Darwin and the Future of Biology
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Transcript

Rick Shangraw – ASU Vice President for Research and Economic Affairs: [0:00] I am certainly more than pleased to welcome a true revolutionary of our time, Edward Wilson. [0:05] [applause]

Edward O. Wilson: [0:23] Thank you, Rick, Dr. Shangraw. [0:26] Friends, colleagues, members of the student body and of the faculty here, I thank you for the honor of giving this first Darwin lecture at a university that I hold in high esteem, which I consider already one of the best in America and possibly, well not possibly, but one of the fastest-rising already world-class and world-leader in a couple of the disciplines that I'm most familiar with.

[0:56] You're fortunate to be here and I feel honored to join you tonight. I also feel honored that you should come on what is certain to be one of our historic nights in this country's history, and I know that you are all with me in hoping that the better man wins the presidency tonight.

[1:20] [laughter, applause]

Edward: [1:23] You betcha! [1:30] [laughter]

Edward: [1:35] Politics aside we return now to the object of our attention tonight and the birth of the evolutionary view, which many consider, myself included among them, the most important in the history of civilization, namely the one that has given us a more solid view, one that has endured of humanity's place in nature and our origin and our future. [2:06] Many of you will remember Paul Gauguin's Tahitian masterpiece, in which he scrolled the title across the front of his canvas of the painting. It was "Where did we come from? Who are we? Where are we going?" Then, a French writer named Vercors kind of rephrased it or put it in a different way in one his books. He said, "All of man's problems come from the fact that we do not know what we are and what we want to become."

[2:42] I think, those are the key existential questions of philosophy, of human thought and, of course, the key to our destiny. So, this is what Charles Darwin did. He set us on the right course to think about these things deeply, critically, analytically, and to give us hope along with what followed in the Darwinian tradition that we would find the right path to self-understanding, which has eluded us for so many millennium.

[3:17] Now, I'll start with the iconic image of Charles Darwin. This is the iconic image taken in 1874 when he was 65 years old. He was born on February 12th, 1809, as mentioned: the same year and day as Abraham Lincoln. Let me pull this up here and make sure that I can be heard. Make a grunting noise if you can.
Edward: [3:44] OK? All right, thank you. In 1869, ten years after the publication of "On the Origin of Species," Darwin wrote his close friend the great botanist, Joseph Hooker, as follows: "If I lived 20 more years and was able to work, how I should have to change and modify 'The Origin' and how much the views on all points will have to be modified. Well, it is a beginning, and that is something." [4:16] Darwin lived 12 more years after writing this letter to Hooker, and he did manage to modify the theory of evolution by natural selection. In 1873, he added "The Descent of Man," in 1872 the "Expressions of the Emotions in Man and Animals" to address the evolution of instinct, and thus was complete, along with his first book, "Voyage of the Beagle," what can be fairly called the four great books of Charles Darwin listed here.

[4:56] In short, for those of you who would like to be prepared for an exam on this subject...

Edward: [5:04] ... I would imagine this is a good question to ask graduate students in biology. Just remember it as "The Voyage, The Origins, The Descent, and Expressions," and you've got it. Here is Darwin at the height of his creative power at about the age of 50 at the time he was writing the Origin of Species. [5:22] I would like to suggest the following rule about the age of peak originality and productivity in different kinds of thinkers. We have some of ASU's most important and effective administrators here to hear this. This is taken lightly, please.

Edward: [5:46] Mathematicians peak in their late teens, physicists in their late twenties, molecular biologists in their late thirties, evolutionary biologists, the field in which ASU is preeminent and flourishes, I would say in their forties, philosophers never. [6:08] [laughter]

Edward: [6:11] Darwin here is the master not long after his five-year voyage on the Beagle when he learned so much of the real world and his mind was churning with new information. That is as I know you students from ASU can understand. Here is the printed piece of the original first edition of "The Origin of Species." [6:42] The 130 years ensuing after the completion of the four great books has seen an enormous growth of the Darwinian heritage. Joined with cell molecular biology, this accumulated knowledge is today a large part of the substance of modern biology and science. Its centrality justifies the famous remark made by the evolutionary geneticist, Theodosius Dobzhansky, the foremost of the modern synthesizers of the twentieth century.

[7:19] He famously said in 1973: "Nothing in biology makes sense except in the light of evolution." In fact, nothing in science as whole has been more firmly established by interwoven factual information or more illuminating than the universal occurrence of biological evolution by natural selection.

[7:43] Further, few natural processes have been more convincingly explained than evolution through the theory of natural selection or as it is properly called 'Darwinism.' Great scientific discoveries are like sunrises. They illuminate first the pinnacles or the steeples of the unknown, then travel into its dark hollows.
[8:12] The first of these books that I'm citing, the four major works, have spread light, not just on the living world but fundamentally the human condition. They have not lost their freshness. More than any other work in histories, a scientific canon, they are both timeless and persistently inspirational.

[8:34] I can recommend to you all that you read them, and read them in the sequence that they were written. They are a good read all the way through, and they're so important. They have so much fresh information.

[8:47] The four great books again, which can be read as I said, as a chronologically flow in a well wrote narrative, tracing the developments of Darwin in thought across almost all his adult life.

[9:05] The first "The Voyage of the Beagle," is one of the literatures great travel books. It's richly stocked with observations of the kind that were to guide the young Darwin in his evolutionary world view. Next comes then "The One Long Argument" as he called it, for evolution by natural selection, arguably history's most single important book.

[9:30] Then, the "Descent of Men" addresses the burning topic foretold by Darwin in the "Origin of Species," when Darwin ventures laconically that light will be thrown on the origin of man and his history. On the writing of the "Descent," Darwin had become confident that natural selection would prevail as a theory, and he delivers his conclusions forthrightly.

[10:02] Finally, in the expressions of the emotions, Darwin draws close to the heart of the matter that concerns us all, the origin and nature of mind. He called it the "Citadel," that we could perceive and know a little about, but that could never be conquered by direct assault.

[10:27] Coming to the "Beagle," we see this epic voyage that covered five years; no TV, no computer, no telephone, no national elections, and just occasional letters. He had been commissioned by the British government to conduct a coast and geodetic survey of much of South America. It took five years, from 1833-1836, and continued on by circumnavigating the globe.

[11:08] Now, imagine, for a 21-year-old man, newly escaped from Cambridge University, isolated, on his own, with only his notebook, a few references, and the exploratory zeal of a true pioneer, setting forth on this great voyage. Now set before him was something far better than an unexplored world really, to navigate and record for history with unimaginable discoveries occurring at every turn.

[11:46] For his contemporaries, who had very little information except from travel books and lectures, it was a rare, detailed look at the exotic four corners of the world. For us and especially for those with any interest in natural history, it is a time machine, a vivid glimpse of the early 1830s as the world looked, and as nature looked.
Here then are a few scenes that Darwin saw as recorded by contemporary artists, some of them traveling on the Beagle with him. Rio de Janeiro, the Mole, and the Cathedral, he's trapped here for awhile, trying to get through the Portuguese customs, desperate to get to the famous Atlantic Forrest, which was distinct from the Amazonian Forest and one of the most beautiful in the world. He just can't get through these people. They won't let him go for a long time.

He writes in his diary, "I would kiss the dust from their feet, if I could just get through and visit the great Rain Forest." Here is the quarterdeck, in which he dwelled for most of his five years. Here is the Beagle as it looked at the time of the voyage - this is 1832, this drawing. Here is the Mole in Montevideo, modern day Uruguay.

Here is the Fuegan, that's the tribe living literally at the end of the world of hunter gatherers, and virtually he alone studied, because they became extinct not long after. Here is the remains of the great Cathedral of Concepcion in Chile, after the earthquake. You could see all of that. That helped him understand that earth changes dramatically, if slowly, and that one needs to think in long spaces of time in order to understand how the world was put together physically. As in fact Lyle had proposed earlier for geology, now Darwin's mind was set to propose it for the diversity of life on earth. And Tahiti, he was an earlier visitor there.

We now come to the master work on the "Origin of Species," evolution by natural selection as opposed to non-living physical systems. In recent decades, it has taken on the solidity of a mathematical theorem. It states simply that the population of organisms, a population that contains multiple hereditary variances in some traits - should we say red versus blue eyes in a bird population - and if one of these variances succeeds in contributing more offspring to the next generation than the other variance, a contribution can be by having lived longer, and getting to reproduce in the first place to producing more offspring during a period of time that one lives, then the overall composition of the population will change, and evolution has occurred, microevolution in this case further. If new genetic variance appears regularly in the population by mutation or immigration, that is new genes flowing in from individuals immigrating there, evolution never ends.

Think of red-eyed and blue-eyed birds in a breeding population, and let the red-eyed birds be better adapted to the environment, the population will in time come to consist mostly or entirely of red-eyed birds. Now, let green-eyed mutants appear, that are even better adapted to that particular environment than the red-eyed former winners of the natural selection race, as a consequence the species eventually become green-eyed. Evolution thus, takes two more small steps.

The full importance of Darwin's theory - and this almost absurdly, simple and elementary process conceived within it - could be understand better by realizing that modern biology is guided by two overwhelmingly powerful and creative ideas. The first idea is that all biological processes are ultimately obedient to, even through far removed in causal change, ultimately obedient to the Laws of Physics and Chemistry.

The second great principle is that all biological processes arose through evolution of these physical, chemical systems through natural selection.

The first principle is concerned with the 'how' of biology, 'how' an organism is put together and works. The second is concerned with the ways those systems adapted through
evolution, over usually long periods of time. In other words, the "Why" of biology, 'why' is a structure here. Then, exactly what is it and how does it work, are the two points of entry into modern biology.

[18:03] Knowledge addressing that first principle, the 'how' principle, is called "Functional Biology," that addressing the second, that of evolution by natural selection, is called "Evolutionary Biology." For years, I thought I had originated the term Evolutionary Biology, and I did in 1962, and to my great disappointment I just discovered that Julian Huxley used it in 1940.

[18:35] If a moving automobile were an organism, Functional Biology would explain how it is constructed and operate, while Evolutionary Biology would reconstruct its origin and history, how it came to be made, and the journey that it has taken thus far, but never would either of those great branches of biology predict where it is headed.

[19:04] The impact of the theory of evolution by natural selection, nowadays grown very sophisticated, and often referred to as the "Modern Synthesis," had become profound to the extent that it could be upheld, and the confidence to date has done so compellingly, we must conclude that life has diversified on earth autonomously without any kind of external guidance.

[19:35] Evolution in a pure Darwinian world is a magnificent creation laid before us of which we are part, but it has no goal or purpose. Unfortunately, that's the hard truth that we seem to be drawing. The exclusive driving force and random mutations sorted out by natural selection, from one generation to the next.

[20:03] Then comes the principle of speciation, of diversification. Darwin realizes that evolution has two dimensions. The first is descent with modification of entire process, the process of natural selection. This dimension was what he principally he had in mind by the expression the "Origin of Species," but he also included the multiplication of species, the splitting and divergence of populations during the course of the overall descent with modification.

[20:43] Darwin never fully came to grips with the second process however, that is Species Multiplication, called "Speciation," in other words the origin of biodiversity. But, it was soon clarified - this is a chapter not known even, well-known to even historians of science, but it was first clarified by Alfred Russel Wallace, the young man who independently hit upon the idea of natural selection, and that was in his 1865 studies of Asian swallowtail butterflies, he laid out the fundamental principles. By the beginning of the 20th Century, others especially the British zoologist E.B. Paulson, had worked out most of the details that were to stand to the present time.

[21:33] The triumph of the origin of species did not spring solely from its logic, it owed as much to the massive documentation that Darwin assembled for over two decades piece-by-piece, upon that theoretical formulation. His master work is impressive enough through the quality of his evidence alone. Much of what he wrote contains valuable information for biological researchers and general readers who open this book today.

[22:06] So, here we have the 1874 portrait of Darwin again, twelve years after the "Origin of Species." This is closer to the time he wrote the other great books, the last two great books. Darwin in a descent of man dropped the other shoe. Victorian society whose wrath Darwin so
feared as to hold back the publication of the "Origin" until 1859, might not have been entirely scandalized if he had only spoken of the descent of plants and animals.

[22:44] They were quite unprepared to except the descent of man from some "pre-existing form," as Darwin first delicately put it, and they were most certainly scandalized by the idea of 'apes' as ancestors as the evidence unfortunately appears to be firming up. Yet Darwin had to take that step, it was implicit from the promise that evolution is universal. The indelible stamp of evolution, he went on in the descent to show, is everywhere to be seen in human anatomy and evolution.

[23:25] But, in 1871, Darwin and other evolutionists lack the 'smoking' gun; there was no fossil evidence about man. Over a century of research, however, has turned up an abundance of pre-human and early human remains, enough to establish the broad outline and many of the early details of the origin of our species.

[23:51] The family of man, of human kind if you prefer, as it turns out and Darwin guessed, originated in Africa, the man was infuriatingly always right, and spread out over the rest of the world and later ways lined as descendent to the human clade evidentially split some six million years ago, from the separate line leading to our closest living relatives, the chimpanzees and the gorillas.

[24:24] At the time Darwin was piecing together the fragments of comparative anatomy, and made his case for human evolution, he was also creating the theory of evolution by sexual selection, a variant of natural selection. As he reported in the second and longer half of that book the "Descent of Man," "a great many of the most striking anatomical and behavioral gender differences of animals and human beings have risen by competition for mates, and mostly through seductive displays, but also and of equal importance, competition among males by display bluff and combat." Sound familiar?

[25:15] As an anthropologist, Darwin was able to start with dramatic examples in the insects. Here, for example, is the sex dimorphism, the two forms of male and female. The male horned, and these horns are used in battle among males, and the females then approach and see who won, and then something similar in the newts, armored males and unarmored females, and lizards, and another kind of lizard.

[25:52] Here they use - you can see these in Florida and through the West Indies very easily - the males display with brightly colored 'dewlaps' they're called, which they open out like a fan and display in the presence of either male or female. And birds - here is the common ruff of Europe to illustrate the same thing - and then the 'ne plus ultra,' the birds of paradise.

[26:27] The expression of the emotions in men and animals to come to the final of Darwin's tetralogy is both an old-fashioned description, a treatise, and at the same time, the most modern of Darwin's major works.

[26:46] On the one hand, it provides a straightforward catalog of human postures and facial expressions - that might have been written in past centuries, in accounts of human behavior - on the other hand, the book is rich and accurate enough in interpretation to have served as a part of the foundation of modern psychology.
Darwin is, in Conrad Lawrence's words, "The patron Saint of psychology." His pioneering contribution was this, he treated emotions, and the way emotions are expressed, as products of evolution, by natural selection.

The expressions of emotions are, in a nutshell, instinct, and as such, they have evolved by natural selection in essentially the same manner as traits of anatomy and physiology. That was the great advance of emotions - expression of emotions in man and animals.

Here, we see a series of familiar examples, which he provided in that book. Displays by dogs, our closest companions, illustrating what we interpret as all of the emotions, but we understand them in detail and exactly in order to... and can thereby handle it. And the displays - this is an aggressive hen - so many birds.

He went on to study studies that had been made by anatomists of the human facial muscles, in order to understand the exact structure that made facial expressions possible and in such great variations to form virtually a language by itself.

He was one of the first to use photographs in a textbook. He got professional actors, to express their emotions, which I think anyone here, after 140 years can readily understand. Using these volunteers and professional actors, an approach one might say was a first, to bridge science, biology and the arts.

Now, let me turn 180 degrees and look forward briefly, before I conclude, to the future of biology, as I see it. This will not be an account, however brief, of biotechnology or applied genetics of cancer research. All of these deserve lectures all on their own, but rather, will have to do with the foundations of biology and the major directions that it's going in.

I think, the most important feature of biology, at the present time, is that it is coming together. Enough of it's disciplines have been linked by cause and effect explanation, to suggest how some of the framework of a unified biology can be visualized and perhaps realized in this century.

At it's foundation, biological knowledge conforms to the two principles, as I mentioned before, which are arguably firm enough to be called - here I'll step out in front a little bit - they can be called laws of science. That is, they're all-inclusive and with no proven exceptions and their consequences can be followed wide and deep.

The first is that, to remind you, that all of the entities and processes defining life are ultimately obedient to the laws of physics and chemistry. The second, still in contention due to claims of counter examples, is that all the diagnostics entities and prosthesis of life, and all of its diversity have evolved by natural selection. The conformity of the life processes to the physical sciences undergird molecular and cell biology.

Its universal application has been challenged by arguments for a supernatural intelligent design. Its champions may think that scientists are in some kind of conspiracy to keep ID up. But, I want to take this opportunity for those of you who have been aware of this little fisher in the culture wars that the opposite is true.

Every researcher, every scientific researcher would love to discover an extra-somatic supernatural force. It would be one of the greatest achievements in the history of science.
[32:00] They would have to ask a rule of the Royal Swedish Academy for one hundred Nobles to be given in that one year. The problem is that not a trace of evidence has ever been found nor has a need for such a theoretical place marker arisen from any database.

[32:24] That is the argument incidentally of the intelligent designers that we can't understand all the biology and, therefore, the gaps where we haven't really filled in, and they are numerous and enormous, that we haven't filled them in yet. They are too difficult to fill in and, therefore, must represent a supernatural intervention causing that.

[32:50] Now, when this is taught in schools, if it's taught in schools, making that part of religion - and that's what it is - part of scientific teaching, then there is a great danger to the religion that support it, for the reason that those gaps are filling in and they are filling in fast.

[33:09] Look, this is what scientists do is fill in these gaps. That's our profession and we are very good at it. So, one system after another has fallen, with new technologies, new experiments, and new ways of looking at it. Re synthesize and that's how biology is progressing.

[33:31] Now, the same can be said for the exclusive role of natural selection in genetic evolution. The ruins of all alternative series of evolution, from Neo-Lamarckism to punctuated equilibrium litter the archives of past decades.

[33:52] The mysterious forces, they imply unspecified and extraneous to the empirical evidence of genetics. Do not aid evolutionary theory. They do not add up.

[34:07] Multiple level selection, working at different levels of biological organization, is going to be a large party of the future of biology. One trait favored at one level, this favored at another or favored is what we must now piece together as, the key to the origin of very complex systems.

[34:35] A familiar example of multi-level selection is inherited predisposition to certain kinds of cancer in allele a form of gene predisposing the unregulated growth of cells is favorite at the level of the cell. Cancer cells just do awfully well; they are Darwinian winners as long as long as they have the organism to live in. But, they are disfavored at the level of the organism.

[35:05] So, we have the natural selection - or however you want to term it; medical selection, it's natural selection really - opposing, two levels opposing, and a selection occurring of different kinds opposing each other in determination of the fate of a single allele.

[35:24] Organisms with cancer are host to multitudinous healthy offspring of the original mutant cell, yet they lose in competition with healthy organisms that lack that cell.

[35:38] So, multi-selection throughout biology puts selections at adjacent levels cell organism often in opposition. To achieve a new level - for example, a multicellular organism, a more complex organism or a complex society - requires some degree of altruism on the part of individuals at the lower level.

[36:07] I might add that this key issue of the levels of organization - going from organism to society, especially superorganisms, tightly organized societies - that's the field of research, very fundamental and rapidly developing - to give kudos to ASU and the planners here - that is the one in which ASU is the world leader, right now.
This type of organization is promoted by group selection as opposed to individual level selection. Such major transitions across levels of organization have very rarely occurred. This is an extraordinary circumstance event. In evolution, it's taken long periods of geological time to be achieved even once. For example, the origin of a eukaryotic organism - that is one that has membranes around the nucleus and other organelles within the cell - took, from the beginning of life, over 3.5 billion years ago, to 1.5 billion years ago - two billion years, approximately, to achieve. And there were astronomical numbers of cells operating, evolving, dividing, and it took all that time to finally achieve it.

The origin of insect superorganisms is a subject that Bert Hoelldobler and I will be talking about tomorrow, and the subject of our new book. In particular, the tightly knit colonies of ants and termites and other forms of social insects was not attained at all during the first great insect burst of evolution in the late Paleozoic era, which was between 350 million to 250 million years ago. The world was teeming with insects, diversifying, of all kinds - flying, burrowing, and all - and not once did they ever produce, in 100 million years, all those insects on the surface of the earth, anything like an ant colony or a colony remotely like it, so far as we can see.

It was not until the early Cretaceous periods, somewhere between 200 million and 140 million years ago that we finally saw the origin of the social insects - ants, termites and others. And when they originated, then they became the dominant insects on Earth, just as, when we finally originated we became the dominant mammal.

It is in the major transitions of evolution that biology will come, predominantly, to dwell. Let me repeat that because it's very important. The major transitions of evolution that I've just described - the study of them, how they were accomplished, what they are, what the emergent properties were going from one to the next and, therefore, what pre-dated, ultimately, us - it is there that the biology will predominantly come to dwell.

The age of reductionism in biology has largely passed. The great era of molecular biology covered almost exactly the second half of the 20th century, and that was one of the great episodes of scientific advance. It was largely reductionistic and will continue to be cutting-edge, but its dominance in studies and conceptions of how to study biology will gradually make way in part for the new approach.

The big problems are those that require a re-synthesis of reduced systems - how to put a cell together, how to put an organism together, how to put a society together. As more biological systems are understood, and with them the major transitions, common principles of emergent evolution should become apparent. In other words, that's what we're seeking right now, that's the horizon.

There appears to be no way to create a unified theory of biology at the present time, but that possibility, that achievement, awaits the more empirical information than we now possess, but we hope to possess. And that's going to require enormous amounts of hard work with real organisms, and it will be exciting every step of the way.

Contemporary biology, then - and this is particularly for students wondering how to get into it, and there are several major points of entry to get into this field. Contemporary biology has been addressed by two different strategies of research, and I'm going to tell you what they are.
The first strategy follows the dictum that for every problem in biology, there exists an organism ideally suited for its solution. Now, the bacterium E. coli thus triumphed for molecular genetics, along with Drosophila. The nematode C. elegans triumphed for the neuronal basis of behavior in genetics. The honeybee triumphed for the instinct and self-organization of insect societies - and that is where ASU, I might add, is leading now, so that's funny.

Chimpanzees, studies of the intricate details of chimpanzee, origination of the societies and interactions and subtleties of behavior and relations, and their abilities, cognitive abilities - chimpanzees are now becoming the model, are the model, for the evolution of the mind.

If those faithful to this dictum, the ideal organism for each problem... and it's a matter of finding what is the ideal organism. If we call those people who follow that strategy the problem-solvers, the second great tribe of biologists may be called the naturalists. Now, the research strategy of the naturalists is the inverse of the strategy of the problem-solvers.

I might pause here and just say, of course there are far more problem-solvers now than there are naturalists, and the reason is that they are richer.

[laughter]

Edward: And I want to clarify one thing about that. And that is, in the history of science - remember this - molecular cell biology, splendid developments of modern science are virtually wedded to medicine. In other words, they receive massive funding - and every cent is deserved, it should be doubled - primarily for what they promise to contribute to human health. So, molecular and cell biology are not rich because they've been very successful; they are very successful because they are rich. And this is worth bearing in mind as we launch into the exploration of life on the planet, the rest of life on the planet.

But anyway, to come to the strategy of the naturalists, it's the inverse of the first - for every organism, there exists a problem which that organism is ideally suited. So what are we talking about here? The procedure of the naturalists is to adopt a group of species, certain kinds of species such as conifers, diatoms, orb-weaving spiders, you choose it, and learn as much as possible about the group across all the levels of biological evolution, that I've just indicated, and organization. In other words, choose a group that you love.

There are people who can get an intense interest by a favorable experience and just intricate esthetics. Let's say dragonflies, or spiders, of course birds or conifers, and so on, let them develop that, studying it for it's own sake. All that information is going to be valuable in one way or the other. It is going to be a basis of a lot of future medicine, of public health, and biotechnology. So, it's all worth wild.

In the study, so much will be revealed by this type of naturalistic studies of new phenomenon, new twists on phenomenon, new relationships seen in the ecosystem. The expert on the group will be able to say - to everyone else, including the problem solvers - here is a new phenomenon, here is something strange, and then draw in the rest of the talent to pour in through that opening, to research and push biology further.

The overarching goal of the scientific naturalist is the complete mapping of biodiversity, while acquiring knowledge of it at each level of biological organization. The daunting nature of
this task is made clearer when an effort is made to estimate even approximately the number of species that exist on earth - plants, animals, and microorganisms.

[46:01] When the hyperdiverse microorganisms - bacteria, archaea, the fungi, and the small invertebrates - are included in the roster, it turns out that we have discovered and given some scientific name, probably, to 10% or fewer of the species living on earth. This is an unexplored, or a very poorly explored, planet.

[46:28] The third great goal then of biology - and it's even more daunting than finding out the total characteristics of a species and the total diversity of a species - has to be the history of all life. Because of the paucity of information on the living species, and their genomes still, the history, the family tree, is only a few of the best known groups, such as birds and flowering plants, can be drawn with any confidence.

[47:07] As to a record of all that has happened in all past stages, this infant discipline called paleobiology, as it's begun a journey, it will likely take centuries, millennia, it will never end. Problem solvers that work mostly in the laboratory, explain the proximate causes of biological phenomenon, usually those visible only at microscopic level.

[47:35] Naturalists working primarily in the field, also experimentally in the laboratory, stress the adaptation of biological phenomena to the environment. This approach is invaluable. It is absolutely fundamental to the future of environmental science and public health.

[47:55] Although the two approaches have seemed at times to represent independent culture, in fact, they are complimentary. With more information, they are beginning to be fitted nicely together. The boundaries between them now are, in fact, being erased.

[48:16] Scientific naturalists as organisms and evolutionary biologists use the methods of molecular and cell biology. Molecular and cell biologists grow more prone to address patterns of diversity in evolution. With increasing frequency, the two tribes of biologists will collaborate and research projects in this century.

[48:43] At the risk of oversimplification, it can be said that the naturalists discover the problems that the problem solvers solve. That was first said to me by Jim Watson, co-solver of the DNA structure and, at one time the great enemy and he speeches against natural history in this end of biology.

[49:05] Think of unified biology as being "T" shaped. The horizontal arm in the "T" is biodiversity at the level of species, and genetic strains within each species. One vertical arm, or shaft, is the model species - described before and addressed by the problem solvers - reaching from the population at that level of organization all the way down to the genes that describe the traits of that particular species. At the present, perhaps as few as a hundred of such model species are in play - that is, have been well worked out. In a decade, there will be thousands, and then tens of thousands.

[49:55] And the process will accelerate as DNA sequencing grows ever faster and cheaper. Existing knowledge will be immediately available and its growth followed, in real time, as the encyclopedia of life. This all-inclusive electronic encyclopedia, with access free to everyone, anywhere, at any time, which is now in operation. And I'll put in a little advertising for this since
I've been so heavily involved in it. You'll find it with the web address eol.org. That will provide complete information in real time, as it's accumulated, for all of the species.

[50:36] A unified biology is a goal worth thinking about. Even if still far from within our grasp, biologists are stretching causal explanations across wider segments of the levels of biological organization and in broader arrays of species. In so doing, they are melding explanations of function and adaptation, as well as molecules themselves, with organisms and of species. As a result, the emphasis in research is shifting from one or two levels of biological organization, to all the transitions between levels of organization.

[51:24] The major questions of biological theory are those of systems biology. They take the following form: How do the elements and processes that define one level, emerge from the level below it, and why? And under what circumstances? Were the evolutionary routes followed the only ones? And, if not, were they at least the optimal ones that life hit upon over, literally, billions of years?

[51:58] A unified biology, to conclude, will be the one that maps the pathways from molecules to ecosystems and unbroken transits of causal explanation. It will disclose the still unimagined commonalities in these transitions, if such exist among them. And it will also provide insight to whatever different genetic codes and rules of transition are possible and which of those might even exist on other worlds, hopefully to be discovered as we continue to explore space.

[52:40] Thank you for having me. And let us salute Charles.

[52:41] [applause]

**Announcer:** [52:45] This lecture is part of the Arizona State University "Darwin Distinguished Lecture" series, and is sponsored by the ASU Office of the President, the College of Liberal Arts and Sciences, the School of Life Sciences, the Center for Biology in Society, and is a production of Grass Roots Studio. [end of audio]