



CollegeBoard

Advanced Placement
Program

AP[®] Biology

2006–2007

Professional Development
Workshop Materials

**Special Focus:
Evolution and Change**

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Special Focus: Evolution and Change

Introduction	
Carolyn Schofield Bronston.....	3
Joining the Scientific Community	
Kenneth R. Miller.....	4
The Darwin I Wish Everyone Knew	
Robert Dennison.....	7
What Have the Courts Said About the Teaching of Evolution and Creationism?	
Randy Moore	15
The Making of Darwin’s Endless Forms	
Sean B. Carroll.....	22
Resources for the Teaching of Evolution in AP Biology	
Sharon A. Hamilton	33
Multiple Choice and Free-Response Questions on Evolution with Scoring Guidelines	
Compiled by Carolyn Schofield Bronston	43
Contributors.....	86
Contact Us.....	88

Important Note: The following set of materials is organized around a particular theme, or “special focus,” that reflects important topics in the AP Biology course. The materials are intended to provide teachers with resources and classroom ideas relating to that focus. The special focus, as well as the specific content of the materials, cannot and should not be taken as an indication that a particular topic will appear on the AP Exam.

Introduction

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Evolution. Just the word evokes high blood pressure and profanity in some, steely-eyed tenacity and “evangelical” zeal in others. How strange that the driving force behind the huge spectrum of life as we know it remains so controversial and so divisive. Originally, the title of this collection was to be “It’s not just a theory . . .,” but in the end, that seemed too flippant. The **fact** is evolution is occurring today as it has in the past. All students need to know of its importance and its consequences. Teachers need to feel confident in their grasp of this subject so that they can convey the elegant simplicity and incontrovertible truth of natural selection.

Religion and science are not at odds—even the pope has pronounced it so. So hopefully we can all move away from that argument and move toward an understanding of how life around us changes and what we can learn from the past to help us in the future. The articles included in these materials run the gamut from historical perspectives of Darwin the man and the legal battles over his ideas, to cutting-edge developmental studies that provide “missing” evolutionary links, to a compendium of resources that will inform and enlighten both teachers and their students.

With a straightforward, scientific approach, you can enable your students to see for themselves the logic and elegance of evolution. For it **is** much more than just a theory: it is the foundation of life itself.

Joining the Scientific Community

Kenneth R. Miller
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Scientific community—what do those words mean to you? To many in the public, they conjure up an image of laboratory workers in white coats, divorced from the reality of daily life, practicing an arcane craft that ordinary folks needn't understand or care about. And that's the problem, a problem that you're about to help solve in your AP course this year. The notion that science is so specialized that it cannot explain itself is clearly one of the reasons why it's fashionable for bright, intelligent adults to joke about how little they know of science and still consider themselves well educated. The sense that science doesn't affect our daily lives allows our society to place a low priority on scientific research. The belief that the scientific community simply exists on its own and does its work without constant attention and renewal is simply false and could easily lead to an abdication of American scientific leadership in the world.

The problem begins with a false understanding of the true nature of the scientific community. As biologists, we know that among the characteristics of life are growth and development, and these traits apply to the scientific community, too. You see the scientific community every day when you enter your classroom. You nurture it every time you work with a student or lead a class through a laboratory exercise, and you have been part of it ever since you took up the great vocation of teacher, the highest calling a society like ours can have. In reality, as an AP Biology teacher you are the single most important part of the scientific community, because you are creating the scientific community of tomorrow. Indeed, the greatest gift you can give to your students is that sense of belonging, of being part of the great project of scientific investigation and understanding that has drawn us out of ages of darkness into the light of knowledge.

And what a light that is. I am tempted to tell my own students that I view them with a sense of envy that they have been born at just the right time to become biologists. For the very first time, we have the capability to ask, in detailed biological terms, what it truly means to be human. Today's ongoing flood of DNA sequence information enables anyone, with a few taps on the computer keyboard, to explore the human genome, chromosome by chromosome, to compare it with those of our closest relatives and to explore the ways in which life has evolved and developed in all of its majesty and glory.

Today's students take biotechnology—from genetically modified foods to DNA fingerprinting—for granted, and well they should. For your students, these are simply part of the age into which they have been born, the context in which they entered your classroom and laboratory. The best part of all of this is that you have the chance to open these worlds to your students, to help them develop an understanding of these technologies and their effects on their lives. Technology is everywhere in modern life, but whether an individual will be its master or be led by it is determined by the extent to which he or she understands the technology of the day. In the coming century, the technology to be mastered, without a doubt, will emerge from the science of life. Your opportunity, your challenge, is to open the minds of your students to that science and to help them see themselves as part of the scientific community.

In many ways, the tools at your disposal have never been more suited to the task of science education. The Internet gives your students direct access to the latest genomic data, as well as contact with research laboratories everywhere in the world. Genetic manipulations and studies that were cutting edge only a few years ago can now be carried out easily and inexpensively in high school teaching labs. Creative and well-planned lab exercises will give your students not only hands-on experience with these technologies but also an even more important gift—the sense of belonging to the scientific community and of participating in the exploration and study of life. Breaking down the illusory barriers that separate your students from “real” scientists should be one of your highest priorities, and if you can do it successfully, it will change many lives.

Albert Einstein once wrote that “the most beautiful thing we can experience is the mysterious—it is the source of all true art and science.” As you look over the curriculum you are planning for your AP students, I hope you will take some time to reflect on the profound and timeless truth of Einstein's observation. All great teachers, in one sense or another, are storytellers, and as biologists, what stories we have to tell! Evolution has opened up the mysteries of the past in a way that yesterday's scientists could never have imagined. Cell biology has revealed an inner world of intricate beauty and balance inside every living thing. Developmental biology has begun to reveal the patterns and processes that build the bodies of plants and animals. Molecular medicine now approaches human disease in a way that the physicians of the past could not have imagined. What we have learned is impressive, but even more enticing are the mysteries that still remain, the vast unexplored territory that lies before us and before your students.

So don't pull any punches on your students. Tell it like it is. Let them know that they really have come along at just the right time, and challenge them not just to learn biology but

Special Focus: Evolution and Change

to do biology. We should never have to remind ourselves that science is a process, not a body of knowledge. The curriculum of AP Biology is not a set of facts to be memorized so much as it is a landscape to explore, a landscape in which the boundaries continue to expand and in which the most exciting territory is still uncharted. From the moment they set foot in your classroom, remind them that they are part of the scientific community, and that the unexplored territory of biology will forever belong to them. Good luck and best wishes in helping to create the scientific community of tomorrow.

The Darwin I Wish Everyone Knew

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Charles Darwin has been and continues to be vilified by those opposed to his views. Perhaps no scientist has been so misrepresented and misunderstood. Contrary to the view many of our students and members of the general public have of him, Charles Darwin was a person any of us would have enjoyed knowing as a friend. That is the Darwin I want my students to come to know, as I have. I want to humanize him for students and thereby open their eyes and minds to the beauty and power of his ideas.

Darwin was born on February 12, 1809, the exact same date as Abraham Lincoln. He was a lover of nature and a scientist from the beginning. In his autobiography, Darwin said, “[M]y love of natural science has been steady and ardent. . . . From my early youth I have had the strongest desire to understand or explain whatever I observed—that is, to group all facts under some general laws.” At the age of 12, Charles and his older brother Erasmus built a chemistry lab in the garden shed where they created lots of “noxious” and explosive gases. In fact, Charles’s nickname among his school friends at the time was “Gas.” He was also an avid collector of rocks, coins, bird eggs, shells, and, of course, insects.

Darwin’s passion and enthusiasm for observing and understanding life never waned. While the iconic image of Darwin is that of a stoic, elderly, balding gentleman with a long, white beard, the true man was much livelier than those images suggest. He certainly was a truly gentle man, but far from being stoic, he talked excitedly, using his hands expressively in conversations. He had a wonderful sense of humor and was a man who laughed easily and loudly, slapping his hands on his thighs in the process.

While sailing around the world on the *Beagle* from the age of 22 to 27, he was adventurous, athletic, and fun-loving, always eager to explore the next vista. He spent weeks riding across the pampas of South America with gauchos. They taught him to throw the bolas to catch rheas (ostriches), which they then ate together around the fire at night (“tasted like beef”). Throughout the voyage, Darwin made a point of eating every type of wild game possible, from armadillo (“tastes like duck”) to the large rodent, the agouti (“the very best meat I ever tasted”), to Galapagos tortoises (“quite good”) and land iguanas (their meat was only enjoyed “by those whose stomachs soar above all prejudice”).

Special Focus: Evolution and Change

Throughout his life, he was a methodical thinker with a penetrating intellect. During the voyage he spent so much time expounding enthusiastically on both science and religion that his fellow shipmates called him “Philos,” short for “The Philosopher,” a title I think he enjoyed hearing as it indicated acceptance of him by the crew. Of course, these discussions took place only at anchor or on very calm waters because Darwin suffered from horrible seasickness whenever at sea. This affliction stayed with him throughout the five-year voyage. He describes being confined to his hammock whenever the ship moved and being able to keep down just “dry biscuit and raisin.” As a result, he spent as much time on land as possible, eventually spending three and a half of the five years on land and a total of only 18 months on board the *Beagle* at sea. The time on land allowed him to make extensive collections of flora and fauna from around the world. These collections, sent home periodically during the voyage, were so voluminous that it eventually required Darwin and his fellow scientists over 10 years just to catalog and describe them. That does not count the time he spent on the very last specimen.

After 10 years he was left with a single barnacle to describe. Charles wanted to know a great deal about barnacles so that he could accurately describe his singular specimen. However, there had been no detailed studies of barnacles to date. So, methodical as ever, he took it upon himself to do such a study. Eight years later, he finished his multivolume, 1,200-page work on fossil and modern forms of barnacles. He spent so much time studying the tens of thousands of barnacles he had sent to him that his children assumed everybody must have barnacles at home, once asking a neighbor to his surprise, “Where does your father work on his barnacles?”

In addition to cataloging specimens, soon after returning home from the voyage in 1836, Darwin began the work with which we are most familiar. Contrary to many popular versions of the story, he did not conceive of evolution at any time during the voyage. It was not until early 1837, while studying the specimens and reflecting on observations made during the voyage, that Darwin first formulated the idea that species changed over time. Fifteen months later he arrived at the mechanism of natural selection to account for how those changes took place. Of course, he would not publish those ideas for another 21 years! Why did he wait so long to publish, and what was the adult Charles Darwin, the author of *On the Origin of Species*, like as a person? Both questions are of interest and importance as we attempt to humanize the man.

From his letters and the recollections of those who knew him best, it is clear that the adult Darwin was a kind, loving, devoted father and husband, as well as a loyal friend and colleague of his scientific confidants. A description of his family interactions and a typical day at home provides the clearest view of the personal side of Darwin.

Charles married Emma Wedgwood, his first cousin, on January 29, 1839, “the day of days!” Methodical as always, Darwin did not decide to get married until he had made an analytical, side-by-side listing of the advantages of the two propositions before him, namely, “Marry” or “Not Marry.” At the bottom of the “Marry” column, he concluded “Marry—Marry—Marry Q.E.D.!” It proved to be the correct choice, for he loved Emma deeply for the rest of his life, often referring to her as his “wise adviser and cheerful comforter.” They made a good life together, settling in the village of Downe, 16 miles from London, in 1842. (Charles would never again leave England.) They spent hours together every day. Emma, who took lessons from Chopin, enjoyed playing the piano and reading novels aloud for Charles and the children. The couple also had a spirited nightly backgammon competition. They would play two games per night, even when visiting friends, and Charles dutifully recorded the results, keeping a running total. In 1876 he wrote, “[S]he, poor creature, has won only 2,490 games, whilst I have won, hurrah, hurrah, 2,795 games!”

Emma spent most of the first 17 years of their marriage pregnant, giving birth in 1839, '41, '42, '43, '45, '47, '48, '50, '51, and '56 for a total of 10 children. The Darwin home (“Down House”) must have been a wonderful place to grow up. Charles and Emma did not worry about the children playing on their expensive furniture, instead giving the children free run of the house and grounds, except for Charles’s study, where he worked every day on his writings. The children piled up the furniture to make railways and coaches, just as the fancy took them. It was not unusual for them to use their father’s rolling microscope stool as a “boat,” punting around the house with a walking stick for propulsion. In looking back at the amount of freedom granted, Emma said, “I believe we have all been much the happier in consequence.” Charles could not have agreed more.

Sadly, three of their children died much too young. Their third child, Mary Eleanor, died just three weeks after birth, and their last child, Charles Waring, died at the age of two of scarlet fever. Charles Waring’s death came just 10 days after Darwin received the famous letter from Alfred Russel Wallace. The baby’s funeral and the parents’ grief prevented Darwin from attending the Linnean Society meeting at which Darwin’s and Wallace’s papers were first presented to the world.

However, the greatest blow in Darwin’s life was the death of his first daughter, Anne Elizabeth (Annie) at the age of 10 from a typhoid-like fever. Charles had taken Annie to a medical establishment in another town in an attempt to save her life, but to no avail, as Annie died and was buried there without ever returning home. Emma was not even able to go along as she was then near delivering yet another child and did so less than three weeks after Annie’s death. Charles returned to Emma as soon as he could after Annie’s

Special Focus: Evolution and Change

passing, and they spent many days “weeping bitterly together.” The loss of his beloved daughter no doubt had a tremendous impact on Darwin’s religious beliefs, probably greater than anything in his evolutionary work. (The story of Annie and the impact her death had on the Darwins is beautifully told in *Annie’s Box: Darwin, His Daughter, and Human Evolution* by Randal Keynes, 2002, Riverhead Books.)

[As a side note: Students are often shocked to learn that Darwin married his first cousin, but such unions were common in Victorian England. Darwin’s sister had earlier married Emma’s brother, so there were two Darwin-Wedgwood first cousin marriages in that single generation. In fact, the two families not so subtly pushed Charles and Emma together as they were thought to be a good match, and indeed they were. Emma was the granddaughter of Josiah Wedgwood, the founder of the Wedgwood pottery company that continues to be successful today.]

Charles did have a life at Down House beyond raising the children. Unfortunately, in contrast to the robust health he had enjoyed as a young man on the *Beagle*, much of the rest of Darwin’s life was spent suffering from ill health. His health problems began shortly after his return from the *Beagle* voyage and continued for the rest of his life with only scattered weeks of reprieve. Many people know of his problems with sickness but may not realize just how sick he often became. Darwin’s troubles were “digestive” with frequent bouts of severe nausea, vomiting, and diarrhea. He describes one period in which he vomited daily for 27 straight days. In one of the worst stretches, he did not correspond with anyone for five straight months in 1840. Darwin was a man who felt a strong obligation to read and answer his letters every day, so a period of five months without a single letter being written indicates he was very ill indeed. There has been much speculation but no resolution regarding the cause of his illness. Possible explanations range from Chagas disease to anxiety over anticipated reactions to his work. Through most of his bouts with illness, Darwin continued to work steadily. Near the end of his life, he managed to put a positive spin on the issue, writing in his autobiography: “Even ill-health, though it has annihilated several years of my life, has saved me from the distractions of society and amusement,” thereby allowing him more time to work.

Either in spite of or because of his ill health, Darwin had a very predictable schedule for his days at home, saying “My life goes on like clockwork.” In looking back, Francis Darwin had no trouble recounting his father’s typical day in *The Life of Charles Darwin*, written 10 years after his father’s death. Darwin would rise every morning at 7 a.m. and take a walk around the Sandwalk, the “thinking path” he constructed encompassing one and a half acres at the back end of his property. At 7:45 he would have breakfast alone, followed by work in his study from 8 to 9:30. From 9:30 to 10:30 he would take a break by going into

the drawing room to hear family letters and/or part of a novel read aloud by Emma. He would return to work from 10:30 to 12, at which time he would often proclaim, “I’ve done a good day’s work!” At noon, he would go outdoors, rain or shine, to check on experiments in the greenhouse, followed by five turns around the Sandwalk with his terrier, Polly, following along. Just to be sure he did not get absorbed in his thoughts and walk to the point of exhaustion, he always stacked five flint rocks at the beginning of the path, then knocked one over with each pass. Once the last rock was gone, he returned to the house for lunch. After lunch and then reading the newspaper, he would spend as much time as needed answering letters. As a matter of conscience, Darwin felt compelled to answer every letter he received, including those from people upset by his writings. Fortunately for us, the majority of that 40,000-letter correspondence survived, and it is being published gradually in annual volumes—a process that is nearly complete. Reading these letters is like eavesdropping on private conversations and provides wonderful insights into the personalities of Darwin and his friends and colleagues. (For a small sampling of key letters, see *Charles Darwin’s Letters: A Selection, 1825–1859*, edited by Frederick Burkhardt, Cambridge University Press, 1996.)

At about 3 p.m. each day, Darwin would go up to his bedroom to rest while again listening to parts of a novel read aloud by Emma. Then at precisely 4 p.m., he would come downstairs for another walk outside, followed by working in the study from 4:30 to 5:30. From 5:30 to 6 he would rest in the drawing room or play billiards with his sons and/or the butler. After some light, nonscientific reading, he would eat a light supper, such as tea and one egg, in the bedroom at about 7:30. Every night after supper, Charles and Emma engaged in their two games of backgammon. Next, Charles would lie on the sofa in the parlor while Emma played the piano, sometimes accompanied by son Leo on the bassoon. Finally, at about 10, he would go to bed for the night, though he often had trouble sleeping because his mind would not stop thinking about scientific problems. This schedule was maintained seven days a week unless interrupted by severe ill health.

Even with interruptions due to health problems, Darwin was a prodigious author of scientific works, completing over 20 major books and countless journal articles. All of this writing was done while voraciously reading the works of other scientists and continually conducting experiments. Darwin was so determined that he had a curtain and washing bowl installed in a corner of the study so that he could “retch in private,” then return to work. Obviously driven, as a young man he once wrote that he had a “burning zeal to add even the most humble contribution to the noble structure of Natural Science.” Still, one might wonder why he waited more than 20 years to publish his most important ideas in *On the Origin of Species*. Again, there has been much speculation, but it is clear there were multiple factors involved in the delay. He certainly worried about the implications of his

Special Focus: Evolution and Change

ideas, telling his closest friend, Joseph Hooker, that it was “like confessing murder” to admit that he no longer felt species were immutable. After writing a 231-page sketch of his views in 1844, rather than publish, he simply sealed the essay in an envelope with instructions to his wife to have it published after his death. Of course, he eventually published *On the Origin of Species* in 1859, but he only began writing that book in 1856 after much prodding by his scientific friends, Charles Lyell and Joseph Hooker.

He also must have been troubled by Emma’s fears that his scientific way of thinking and his religious doubts might prevent their spending eternity together. A few months after their wedding, Emma wrote Charles a heartfelt letter expressing her love for him and those fears. Years later, after Charles died, Emma found that letter with a note from him added at the bottom stating, “When I am dead, know that many times, I have kissed & cried over this.”

In the end Darwin knew that none of these factors outweighed the importance of the ideas to be contained in *On the Origin of Species*. So he finally published in November 1859 at the age of 50. He spent the rest of his life expanding on those ideas, continuing his experiments and writings. He remained a staunch defender of his two key aspects of evolution, meaning natural selection and, most importantly, descent with modification. He defended his ideas in thousands of letters sent to colleagues and journals, as well as in his books, but he never gave public talks or speeches again. The very thought of such talks was enough to upset his stomach. He wrote, “I find the [brain] and the stomach are antagonistic powers and that it is a great deal easier to think too much in a day than to think too little. What thought has to do with digesting roast beef—I cannot say.” Fortunately for Darwin, he had friends who were eager to promote and defend his views in public. Chief among these friends were, of course, Joseph Hooker and the famous Thomas Huxley, one of the greatest orators of the day.

Though initially there were negative reactions to his book from both scientific and religious circles, within 20 years the idea of common descent was almost universally accepted by scientists and many others. Darwin always maintained that *The Origin* had no relation whatever to theology, and that when he wrote it, his belief in what is called a personal God was as firm as that of any vicar.

He could speak with authority in both cases, having received a degree in theology from Cambridge before sailing on the *Beagle*. In fact, he had originally intended to become a country parson upon returning from the voyage. Later in life, his belief in a personal God “has very gradually, with many fluctuations, become weaker,” and he no longer considered himself a Christian. Instead, his descriptions of himself to friends ranged from “theist” to “agnostic.” Darwin wrote, “In my most extreme fluctuations I have never been an Atheist in the sense of denying the existence of a God.”

As mentioned earlier, Darwin worked diligently for the rest of his life. He conducted groundbreaking experiments on plants, the study of emotions, and human origins, to cite just a few examples. Near the end of his life, his health did begin to slow him down greatly, but he never lost his “zeal” for studying nature and was making experiment notes for his son Francis the day before he died.

Charles Darwin died on April 19, 1882. There was no deathbed conversion or return to Christianity, nor any recanting of his views (see references). He and his family wanted him to be buried in the Downe graveyard, but the outcry from scientists, politicians, and the public convinced Emma to agree to Charles’s burial in Westminster Abbey. His grave is below Newton’s and marked with a stone in the floor that simply lists his name and the dates of his birth and death.

We biologists are fortunate to have had this gentle, thoughtful, modest, passionate, adventurous, enthusiastic lover of life as the founder of the most important theory in our discipline. My last words come from Darwin himself. In his autobiography, while reflecting on what qualities made him a successful scientist, he wrote, “[T]he most important have been—the love of science—unbounded patience in long reflecting over any subject—industry in observing and collecting facts—and a fair share of invention as well of common sense. With such moderate abilities as I possess, it is surprising that I should have influenced to a considerable extent the belief of scientific men on some important points.”

References and Suggestions for Further Reading

My favorite biographies of Charles Darwin are:

Browne, Janet. *Charles Darwin: Voyaging*, vol. 1, and *Charles Darwin: The Power of Place*, vol. 2. New York: Alfred A. Knopf, 1995 and 2002, respectively.

Desmond, Adrian J., and James Moore. *Darwin*. New York: Warner Books, 1991.

Other books of interest to readers wishing to learn more of Darwin’s personal side:

Barlow, Nora, ed. *The Autobiography of Charles Darwin, 1809–1882: With Original Omissions Restored. Edited with Appendix and Notes by His Grand-Daughter*. New York and London: W. W. Norton, 1958 (the edition I used was published in 1969).

Burkhardt, Frederick, ed. *Charles Darwin’s Letters: A Selection, 1825–1859*. Cambridge: Cambridge University Press, 1996. (For those interested in reading all of Darwin’s letters, 14 volumes of *The Correspondence of Charles Darwin* are currently available from Cambridge University Press, with more expected in the future.)

Special Focus: Evolution and Change

Darwin, Francis. *The Life of Charles Darwin*. London: John Murray, 1902.

Keynes, Randal. *Annie's Box: Darwin, His Daughter, and Human Evolution*. New York: Riverhead Books, 2002.

Note: Many of Darwin's letters and writings, including his autobiography, are available online.

For the true story surrounding the myth that Darwin converted to Christianity on his deathbed, recanting all of his evolutionary views, please see:

Moore, James. *The Darwin Legend*. Grand Rapids, Michigan: Baker Books, 1994.

What Have the Courts Said About the Teaching of Evolution and Creationism?

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The basic tenets of evolution have been supported by thousands of scientific studies from diverse disciplines such as geology, paleontology, developmental biology, molecular biology, comparative anatomy, and biogeography. Although biologists continue to debate details about evolution (for example, rates of evolution, relative effects of different selection pressures), virtually no biologist questions whether evolution occurs. Evolution is simply a fact.

Nevertheless, the overwhelming evidence supporting evolution has not stopped many religious and political leaders from trying to eliminate or subvert the teaching of evolution. These individuals have used a variety of tactics in their antiscience crusade, ranging from political pressure on biology teachers to the widespread dissemination of misleading and/or factually inaccurate information (Moore 2002b; Moore and Kraemer 2005). In many instances these tactics have been successful; for example, Kansas voters have elected education officials who campaigned to eliminate evolution from the state's educational guidelines. In other instances, the antiscience activities have led to lawsuits addressing various aspects of the teaching of evolution and, in some cases, the scientific validity of creationists' claims.

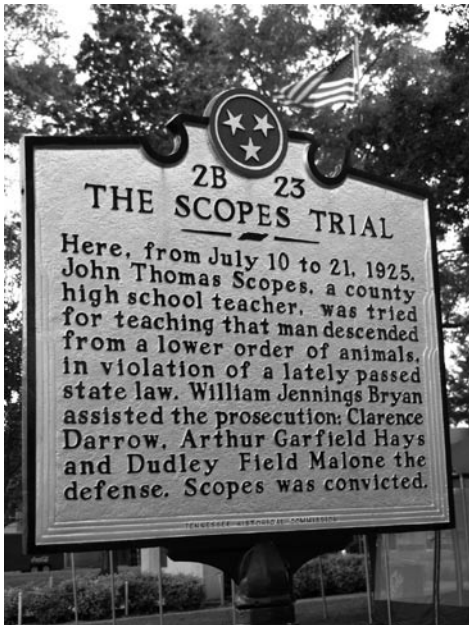
The following list summarizes the major U.S. court cases dealing with the teaching of evolution and creationism in public schools, providing the year of the final decision in the case and the name of the lawsuit. The first name is the person or organization asking the court to rule on the case, and the second name is either the defendant in a trial case or the appellee in a court of appeals. Cases are presented chronologically so readers can appreciate how the controversy has evolved over the past 80-plus years. Although the educational and philosophical issues associated with these cases are often diverse, the following court decisions offer interesting insights into how a multifaceted, ongoing controversy has been addressed by the U.S. legal system. Details of many of these cases are provided elsewhere (Moore 2002a).

Special Focus: Evolution and Change

1925

State of Tennessee v. John Thomas Scopes

In one of the original “trials of the century,” coach and substitute science teacher John Scopes was convicted of the misdemeanor of teaching human evolution in a public school in Tennessee. Scopes’s trial, which William Jennings Bryan described as “a duel to the death” between evolution and Christianity, remains the most famous event in the history of the controversy over evolution and creationism. The Scopes “Monkey Trial” also provided a framework for the fictitious movie, *Inherit the Wind*.



The Scopes trial, which was held in Dayton, Tennessee, in July 1925, accomplished nothing from a legal perspective yet remains the most famous event in the history of the controversy over evolution and creationism. Photograph by Randy Moore.

1927

John Thomas Scopes v. State of Tennessee

The Tennessee Supreme Court upheld the constitutionality of a Tennessee law banning the teaching of human evolution but urged that Scopes’s conviction be set aside. This decision ended the legal issues associated with the Scopes trial, and the ban on teaching human evolution in Tennessee, Mississippi, and Arkansas remained unchallenged for more than 40 years.

1968

Epperson v. Arkansas

The U.S. Supreme Court struck down an Arkansas law making it illegal to teach human evolution. As a result of this decision, all laws banning the teaching of human evolution in public schools were overturned by 1970.

1972

Willoughby v. Stever

The D.C. Circuit Court of Appeals ruled that government agencies such as the National Science Foundation can use tax money to disseminate scientific findings, including evolution. The government is not required to provide money to disseminate creationism.

1973

Wright v. Houston Independent School District

The Fifth Circuit Court of Appeals ruled that (1) the teaching of evolution does not establish religion, (2) there is no legitimate state interest in protecting particular religions from scientific information “distasteful to them,” and (3) the free exercise of religion is not accompanied by a right to be shielded from scientific findings incompatible with one’s beliefs.

1975

Daniel v. Waters

The Sixth Circuit Court of Appeals overturned the Tennessee law (also known as the “Genesis Bill”) requiring equal emphasis on evolution and the Genesis version of creation.

1977

Hendren v. Campbell

The county court in Marion, Indiana, ruled that it is unconstitutional for a public school to adopt creationism-based biology books because these books advance a specific religious point of view.

1980

Crowley v. Smithsonian Institution

The D.C. Circuit Court of Appeals ruled that the federal government can fund public exhibits that promote evolution. The government is not required to provide money to promote creationism.

Special Focus: Evolution and Change

1982

McLean v. Arkansas Board of Education

An Arkansas federal district court ruled that creation science has no scientific merit or educational value as science. Laws requiring equal time for “creation science” are unconstitutional.

1987

Edwards v. Aguillard

The U.S. Supreme Court overturned the Louisiana law requiring public schools that teach evolution to also teach “creation science,” noting that such a law advances religious doctrine and therefore violates the First Amendment’s establishment of religion clause.

1990

Webster v. New Lenox School District #122

The Seventh Circuit Court of Appeals ruled that a teacher does not have a First Amendment right to teach creationism in a public school. A school district can ban a teacher from teaching creationism.

1994

Pelozo v. Capistrano Unified School District

The Ninth Circuit Court of Appeals ruled that evolution is not a religion and that a school can require a biology teacher to teach evolution.

1996

Hellend v. South Bend Community School Corporation

The Seventh Circuit Court of Appeals ruled that a school must direct a teacher to refrain from expressions of religious viewpoints (including creationism) in the classroom.

1999

Freiler v. Tangipahoa Parish Board of Education

The Fifth Circuit Court of Appeals ruled that it is unlawful to require teachers to read aloud a disclaimer stating that the biblical view of creationism is the only concept from which students are not to be dissuaded. The effect of such disclaimers is “to protect and maintain a particular religious viewpoint.”

2001

LeVake v. Independent School District #656

A Minnesota state court ruled that a public school teacher's right to free speech as a citizen does not permit the teacher to teach a class in a manner that circumvents the prescribed course curriculum established by the school board. Refusing to allow a teacher to teach the alleged evidence against evolution does not violate the teacher's free-speech rights.

2001

Moeller v. Schrenko

The Georgia Court of Appeals ruled that using a biology textbook that states creationism is not science does not violate the establishment or the free-exercise clauses of the Constitution.

2005

Selman et al. v. Cobb County School District

The U.S. District Court for the Northern District of Georgia ruled that it is unconstitutional to paste stickers claiming that, among other things, "evolution is a theory, not a fact," into science textbooks. The use of these stickers conveys "a message of endorsement of religion" and "aids the belief of Christian fundamentalists and creationists."

2005

Kitzmiller et al. v. Dover Area School District

The U.S. District Court for the Middle District of Pennsylvania ruled that (1) "intelligent design (ID) is a religious view, a mere re-labeling of creationism, and not a scientific theory," and, instead, is nothing more than creationism in disguise, (2) the advocates of ID wanted to "change the ground rules of science" to make room for religion, and (3) "ID is not supported by any peer-reviewed research, data, or publications." The judge also noted the "breathhtaking inanity" of the school board's policy and the board's "striking ignorance" of ID and made the following point: "It is ironic that several of [the members of the school board], who so staunchly and proudly touted their religious convictions in public, would time and again lie to cover their tracks and disguise the real purpose behind the ID Policy."

Special Focus: Evolution and Change

Future Prospects

Although U.S. courts have struck down all attempts to introduce creationism into science classes of public schools, many politicians continue to endorse creationism. For example, most of the major candidates in the 2000 and 2004 presidential elections (e.g., George W. Bush) endorsed the teaching of Biblical creationism and intelligent design, as have many previous presidents.* The Republican Party in many states endorses creationism, and politicians often vilify evolution to energize their supporters. For example, in 1999 the U.S. House of Representatives' majority whip, Tom DeLay, linked the teaching of evolution with school violence, and a state legislator in Louisiana introduced a bill blaming evolution for racism (in fact, both evolution and creationism have often been used to justify racism; see Moore 2001a and references therein). Former presidential candidate Pat Robertson claims that scientists are involved in a vast conspiracy to hide the evidence supporting biblical creationism, and others have alleged that the acclaimed PBS *Evolution* series "has much in common" with terrorist attacks in the U.S. Do not expect the controversy over evolution and creationism to end.

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The Making of Darwin’s Endless Forms: New Discoveries in “Evo Devo” Are Revealing How, at the Most Fundamental Level, the Great Diversity of the Animal Kingdom Has Evolved

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This article is adapted from *Natural History* July/2005; copyright © Natural History Magazine, Inc., specifically Sean B. Carroll’s piece titled “The Origins of Form: Ancient Genes, Recycled and Repurposed, Control Embryonic Development in Organisms of Striking Diversity.” The text below is also drawn from Carroll’s book, *Endless Forms Most Beautiful: The New Science of Evo Devo and the Making of the Animal Kingdom* (W. W. Norton & Company, 2005).

When we no longer look at an organic being as a savage looks at a ship, as something wholly beyond his comprehension; when we regard every production of nature as one which had a long history; when we contemplate every complex structure and instinct as the summing up of many contrivances, each useful to the possessor . . . how far more interesting—I speak from experience—does the study of natural history become!

— Charles Darwin,
On the Origin of Species by Means of Natural Selection (1859)

Darwin closed the most important book in the history of biology by inspiring his readers to see the grandeur in his new vision of nature—in how “from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved.” For the next century, many kinds of biologists—paleontologists, taxonomists, and geneticists—sought to test and expand that vision, culminating in the so-called “modern synthesis,” which organized many of the basic principles that have guided evolutionary biology for the past 60 years.

However, despite the labels “modern” and “synthesis,” it was incomplete. At the time of its emergence and for decades afterwards, we could say that forms evolve, and natural selection is an important force, but we could say nothing about **how** forms evolve. We

were entirely ignorant of how bodies or body parts change, or how new structures arise. We are no longer savages staring at passing ships.

Over the past 20 years, a new revolution has unfolded in biology in understanding the making and evolution of animal forms and their complex structures. The key to understanding form is **development**, the process through which a single-celled egg gives rise to a complex, multibillion-celled or trillion-celled animal. And development is intimately connected to evolution because all changes in form come about through changes in development. As an embryo grows, countless decisions are made as to the number, position, size, and color patterns of body parts. Changes in these decisions during development have produced the great variety of animal forms of the past and present.

Advances in the new science of evolutionary developmental biology—dubbed “evo devo” for short—have enabled biologists to see beyond the external beauty of animal forms and into the mechanisms that shape their diversity. Much of what we have learned has been so stunning and unexpected that it has profoundly expanded and reshaped our picture of how evolution works. In the same stroke, evo devo provides some crushing blows against the outdated rhetoric of evolution’s doubters concerning the implausibility of the evolution of complex structures.

In this article, I will highlight some of the major discoveries and general lessons that have emerged from evo devo and discuss how they have led to a much deeper understanding of how diverse and complex forms have evolved.

Darwin always insisted that embryology was crucial to understanding evolution. In a letter to botanist Asa Gray shortly after the publication of *On the Origin of Species*, he lamented, “[E]mbryology is to me by far the strongest single class of facts in favor of change of forms, and not one, I think, of my reviewers has alluded to this.” The challenge for more than 100 years after Darwin was to explain **how** embryos—and thus the adult forms they produce—change.

The puzzle of how a single egg gives rise to a complete individual long stood as one of the most elusive questions in all of biology. Many biologists once thought that development was hopelessly complex and would involve entire different explanations for different kinds of animals. With the advent of genetics, everyone knew that genes must be at the center of the mysteries of both development and evolution. After all, butterflies look like butterflies, elephants look like elephants, and we look like we do because of the genes we carry. The problem was that until relatively recently there were very few clues as to which of the thousands of genes in every animal shaped their formation and appearance.

Special Focus: Evolution and Change

The impasse was finally broken by the humble fruit fly. Long a favorite subject of geneticists, schemes were eventually devised to find the relatively small fraction of genes that controlled the patterning of the fly's body and the formation of its parts. The discovery and study of these genes, beginning in the 1980s, gave birth to an exciting new vista on development. As is true throughout scientific history, conceptual breakthroughs are often catalyzed by new technologies, especially new ways of seeing previously hidden processes (for example, the invention of the telescope). This was especially true in the new era of embryology when new tools from molecular biology and new kinds of microscopes enabled us to visualize these body-building genes in action—to peer into the previously invisible world of the embryo. The resulting images revealed a logic and order to the building of the fruit fly—a foreshadowing in the embryo of the physical form that would later take shape (see figure 1 and its caption).

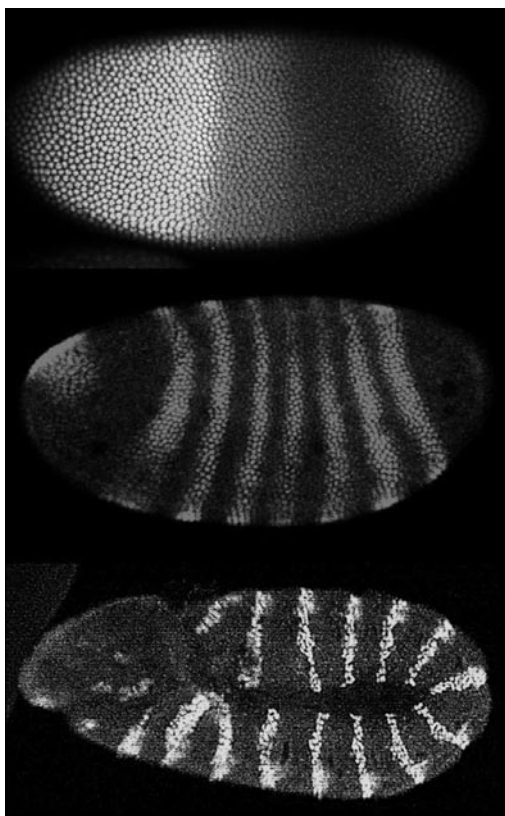


Figure 1: Seeing the invisible—some of the key catalysts to advances in developmental biology and evo devo were technologies that make the events going on inside embryos visible. Long before we see physical changes in embryos such as the segments, limbs, or brain forming, we can see chemical changes taking place in embryos where the structures will eventually appear. These chemical changes are the activities tool kit proteins that act in succession and in combinations to build animals. Here, early steps in the organization of the fruit fly embryo are revealed in the patterns of tool kit proteins that act in broad regions (top micrograph), then in periodic patterns corresponding to every other future segment (middle), and then every segment (bottom). Each of the three circles is the nucleus of one cell. With these technologies, differences between species can be traced back to the key moments in development when the different uses of tool kit proteins are first manifest. These types of images are biology's equivalent of those from the Hubble telescope—they allow us to peer into the process of the making of animals and to look back in time at the evolution of the animal kingdom. The three micrographs were taken by James A. Langeland and Stephen W. Paddock, both of the University of Wisconsin-Madison (copyright © 1993 James A. Langeland and Stephen W. Paddock).

I realize it may be hard to get excited about how a maggot develops. What can that teach us about the more majestic creatures we care about, such as mammals, our own species, or the rest of the animal kingdom? Indeed, the common perception 20 years ago—

reinforced by decades of zoology and a wide cultural divide between biologists who worked with furry animals and those who worked with bugs or worms—was that the rules of development would differ enormously between such different forms.

For example, the body parts of fruit flies would not appear to have much in common with our own—we don't have antennae or wings, and we have two long, bony legs, not six little walking legs. We have a single pair of movable camera-type eyes and not compound bug eyes staring out from a fixed position. And our blood is pumped by a four-chambered heart through a closed circulatory system with arteries and veins, not just sloshing around in our body cavity. With such great differences in structure and appearance, one wouldn't think that there would be anything a fly could tell us about how our organs and body parts are formed.

But that would be so wrong.

Looks Are Deceiving

The first and most important lesson from evo devo is that looks are quite deceiving. Contrary to the expectation of **any** biologist, most of the genes first identified as body-building and organ-forming genes in the fruit fly were found to have exact counterparts that performed similar jobs in most animals, including ourselves.

These first shots in the evo devo revolution revealed that despite their great differences in appearance, most all animals share a common “tool kit” of body-building genes. This discovery (actually a series of discoveries) vaporized previous notions of what made animals different, and has opened up a whole new means of reconstructing evolution.

For example, the origin of eyes has received great attention throughout the history of evolutionary biology, and well before. Darwin devoted an entire chapter in *Origin* to explaining how such “organs of extreme perfection” could evolve by natural selection. What has puzzled and intrigued biologists ever since Darwin is the variety of eye types in the animal kingdom. We and other vertebrates have camera-type eyes with a single lens. Flies, crabs, and other arthropods have compound eyes in which many fixed independent unit eyes gather visual information. Even though they are not close relatives of ours, squids and octopi also have camera-type eyes, while their close relatives clams and scallops display three types of eyes—camera, compound, and a mirror-type.

This great diversity and distribution of eyes throughout the animal kingdom was, for more than a century, believed to be the result of the independent invention of eyes, from

Special Focus: Evolution and Change

scratch, in different animal groups. The great evolutionary biologist Ernst Mayr and his colleague Luitfried von Salvini-Plawen suggested, based on cellular anatomy, that eyes had been invented independently some 40 to 65 times.

But discoveries in evo devo have forced a reexamination of this accepted idea. In 1994, Walter Gehring and his colleagues at the University of Basel (Switzerland) discovered that a gene required for eye formation in fruit flies was the exact counterpart of a gene required for eye formation in humans and mice. The gene, dubbed Pax6, was subsequently found to be involved in eye formation in a host of other animals, including a squid. These discoveries suggested that despite their vast differences in structure and optical properties, different eyes were made using a common genetic ingredient. Mayr and von Salvini-Plawen had suggested that

If there is only one efficient solution for a certain functional demand, very different gene complexes will come up with the same solution, no matter how different the pathway by which it is achieved. The saying “Many roads lead to Rome,” is as true in evolution as in daily affairs.

This view was incorrect. The architects of the modern synthesis had no knowledge of the relationship between genome and form, and they expected the content of very different species’ genomes to differ entirely. They had no idea, as we now understand from evo devo today, that such different forms could be built with similar sets of genes. The late Stephen Jay Gould, in his monumental work *The Structure of Evolutionary Theory*, saw the unexpected discovery of common body-building genes as overturning a major view of the modern synthesis.

It appears that there are not as many roads to Rome (to complex structures such as eyes) as once believed. The story of Pax6 suggests that many types of animal eyes took the Pax6 road, and we now know about other tool kit genes that are also used in building different kinds of limbs, hearts, and other structures. Natural selection has not repeatedly forged eyes completely from scratch. Rather, the common genetic ingredients of eye formation reveal that some parts, such as photoreceptor cells and light-sensing pigments, have long been under the command of the Pax6 gene and have been repeatedly recruited into the evolution of all sorts of arrangements in the fashioning of different kinds of eyes.

Because components of the tool kit are shared among most branches of the animal kingdom, their origin must date back to at least the common ancestor of these animals. This would place the origin of many tool kit genes deep into the mists of time, prior to

the Cambrian explosion that marked the emergence of large, complex animal bodies more than 500 million years ago. Here, then, is another somewhat counterintuitive insight from evo devo. One might think that increases in animal complexity and diversity would be driven by the evolution of new genes. But we now know that most body-building genes were in place long before most types of animal body plans and complex organs emerged.

Same Tools, Different Results

The discovery of this ancient genetic tool kit, while very exciting and rewarding, raises a paradox. If the sets of body-building genes among animals are so similar, how do such vast differences in forms arise? Studies of many animal groups have revealed that diversity is not so much a matter of the content of the tool kit, but how it is used. Different animal architectures are the products of using the same genetic tools in different ways.

For example, one of the most obvious features of large, complex animals such as vertebrates (fish, amphibians, reptiles, birds, mammals) and arthropods (centipedes, spiders, crustaceans, insects) is their construction from repeating parts. Segments are the building blocks of arthropod bodies, vertebrae the building blocks of our backbones, and many structures are reiterated that emerge from these blocks, such as the many appendages of arthropods and ribs of vertebrates. One of the widespread trends in the large-scale evolution of these animals' bodies is changes in the number and kind of repeating parts. The major features that distinguish classes of arthropods are the number of segments and the number and kind of appendages. Similarly, vertebrates differ in the number and kind (cervical, thoracic, lumbar, sacral) of vertebrae.

Extensive study of arthropod and vertebrate development has revealed that a special set of tool kit genes, called the *Hox* genes, shape the number and appearance of repeated structures along the main body axes of both groups of animals. Individual *Hox* genes shape the identity of particular zones along the main axis of each animal and determine whether and where various structures will form. A large body of work—on mammals, frogs, birds, and snakes as well as shrimp, spiders, and insects—has revealed that shifts in where *Hox* genes are deployed are responsible for the major differences among both vertebrates and arthropods. These shifts account, for example, for how a snake forms its unique trunk with hundreds of rib-bearing vertebrae, and why insects have just six legs and other arthropods have eight or more.

Special Focus: Evolution and Change

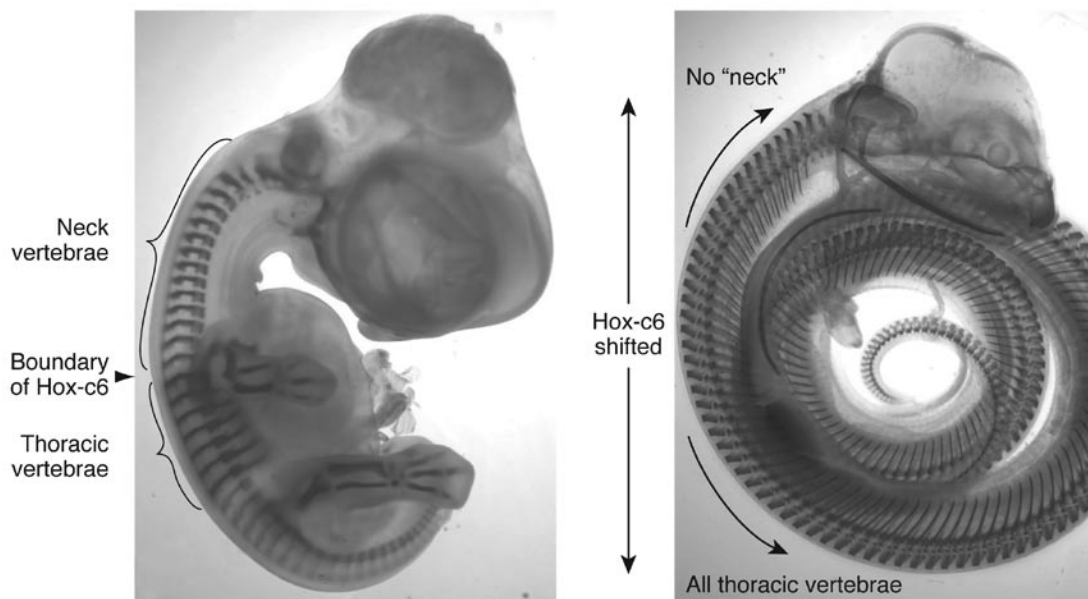


Figure 2: *Hox* genes determine the number, form, and evolution of repeating body parts, such as the number and type of vertebrae in vertebrates. In the developing chick (left), the HOXC6 gene controls the pattern of the seven thoracic vertebrae, all of which develop ribs. In the garter snake (right), the region controlled by the HOXC6 gene is expanded forward to the head and rearward to the cloaca, and all of these vertebrae will form ribs. The photographs were taken by Brian McOmber and Ann C. Burke, both of Wesleyan University (copyright © 2005 Brian McOmber and Ann C. Burke).

We can pinpoint when and how the course of development of these animals diverges, and we can see at a whole new, fundamental level how these animals, so well adapted to different lifestyles, are products of variations on ancient body plans, not wholly independent inventions.

Shifts in the use of tool kit genes account not only for large-scale differences in animal forms but also for differences among closely related species or populations. For example, the threespine stickleback fish is found in two forms in many lakes in northern North America—a shallow-water, bottom-dwelling, short-spined form and an open-water, long-spined form. The two forms have evolved very rapidly in these lakes since the last ice age, only 10,000 years ago. The fishes' pelvic spine length is shaped by predation pressure. In the open water, longer spines help protect the stickleback from being swallowed by larger predators. But on the lake bottom, long pelvic spines are a liability. Dragonfly larvae seize and feed on young sticklebacks by grabbing them by their spines.



Figure 3: Major differences in the skeletal patterns of closely related populations reflect a difference in how a single tool kit gene is used. Two forms of the three-spined stickleback fish (*Gasterosteus aculeatus*), which differ in the size of their pelvic fins, have repeatedly evolved in freshwater lakes. Long pelvic spines protect the open-water form (top) from attack by other fish. In the bottom-dwelling form (bottom), spines are a liability because they can be grabbed by dragonfly larvae that prey on young fish. The spines are reduced in the bottom form by the selective turning off of a tool kit gene in development. This photograph was taken by David M. Kingsley and Michael D. Shapiro, both of Stanford University and HHMI (Howard Hughes Medical Institute). Copyright © 2006 David M. Kingsley and Michael D. Shapiro.

The pelvic spines are part of the fishes' pelvic fin skeleton. Their reduction in bottom-dwelling populations is due to a reduction in the development of the pelvic fin bud. David Kingsley and his collaborators at Stanford University and the University of British Columbia in Vancouver have pinpointed the tool kit gene whose use is altered in the pelvic fin bud of short-spined sticklebacks so that their pelvic skeleton is reduced. This achievement connects a change at the DNA level to a specific event in embryonic development, which produces a major adaptive change in body form, which directly affects the ecology of a species.

The insights from these little fish may reach far beyond their particular history. The pelvic fin of some ancient fish was the evolutionary precursor to the vertebrate hindlimb. Hindlimb reduction is not at all rare in vertebrates. Two different groups of mammals—

Special Focus: Evolution and Change

cetaceans (dolphins and whales) and manatees—evolved greatly reduced hindlimbs as they evolved from their land-dwelling ancestors into fully aquatic forms. And legless lizards have evolved multiple times. The study of sticklebacks has revealed how such changes in major features of animal skeletons can change in a short period of time under natural selection.

Old Genes Learn New Tricks

In addition to evolutionary changes in the number and kind of repeated body structures, *evo devo* is shedding new light onto how novel structures and new patterns evolve. Bird feathers, the hands and feet of four-legged vertebrates, the insect wing, and the geometrical color patterns on butterfly wings are prominent examples of novelties in natural history whose origins are being illuminated by the study of how tool kit genes are used in their formation. A recurring theme emerging from these studies is the creative role of evolutionary changes in how tool kit genes are used.

While it may be intuitive that insects might have invented “wing” genes, or birds “feather” genes, or vertebrates a “hand” or “finger” gene, we find no such evidence. On the contrary, innovation seems to be more a matter of teaching old genes new tricks.

The implications of this insight are especially significant for understanding human evolution. We have long imagined ourselves as holding some unique position in the animal kingdom. Speculation once abounded that we would be the most genetically well-endowed species. The reality we now know from the sequencing of our genome—and that of fish, mice, and more—is that we have **very** similar numbers and kinds of genes as the mouse and other vertebrates. Thus we should not expect to account for the evolution of bipedalism, speech, language, or other human traits by finding novel genes but in understanding how “old” genes shared with other primates, mammals, vertebrates, and more distant animal relatives have been taught new tricks during our evolution.

The Refutation of Design

Darwin knew very well the difficulty people would have in picturing how complex structures or “contrivances” arose. In fact, Darwin’s choice of this latter term, used 15 times in the course of *On the Origin of the Species* was, as has been pointed out by scholars such as Randy Moore of the University of Minnesota (see his article in this collection on page 15) and Stephen Jay Gould, a deliberate one for rhetorical effect. Darwin was evoking a term used by Reverend William Paley in his book *Natural Theology* (1802). Paley saw the fashioning of contrivances in nature for specific purposes as revelations of God’s design. He wrote, “Contrivance must have had a contriver; design,

a designer;” and later in the book stated, “It is only by the display of contrivance that the existence, the agency, the wisdom of the Deity, **could** be testified to his rational creatures. Paley’s argument is the essence of the notion of intelligent design, now being touted as a new “alternative” to evolutionary science.

Darwin admired Paley’s book and declared that he had virtually committed it to memory. He then structured much of his argument in *The Origin* as a direct refutation of Paley. While Paley compared the design of the eye with the design of the telescope, Darwin explained how such contrivances arose by natural selection, without a divine contriver.

Darwin’s explanation, no matter how brilliant, was founded on the extrapolation of natural selection over vast periods of time, not on fundamental knowledge of the development of or history of eyes. Our new knowledge of tool kit genes reveals how such complex structures are built, and evo devo enables us to connect this everyday, observable, and experimentally accessible process to the long-term process of evolutionary change. Evo devo reveals how the evolution of complex forms and structures occur, from the level of individual species to the making of body plans characteristic of higher taxonomic ranks. For those who have withheld their acceptance of the major tenet of modern synthesis that the large-scale evolution of forms above the species level (“macroevolution”) can be extrapolated from processes operating at the level of populations (“microevolution”), the new insights from evo devo should obliterate that reservation. And for those who have retreated to supernatural explanations of biological design, evo devo dismantles that refuge.

Through the lens of evo devo, we have a whole new kind of evidence about the mechanisms of the evolutionary process. We can finally see beyond external forms into the very processes that make them and look back at how the entire kingdom was made. The power of evo devo is in the independent nature of this new evidence and its manifestation at the most fundamental level of genes and embryos—the agents through which the evolution of form arises. The emergence of evo devo marks a new episode in a continuing evolutionary synthesis that promises to complete the picture of how the endless forms of nature have been, and are being, evolved.

Special Focus: Evolution and Change

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Resources for the Teaching of Evolution in AP Biology

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Evolution. It's not a dirty word! More than likely, you, the person reading this collection, are the only AP Biology teacher at your school and, quite possibly, the only one in your town or district. As you approach the challenge of teaching your students about evolution, take heart. Students, parents, and administrators may question the importance and the validity of evolution in a biology class; you must have the courage and the conviction that your students deserve the best class you and your school can give them in college-level biology. The following is a list of text and Web-based resources that have helped many AP Biology teachers. I hope that you find them valuable in your teaching.

Books for Teachers and Students of Evolution

Books on Darwin's Writings and Life

Charles Darwin: Voyaging, Princeton University Press, 1995, and *The Power of Place*, Alfred A. Knopf, 2002, both by Janet Browne

The first volume traces the interesting life of Darwin from birth to 1858 just before his publishing of *On the Origin of Species by Means of Natural Selection*. The second begins with the arrival of letters from Wallace and follows through to Darwin's death. These two volumes combine to make what Robert Dennison says is "absolutely the best detailed and in-depth biography of Darwin ever written." (See Dennison's article in this collection on p. 7.)

Darwin: The Indelible Stamp; The Evolution of an Idea, edited by James D. Watson, Running Press Book Publishers, 2005

This anthology of Charles Darwin's work includes *On the Origin of Species by Means of Natural Selection*, *The Voyage of the Beagle*, *The Descent of Man, and Selection in Relation to Sex*, and *The Expression of Emotions in Men and Animals*. Each book is accompanied by commentary from James Watson, codiscoverer of the structure of DNA.

Darwin: The Life of a Tormented Evolutionist, Adrian Desmond and James Moore, W. W. Norton & Company, 1991

This book is fairly complete and very readable, though not as detailed as Browne's (see "Charles Darwin: Voyaging" above).

Special Focus: Evolution and Change

Darwin's Ghost: The Origin of Species Updated, Steve Jones, the Ballantine Publishing Group, 1999

Jones makes Darwin's arguments accessible to modern audiences. If you're too intimidated by the original Darwin, read this book first.

From So Simple a Beginning: Darwin's Four Great Books (Voyage of the Beagle, Origin of Species, The Descent of Man, The Expression of Emotions in Man and Animals), edited by Edward O. Wilson, W. W. Norton & Company, 2005

Another collection of Darwin's great works, this edition includes an introduction, a commentary, an afterword by Harvard biologist E. O. Wilson, and a new index that links Darwin's original concepts to modern biological thinking. The volumes include illustrations restored from the original printing.

Books on the Teaching of Evolution

At the Water's Edge: Fish with Fingers, Whales with Toes, and How Life Came Ashore and Went Back to Sea, Carl Zimmer, Touchstone, 1998

Zimmer presents an intriguing history of vertebrate evolution, with elaborate examples.

The Beak of the Finch: A Story of Evolution in Our Time, Jonathan Weiner, Vintage Books, 1994

In this portrait of scientists Peter and Rosemary Grant, Weiner describes their work: recording evolution as it occurs among the species of Galápagos finches first described by Darwin.

Ecology and Evolution: Islands of Change, Richard Benz, National Science Teachers' Association (NSTA) Press, 2000

This text includes plenty of strategies and lessons for students, especially those in grades 5 to 8.

Endless Forms Most Beautiful: The New Science of Evo Devo and the Making of the Animal Kingdom, Sean B. Carroll, W. W. Norton & Company, 2005

Evolutionary developmental biology, a fascinating new area of study, examines the relationship between embryonic development and evolutionary changes. Carroll, who is professor at the University of Wisconsin-Madison, has written a clear and useful book about this field. (A chapter from the book is reprinted on p. 22 of this collection.)

Ever Since Darwin: Reflections in Natural History (1977), *The Panda's Thumb: More Reflections in Natural History* (1980), *Hen's Teeth and Horse's Toes* (1983), *The Flamingo's Smile: Reflections in Natural History* (1985), *Bully for Brontosaurus: Reflections in Natural History* (1991), *Wonderful Life: The Burgess Shale and the Nature of History* (1989), and *The Mismeasure of Man* (1996), all by Stephen Jay Gould, all published by W. W. Norton & Company

These are interesting and funny essays on evolution and natural history; anything by Gould should be near the top of your list. They are short and easily read. (For information about an interview with Gould, see "Spinning Evolution, November 26, 1996, Transcript" at the end of this article.)

Evolution in Perspective: The Science Teacher's Compendium, edited by Rodger W. Bybee, 2003

This collection includes articles originally published in the National Science Teachers' Association (NSTA) journal *The Science Teacher*. The articles cover evidence for evolution, evolution in *National Science Education Standards*, lesson plans, and the NSTA's position statement on evolution.

Evolution: The Triumph of an Idea, Carl Zimmer, Perennial, 2001

This "coffee table" volume is also an incredibly well-written book on basic evolution for the layperson.

Evolution's Workshop: God and Science on the Galápagos Islands, Edward J. Larson, Basic Books, 2001

A history of human activities on the Enchanted Islands, this book is a great read for those who have been fortunate enough to visit the Galápagos or for those who wish to visit the islands.

The Nature of Science and the Study of Biological Evolution, edited by Rodger W. Bybee, BSCS and National Science Teachers' Association (NSTA) Press, 2005

The text, designed for high school students, is accompanied by a teacher's guide on CD. After an introduction to the nature of science, the book reviews how Darwin's experiences influenced his thinking, lines of evidence that support evolution, population genetics, natural selection, and human evolution.

Special Focus: Evolution and Change

Teaching About Evolution and the Nature of Science, National Academy of Sciences, National Academies Press, 1998, and available for free in electronic format at www.nap.edu

As described on the National Academies Press Web site, this book includes sections on “frequently asked questions about evolution and the nature of science,” “activities for teaching about evolution and the nature of science,” and “selecting instructional materials.”

Books Arguing Against Creationism and Intelligent Design

The Blind Watchmaker: Why the Evidence of Evolution Reveals a Universe Without Design, Richard Dawkins, 1st ed., W. W. Norton & Company, 1986.

To counter intelligent design supporters, Dawkins provides a rationale for Darwinism as an explanation of our existence. (Also by Dawkins: *River Out of Eden: A Darwinian View of Life*, which is described below.)

The Creation Controversy and the Science Classroom, James W. Skehan and Craig Nelson, National Science Teachers’ Association (NSTA) Press, 2001

This 56-page booklet includes an excellent section called “Effective Strategies for Teaching Evolution and Other Controversial Topics.”

Evolution vs. Creationism: An Introduction, Eugenie Scott, University of California Press, 2004

The executive director of the National Center for Science Education, Scott has written an accessible volume that presents not only the history of the evolution–creationism debate, but also examines the legal, educational, political, and scientific aspects of the issue in a scientific, scholarly context, using excerpts from authors on both sides.

Finding Darwin’s God: A Scientist’s Search for Common Ground Between God and Evolution, Kenneth R. Miller, Cliff Street Books, 1999

Miller is the scientist in the PBS *Evolution* series who discusses this same topic; he is also the coauthor of the famous “dragonfly” textbook. See his discussion of the flaws in Behe’s logic in the chapter “God the Mechanic.” (See, too, Miller’s article in this collection on p. 4.)

Intelligent Design Creationism and Its Critics: Philosophical, Theological, and Scientific Perspectives, edited by Robert T. Pennock, MIT Press, 2001

Published after Pennock's *Tower of Babel* (which is described later in this list), this book is a collection of works by well-known creationists and by those who disagree with them; Pennock points out the novel aspects of the intelligent design creationism (IDC) movement using articles from past publications as well as new material. The discussions cover politics, philosophy, and the debate over the apparent conflict between evolution and the Bible, as well as IDC's scientific claims. The book concludes with Pennock's "Why Creationism Should Not Be Taught in the Public Schools."

Science and Creationism: A View from the National Academy of Sciences, 2nd ed., Steering Committee on Science and Creationism, National Academy of Sciences, National Academies Press, 1999, and available for free in electronic format at www.nap.edu

As described on the publisher's Web site: "Briefly and clearly, this booklet explores the nature of science, reviews the evidence for the origin of the universe and earth, and explains the current scientific understanding of biological evolution. This edition includes new insights from astronomy and molecular biology."

Summer for the Gods: The Scopes Trial and America's Continuing Debate over Science and Religion, Edward J. Larson, Harvard University Press, 1997

This is a fascinating history of the real Scopes trial, which was a mix of law and theater.

Tower of Babel: The Evidence Against the New Creationism, Robert T. Pennock, MIT Press, 1999

Pennock describes the wide range of creationist beliefs, highlighting inconsistencies. He discusses languages and linguistic evolution. (Edited by Pennock: *Intelligent Design Creationism and Its Critics: Philosophical, Theological, and Scientific Perspectives*, which is described above.)

Special Focus: Evolution and Change

River Out of Eden: A Darwinian View of Life, Richard Dawkins, Basic Books, 1995

This very readable short text looks at genetic and mitochondrial evidence for evolution and takes the “gene’s eye view” of natural selection. The author’s analogy of DNA as the “river out of Eden” is a powerful one. (Also by Dawkins: *The Blind Watchmaker: Why the Evidence of Evolution Reveals a Universe Without Design*, which is described above.)

Evolution Web Sites

General Reference

Evolution and the Nature of Science Institutes,
www.indiana.edu/~ensiweb/home.html

The University of Indiana site contains numerous lessons, including “Date a Rock,” “Deep Time,” “13 Ways to Tell Time Backwards,” and many more.

Evolution on the Front Line,
www.aaas.org/teachscience

This site provides a collection of resources and articles, as described on the site’s home page: “AAAS [Advancing Science, Serving Society] has played a prominent role in responding to efforts in Kansas and elsewhere to weaken or compromise the teaching of evolution in public school science classrooms. The organization has also spoken out in the media about the importance of objective science teaching in schools.”

Evolution Resources (Kenneth R. Miller),
www.millerandlevine.com/km/evol

This site includes links to many informative articles as well as refutations of several antievolution arguments, such as the “irreducible complexity” of the bacterial flagellum, a discussion of peppered moths, a review of Behe’s book, *Darwin’s Black Box*, and videos of debates. You’ll also find information on Haeckel’s embryos. (See also the summary above of Miller’s book *Finding Darwin’s God*, as well as his article in this collection on p. 4.)

Evolution: Where We're From and Where We're Going To,

www.pbs.org/wgbh/evolution

This site supports PBS's eight-hour miniseries with extensive information, art and photographs, video clips, and interactive Web activities. Some animations are slow-loading but are worth the wait; many such as the hominid species time line lend themselves to projection for class discussion. The "Evolution Library" is divided into the following nine sections:

- What Is Science?
- The Age of Darwin
- Adaptation and Natural Selection
- Deep Time/History of Life
- Evolutionary Diversity
- Evidence for Evolution
- Human Evolution
- Why Evolution Matters
- Science, Faith, and Politics

National Center for Science Education: Defending the Teaching of Evolution in the Public Schools,

www.natcensci.org

This site provides the following, as described on its home page:

- Reviews of current anti-evolution activity in the United States and around the world
- Background to the fundamentally creationist and anti-evolution movement known as "Intelligent Design"
- Detailed information on the Creation/Evolution controversy from 1859 to the present
- Resources for parents, teachers, school boards, and the general public

NOVA Teachers,

www.pbs.org/wgbh/nova/teachers

Teaching guides to all the NOVA programs are available for downloading.

Special Focus: Evolution and Change

Special Online Collection: Breakthrough of the Year 2005,

www.sciencemag.org/sciext/btoy2005

“Evolution in Action” was *Science* magazine’s top pick for 2005; the site includes online articles, video presentations, and Web site links on current evolution issues.

The Talk.Origins Archive: Exploring the Creation/Evolution Controversy,

www.talkorigins.org

This is an important, as stated on the site’s home page, “collection of essays [which] provide mainstream scientific responses to the many FAQs that appear in the Talk.origins newsgroup and the frequently rebutted assertions of those advocating intelligent design or other creationist pseudosciences.” If you are uncomfortable about or unprepared for student’s confrontations refuting evolution, this site is a must. (See “Icon of Obfuscation” for a discussion of Wells’ *Icons of Evolution* as counterpoint to several student questions: www.talkorigins.org/faqs/wells/iconob.html.)

Time Archive: 1923 to the Present—Teaching Evolution,

www.time.com/time/archive/collections/0.21428.c_evolution.00.shtml

This collection of articles from *Time Magazine* covers evolution and the various controversies surrounding it.

Understanding Evolution: Your One-Stop Source for Information on Evolution,

<http://evolution.berkeley.edu>

Created by the Museum of Paleontology at the University of California, Berkeley, this Web site allows exploration of exhibits and university collections of fossils. It offers five major sections:

- What Is Evolution and How Does It Work?
- How Does Evolution Impact My Life?
- What Is the Evidence for Evolution?
- What Is the History of Evolutionary Theory?
- Evo in the News (kept current with monthly updates)

Special Topics

Becoming Human,

www.becominghuman.org

Focusing on a human evolution documentary narrated by Donald Johanson, this site includes related exhibits, a “Learning Center” with classroom activities, and “News and Reviews” containing current info on related topics in science.

Court TV: The Scopes Monkey Trial,

www.courttv.com/archive/greatesttrials/scopes/index.html

This site presents good information on the trial from a legal point of view.

The Discovery of Evolution and Evolutionary Processes,

<http://www.geol.umd.edu/~jmerck/evolution>

This is John W. Merck Jr.'s presentation with lecture notes and photos. Merck is the assistant director of the Earth, Life and Time Program, part of the University of Maryland's Department of Geology.

Early Theories of Evolution: 17th–19th Century Discoveries That Led to the Acceptance of Biological Evolution,

<http://anthro.palomar.edu/evolve/default.htm>

Divided into sections on “Pre-Darwinian Theories,” “Darwin and Natural Selection,” and “Evidence of Evolution,” this site provides tutorial abilities, video links, and practice quizzes.

Genetic Origins,

www.geneticorigins.org/geneticorigins

This site offers human evolution information plus animations showing how to isolate mitochondrial DNA and create a mitochondrial clock (actual kit from Carolina Biological Supply Company), applications to research into origins of the Neanderthals and the mystery of the Romanovs, and video interviews with researchers.

Hardy-Weinberg Equilibrium: Judith Stanhope—1994 Woodrow Wilson Biology Institute,

www.woodrow.org/teachers/bi/1994/hwintro.html

This part of the Woodrow Wilson National Fellowship Foundation Web site provides an excellent explanation of and several activities of varying difficulty on Hardy-Weinberg equilibrium.

Lab 5: Population Genetics,

<http://io.uwinnipeg.ca/~simmons/lab5cont.htm>

This site provides information about the Hardy-Weinberg law, animations of equilibrium and bottleneck situations, and a peppered moth simulation (possible “makeup” for the population genetics lab).

Special Focus: Evolution and Change

Literature.org: The Online Literature Library—The Origin of Species,
www.literature.org/authors/darwin-charles/the-origin-of-species
Access the complete text of Darwin's *On the Origin of Species* for free.

Natural Selection,
www.mhhe.com/biosci/esp/2001_gbio/folder_structure/ev/m2/s1/evm2s1_6.htm
These McGraw-Hill animations depict natural selection that results in pesticide resistance. Real numbers are generated, and losses after each spraying are depicted—good for classroom teaching.

Science and Creationism: A View from the National Academy of Sciences,
<http://fermat.nap.edu/html/creationism>
Teachers get the complete text of “Science and Creationism,” 2nd ed. This is an excellent background source for teachers.

Science and Nature: Prehistoric Life—Walking with Beasts,
www.bbc.co.uk/sn/prehistoric_life/tv_radio/wwbeasts
The companion site for the BBC's TV series documents changes on Earth in the last 65 million years and how animals adapted or became extinct.

Spinning Evolution, November 26, 1996, Transcript,
www.pbs.org/newshour/bb/science/gould_11-26.html
In this interview, Stephen Jay Gould talks about punctuated equilibrium and challenges the common notion that life evolves toward the more complex. It's a terrific debate-starter. (For information about Gould's books, see this article's listing that begins “*Ever Since Darwin.*”)

Multiple-Choice and Free-Response Questions on Evolution with Scoring Guidelines

Carolyn Schofield Bronston
Robert E. Lee High School
Tyler, Texas

Evolution questions take so many forms. They may probe Darwin's original theory or query the new synthesis and punctuated equilibrium. They spill over into taxonomy and genetics, molecular biology and embryology. Students should recognize and be reminded often that "Nothing in biology makes sense except in the light of evolution," as Theodosius Dobzhansky put it. Good multiple-choice questions of all kinds will do that!

Multiple-Choice Questions from AP Biology Exams

1990 AP Biology Exam

1. The bones of a human arm are homologous to structures in all of the following EXCEPT a
 - (A) whale flipper
 - (B) bat wing
 - (C) butterfly wing
 - (D) bird wing
 - (E) frog forelimb

12. Which of the following features of angiosperms has probably contributed most to their evolutionary success relative to all other land plant groups?
 - (A) Phloem
 - (B) Cutinized aerial surfaces
 - (C) Flowers and fruits
 - (D) True leaves and roots
 - (E) Xylem

45. S. L. Miller's classic experiment demonstrated that a discharge of sparks through a mixture of gases could result in the formation of a large variety of organic compounds. All of the following gases were used in this experiment EXCEPT
 - (A) hydrogen
 - (B) methane
 - (C) ammonia
 - (D) oxygen
 - (E) water vapor

Special Focus: Evolution and Change

50. Some varieties of *Neisseria gonorrhoeae* are now resistant to penicillin. These varieties of bacteria most probably developed as a result of
- (A) natural selection
 - (B) hybrid vigor
 - (C) coevolution
 - (D) adaptive radiation
 - (E) convergent evolution
51. The differences in cricket calls among sympatric species of crickets are examples of
- (A) habitat isolation
 - (B) temporal isolation
 - (C) physiological isolation
 - (D) behavioral isolation
 - (E) geographic isolation
61. In a population that is in Hardy-Weinberg equilibrium, the frequency of a recessive allele for a certain hereditary trait is 0.20. What percentage of the individuals in the next generation would be expected to show the dominant trait?
- (A) 8%
 - (B) 16%
 - (C) 32%
 - (D) 64%
 - (E) 96%
73. Which of the following statements best describes the effect of genetic drift on the gene frequencies of a population?
- (A) Genes enter a population through immigration, thus changing gene frequencies.
 - (B) Genes leave a population through emigration, thus changing gene frequencies.
 - (C) Chance alone can cause significant changes in gene frequencies of small populations.
 - (D) Mutations over time cause gene frequencies to change.
 - (E) Selection against one allele causes gene frequencies to change.

1994 AP Biology Exam

3. Members of which of the following animal groups were among the first to inhabit land and were ancestors of the reptiles?
- (A) Amphibia
 - (B) Arthropoda
 - (C) Aves
 - (D) Mammalia
 - (E) Echinodermata
7. The wing of a bat, the flipper of a whale, and the forelimb of a horse appear very different, yet detailed studies reveal the presence of the same basic bone pattern. These structures are examples of
- (A) analogous structures
 - (B) homologous structures
 - (C) vestigial structures
 - (D) balanced polymorphism
 - (E) convergent evolution
9. Which of the following is a correct statement about mutations?
- (A) They are a source of variation for evolution.
 - (B) They drive evolution by creating mutation pressures.
 - (C) They are irreversible.
 - (D) They occur in germ cells but not in somatic cells.
 - (E) They are most often beneficial to the organisms in which they occur.
25. Which of the following characteristics indicates that molluscs are more closely related to arthropods than to chordates?
- (A) Presence of a skeleton
 - (B) Type of respiratory structure
 - (C) Pattern of coelom formation
 - (D) Segmentation
 - (E) Symmetry

Special Focus: Evolution and Change

28. Although the seal and the penguin both have streamlined, fishlike bodies with a layer of insulating fat, they are not closely related. This similarity results from
- (A) convergent evolution
 - (B) adaptive radiation
 - (C) homologous evolution
 - (D) coevolution
 - (E) parallel evolution
39. Which of the following is probably the best explanation for the fact that Antarctica penguins cannot fly, although there is evidence that millions of years ago their ancestors could do so?
- (A) Penguins live on land and feed in the water; therefore they have no need to fly.
 - (B) The Antarctic home of penguins is flat and barren; therefore there is no place to fly.
 - (C) Ancestral penguins without large wings were better able to swim and feed in the water; therefore, they passed their genes for shorter wing structure on to their offspring.
 - (D) Ancestral penguins did not use their wings for long periods of time; therefore today's penguins have only tiny, nonfunctional wings.
 - (E) The cold and wind of Antarctica make flight impossible; therefore penguins that live there have lost the ability to fly.
41. The appearance of a fertile, polyploidy individual within a population of diploid organisms is a possible source of a new species. If this individual is capable of reproducing to form a new population, scientists would consider this to be an example of
- (A) allopatric speciation
 - (B) sympatric speciation
 - (C) polygenic inheritance
 - (D) genetic drift
 - (E) Hardy-Weinberg equilibrium
42. Which of the following is a characteristic of mitochondria and chloroplasts that supports the endosymbiotic theory?
- (A) Both have bacteria-like polysaccharide cell walls.
 - (B) Both can reproduce on their own outside of the cell.
 - (C) Both contain DNA molecules.
 - (D) Both contain endoplasmic reticulum and Golgi bodies.
 - (E) Both contain ribosomes that are identical to ribosomes of the eukaryotic cytoplasm.

Questions 68-71:

- (A) Comparative biochemistry
- (B) Comparative anatomy
- (C) Comparative embryology
- (D) Geographical distribution
- (E) Paleontology

From the fields of study listed above, choose the field that has provided each of the following pieces of evidence that biological evolution has occurred.

68. *Archaeopteryx* is an extinct feathered reptile.

69. *Peripatus* has claws like an insect and paired nephridia like a segmented worm.

70. Most human diabetics can use insulin derived either from pigs or from humans.

71. During early development, a human fetus has a tail and gill arches.

1999 AP Biology Exam

8. The condition in which there are barriers to successful interbreeding between individuals of different species in the same community is referred to as
- (A) latent variations
 - (B) sterility
 - (C) structural differences
 - (D) geographic isolation
 - (E) reproductive isolation
13. Which of the following best supports the statement that mitochondria are descendants of endosymbiotic bacteria-like cells?
- (A) Mitochondria and bacteria possess similar ribosomes and DNA.
 - (B) Mitochondria and bacteria possess similar nuclei.
 - (C) Glycolysis occurs in both mitochondria and bacteria.
 - (D) Both mitochondria and bacteria have microtubules.
 - (E) Neither mitochondria nor bacteria possess chloroplasts.

Special Focus: Evolution and Change

20. Which of the following statements best expresses the concept of punctuated equilibrium?
- (A) Small variations gradually accumulate in evolving lineages over periods of millions of years.
 - (B) Random mating ensures that the proportions of genotypes in a population remain unchanged from generation to generation.
 - (C) Stability is achieved when selection favors the heterozygote, while both types of homozygotes are at a relative disadvantage.
 - (D) Evolutionary changes consist of rapid bursts of speciation alternating with long periods in which species remain essentially unmodified.
 - (E) Under competition for identical resources, one of the two competing species will be eliminated or excluded.
39. All of the following were likely present on the primitive Earth during the evolution of self-replicating molecules EXCEPT
- (A) amino acids and nucleotides
 - (B) nitrogen
 - (C) simple carbohydrates
 - (D) freestanding liquid water
 - (E) an O₂-rich atmosphere
44. In a small group of people living in a remote area, there is a high incidence of “blue skin,” a condition that results from a variation in the structure of hemoglobin. All of the “blue-skinned” residents can trace their ancestry to one couple, who were among the original settlers of this region. The unusually high frequency of “blue skin” in the area is an example of
- (A) mutation
 - (B) genetic drift
 - (C) natural selection
 - (D) sexual selection
 - (E) heterozygote advantage

46. A number of different phylogenies (evolutionary trees) have been proposed by scientists. These phylogenies are useful because they can be used to
- (A) determine when two similar populations of a species evolved into two separate species
 - (B) evaluate which groups of organisms may be most closely related
 - (C) demonstrate that all photosynthetic organisms are members of the Kingdom Plantae
 - (D) demonstrate that natural selection is the prevailing force in evolution
 - (E) demonstrate which taxa (groups of organisms) contain the most highly evolved species
49. Which of the following pathways for the transformation of cellular energy most likely evolved first?
- (A) Cyclic photophosphorylation
 - (B) Citric acid (Krebs) cycle
 - (C) Calvin cycle
 - (D) C₄ photosynthesis
 - (E) Glycolysis
53. Which of the following principles is NOT part of Darwin's theory of evolution by natural selection?
- (A) Evolution is a gradual process that occurs over long periods of time.
 - (B) Variation occurs among individuals in a population.
 - (C) Mutations are the ultimate source of genetic variation.
 - (D) More individuals are born than will survive.
 - (E) Individuals that possess the most favorable variations have the best chance of reproducing.
54. In certain Native American groups, albinism due to a homozygous recessive condition in the biochemical pathway for melanin is sometimes seen. If the frequency of the allele for this condition is 0.06, which of the following is closest to the frequency of the dominant allele in this population? (Assume that the population is in Hardy-Weinberg equilibrium.)
- (A) 0.04
 - (B) 0.06
 - (C) 0.16
 - (D) 0.36
 - (E) 0.94

Special Focus: Evolution and Change

2002 AP Biology Exam

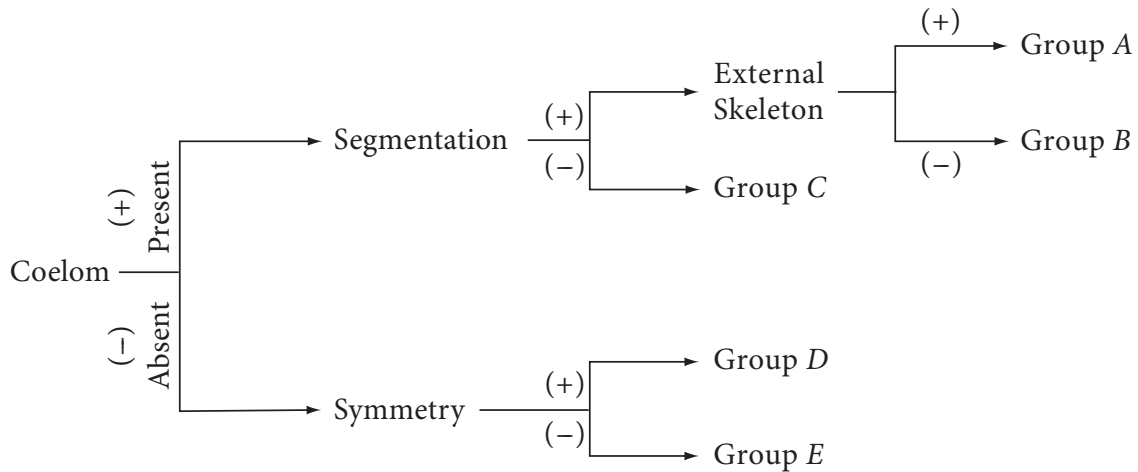
4. The different species of finches on the Galapagos Islands are believed to have arisen as a result of natural selection acting on the populations of finches that had experienced
- (A) convergent evolution
 - (B) gene flow
 - (C) the bottleneck effect
 - (D) geographic isolation
 - (E) hybrid sterility
13. Toads in a particular population vary in size. A scientist observes that in this population, large males mate with females significantly more often than small males do. All the following are plausible hypotheses to explain this observation EXCEPT:
- (A) Females select large males more often than they select small males as mates.
 - (B) Small females are more likely to mate with small males and large females are more likely to mate with large males.
 - (C) Large males are successful in competing for mates more often than small males are.
 - (D) Large males occupy more breeding territory than small males do.
 - (E) The calls produced by large males are more attractive to females than the calls made by small males.
18. If organisms *A*, *B*, and *C* belong to the same order but to different families and if organisms *D*, *E*, and *F* belong to the same family but to different genera, which of the following pairs of organisms would be expected to show the greatest degree of structural homology?
- (A) *A* and *B*
 - (B) *A* and *C*
 - (C) *B* and *D*
 - (D) *C* and *F*
 - (E) *E* and *F*
22. The fruit produced by angiosperms is an evolutionary adaptation that most often
- (A) nourishes the seeds within the fruit on ripening
 - (B) aids in seed dispersal
 - (C) attracts pollinators
 - (D) inhibits seed germination until favorable environmental conditions occur
 - (E) provides an energy source for the plant egg cell prior to fertilization

29. Which of the following provides the weakest evidence that mitochondria were once free-living prokaryotes?
- (A) Mitochondrial ribosomes resemble those of prokaryotes.
 - (B) Mitochondria have DNA that is circular and does not have associated protein.
 - (C) Enzyme pathways on mitochondrial membranes resemble those found on modern prokaryote membranes.
 - (D) Mitochondria reproduce by a process similar to binary fission.
 - (E) Mitochondria and prokaryotes both are found in a variety of sizes.
31. Analysis of DNA sequences from two individuals of the same species results in a greater estimate of genetic variability than does analysis of amino acid sequences from the same individuals because
- (A) different DNA sequences can code for the same amino acid
 - (B) some amino acid variations cannot be detected by protein electrophoresis
 - (C) DNA sequencing is a more reliable technique than protein electrophoresis
 - (D) proteins are more easily damaged than is DNA
 - (E) DNA is more heat-sensitive and therefore varies more

Special Focus: Evolution and Change

Directions: Each group of questions below concerns an experimental or laboratory situation or data. In each case, first study the description of the situation or data. Then choose the one best answer to each question following it and fill in the corresponding oval on the answer sheet.

Questions 87-89 refer to the following dichotomous key.



87. Centipedes and millipedes should NOT be placed in group *B* because they

- (A) have an exoskeleton
- (B) display radial symmetry
- (C) lack a coelom
- (D) are unsegmented
- (E) have an endoskeleton

88. Which of the following phyla is represented by group *E*?

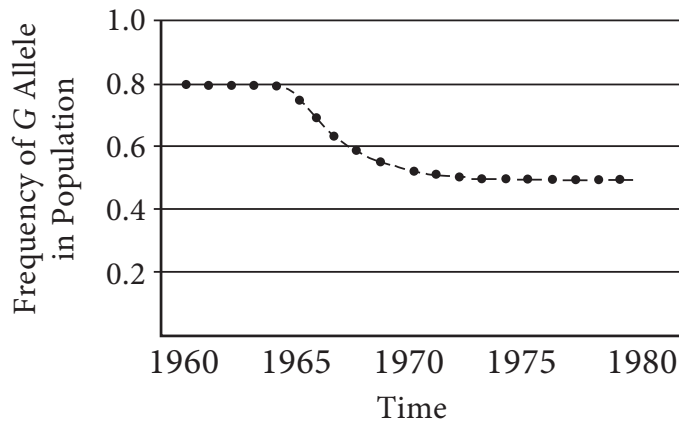
- (A) Mollusca
- (B) Cnidaria (Coelenterata)
- (C) Porifera
- (D) Chordata
- (E) Annelida

89. Clam, octopus, and oyster are classified in which group?

- (A) *A*
- (B) *B*
- (C) *C*
- (D) *D*
- (E) *E*

Questions 106-110 refer to the following:

A moth's color is controlled by two alleles, G and g , at a single locus. G (gray) is dominant to g (white). A large population of moths was studied, and the frequency of the G allele in the population over time was documented, as shown in the figure below. In 1980 a random sample of 2,000 pupae was collected and moths were allowed to emerge.



106. During which of the following time periods could the population have been in Hardy-Weinberg equilibrium for the G locus?

- I. 1960–1964
- II. 1965–1972
- III. 1973–1980

- (A) I only
- (B) II only
- (C) III only
- (D) I and III only
- (E) I, II, and III

107. Assuming that the population was in Hardy-Weinberg equilibrium for the G locus, what percentage of the moths in the natural population was white in 1962?

- (A) 2%
- (B) 4%
- (C) 8%
- (D) 20%
- (E) 64%

Special Focus: Evolution and Change

108. Assuming that the population was in Hardy-Weinberg equilibrium for the *G* locus, what percentage of the gray moths that emerged in 1980 was heterozygous?
- (A) 0%
 - (B) 25%
 - (C) 33%
 - (D) 67%
 - (E) 100%
109. Assuming that the population was in Hardy-Weinberg equilibrium for the *G* locus, what was the frequency of allele *G* in the gray moths that emerged in 1980?
- (A) 0.33
 - (B) 0.50
 - (C) 0.67
 - (D) 0.75
 - (E) 1.00
110. Which of the following is the most likely reason for the observed differences in the frequency of the *G* allele between 1965 and 1972?
- (A) Emigration of white moths from the population
 - (B) Chance
 - (C) Selection against gray phenotypes
 - (D) Speciation
 - (E) Mutation

Special Focus: Evolution and Change

Answer Key for the Questions Above and Percentage of Exam Takers Who Answered Correctly

Year	Item Number	Correct Answer	Percent Correct
1990	1	C	77%
1990	12	C	65%
1990	45	D	43%
1990	50	A	53%
1990	51	D	54%
1990	61	E	35%
1990	73	C	21%
1994	3	A	77%
1994	7	B	64%
1994	9	A	85%
1994	25	C	42%
1994	28	A	46%
1994	39	C	73%
1994	41	B	28%
1994	42	C	41%
1994	68	E	86%
1994	69	B	94%
1994	70	A	95%
1994	71	C	95%
1999	8	E	66%
1999	13	A	64%
1999	20	D	57%
1999	39	E	71%
1999	44	B	56%
1999	46	B	53%
1999	49	E	47%
1999	53	C	54%
1999	54	E	63%

Year	Item Number	Correct Answer	Percent Correct
1999	8	E	66%
1999	13	A	64%
1999	20	D	57%
1999	39	E	71%
1999	44	B	56%
1999	46	B	53%
1999	49	E	47%
1999	53	C	54%
1999	54	E	63%
2002	4	D	73%
2002	13	B	79%
2002	18	E	73%
2002	22	B	49%
2002	29	E	73%
2002	31	A	73%
2002	87	A	48%
2002	88	C	43%
2002	89	C	28%
2002	106	D	67%
2002	107	B	25%
2002	108	D	28%
2002	109	B	62%
2002	110	C	59%

Special Focus: Evolution and Change

Past AP Exam Free-Response Questions on Evolution

A student's deep understanding of evolution and all its ramifications is hard to gauge with a multiple-choice exam; familiarity with key buzzwords or good guessing may disguise lack of knowledge and confusion. Enter the essay, where it is hard to hide ignorance and misunderstanding. Teachers can readily see where their charges fall down or fall short. After grading enough essays, teachers can also see where their weaknesses in communication lie and how they might more successfully guide students toward deeper insight. Essays take much more time to grade, but the rewards are worth it for everyone concerned!

Following are past AP Exam free-response questions concerning evolution, including scoring guidelines (formerly called “standards”), through 2001. The most recent questions (from the 2002 through 2006 AP Biology Exams), plus their scoring guidelines and sample student responses (including each Form B, the overseas version of the exam), are all posted online on the AP Biology Exam page on AP Central—go to the AP Biology Course Home Page at apcentral.collegeboard.com/biology, and select the “AP Biology Exam” link under the heading “Exam Information.”

1990 AP Biology Exam Free-Response Question 3

Discuss the adaptations that have enabled flowering plants to overcome the following problems associated with life on land.

- a. The absence of an aquatic environment for reproduction
- b. The absence of an aquatic environment to support the plant body
- c. Dehydration of the plant

1990 AP Biology Exam Free-Response Question 3: Scoring Guidelines

a. Absence of an aquatic environment for reproduction

1 pt. flowers - attraction for insects - shape, color, smell, chemical, nectar
Mimicry for pollination (coevolution)

1 pt. timing of reproduction

male: 1 pt. (micro)spores - pollen is reduced gametophyte

1 pt. lack of motility of gamete - pollen grain modification for transport,
e.g., light weight/structure

1 pt. pollination - transport of male gametes, wind, insects, self pollination

female: 1 pt. reduced gametophyte (in megaspore or megasporangium)

1 pt. protected gametophyte - embryo inside ovary, carpel, pistil

1 pt. evolution of seed

1 pt. fertilization - internal - pollen tube, endosperm

1 pt. fruit and seed dispersal

* 1 pt. seed dormancy (See part c.)

4 pts. maximum

b. Absence of an aquatic environment to support the plant body

1 pt. stem - support

1 pt. root - anchorage

1 pt. vascular tissue or vascularization - xylem fibers, tracheids, vessels,
heartwood, dead tissues

1 pt. vines, tendrils

1 pt. cell wall - lignin, cell wall support, cellulose

1 pt. cambium - secondary thickening

1 pt. sclerenchyma - whole wall support;
collenchyma - corner wall support

1 pt. prop, buttressed roots

1 pt. turgor pressure

4 pts. maximum

Special Focus: Evolution and Change

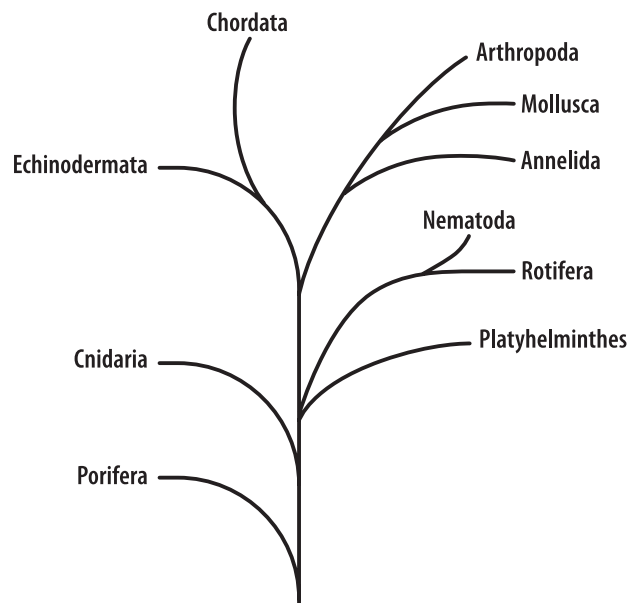
c. Dehydration of the plant

- 1 pt. root hair, absorption
- 1 pt. cuticle, wax, acellular
- 1 pt. bark - suberin, cork
 - scales - bud protection
 - sepal/petals - floral part protection
- 1 pt. seed coat
 - pollen grain wall
- 1 pt. stomates - function to control water movement
- 1 pt. xylem - water transport
- 2 pt. leaf/stem/root modifications
 - surface area reduction in desert plants/succulents
 - stomates under surface
 - stomates sunken
 - leaf rolling
 - hairs and trichomes
 - interlocked epidermal cells
 - hypodermis
 - cortex - water storage or retention
 - loss of leaves / abscission layer
- 1 pt. CAM/C₄ plants - modified stomate functions
- * 1 pt. seed dormancy (if not mentioned in part a)

4 pts. maximum

1990 AP Biology Exam Free-Response Question 4

- a. Describe the differences between the terms in each of the following pairs.
- (1) Coelomate *versus* acoelomate body plan
 - (2) Protostome *versus* deuterostome development
 - (3) Radial *versus* bilateral symmetry
- b. Explain how each of these pairs of features was important in constructing the phylogenetic tree shown below. Use specific examples from the tree in your discussion.



1990 AP Biology Exam Free-Response Question 4: Scoring Guidelines

a. (1) Coelomate vs. acoelomate

- 1 pt. coelomate: internal body cavity lined with mesoderm (not sufficient to say “true body cavity”)
- 1 pt. acoelomate: lacking internal cavities altogether or having
- a pseudocoelom (Nematoda and Rotifera)
 - a spongocoel (Porifera)
 - mesoglea (Cnidaria)
 - a solid layer of mesoderm (Platyhelminthes)

2 pts. maximum — must define both for full credit

Special Focus: Evolution and Change

(2) Protostome vs. deuterostome development

- 1 pt. protostome: mouth develops near/at the blastopore or anus forms secondarily (later), or featuring
 - spiral cleavage (micromeres between macromeres)
 - determinate/mosaic development (blastomere fate is established at very early stages of development)
 - mesoderm from cells that migrate into the blastocoel near blastopore
 - schizocoelous coelomation (internal split in solid wedge of mesoderm that is independent of gut);
 - trochophore larva
- 1 pt. deuterostome: anus develops near/at the blastopore or the mouth forms secondarily (later), or featuring
 - radial cleavage (micromeres directly above macromeres);
 - indeterminate/regulative development (blastopore fate is variable and not established until late in development)
 - mesoderm arises from outpocketings of the gut
 - enterocoelous coelomation (outpocketing of gut)
 - dipleurula larva

2 pts. maximum — must define both for full credit

(3) Radial vs. bilateral symmetry

- 1 pt. radial: several planes passing through the long or central axis can divide the organism into similar parts
- 1 pt. bilateral: (only) one plane passing through the long axis divides the organism into similar right and left sides — exhibits cephalization
- 1 pt. echinoderms: bilaterally symmetrical larvae, but appear to have radially symmetrical adult forms

2 pts. maximum

- b.** 1 pt. each for examples of *contrasting pairs* (phyla or organisms) using terms from 4a; answer here or in 4a
- 1 pt. each for using 4a terms in explanation of why phyla are in separate groups (*on separate branches*) of tree
- 1 pt. body symmetry (cephalization) permits separation of Porifera and Cnidaria (radially symmetrical) from other phyla (bilaterally symmetrical)
- 1 pt. coelomation permits separation of Platyhelminthes, Nematoda, and Rotifera from other phyla above Cnidaria: flatworms are acoelomate, whereas those other than nematodes and rotifers are coelomate

Special Focus: Evolution and Change

- 1 pt. origin of the mouth and anus permit separation of Echinodermata and Chordata (deuterostomes) from Arthropoda, Annelida, and Mollusca (protostomes)
[Some include Platyhelminthes, nematodes, and rotifers as protostomes]
 - 1 pt. nematodes and rotifers are grouped separately because both are pseudocoelomate
 - 1 pt. phylogenetic trees base taxonomic relationships on homologous structures, patterns of embryonic development, and common ancestry
-
- 6 pts. maximum

Special Focus: Evolution and Change

1991 AP Biology Exam Free-Response Question 4

Discuss how each of the following has contributed to the evolutionary success of the organisms in which they are found.

- Seeds
- Mammalian placenta
- Diploidy

1991 AP Biology Exam Free-Response Question 4: Scoring Guidelines

Seeds: (max of 4 points/7 points total)

Protection: from drying, infection, mechanical injury (tough coat)

Food: source: cotyledons, endosperm. Result: more pre-germination (embryonic) development, i.e. radicle, hypocotyl, epicotyl, etc.

Dispersal: examples incld fruit, hooks, animals, wind, water, etc.

Dormancy: timing of germination increases competitive success (possible reduction in overcrowding)

Adaptation: to or Colonization of new land environments

Options for variation in number of seeds vs. parental investment

Hormone production/internal regulation

Placenta: (max of 4 points/8 points total)

Exchanges of food & O₂ and/or waste or CO₂ (description of placental structures)

Homeostatic environment (stable/temp. or chem.; amniotic fluid)

Immunity (antibodies cross placenta)

Predation reduction

More developed organism at time of birth (retained longer)

Survival chances increased, therefore fewer offspring needed

Mobility and independence of parents during fetal development

Developmental signals/hormone regulation/communication through mother/fetus connection

Diploidy: (max of 4 points/9 points total)

Variation through fertilization/syngamy/two parents

Variation through meiosis/crossing over/recombination/independent assortment/segregation

Modes of Inheritance: co-dominance, polyploidy

Result of variation is potential for adaptation

Masks Mutation or hides variability/heterozygosity/recessive alleles retained in gene pool

Hybrid vigor provides certain advantages

Back-up set of chromosomes for gene replacement/repair/conversion

Life cycles/alternation of generations

Overview: (1 point)

Definition of evolutionary success in terms of Survival of fittest or natural selection.

Special Focus: Evolution and Change

1992 AP Biology Exam Free-Response Question 4

Evolution is one of the major unifying concepts of modern biology.

- a. Explain the mechanisms that lead to evolutionary change.
- b. Describe how scientists use each of the following as evidence for evolution.
 - (1) Bacterial resistance to antibiotics
 - (2) Comparative biochemistry
 - (3) The fossil record

1992 AP Biology Exam Free-Response Question 4: Scoring Guidelines

A. (Max 7 points) Explain the mechanisms that lead to evolutionary change.

The Big Picture:

- 1- Punctuated equilibrium, mass extinction, etc.
- 1- Definition of evolution - change through time
- 1- Mutation - change in genes yields genetic variation
- 1- Natural selection/selective pressure (Darwin)
 - 1- Genetic variation exists
 - 1- Over production
 - 1- Competition - survival of fittest (Best genes)
 - 1- Survivors reproduce (Best genes to offspring)
- 1- Adaptive/non adaptive nature of variation

Specific Mechanisms:

(1- List, no elaboration/ 1 - Elaboration of mechanisms)

Population level mechanisms:

- 1+1- Genetic drift/change in allele frequencies in small pop. /founder effect/
bottle neck
- 1- Migration/gene flow in populations
- 1- Non-random mating/inbreeding
- opt. 1- Hardy-Weinberg disruption leads to evolution
- 1+1- Speciation: prezygotic/postzygotic isolating mechanisms
Examples: seasonal/behavioral/ temporal
- 1- Chromosomal abnormalities/ polyploidy/change in chromosome number
- 1- Development of genetic variation through: recombination/x-over/indep.
segregation/meiosis

B. (Max 6 points) Describe how scientists use each of the following as evidence for evolution:

(1) Bacterial resistance to antibiotics (max 2 points)

- 1- Genetic variation/ mutants
- 1- Selection for resistance
- 1- Survival to reproduce
- 1- Transduction/ transformation/ “sex” reprod./ DNA plasmid transfer

(2) Comparative biochemistry (max 2 points)

- 1- Common biochemical pathways (as evidence for evolution)
 - 1- Respiration-Examples: Electron flow, proton pump, chemiosmosis, Krebs, citric acid cycle
 - 1- ATP, etc.
 - 1- Photosynthesis-light Rxn, Calvin
 - 1- Protein synthesis
 - 1- Proteins- Examples: Amino acid sequence, isoenzymes, cytochrome C, hemoglobin (addn'l point for elaboration), insulin
 - 1- Cell structure based on similarity in molecular composition
- Molecular structure commonality:
- 1- DNA base sequence/ homology/ hybridization (1 addn'l explanation)
 - 1- RNA “ “ “ (1 addn'l explanation)

(3) The fossil record (max 2 points)

- 1- Stratification of fossils as evidence of change
- 1+1- Examples with description of change:
Humans, horses, vascular plants, shellfish
- 1+1- Limb homology + elaboration of example
- 1- Chronology- radioactive dating
- 1- Cladistics/ phenology
- 1- Extinction of Species

Special Focus: Evolution and Change

1994 AP Biology Exam Free-Response Question 1

Genetic variation is the raw material for evolution.

- Explain **three** cellular and/or molecular mechanisms that introduce variation into the gene pool of a plant or animal population.
- Explain the evolutionary mechanisms that can change the composition of the gene pool.

1994 AP Biology Exam Free-Response Question 1: Scoring Guidelines

2 points maximum for each category

1 point for general explanation + 1 point for an elaboration

The second point may be earned with an elaboration **or** an explained example.

(6 POINTS MAX)

PART A Explain **three** cellular and/or molecular mechanisms that introduce variation into the gene pool of a plant or animal population

- 1 Mutation is a change in the DNA
- 1 Mutagenesis— explanation
- 1+1 Point mutations
- 1+1 • Substitution
- 1+1 • Frame shift
 - Insertion
 - Deletion
- 1+1 • Editing error (repair)
- 1+1 Chromosomal mechanisms
- 1+1 • Translocation (Transposition)
- 1+1 • Inversion
- 1+1 • Deletion
- 1+1 • Duplication
- 1+1 • Crossing over
 - (new combinations of linked alleles)
- 1+1 • Aneuploidy (non-disjunction)
- 1+1 • Polyploidy

(6 POINTS MAX)

PART B Explain the evolutionary mechanisms that can change the composition of the gene pool.

- 1+1 Natural selection explanation
- Minimum—**
 - Differential reproductive success (Survival of the fittest not enough)
- Elaboration—**
 - Adaptation viewed as a “result”
 - Adaptive radiation
 - Importance of variation
 - Occurs in populations not individuals
- Example**
- 1+1 Gene Flow
- Minimum—**
 - Immigration or emigration of alleles
- Elaboration—**
 - Outbreeding
 - Geographic isolation

Special Focus: Evolution and Change

1+1 **Other Mechanisms**

- 1+1 • Transposable elements
- 1+1 • Virus induced changes
- 1+1 • Genetic engineering

1+1 **Sexual reproduction**

- Meiosis as a reshuffling mechanism
- Recombination of genes (alleles)
- Independent assortment
- Random fertilization
- Cross breeding
(Elaboration point is for gene pool connection not for individual variation)

- Barriers- addition/removal geography/ temporal/reproductive/ behavioral

Example

1+1 **Genetic Drift** (Neutral Selection)

Minimum—

- Non representative, random change in allelic frequency - linked with small population size

Elaboration—

- Bottleneck effect, founder effect
- Effect of a small population

Example

1+1 **Mutation**

Minimum—

- (Δ in genes or alleles in context as an evolutionary mechanism)

Elaboration—

- Randomness
- Non-directionality
- Change in phenotypic traits
- Gametic not somatic change

Example

1+1 **Assortative mating**

Minimum—non-random/choice

Elaboration—

- Sexual selection
- Artificial selection
- In-breeding

Example

Special Focus: Evolution and Change

1994 AP Biology Exam Free-Response Question 4

Select two of the following three pairs and discuss the evolutionary relationships between the two members of each pair you have chosen. In your discussion include structural adaptations and their functional significance.

PAIR A:

green algae
vascular plants

PAIR B:

prokaryotes
eukaryotes

PAIR C:

amphibians
reptiles

1994 AP Biology Exam Free-Response Question 4: Scoring Guidelines

The question was designed to elicit a wide knowledge of organismal structure and function considered specifically in an evolutionary framework. The question required that structural adaptations, tied to their functional significance, be included, but did not restrict the student's response to such discussion. Points, therefore, were also provided for discussion of: structural adaptation not linked to functional significance; differences in functional ability not tied to structural difference base; and, appropriately, a discussion of evidence which exists to support the relationship stated.

{Maximum: 6 pts. total for each pair discussed:

3 points max. for unlinked items; 2 pts./ each linked item}

PAIR A: GREEN ALGAE ---> VASCULAR PLANTS (Maximum: 6 pts.)

I. Evolutionary Overview: Aquatic ---> Terrestrial

II. Evolutionary Relationships/Evidence:

- A.) similar pigments (similar chlorophylls, chlorophyll b)
- B.) similar food storage compounds, carbohydrates (starch)
- C.) similar flagellated cells (whiplash type)
- D.) Other - cell wall composition, chloroplast anatomy, cytokinesis, cell plate

III. Evolutionary Adaptations*	Functional Significance
1.) cuticle	1.) prevents desiccation
2.) xylem & phloem	2.) water & mineral/organic transport
3.) stomata	3.) gas exchange/transpiration
4.) lignified tissues/xylem	4.) support
5.) undifferentiated -> differentiated tissues (roots, stems, leaves)	5.) functional specialization (division of labor)
6.) sterile jacket	6.) prevents desiccation
7.) flagellated -> non flag. Cells	7.) terrestrial fertilization
8.) spores -> seeds	8.) protection/dormancy/food
9.) haploid -> diploid	9.) variation
10.) no embryo -> embryo	10.) protection/nourishment
11.) homospory -> heterospory	11.) variation

PAIR B: PROKARYOTES ---> EUKARYOTES (Maximum: 6 pts.)

I. Evolutionary Overview: Endosymbiotic &/or Autogenous Theory
(explanation of)

II. Evolutionary Relationships/Evidence:

- | |
|--|
| A.) ribosomes (in prokaryotes and in organelles) |
| B.) nucleic acids (in prokaryotes and in organelles) |
| C.) other; see addenda |

III. Evolutionary Adaptations*	Functional Significance
1.) nuclear membrane	1.) compartmentalization
2.) histones/nucleosomes	2.) packaging of DNA
3.) cytoskeleton	3.) movement/support/etc.
4.) membranous organelles	4.) specialization
5.) multicellularity	5.) complexity
6.) spindle apparatus	6.) necessary for sexual reproduction (meiosis)
7.) membrane steroids	7.) membrane stability
8.) other; see addenda	

Special Focus: Evolution and Change

PAIR C: AMPHIBIANS ----> REPTILES (Maximum: 6 pts.)

I. Evolutionary Overview: Aquatic -> Terrestrial

II. Evolutionary Relationships/Evidence:

- A.) anatomical (homologous structures - 3 chambered heart, appendicular structures)
 B.) fossil record: common amphibian ancestor, Labyrinthodon, Devonian period

III. Evolutionary Adaptations*	Functional Significance
1.) moist -> keratinized (scales) skin	1.) prevents desiccation
2.) 3 chambers -> septated ventricle	2.) less mixing of oxy, deoxy blood/better O ₂ delivery
3.) urea -> uric acid	3.) water conservation
4.) absence/presence, apparatus for response to environmental temperature	4.) temperature regulation/poikilothermy -> ectothermy (cold blooded)
5.) other:	5.) see addenda
• skeletal system	• excretory system
• nervous system	• respiratory system
6.) jelly coat -> amniotic egg (meiosis)	6.) prevents desiccation
7.) lack of -> copulatory organs	7.) internal fertilization
8.) metamorphosis -> no larval stage	8.) adaptation to terrestrial environment

* citation of more advanced character alone was allowed;
 citation of more primitive character alone received no credit

**1994 AP Biology Exam Free-Response Question 4:
Scoring Guidelines—Addenda**

PAIR A: GREEN ALGAE ---> VASCULAR PLANTS

Part II. Evidence for Evolutionary Relationships

- Similar pigments (similar chlorophylls, chlorophyll b)
- Similar food storage compounds, carbohydrates (starch)
- Similar flagellated cells (whiplash type)
- Similar cell wall composition (cellulose)
- Similar cytokinesis (cell plate, phragmoplast)
- Similar chloroplast design

Part III. Structural Adaptations*

- no cuticle -> cuticle
- no vascular tissue -> xylem and phloem
- absence of stomata -> presence of stomata
- absence of lignin -> presence of lignin
- lack of specialization/little differentiation -> organs (roots, stems, leaves)
- absence of sterile jacket -> presence of sterile jacket
- flagellated reproductive cells -> reproductive cells not flagellated
- spore -> seed
- “N” dominance (gametophyte) -> “2N” dominance (sporophyte)
- no embryo -> embryo with protection
- homosporous -> heterosporous

Part III. Functional Significance

- desiccation
- transport of water/minerals and organic molecules
- gas exchange/transpiration
- support in the absence of water
- division of labor {increase in efficiency, adaptation to a terrestrial environment (less CO₂, less H₂O, more radiant energy)}
- mechanical protection and to prevent desiccation (gametangia)
- dispersal of reproductive materials in a terrestrial environment
- food for developing embryo, protection, dormancy
- increases variation and diversity
- feeding and protecting the next generation
- increases variation and diversity

Special Focus: Evolution and Change

PAIR B: PROKARYOTES ----> EUKARYOTES

Part II. Evidence that supports Endosymbiotic Theory:

(“organelles” denotes mitochondria &/or chloroplasts)

- ribosomes are found in organelles/organelles contain their own synthetic machinery
- organelle ribosomes are of a prokaryotic type (30S, 50S, 70S polysomes)
- antibiotic effects similar on prokaryotic and organelle ribosomes
- r-RNA sequences similar in prokaryotes and organelles
- DNA is found in organelles
- DNA is circular; supercoiled; not associated with histones; not arranged in nucleosome packages
- organelles = size of prokaryotic cells
- organelles arise only from pre-existing organelles
- organelle reproduction similar to binary fission
- oxygenic photosynthesis present in certain prokaryotes
- chlorophyll a present in certain prokaryotes
- chlorophyll b (as well as chlorophyll a) present in certain prokaryotes
- inner organelle membranes and prokaryotic cell membranes have some similar transport and enzyme systems
- fossil evidence: prokaryotes: 3.5×10^9 yrs., eukaryotes: 1.5×10^9 B.P.
evidence of atm. O_2 : 2.5×10^9 yrs. B.P.

Part II. Evidence that supports Autogenous Theory:

- association of the nuclear membrane, ER and plasma membrane
- fossil evidence as above

Part III. Structural Adaptations *

- (“prokaryotes” defined as eubacteria)
- nucleoid/ nucleus
- lack of histones (divalent cations instead)/histones
DNA packaging by supercoiling/DNA wrapping around histones
- lack of cytoskeleton/cytoskeleton
- membranous organelles
- unicellular, plates, filaments clusters/true multicellularity
- spindle apparatus
- absence/presence of membrane steroids (i.e. cholesterol)
- peptidoglycan cell wall/cell walls of other composition
- circular DNA/linear DNA
- one chromosome per cell/more than one chromosome per cell

- 30S, 50S, 70S ribosomes/40S, 60S, 80S ribosomes
(30S, 50S, 70S ribosomes found in organelles)
- polycistronic m-RNA/monocistronic m-RNA
- absence/presence of cap and tail on m-RNA
- typically 1-5 microns/10-100 microns diameter
- flagellar design for rotary motion vs. “9 + 2” design for whipping motion/
flagellum not surrounded by cell membrane/surrounded by cell
membrane/diameter of prokaryotic flagellum/diameter of eukaryotic
flagellum (diameter of prokaryotic flagellum approx. = diameter
eukaryotic microtubule)

Part III. Functional Significance

- nucleus provides a microenvironment for RNA and DNA polymerases,
allows separation of transcription and translation
- stability/packaging of larger amounts of DNA/finer control of
transcriptional regulation vs. rapidity of transcription
- movement, orientation of organelles; cytoplasmic streaming, amoeboid
movement, phagocytosis
- specialization of function (within a cell)
- specialization of function (between cells)
- distribution of large amounts of DNA to daughter cells
- membrane strength in eukaryotic groups without cell walls
- size of cell that can be protected by a single molecular wrap/construction
of cellulosic and other eukaryotic cell walls places no demand on cell
supplies of nitrogen
- only small amounts of DNA can be packaged in supercoiled circles
- allows transcription and replication of large amounts of DNA
- coincidence of the original endosymbiotic event
- finer control of translation vs. rapidity of response to rapidly
changing environment
- protection of m-RNA/transport of m-RNA out of the nucleus
- larger size permits greater complexity of cellular structure
- eukaryotic design permits more variability in movement, is necessary for
movement of larger cells

Special Focus: Evolution and Change

PAIR C: AMPHIBIANS ----> REPTILES

Part I. Evidence for Evolutionary Relationships

- anatomical similarities of recent derivation only (structural similarities at branch point only)
 - three-chambered heart
 - tetrapod character
 - lungs
- fossil record (common amphibian ancestor, Labyrinthodon, Devonian Period)

Part II. Structural Adaptations*

- keratinized (scales) skin
- septated ventricle/four chambers
- uric acid
- apparatus for response to environmental temperature (parietal gland)
- skeletal system modifications
 - articulated vertebrae
 - reposition of appendages from lateral to ventral side
- muscular system modifications: muscular tissue in dermis
- respiratory system modifications
 - development of thoracic/abdominal septum
 - development of nasal cavity
 - increased surface area of the lungs (alveoli)
- excretory system modifications
 - uric acid vs. urea
 - metanephric vs. mesonephric kidneys
 - ureter, separation of excretory/reproductive components
 - collecting tubules, increased length of loop of Henle
- nervous system modifications
 - increased sophistication of the limbic system
 - presence of the parietal glands/ temperature control site
- amniotic (cleidoic/shelled) egg
- copulatory organs
- no larval stage

Part III. Functional Significance

- prevents desiccation
- less mixing of oxy/deoxygenated blood, better oxygen delivery
- water conservation
- temperature regulation/poikilothermy to ectothermy

- skeletal system modifications
 - agility/ flexibility
 - weight support/locomotive speed
- muscular system modifications
 - increased insulation/protection/ motility (snakes)
- respiratory system modifications
 - ability to generate negative pressure breathing
 - ability to breathe with food in mouth/ability to warm and humidify respired air
 - increased gas exchange
- excretory system modifications
 - decrease water loss in terrestrial environment
 - increased ability to reabsorb water
- nervous system modifications
 - increased ability to respond/adapt to environmental conditions
 - ability for behavioral modification of body temperature
- embryo: mechanical protection, food source, water conservation, waste elimination
- internal fertilization
- adaptation to terrestrial environment

*citation of more advanced character alone was allowed;
citation of more primitive character alone received no credit

Special Focus: Evolution and Change

1995 AP Biology Exam Free-Response Question 2

The problems of survival of animals on land are very different from those of survival of animals in an aquatic environment. Describe four problems associated with animal survival in terrestrial environments but not in aquatic environments. For each problem, explain an evolutionary solution.

1995 AP Biology Exam Free-Response Question 2: Scoring Guidelines

3 points maximum per problem

1 point for a description of a problem, or a comparison of a problem between water and land environments

1 point for an explanation of a solution clearly linked to an appropriate problem

1 point for an elaboration of a problem, or a solution description, or an additional solution

Problem and Examples of Descriptions

Examples of Solutions

(including but not limited to)

Does not require description (description inherent in words of problems)

- | | |
|---------------------------------------|---|
| • Water Acquisition | drinking, “metabolic water”, absorption, etc. |
| • Water Conservation/Retention | kidney differences (i.e., Loop of Henle), ADH, storage, behavioral adaptations (i.e., nocturnal, estivation, burrowing), etc. |
| • Desiccation of Body Surfaces | scales, feathers, mucus, cutin, exoskeletons, keratinized skin, etc. |
| • Desiccation of Respiratory Surfaces | invagination of gas exchange surfaces, moist mucus membranes, etc. |
| • Desiccation of Embryos | shelled (amniote) egg, calcareous shell of birds, ovovivipary, vivipary, invertebrate egg sacs, internal development, etc. |
| • Desiccation of Gametes | internal fertilization, seminal/vaginal fluids, etc. |

Requires description

- Sperm Transport
(due to lack of fluid medium) internal fertilization, seminal/vaginal fluids, etc.
- Excretion/Electrolytes/Water
(due to more extreme conditions on land) liver/kidney adaptations, skin excretion, large intestine absorption, salt glands, excrete urea and uric acid, behavioral adaptations, etc.
- Body Support
(difference in net gravity effect) reinforced or hydrostatic skeletons, muscular walls, appendages, etc.
- Food Acquisition
(due to absence of “filter feeding”) specialized nervous and sensory systems, legs, claws, behavioral adaptations, etc.
- Temperature Fluctuations
(without water’s modifying effect) physiological adaptations (sweating, shivering, cardiovascular adaptations, endothermy), behavioral adaptations, morphological adaptations; counter-current principle, etc.
- Radiation (ultraviolet)
(due to damage to nucleic acids, cells, reduced immune function, etc.) pigmentation, body covering, behavioral adaptations, repair enzymes, etc.
- Sensory Differences
(due to lower density of air) balance, sound reception, stereoscopic vision, ear, etc.

Special Focus: Evolution and Change

1997 AP Biology Exam Free-Response Question 4

In a laboratory population of diploid, sexually reproducing organisms a certain trait is determined by a single autosomal gene and is expressed as two phenotypes. A new population was created by crossing 51 pure-breeding (homozygous) dominant individuals with 49 pure breeding (homozygous) recessive individuals. After four generations, the following results were obtained.

<u>Generation</u>	<u>NUMBER OF INDIVIDUALS</u>		<u>Total</u>
	<u>Dominant</u>	<u>Recessive</u>	
1	51	49	100
2	280	0	280
3	240	80	320
4	300	100	400
5	360	120	480

- Identify an organism that might have been used to perform this experiment, and explain why this organism is a good choice for conducting this experiment.
- On the basis of the data, propose a hypothesis that explains the change in the phenotypic frequency between generation 1 and generation 3.
- Is there evidence indicating whether or not this population is in Hardy-Weinberg equilibrium? Explain.

1997 AP Biology Exam Free-Response Question 4: Scoring Guidelines

Part A (maximum 4 points) *Choice of organism*

1 pt name of organism that could be used to produce the kind of data shown:

Drosophila melanogaster, or fruit fly, housefly, mouse, dog, cat, rabbit, slug, named diploid plant e.g. maize, pea, or Brassica; any other organism which reproduces sexually, is diploid, reproduces often, and has a reasonably short life cycle. (Peas accepted only because they may have been crossbred by the experimenter.) (not: long-lived, prokaryotic, fungal (except diploid yeast), polyploid, protistan, or human organisms)

1-3 pts Reasons for choice:

- large number of offspring/generation
- reasonably short life cycle/generation
- easily maintained organisms -or- easily controlled conditions
- clear, easily identified phenotypic traits/clear gender dimorphism
- interbreed freely (without inbreeding)

Part B (maximum 4 points) on the basis of data, hypothesis to explain change from generation 1 - 3; Mendelian genetics

- 1 pt correct formulation of a hypothesis; (if . . . then) logical statement
- 1 pt explanation of genotypic change from generation 1 to 2 ($AA \times aa \rightarrow Aa$)
- 1 pt explanation of genotypic change from generation 2 to 3
($Aa \times Aa \rightarrow 1/4 AA, 1/2 Aa, 1/4 aa$) or Punnett square
- or** 1 pt for only description of phenotypic change if neither of the above two pts are given
- 1 pt explanation of dominance (not just use of the word)/ explanation of heterozygosity
- 1 pt explanation of Mendel's law of segregation

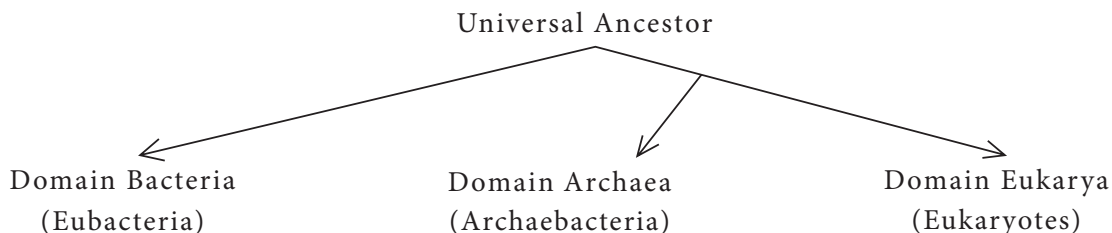
Part C (maximum 4 points) evidence for Hardy-Weinberg equilibrium

- 1 pt yes, with some correct explanation
- 1 pt recognition that, at equilibrium, allele and genotype frequencies do not change
- 1 pt describes Hardy-Weinberg equilibrium ($p^2 + 2pq + q^2 = 1$ after 1 generation)
- 1 pt calculation of p and/or q ($q^2 = 0.25$; $q = 0.5$)
- 1 pt elaboration: H-W only maintained if population is large, randomly mating, has no (net) mutation, no migration, or no selection for alleles in question (min. of 3 stated)

Special Focus: Evolution and Change

1999 AP Biology Exam Free-Response Question 3

Scientists recently have proposed a reorganization of the phylogenetic system of classification to include the domain, a new taxonomic category higher (more inclusive) than the Kingdom category, as shown in the following diagram.



- **Describe** how this classification scheme presents different conclusions about the relationships among living organisms than those presented by the previous five-kingdom system of classification.
- **Describe** three kinds of evidence that were used to develop the taxonomic scheme above, and **explain** how this evidence was used. The evidence may be structural, physiological, molecular, and/or genetic.
- **Describe** four of the characteristics of the universal ancestor.

1999 AP Biology Exam Free-Response Question 3: Scoring Guidelines

For full credit, a student must receive at least one point from each section I, II, and III.

Section I

Describe how this classification system presents different conclusions about the relationships among living organisms than those presented by the previous five-kingdom system of classification.

Maximum of 4 points from this section

- (1) Not all prokaryotes are closely related (not monophyletic).
- (1) Prokaryotes split early in the history of living things (not all in one lineage).
- (1) Archaea are more closely related to Eukarya than to Bacteria.
- (1) Eukarya are not directly related to Eubacteria.
- (1) There was a common ancestor for all extant organisms (monophyletic).
- (1) Eukaryotes are more closely related to each other (than Prokaryotes are to each other).
- (1) Correct description of the five-kingdom system.

Section II

Describe three kinds of evidence that were used to develop the taxonomic scheme above, and **explain** how this evidence was used. The evidence may be structural, physiological, molecular, and/or genetic.

Maximum of 6 points, 3 points from the first three descriptions of evidence mentioned and 3 from the explanations. The explanations must differentiate between at least two of the groups.

Descriptions	Explanations		
	Eukaryotes	Archaea	Eubacteria
Differences	Eukaryotes	Archaea	Eubacteria
Habitat - mostly extreme (halophilic, thermophilic, acidic)	-	+	-
Reproduction	Mitosis/ meiosis	Binary fission	Binary fission
Multicellularity exists	+	-	-
Nucleus	+	-	-
Membrane-bound organelles	+	-	-
Microtubules/microfilaments	+	-	-
Cell walls with peptidoglycan	-	-	-
Chromosomes: Shape Number Histones present	Linear More than one +	Circular One -	Circular One -
Ribosomes: Size Base sequence of rRNA	Large Similar	Small Similar	Small Unique

Special Focus: Evolution and Change

Structure of tRNA	Similar	Unique	Similar
RNA polymerase	Multiple types	Multiple types	Single type
Introns	Present	Some	None
Operon organization of genes	-	+	+
Initiator amino acid in protein formation	Methionine	Methionine	formyl-methionine
Phospholipids: Bonds Hydrocarbon structure	Ester Unbranched	Ether Branched	Ester Unbranched
Can be pathogens	+	-	+
Response to antibiotics such as streptomycin or chloramphenicol	-	-	+
Response to diphtheria toxins	+	-	-
Metabolism Can be methanogens	-	+	-
Enzymatic make-up differs Enzyme location differs Photosynthetic pigments differ	Must correctly describe what the difference is.		
Differences in gene sequences of DNA	Must correctly describe what the difference is.		
Differences in whole genome sequences	Must correctly describe what the difference is.		

Section III

Describe four of the characteristics of the universal ancestor.

Maximum of 4 points for this section. Described characteristics can earn one point each OR one point may be earned for a list of the first four correct characteristics.

Characteristic (possible explanations)

- (1) Small (surface to volume ratio, no internal transport system)
- (1) Unicellular (all functions self-contained)
- (1) Prokaryote (no membrane-bound organelles)
- (1) Had cell membrane (containment, protection, semipermeable)
 - (1) cell membrane made of a phospholipid bilayer (barrier)
 - (1) cytoplasm (different from external environment)
 - (1) DNA for the genetic material (**or** nucleic acid **or** RNA)
 - (1) mRNA for information transfer (common to all organisms)
 - (1) tRNA to carry amino acids and/or aminoacylsynthetase (common to all organisms)
- (1) ability to reproduce (asexual)
- (1) ability to mutate, adapt, or evolve through natural selection
- (1) ability to make proteins **or** had ribosomes on which proteins could be constructed
- (1) metabolism: carbon-based **or** organic; Energy transformations, ATP as energy molecule
- (1) enzymes for amino acid, nucleotide, and coenzyme synthesis as well as enzymes for glycolysis and the Krebs cycle (common to all organisms)
- (1) Heterotrophic/Autotrophic* with explanation (* not photosynthetic)
- (1) Anaerobic/aerobic with explanation
- (1) Aquatic with explanation

Special Focus: Evolution and Change

2001 AP Biology Exam Free-Response Question 2

Charles Darwin proposed that evolution by natural selection was the basis for the differences that he saw in similar organisms as he traveled and collected specimens in South America and on the Galapagos Islands.

- (a) **Explain** the theory of evolution by natural selection as presented by Darwin.
- (b) Each of the following relates to an aspect of evolution by natural selection. **Explain** three of the following.
- Convergent evolution and the similarities among species (ecological equivalents) in a particular biome (e.g., tundra, taiga, etc.)
 - Natural selection and the formation of insecticide-resistant insects or antibiotic-resistant bacteria
 - Speciation and isolation
 - Natural selection and behavior such as kinesis, fixed-action-pattern, dominance hierarchy, etc.
 - Natural selection and heterozygote advantage

2001 AP Biology Exam Free-Response Question 2: Scoring Guidelines

- (a) A maximum of 6 points may be given for part (a). A single point may be awarded for each concept that follows. Beware of anything that sounds like a Lamarckian statement.
- Reproductive potential** — the ability to over produce
 - Variability** — inheritable changes or mutations linked to variability
 - Limited resources** — biotic or abiotic
 - Competition** — intraspecific struggle for existence
 - Differential Reproduction** — reproductive success of variants
 - Generations** — time needed for evolution to occur
 - Elaboration** — expansion of Darwin's ideas such as the effects of environmental change or artificial selection or good, linked example

(b) A maximum of 6 points can be scored in part (b). A student may not receive a total score of ten without attempting to respond to three sections of part (b). A single point may be awarded for each of the following:

(i)

1 point Different species exhibit adaptations as a result of the same environment

1 point Correct descriptive example linked to biome and survival value or linked to natural selection

(ii)

1 point An inherited characteristic enables the organism to resist the effect of the toxin

1 point Specific example, mechanisms of resistance, or extensive elaboration or link to natural selection

(iii)

1 point A single population divides into two reproductively isolated populations or equivalent (use of gene pools)

1 point Role of barriers in speciation or discuss gene pool separation or link to natural selection

(iv)

1 point Define or describe the behavior

1 point Give a clear example of how this behavior enhances survival or link to natural selection

(v)

1 point Survival value of heterozygote over both homozygotes

1 point An example of how the heterozygous enhances the survival of the organism or link to natural selection

Contributors

About the Editor

Carolyn Schofield Bronston earned biology degrees at the University of Texas and has taught at two Texas schools: Spring Branch's Memorial High School and Tyler's Robert E. Lee High School. Traveling as a consultant for the College Board since 1979, she has served as a Reader and Table Leader for the AP Reading and is currently a member of the AP Biology Development Committee. She also serves as the biology content adviser for AP Central and is a past president of the Texas Association of Biology Teachers. She is a winner of the Presidential Award for Excellence, the OBTA (Outstanding Biology Teacher Award) for Texas, the Tandy Award, the Texas Excellence Award for Outstanding Teachers, and the 2004 Siemens Award for Advanced Placement.

Sean B. Carroll is professor of molecular biology and genetics and investigator with the Howard Hughes Medical Institute at the University of Wisconsin. From the large-scale changes that distinguish major animal groups to the finely detailed color patterns on butterfly wings, his research has centered on those genes that create a "molecular blueprint" for body pattern and play major roles in the origin of new features. He is author of the book *Endless Forms Most Beautiful: The New Science of Evo Devo and the Making of the Animal Kingdom* (W. W. Norton & Company, 2005) and the upcoming title *The Making of the Fittest: DNA and the Ultimate Forensic Record of Evolution* (W. W. Norton & Company, 2006). He is also coauthor of the textbook *From DNA to Diversity: Molecular Genetics and the Evolution of Animal Design*. He has received the National Science Foundation Presidential Young Investigator Award, the Shaw Scientist Award of the Greater Milwaukee Foundation, and numerous honorary lectureships. He was chosen as one of America's most promising leaders under 40 by *Time Magazine* in 1994. He is also past president of the Society for Developmental Biology.

Robert Dennison has taught all levels of biology during his 28-year career at Jersey Village High School in Houston. He began teaching AP Biology in 1985 and has been a consultant for the College Board since 1995. He has also been a presenter at local, state, national, and international science conferences. In 1999, he was a featured general-session speaker for the National Association of Biology Teachers (NABT) annual convention, performing as Charles Darwin. His portrayals of Darwin have garnered much acclaim over the past 15 years as he has performed throughout the United States as well as Canada and England. He was the 2003 president of the Texas Association of Biology Teachers (TABT). He has won numerous teaching awards, including the Outstanding Biology Teacher Award from NABT, Honorary Life

Membership from TABT, the Siemens Award for Advanced Placement, and an Advanced Placement Special Recognition Award from the College Board.

Sharon Hamilton has taught biology and chemistry at Fort Worth Country Day School in Fort Worth, Texas, since 1978 and has been science department chair since 2003. She began teaching AP Biology in 1982 and has been a consultant for the College Board since 1985, presenting workshops and serving as lead consultant for AP Summer Institutes in the Southwest region. She has also been a Reader for the AP Biology Exam. She earned her master's degree in biology from the University of Texas at Arlington in 1988 and her bachelor's degree in biochemistry from the University of Texas at Austin in 1978.

Kenneth R. Miller is professor of biology at Brown University. He earned his Ph.D. in 1974 at the University of Colorado and spent six years teaching at Harvard University before returning to Brown. He is a cell biologist and chairs the Education Committee of the American Society for Cell Biology. He serves as an adviser on life sciences to the *NewsHour with Jim Lehrer*, a daily PBS television program on news and public affairs. His research work on cell membrane structure and function has produced more than 50 scientific papers and reviews in leading journals, including *Cell* and *Nature*, as well as leading popular sources such as *Natural History* and *Scientific American*. He is coauthor, with Joseph S. Levine, of three different high school and college biology textbooks used by millions of students nationwide. He has received five major teaching awards and in 2005 was given the Presidential Citation of the American Institute for Biological Sciences for distinguished service in the field of biology.

Randy Moore is a professor of biology at the University of Minnesota. He edited *The American Biology Teacher* for 20 years and now teaches introductory biology and evolution. He has won a variety of awards for his teaching, research, and writing.

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