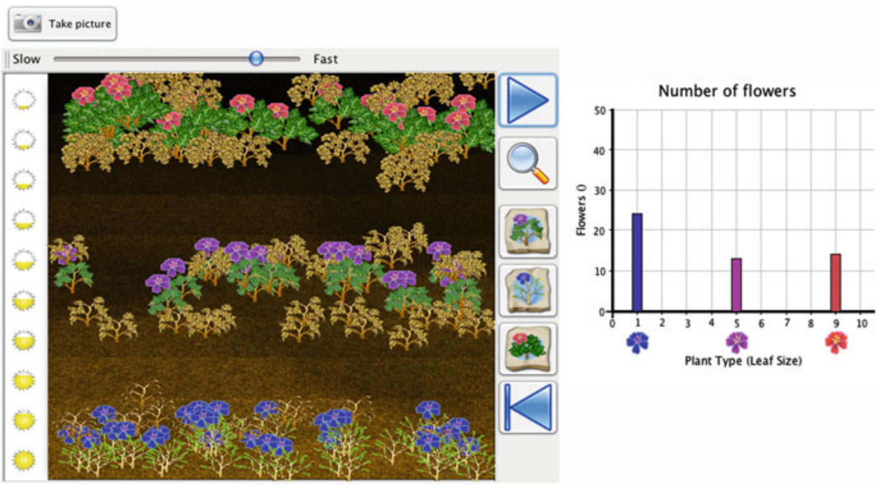

Fig. 8.3 The virtual field. Note that without variation, the three types of plants occupy distinct regions in the field, due to the gradient of light across it. The bar graph shows only those three types

Mystery Plant Adaptation

The third activity revisits the zoomed-in scenario of inheritance with variation which ended the previous activity. It then returns to the same field as before, with the ambient light level varying smoothly from top to bottom. The students are given only a single type of seed to plant: the type that grows best in the center of the field. But this time the model has been altered to include a critically important feature: *variation*. A small

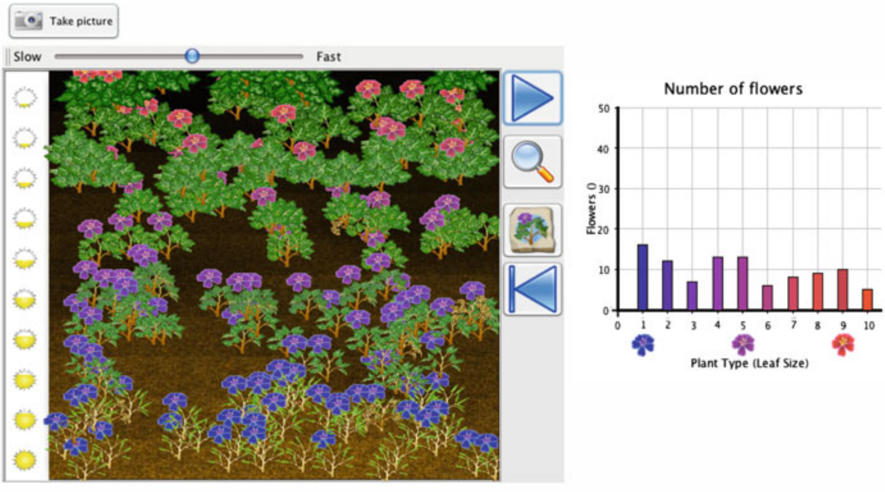

Fig. 8.4 Mystery plant adaptation. Note the bar graph which indicates that every type of plant is present in the population

fraction of the seeds from a plant will grow into new plants that differ slightly from the parent and thrive in the row just above the parent plant's row or just beneath it. Since each plant scatters seeds randomly, it happens occasionally that some of these different seeds fall in a location where the light level is just right for it. When this happens, the seed will grow into a healthy plant that will produce seeds of its own. In this way, the single type of plant planted by the student, which could only live in a particular horizontal slice of the field, eventually evolves into the full spectrum of different varieties that we observed in Fig. 8.1. When this happens, the population of plants is capable of living and reproducing in every area of the virtual field. In this activity, a small fraction of the planted seeds from one type of plant will actually grow into a neighboring type. In the presence of this source of variation, a single type of plant—capable of growing only in one region—can evolve to cover the entire field. The effect is quite dramatic, as shown in Fig. 8.4.

Changes in the Environment

The fourth activity places the control of the environment under the control of the student. The field starts off with a uniform light level midway between the maximum and the minimum, thus capable of growing plants with medium-sized leaves. Students can alter the environment, however, by "growing" a chain of mountains of variable height right down the middle of it. In the presence of these mountains, depending on their height, the light level increases by 1–4 units on one side of them and decreases by the same amount on the other side. Students are challenged to grow the mountains to their maximum height (corresponding to the maximum change in light level) while maintaining a viable population of plants on each side. If the students make the changes too abruptly, their plant populations will not have time to adjust to the change, and all the plants will die out. However, if they change the environment one step at a time, being careful to wait before making each change until there are sufficient numbers of *mutant* plants on each side, then the *normal* plants will die, but roughly half of the mutants will survive, and it is they who constitute the basis for the next generation.

Mystery Plant Mystery

The final plant activity is intended to assess what the students have learned in the first four. In previous research (Horwitz & Christie, 2000; Horwitz, Gobert, Buckley, & O'Dwyer, 2009), we have found quite often that students who are taught with game-like activities may get proficient at the game but fail to learn the science concepts that underlie it. To test whether this was happening, we introduced a new environmental variable (water level) and added 10 new varieties of plants with different root types, ranging continuously from deep to shallow, adapted to different water levels. (Plants with long "taproots" are adapted to dry conditions; those with shallow, wide-spreading roots need lots of water.) Using these plants, we constructed an activity to use as a transfer exercise and a test of whether or not a student has really understood the target concepts. The new activity involves the same concepts of reproduction with variation, natural selection, and adaptation but uses the water level to root type mapping, rather than the light level to leaf size mapping. This is a significant change, particularly since the roots of the plants are not normally visible: They can only be seen if the student *uproots* the plant with a special *hand* tool or observes it closely with a *magnifying glass* tool.

The activity starts with five flower boxes, as in the virtual greenhouse, and three types of seed. The flower boxes differ in the amount of water they receive, and the challenge, as before, is to discover which seeds thrive in which environment. This time, though, the plants all look the same above the ground (they all have medium-sized leaves and pink flowers), so it is not obvious that they are different. Beneath the surface, however, their roots are different. Once the students have discovered this, using the hand tool or the magnifying glass to examine the roots, they are presented with a field where the water level varies continuously from left to right, from one end of the field to the other. They are provided with a packet of seeds, all of which grow the same type of plants. The seeds cost virtual money, and the challenge to the students is to spend as little as possible on seeds but still produce a bumper crop of plants that can grow everywhere in the field. To do this, the students must notice and take advantage of the small variation in root type from one generation to the next.

Animal Activities

For pedagogical purposes, the main difference between plants and animals is that plants, in our model at least, depend only on abiotic (nonliving) factors, such as light and water, while animals consume other living things—plants and other animals.

So by bringing in animals, we are able to introduce the concept of a food chain, with its related notion of competition for scarce resources. Moreover, the interdependence of species at each level of the food chain means that the environment of each species comprises, in part, all the other species with which it interacts. Thus, evolutionary changes in one species will affect others, and vice versa, resulting in a sort of *adaptation arms race* qualitatively different from the one-way response of the plant population to external changes in a nonliving environment. In this, the third year of the project, the *Evolution Readiness*, students in all three school districts are exploring these related concepts through a sequence of five animal activities, which we describe below.

The Virtual Ecosystem

With this activity, we introduce students to the idea that all living organisms must compete for food with other living organisms. We do this interactively by having the students take on the role of a rabbit in a field with edible plants. The students can control the movements of their rabbit using the arrow keys on the keyboard, and in this way they move the rabbit from one plant to another. When the rabbit moves onto a plant, it *eats it*, the plant's icon disappears, and the rabbit's hunger level is decreased. At first the students' rabbit is alone in the field, but then other, computer-controlled, rabbits appear, one by one. With all this competition, it becomes harder and harder for the students to keep their rabbit alive.[3] Even if their particular rabbit starves, however, the population of rabbits survives, and from the evolutionary point of view, that's all that matters. Accordingly, an important goal of this activity is to encourage students to think globally: shifting from a focus on individual organisms to a concern for the well-being of the population as a whole.

Variations and Adaptations

This activity introduces three varieties of plant: tall, medium, and short; students experiment to determine how climate can affect ecosystems. First, they investigate the effect of rainfall on the plants and discover that the larger plants can live in near-drought conditions, while the smaller ones perish. Next, we introduce variation in the rabbit population and challenge the students to figure out which variety of rabbit eats which kind of plant. The students are encouraged to make the connection between rainfall amount and the rabbit population's ability to survive by thinking first about rainfall and plants, then about plants and rabbits, to infer that when certain plants cannot grow and reproduce, the rabbits that eat those plants will not have enough food to survive. In this way, students are introduced to the concept of interdependence in an ecosystem and its effect on the evolution of populations.

Natural Selection

In the third activity of the animal sequence, students explore how changes in the environment affect both the plants and animals in a simple ecosystem with just two species living in it: grass and rabbits. They build a dam in the middle of the field, dividing the ecosystem in half. The area below the dam gradually dries out, which affects both the grass and the rabbit populations in that region. As the smaller plants die out, the rabbits that eat them soon follow suit. Once the students have observed this progression and entered data into their virtual laboratory notebooks, they remove the dam and observe as the ecosystem slowly returns to its original state.

Predators and Prey

This activity uses a model of the virtual ecosystem with three species in it—grass, rabbits, and hawks—enabling the students to explore the effect of predation on the prey population. At first, they *become* a hawk and try to catch and eat brown and white rabbits on a snowy field. The latter blend into the background and are harder to see, so they have a selective advantage. Having discovered through personal experience the reason for this selective advantage, the students proceed to explore an environment that changes over time starting out white and turning brown as the snow melts. A line graph shows plainly the shifting of the relative proportions of white and brown rabbits in response to this environmental change.

Experiment with Ecosystems

This is the most open-ended of all the *Evolution Readiness* activities and perhaps the most challenging for students. The goal is to give the students the opportunity to *think like a scientist*, making hypotheses, doing experiments, observing what happens, and analyzing and thinking about data. Students are encouraged to construct and conduct their own experiments with ecosystems comprising grass, rabbits, and up to two predator species: hawks and foxes. First, they are prompted to come up with a hypothesis for a particular question—for example, *What will happen to the hawk population if the grass is removed from the field?* Then, they are challenged to experiment with the model ecosystem in a way that allows them to test their hypothesis.

Off-Line Activities and Teacher Support

We supplemented the computer-based activities described above with off-line activities involving manipulable objects of various kinds. These activities were borrowed or adapted from existing curricula. Any required physical materials were supplied by the project to all the participating teachers. These materials included

- Several books about evolution written for children
- An 18-ft-long vinyl timeline with graphics and text depicting the evolution of life over the past 600 million years
- A set of fast plants[4] together with a simple lighting and watering system, designed by the project, to facilitate their maintenance
- A game called the Lego Tree of Life designed to illustrate phylogenetic trees; materials included sets of large Lego pieces and special-purpose plastic laminated cards
- Another game called Clip Birds that illustrates selective pressure by challenging students to pick up three different sizes of *seeds* using three different kinds of clips
- An activity that introduces the complex interdependence of species in an ecosystem by having students literally construct a *food web* by passing a ball of yarn between them to illustrate interactions between different trophic levels

The subject matter of the *Evolution Readiness* project is challenging for teachers as well as students. Accordingly, we offered extensive support for teachers through a variety of channels: face-to-face workshops, an online course, and a comprehensive teacher guide that introduces each of the activities and covers both content and pedagogical content knowledge. Teachers were compensated for the time they spent on professional development, as well as any other time devoted to activities outside their normal duties (e.g., administering tests).

Results from Second-Year Implementation

In the second year of the project, that is, Year 2, we evaluated the plant activities and the first four of the off-line activities in all three participating school districts. In what follows, we refer to this treatment as the *trial curriculum*. At this writing, halfway through Year 3, implementation of the full curriculum, which includes the animal activities and food web off-line activity, has begun with an implementation in the Massachusetts school district. Results from the full curriculum are not yet available, so we report only on the trial curriculum here.

We compared the learning gains of students exposed to the trial curriculum in Year 2 to a baseline cohort consisting of students taught by the same teachers using a traditional curriculum in Year 1. The comparison is meaningful because the topics covered by the *Evolution Readiness* materials, designated by us as *Big Ideas*, as shown in Table 8.1 are all contained within the science standards of each of the three states we worked in, Massachusetts,[5] Missouri,[6] and Texas,[7] and were therefore covered by the traditional curriculum, but without the assistance of the online and off-line activities, and lacking the integrative, evolution-based explanatory approach adopted by the *Evolution Readiness* project.

Table 8.1 Big ideas of evolution readiness

Big ideas and standards	Learning goals
1. Basic needs of organisms	Both plants and animals need air and water; plants also need light and nutrients; animals also need food and shelter
	Different species have different preferred conditions for survival
2. Life cycle—birth and death cycle	Organisms are born, live, and die
	A species can survive even though every individual in a given generation eventually dies
	All organisms have a finite lifetime, and populations will survive only if their constituent organisms have enough offspring over time to compensate for the number of deaths
3. Organisms and their environment	Organisms thrive in environments that match their specific needs
4. Classification of organisms	Plants and animals are classified into species and other groups based on shared characteristics
5. Interspecific differences	There are differences between species
6. Interactions between species	Organisms with similar needs compete with one another for resources
	Animals obtain energy and resources by eating other animals and plants. Plants produce their own food
	The presence of other plants and animals, as well as environmental factors, can affect the survival of plants and animals
7. Intraspecific differences	Individuals of the same species may differ. Not all offspring from the same parents look alike, even with respect to inherited traits
	Purposeful selection of certain traits over many generations can result in substantial changes in the physical characteristics of organisms in a population
8. Adaptation and evolution	Species are adapted to their environments. If the environment changes, only certain species survive
	Organisms carrying traits that are better suited for a particular environment will have more offspring on average
	Selection pressure can lead to a change in the characteristics of a population
9. Heritability of traits	Offspring inherit some, but not all, of their traits from their parents
10. Reproduction	Organisms have offspring, and without reproduction, the species cannot continue. Only members of the same species can have viable fertile offspring
11. Descent with modification	Species evolve from common ancestors. Different species can arise from one species if different groups have different selection pressures

Development of the Assessment Instrument

In Year 1 of the project, we developed a Concept Inventory for Evolution Readiness (CIER)[8] that covers the projects learning goals (see Table 8.1) and is aimed at uncovering students' preconceptions. Designed to be administered in two sessions, the CIER includes 32 multiple-choice, 5 short-answer, and 24 open-response questions and measures students' understanding of the fundamental concepts related to the theory of evolution.

We conducted Rasch analyses before we used the CIER and measured high item and person reliability (0.88 for person reliability and 0.97 for item reliability). The Wright map from Rasch measurement and person-item separation indices indicated that the CIER was a valid measure and its results matched expected typical fourth grade students' ability. We include the Wright maps from the baseline and Year 2 cohorts as shown in Figs. 8.5 and 8.6, respectively.

In the northern spring of Year 1 of the project, we used the CIER to collect baseline data from 132 students (Cohort 1) taught using the traditional curriculum in each state. In Year 2, we used the same instrument to collect data from 186 students (Cohort 2) in the same schools taught by the same teachers but using the *Evolution Readiness* trial curriculum (all the plant activities and four out of five off-line activities). To avoid unintentional bias, the tests from both cohorts were combined and scored by trained scorers who did not know which student belonged to which cohort. Estimates of students' knowledge of the concepts were computed using both classical test theory and item response theory.

The test results indicated that the students in the post-implementation cohort had a deeper understanding of the concepts underlying the theory of evolution than did the pre-implementation cohort and that this difference was sharpest for the more advanced topics. For instance, none of the students in Cohort 1 achieved a maximum score on the open-ended response questions relating to adaptation and evolution, indicating that the pre-implementation cohort did not have a deep understanding of these core concepts. In contrast, several students in Cohort 2 did achieve the maximum score on these questions. The Cohort 2 also outperformed Cohort 1 on questions relating to descent with modification, indicating that they understood that new species could arise from a single species if different subgroups were subjected to different selection pressures for a long time.

Overall, the mean for the pre-implementation Cohort 1 was 530.87 (SD = 67.78), and the mean for the post-implementation Cohort 2 was 555.71 (SD = 78.97). An independent means *t*-test showed that the students in Cohort 2 performed significantly higher on the CIER than did students in Cohort 1, with an effect size difference of 0.35 standard deviations. It should be noted that the test instrument was identical for the two different cohorts.

What Did We Leave Out and Why?

According to national polls conducted in the United States,[9] approximately half of the US adult population does not *believe in* evolution (the exact number depends on how the question is asked), and a substantial majority believe that the various creationist theories should be given *equal time* in precollege science courses.[10] Should we be concerned about that? If it's a problem, is it one that a model-based pedagogy can address?

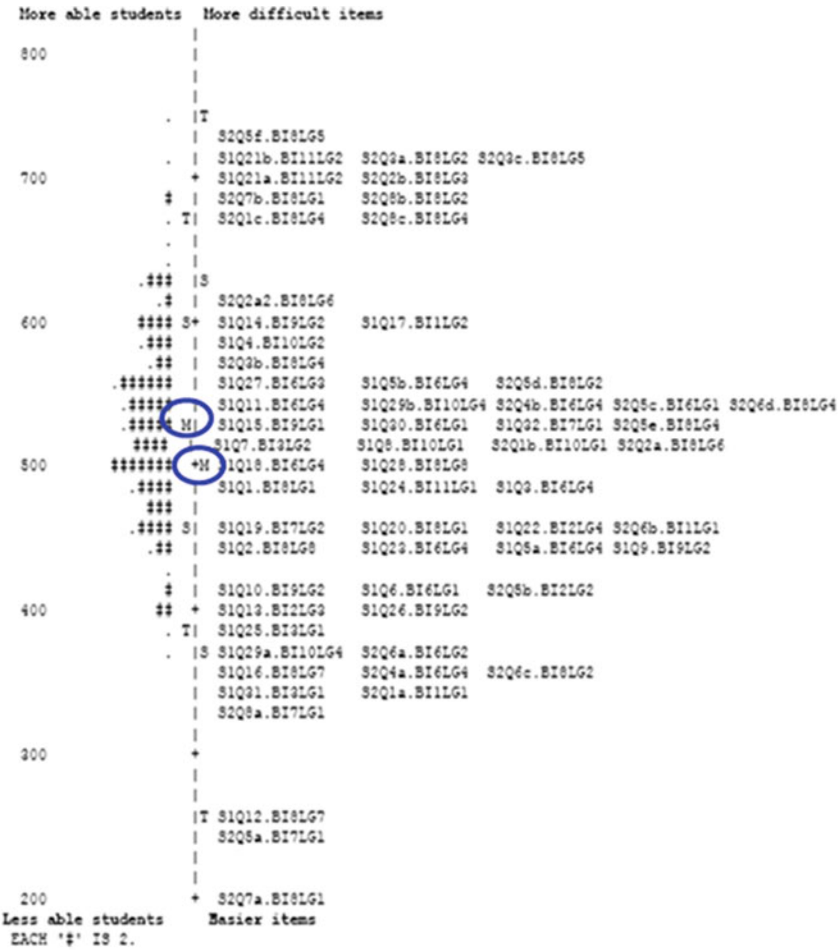

Fig. 8.5 Wright map of baseline data from Cohort 1, collected in Year 1 prior to treatment

I have commented elsewhere, for example, in an interview by Sparks (2010), that the goal of the *Evolution Readiness* project is not to try to persuade students to believe in evolution but rather to help them to understand it as an explanatory model that ties together diverse findings from a wide variety of fields. I would generalize that statement: I don't think the primary goal of any course in science should be to induce the students to believe in the science being taught—in fact, the whole idea of *believing in* science strikes me as somewhat bizarre.

Students in high school are taught the Pythagorean theorem, but we do not therefore infer that the primary purpose of their geometry course is to induce those students to believe that the square of the hypotenuse of a right triangle is equal to the sum of the squares of the other two sides. We recognize that the

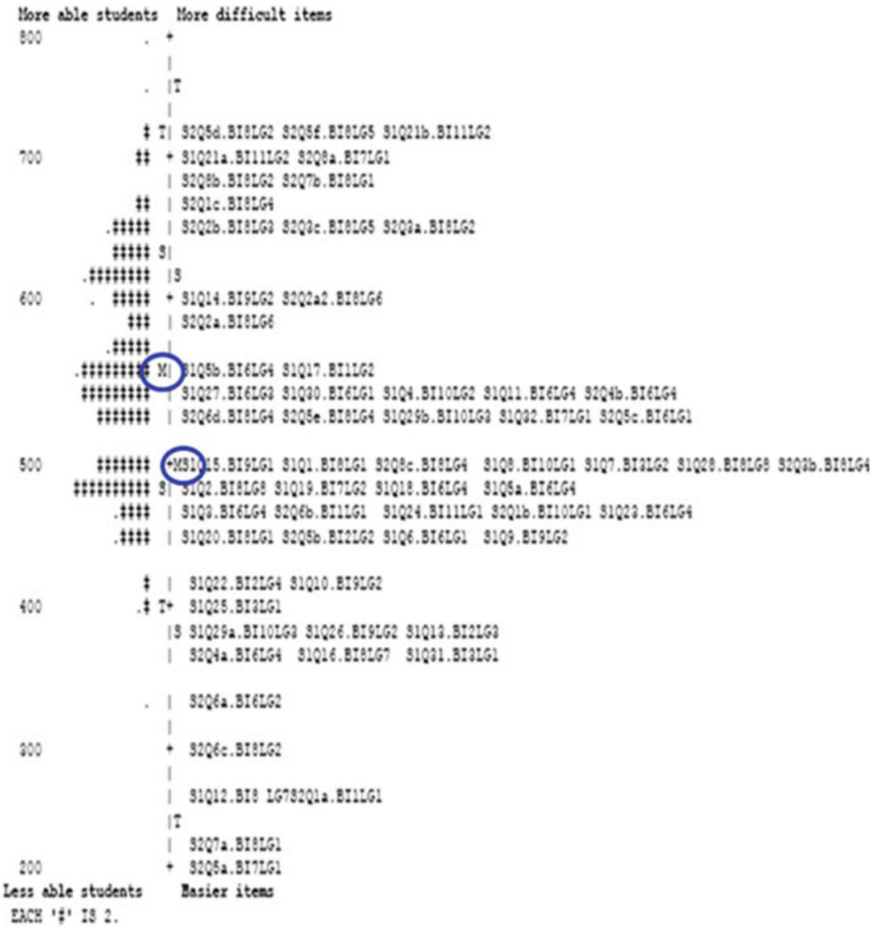

Fig. 8.6 Wright map of data from Cohort 2 collected in Year 2, after treatment

important aspects of this celebrated result of Euclidean geometry lie in the various ways that it can be proved, as well as in the multitude and variety of its applications to mathematics and other disciplines. So it is with evolution: Whether or not students come away with a firm belief that every living thing on Earth evolved is less important than that they understand the model of evolution driven by natural selection[11] and appreciate how such a model is supported by evidence. We believe that our project is accomplishing the first of these goals; the second we have largely ignored.

At the start of the *Evolution Readiness* project, we were faced with the task of identifying which aspects of the evolutionary model we were going to try to teach to fourth graders. After much discussion, we decided to leave out those aspects of the model that take place on time and space scales that are unfamiliar and largely inaccessible to the young children who were our audience. Accordingly, we left out phenomena and processes that are either very small or very slow: We do not introduce the molecular basis for inheritance, for instance, nor do we emphasize, with the exception of the timeline, the nature and interpretation of the fossil record. This intentional pruning of the curriculum has the somewhat unfortunate consequence that we have had to skip over much of the supporting evidence for the evolutionary model; we have instead resorted to presenting that model in a manipulable form and guiding students to explore and come to understand it by experimentation, in response to specific prompts. For 10-year-olds, we feel, this is challenge enough; we look forward to developing similar interactive curricula, based on more complex challenges and models, for use with older children.

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Notes

1. This project is supported by the US National Science Foundation under grant # 0822213. For more information, visit http://er.concord.org
2. http://concord.org/projects/evolution-readiness
3. It turns out, in fact, that the only way to stay alive for the required 100 s is not to eat if you are not hungry, thereby conserving resources that you're going to need later on when more and more rabbits arrive—a useful lesson even without evolution!
4. See examples at http://www.fastplants.org
5. See http://www.doe.mass.edu/frameworks/current.html for a detailed description of the standards for this state.
6. http://dese.mo.gov/divimprove/curriculum/frameworks/science.html and ancillary documents available for download from this site.
7. http://ritter.tea.state.tx.us/rules/tac/chapter112/ch112a.html#112.15 gives an overview of the Texas standards for 4th grade life science.
8. This work was done primarily by the research team at Boston College.
9. A CBS poll conducted in 2006 reported that 55 % of those questioned believed that "God created humans in their present form," 27 % believed that "humans evolved but God guided the process," and only 13 % believed that "humans evolved and God did not guide the process." A 2007 Gallup poll found that when asked "Do you personally believe in evolution?" 49 % of the respondents answered "yes," and 48 % answered "no"—a statistical tie. (2 % had no opinion.) Both polls were restricted to adult citizens of the United States. Evidently, the explicit mention of humans had a dramatic effect on the result.
10. In 2005, a poll conducted by the Pew Forum on Religion and Public Life and the Pew Research Center for the People and the Press found that nearly two-thirds of Americans say that creationism should be taught alongside evolution in public schools. Sixty-four percent of the respondents said they were open to the idea of teaching creationism in addition to evolution, while 38 % favored replacing evolution with creationism.
11. In fact, several forces drive evolution, but natural selection is foremost among them and was the focus of the Evolution Readiness project, as we have seen.

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