

The Genome as an Ecosystem: Good News/Bad News Implications

Wes Jackson*

PROFESSOR MYRL DUNCAN: I'm going to assume that you all can read the program and understand that Wes has degrees from Kansas Wesleyan, K.U., and a Ph.D. from North Carolina State and that he's going to talk tonight about the genomes and ecosystem—the good news, bad news, and implications, but I'd like to, in my introductory remarks, be a little bit more personal.

I remember vividly the first time I heard Wes Jackson speak. It was a night, I don't remember the year, but I'm guessing it was twenty years ago or so on a cold November night, not unlike this one, at the YMCA camp down in the Flint Hills. Bourbon around the campfire tasted good when it was over. But it was one of those rare times in life where you knew you were in the presence of a true genius. And I'm not the only one who has understood that.

Not so many years ago, our speaker was awarded one of America's most coveted awards, the MacArthur Genius Grant. *Life Magazine* has called him one of the most important figures of the twentieth century—one of the two most important Americans of the twentieth century. And Professor McCulla told me just this afternoon that a document he had seen on his desk refers to Wes as one of the one hundred people that will most affect agriculture in the future of this country. Why all these accolades? Well, when Wes is done, you'll be able to answer that question for yourself.

But suffice it to say for now, it's because he's asking all the right questions, hard questions about the way we feed ourselves and because he's trying to resolve them. He's working on solutions at The Land Institute. I have asked him to bring some fliers, and I hope he did, about The Land Institute, if you don't know about his work. He works there with perennial crops, perennial polyculture crops, not these huge fields of Monsanto wheat that cover America, the total antithesis of a current operating procedure for agriculture in this country.

Now, whether or not Wes is ever going to feed us with eastern gamma grass or Illinois bundle flower, I don't know. And I confess it doesn't sound very appetizing. But I do know this—he's going to change the way we think about the way the world feeds itself by chal-

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lenging the paradigm and by asking those hard questions. It's because of all this that Wes has become a mentor and a teacher to many of my friends and to me, one whose mantras I think we have memorized and take in like the air we breathe and the water we drink.

To the environmental community in this state, and to frankly much of America, he's nothing short of an intellectual godfather. He's also a good friend who once read one of my law review articles and told me I wrote footnotes by the furlong. I, of course, blamed it on the editors. He's also a hellfire and brimstone preacher about causes in which he believes passionately. So it's my great honor and my pleasure tonight to introduce to you the Reverend Dr. Jackson.

DR. WES JACKSON: This is one of those times that I'm not going to say you read it right like I wrote it. It's a pleasure to be here.

I'm an alumnus, of sorts, of Washburn. I took one, three-hour course here one summer, and I think that must count for something. I think I probably got a B though, so don't ask me for any money. I'm the one who asks for money.

We're not talking about eastern gamma grass so much or Illinois bundle flower—well, Illinois bundle flower, yes, but now we're perennializing the major crops—the wheat and sorghum. And if we had 150 million dollars spread over fifty years, we could perennialize corn, which has really been the primary killer of our continent. Soybeans now cause more soil erosion than corn, but corn and soybeans, the two of them together, are the primary killers. We've got to do something about those two major crops in addition to the wheat and the sorghum and other species.

But the topic tonight is "The Genome as an Ecosystem." This is a topic that I presented in Australia in 1992. I put the idea out among a bunch of geneticists, plant breeders, ecologists, and others to get some thought going. And the more I thought about the topic, the more convinced I was that it's actually more than a metaphor. I think it's reality. The main value of the idea of the genome as an ecosystem is that it gives us a way to organize our thoughts about the appropriate role of biotechnology.

Biotechnology is a generic term. It's a big tent. We do biotechnology at The Land Institute. Our scientists are involved in what's called embryo rescue. A wide cross is made, an embryo forms, but the endosperm that nurtures the embryo and feeds it until it can capture sunlight does not form properly. In a lot of those crosses, the endosperm, which is triploid (three sets of chromosomes), breaks down, and so our scientists with little tweezers under a microscope rescue the embryo and place it in a gel in a test tube. Eventually the plant takes off on its own. Later, as a larger plant, it is transferred to a pot. Our

scientists can often back-cross that plant in both directions and re-establish that endosperm. That is biotechnology. What most people, of course, are considering when they use the term biotechnology is gene-splicing, which is what the gene jockeys do at places like Monsanto and DuPont.

Before we warm to the subject before us, it is worth considering that one of the problems we Americans have is that we seldom state our underlying presuppositions. Europeans do it ad nauseam. At a meeting of European scientists, it seems as though you wait fifty-five minutes to hear the underlying presuppositions. In the last five minutes they get to what they're going to talk about. On the other hand, I think we seldom do state our assumptions, or we don't do it adequately. So here are some reminders about a few realities that we often forget or ignore.

First, science is merely a way of organizing our experiences so that we can find out what's going on. We're pretty good at it. When we contemplate what science has brought us, we often think of those early giants of the Enlightenment, which began with Copernicus a little before the 1600s. These include Kepler, Galileo, and Newton, with his insights of gravity and the inventor of the calculus.

Later we think of Einstein and his equations and more recently the discoverers of plate tectonics or the cosmologists who tell us what happened and what is going on in the heavens. Our judgment in all of these matters is always dependent on organizing our thoughts. It's a taxonomic problem.

My friend at Harvard, the ecologist Richard Levins, who has pointed this out, has gone on to say that "ignorance is not passive absence of knowledge but an active structure that must be maintained by expenditures of energy." In other words, we expend energy in order to maintain ignorance. I think it is essential in our discussion about biotechnology for us to deal with this insight.

There is more to human society than how we come to learn about the world. Some scientists tend to think that any result stemming from the methods of science should be persuasive to all. Of course this is not true. There is the reality of cultural and regional history, the shared bias of a culture, often so powerful that education about the new reality is ignored.

I will give you a little story to illustrate this reality. Dick Lewontin, now at Harvard, and Carl Sagan, the astronomer at Cornell in the 1960s, went to Little Rock, Arkansas, to debate a zoologist who had done his Ph.D. at the University of Texas but was now teaching at a church-related college where his dad was president. It was a debate on evolution versus creationism. These two Jewish scientists with

roots in New York City gave their pitch regarding the evidence for evolution. The creationist gave his pitch for the creation story, the Genesis version. At the end, the chair asked for a show of hands in this church-related audience, and the majority of the hands signaled that the creationist had won. In the cab going back to the airport, Carl Sagan concluded, "This is a problem of education." And Dick Lewontin said, "This is cultural and regional history." As powerful as the methods and tools of science may be, many times, at least, cultural and regional history cannot be overridden. It's how you're raised, not logic, that divides us on important issues. This reality is worthy of some pondering. If education is more or less useless in dealing with cultural biases, what are educators to do? This is a question, to my mind, that goes beyond any available answers, which introduces another subject.

I have been telling university presidents and deans lately that no university is worth its salt if it doesn't feature questions that go beyond the available answers. They agree but, of course, are associated with faculties devoted to featuring questions for which there are answers. In my view if we're to get ourselves out of this nose dive as a culture that we find ourselves in, we better start raising questions for which there are no answers. This will give us more yeasty minds, for to embrace such a question can generate much useful thought and discussion that could provide new insights eventually towards a useful answer.

We scientists are guilty, too. The scientist, Karl Popper, has talked about "The Myth of the Framework." He said that we're so imprisoned into our frameworks that we can't communicate with those imprisoned in radically different frameworks. If we're imprisoned within our own framework, we're also imprisoned within our own theories.

So much for a few reminders. Now to more precisely consider the purpose of this conference. Jacob Monod, the Frenchman, is a famous molecular biologist of the early DNA era. Monod thought of evolution as tinkering, not engineering, since there's no evidence that evolution has a plan. Engineers plan structures. A tinkerer in his shop will work with what happens to be lying around. Various artifacts will suggest possibilities.

Of course, no tinkerer is ever without some engineering impulse, and no engineer is without the tinkerer's impulse. It is not an absolute. Nevertheless, some people are more tinkerers than engineers, and engineers are not defined as tinkerers. One could say that engineering is intelligent tinkering.

We all know that because engineers bring the lessons and laws of science to materials and energy relationships, they tend to make better products than tinkerers. Why shouldn't bioengineers try to improve on the living world assembled through tinkering? First off, most thoughtful engineers stand in awe of nature's designs and might ask, "How can this living world, made up by tinkering, result in elegant designs?" At least two realities must be considered to answer this question. One, natural selection is mostly about energy wars among life forms. This happens within and between populations. All life, like everything else, is forced to obey the second law of thermodynamics, the entropy law. That's one law that will not be repealed.

The second reason an elegant design can result from tinkering has to do with time. Genetic sorting going over millions and millions of years, genetic recombination through trial and error, through tinkering, has yielded elegant designs in all of those energy wars.

Evolution appears to have no boundaries in this tinkering process. A single genetic trait selected as a mechanism for one purpose in time is sometimes available to be used for another purpose later on. Our inner ear bones were once the jaw of our reptilian ancestors. Why nature's tinkering can beat modern engineering design is the time available to refine the product. A trait selected as a mechanism for one purpose at one time is often available to be used for another purpose later.

There is another subject that I want to insert at this point. It causes me to draw on a bit of my personal history. I finished my work in genetics for the Ph.D. in '66. Since that time, several discoveries have undone what my fellow students and I had been led to believe during our training. Much of what we were learning was beginning to be recognized as wrong as we were learning it. Evidence was piling up that didn't fit the accepted model. Special labels were assigned to these exceptions. As devotees to our training in Mendelian genetics, we "knew" about genes and how they were arranged on the chromosomes. We knew about the dominant and recessive. When we saw anomalies, we assigned words to them, modifier genes, for example. Another anomaly we attributed to "position effect." Some genes had multiple effects. We learned the word pleiotropy. These labels were part of our lexicon, all exceptions to the model.

This is 1966. I felt pretty smart. I'm ready to go. Give me some plants. We'll do something here. We know what to do. Well, these anomalies piled up to the point that phenotypic modification turned out to be the rule rather than the exception. The anomalies were the rule.

By the 1990s it finally became widely accepted that the genetic background influences how most genetic variance is expressed. My major prof would say, "Well, we all know that all genes interact." But we were just left with that. So we thought, "Well, they interact, but they're interacting in rather weak ways, so we'll go our merry way."

To identify these modifier genes is now a formidable challenge. And now, a very interesting reality is with us.

The very scientists at work in molecular biology, working with genomics, are the ones that have helped us understand the nature of these anomalies and that the anomalies are the rule, and yet it is the biotechnologists out of roughly the same camp that are still acting like it's 1966. How can that be? Does it have to do with the desire to market genes? I should add that the growing field of genomics should help us understand the nature of these anomalies. The problem at this point is that the story seems to get more complicated, not less.

In the mid-sixties, in our minds, the origin of genetic variation was clear. We knew there were hot spots on the chromosomes, that mutation was not random, that all variation was not random, and more. But the early triumphs of molecular biology were all around us and had a firm hold on our minds.

I took a course entitled biochemical genetics in about '65, not that long after Watson and Crick and the discovery of the double helix in '53. The code was being deciphered. They learned that the code had an alphabet of four letters and that each word consisted of three letters. With four letters of an alphabet and three to make a word, there are sixty-four possible combinations but only twenty amino acids. So the code had to be redundant. Some of the words coded for the same amino acid.

All over the country the code was being deciphered. We all ran to PNAS, the Proceedings of the National Academy of Sciences, to find out the latest. It was a hot time. We were all excited. In this biochemical genetics course, there was a professor who was really good who we all liked. On the way out of class one day he handed me a book entitled *Nucleic Acids* by Erwin Chargaff. We all knew the name Chargaff because of Chargaff's rule. He said, "Here, I think you'll like this book," as he thrust it at me. "Look especially at the play at the back of the book." This book on nucleic acids by Chargaff, at Rockefeller University, had a play he had written entitled, *Amphisbaena*. The play was a dialogue between two scientists sitting on a bench in Central Park in New York. One was an old chemist and the other a young molecular biologist. And if you get a chance, check it out of the library. It was absolutely prophetic.

The old chemist is telling the young molecular biologist a thing or two, and the young molecular biologist was like us graduate students, all a bit full of ourselves, thinking that we really understood what was going on. Well, the old chemist actually said at one point, “There’s a killing to be made on DNA.” And the young molecular biologist was effectively telling him, “This is a new age, old man. You better get used to it. There’s a new crop out here,” and so on.

The discussion that we’re having now is a discussion that only a very few were having then. And I have to say I was more like the young molecular biologist than the old chemist in that play, although the old chemist’s words did resonate somewhat.

Let’s go back to what we thought we knew. We knew that all variation was not random, but so what? “Yes, the DNA molecule expressed errors in replication, but overall it’s a stable molecule. Don’t worry about it. You’re going to get what you want.” We were able to push all exceptions aside because of the central dogma. The holy trinity was DNA, RNA, and protein synthesis, and that denied any contribution from the rest of the cell to be possible. The rest of the cell is sitting there waiting for orders and new parts when necessary. What’s in charge of everything is DNA, RNA, and those amino acids.

We also thought the sequence of bases in DNA was autonomous. I didn’t know it then. I didn’t know it until decades later that my intellectual father was René Descartes from 1620. It was René Descartes that placed priority on the part over the whole without acknowledging the inner penetration between part and whole—that whole influences part as part influences whole. Reductionism was an easy religion to embrace, and we embraced it. Levins and Lewontin’s book, *The Dialectical Biologist*, helped me understand this reality.

Imagine the rip tide that went through our thought processes when we learned that information does not flow in one direction in the cell. When stressed, the genome can become unstable. Well, yes, okay. When the stress passes, it can switch back to stability. Wait a minute. Cells can generate variability in local regions of the genome. What’s going on here? By now, if not before, it should have been clear that we were profoundly ignorant. And, so, I’m back to the way I opened this topic.

As ecologist Richard Levins said, “Ignorance is not a passive absence of knowledge but an active structure that must be maintained by expenditures of energy.” The first time I pondered that sentence, a dark cloud came over me, but then I read on, “Structured ignorance is a prerequisite for knowledge.” Before you have knowledge, you have got to structure ignorance. You have to partition it out. Therein, I

believe, lies the fundamental problem in the argument today on biotech.

What is before us today is “the myth of the framework” problem. We are so imprisoned into these frameworks, Popper said—and remember I mentioned this earlier. We cannot even communicate with those imprisoned in a radically different framework. “Imprisoned within our own frameworks, we’re imprisoned within our own theories.” In the era of biotechnology—as a new ship of promise—the framework becomes the context for discussion. It is worth remembering that several other ships of promise in the area of crop improvement have come and gone leaving little of value in their wakes. How much being imprisoned within a particular framework has to do with it deserves looking into. Here are a few examples.

In the 1930s, great hope rested on the possibilities of polyploidy, a reality more prevalent in plants than animals. Early on there was a widespread belief that gigantism accompanied multiple sets of chromosomes. Some thought that we will simply double chromosome numbers through using colchicine or some other method.

Then came the era of radiation genetics. I remember biology departments in which an office or lab would have “Biophysics” on the label. A visit to some of those places later reveals little holes where the nails were. That label is down. Something else is in its place. Something did come out of that era but often not what we were expecting.

There was the quantitative genetics era. I remember coming home one Christmas and telling my farming brothers that the day would come when we wouldn’t need to get hybrid seed corn because the quantitative gene would give high yields and that a farmer would be able to save his own seed. The theory was worked out, and it had been adequately tested. Why is it that we still have the seed houses when it would be so easy to have our own seed? We don’t need these hybrids.

Now we are forced to start looking at the inner penetration of the social-economic realm, and we can readily see that it isn’t simply a matter of science and technology. There is the big equation that includes science, technology, and the heavy hand of economic control over policy. That is more of a holy trinity than DNA, RNA, and the code.

Consider the typical genome. Whether we’re talking about a corn plant, a mouse, a human, a redwood, a whale, or a cockroach, most of the genes are small-effect genes. Monsanto wants to market large-effect genes.

From conception through the first five years, most of the diseases that affect children involve single genes. In the twentieth century we've figured out a way to wipe out a lot of childhood diseases. At the other end of our lives, the diseases that get us are multifactorial, that is multiple genes.

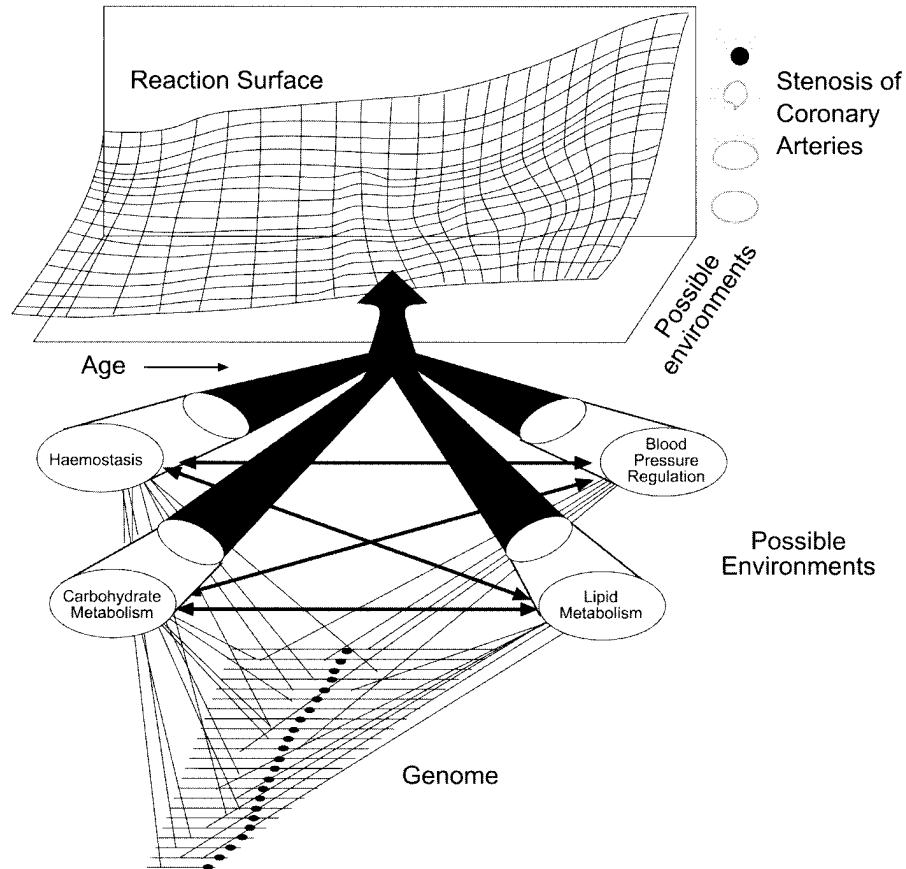


Figure 1. A reaction surface illustrating how possible environments over time interact with a particular genotype (Redrawn from Sing et al., 1996).

Figure 1 shows twenty-three chromosomes of the human. Imagine each one of those dots being associated with heart disease or the chance of having a stroke. Everything including blood pressure regulation, lipid and carbohydrate metabolism, haemostasis, and more, is involved. That is the genetic component. Many environments are a part of reality for this genotype. Do you smoke? Do you exercise? Do you overeat? As you age, you move through several environ-

ments. The reaction surface shown in the figure shows the interaction genotype.

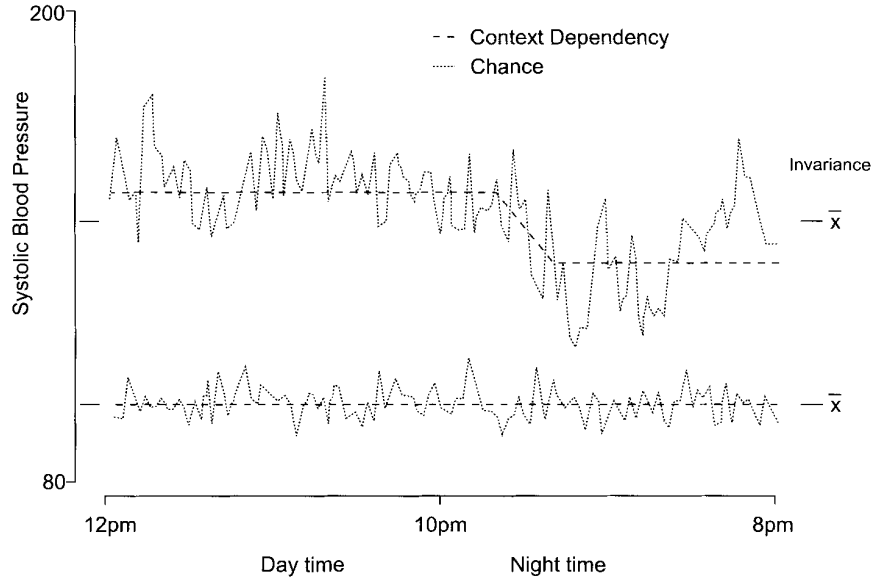


Figure 2. Systolic blood pressure of two people in which the individual with the higher average blood pressure is at higher risk of stroke or heart attack (CF Sing, unpubl.).

Now, let's say that you look inside. Everybody assumes that we have to keep our blood pressure down in order to avoid stroke or heart attack, but look at Figure 2. Here is the blood pressure of two individuals. The individual represented at the top cycles deeply for high blood pressure. The bottom one is lower on the average and has little fluctuation. The one most likely to have a stroke or heart attack is the bottom one. Why?

MALE SPEAKER: You don't blow out the cobs.

DR. WES JACKSON: That's right. Keep yourself toned up. We all know the first thing they do when we go to the doctor is take our blood pressure. The story is more complicated than we have been led to believe. With complication in mind, here are three words: invariance, context dependency, and chance.

Humans are given to talking about ideals. So now let's talk about an ideal genotype. We'll start with a child. Children have both carbohydrate and lipid metabolism and blood pressure. See the child in Figure 3 on the left and the relative size of ovals. Now compare them to the adult on the right and note the differences in the size of the ovals. Different genes are at work. Let us say we wanted to build a

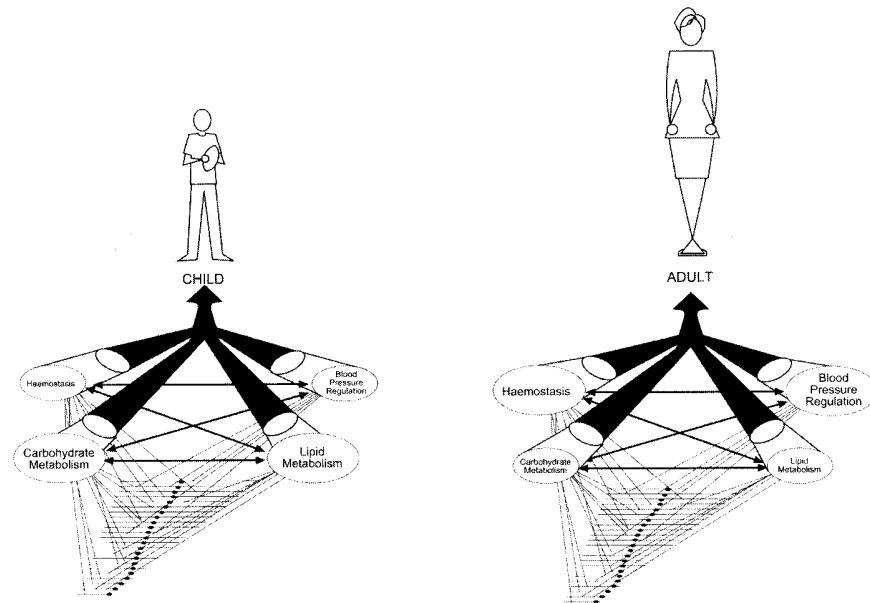


Figure 3. A beneficial genetic quality at one age may not be so at another (Redrawn from Sing et al., 1996).

super human. A super human for what age? Do we want a superior child or superior adult? It's context dependent.

Now think about Monsanto wanting to market a gene. Market a gene for what performance? A plant breeder can select for resistance to a particular insect and get very strong resistance to that insect, but a wise breeder also is looking at other factors. Superiority in one direction may be at the cost of inferiority in another.

The Aristotelian view dominated genetics from around 1900 to the 1990s. In the 1990s we began to talk about complex adaptive systems. It's not genes or environment. It is both. We now know that a cell can organize the DNA within it and even how the DNA is expressed.

A few years ago I took a picture of the cathedral of San Marcos in Venice. A few years earlier, Steven J. Gould and Richard Lewontin at Harvard had written about the cathedral of San Marcos as an example of the mistakes that geneticists often make. The cathedral has arches, and between the arches is what's called a spandrel. It is the arches that hold the church up. To keep the rain out, the spandrel gets bricked. With brick in the spandrel, humans often plaster the inside, and in Italy an artist comes along and paints a fresco. A lot of genetic characters are like spandrels. They are not genes that have been under selection pressure. What's been under selection pressure are

the columns in the arches. The spandrel is a derivative. And so, when geneticists ask questions such as, what is the adaptive value of that particular characteristic, we have failed to realize that a partial characteristic may have no adaptive value at all. It is like a spandrel, a derivative of the arch that has been under selection pressure.

The story gets complicated. Let's say that south of Venice, around Padua, in Italy, someone says, "Have you seen that cathedral of San Marcos? We should have a church like that." And a member of the committee says, "Why?" "Well," he replies, "I love frescos." If they're to have frescos, they need at least one spandrel, and spandrels are derivatives of arches.

Let's say that Monsanto wants to market a fresco. Multiple genes will be involved because of all the other architecture that is necessary. Recall my earlier remarks about small-effect genes. In order to get at that one derivative, how much of the genome should Monsanto be allowed to own?

The Aristotelian view before 1990 is still with us. We're going to make a lot of mistakes in assuming that one gene over here can be spliced in over there and that it will do over here what we want it to do.

I'll tell you a real live story. Don Duvick, former Vice President for Research at Pioneer in Des Moines, is a good friend, a member of the National Academy of Sciences, and a distinguished geneticist. I was talking to him about some of these issues once, and he said something like, "You know, some of these genes, we splice them in, and they work for a while. But after a while, it's like tar is smeared over them." The genetic background shifts.

Populations crash in the experimental plots. Pioneer is smart enough to test and retest and test again before they release a variety. We all remember the corn blight that wiped out nearly a third of the corn population in 1970. That blight was due to a gene that was not on the chromosome but in the cytoplasm.

Sewell Wright was a brilliant geneticist who caused two generations of geneticists to think about the adaptive fitness of a population. It was analogous to climbing a mountain to reach an adaptive peak. Richard Lewontin said that reality is not like climbing a hill or a mountain, but is more like walking on a trampoline. The implication is that when you walk on a trampoline, you put your foot down one place and you change the surface of your trampoline, and then you take another step and you change the surface again, and you take another step and you change the surface again. This is the way evolution works. Environments change, and populations respond to changing environments. If populations did not have that ability, we wouldn't be

here. For a couple of generations, geneticists were measuring where the foot went down in one spot and measured the adapting peak.

Roundup Ready soybean fields look good. So as my friend Charlie Sing said, "There aren't going to be any big whoops but lots of little whoops," and I would add that they will come mostly twenty years from now.

We started talking about different conceptual frameworks. Molecular biology has one framework. Genetics and ecology have another. We need both, but we've got to change the emphasis. We need to go from invariance to order, context dependence to interaction, and chance to disorder.

The biotechnology revolution will yield us insights into the nature of the genome. It will help our work at The Land Institute in perennializing major crops. The corn genome will probably be sequenced within two years. Molecular markers are being used now. The long distance runners will one day benefit from insights into the genome. I just wish I could live another sixty-seven years and see what gets turned over. I suspect that the next sixty-seven years will undermine much of what we think to be truth today.

What does what I have said thus far add up to? Simply this. As we anticipate what we will need to put on the table to eat in the coming decades, we had better put on the table to discuss the two competing emphases of agricultural research.

An increasing emphasis in biology generally is to better understand the molecular basis of life. The pecking order within the sciences, at least since the time of René Descartes, has the most prestige assigned to those who are the most reductive. It is called physics-envy. I have no objection to attempts to understand life at the molecular level. However, when it comes to agricultural research, a problem arises when we de-emphasize applying what we already know and anticipate applying what we hope to discover. This needs to be examined because the gap between our molecular understanding and standing grain crops has remained very wide from the early days of molecular genetics to the present. There is no clear signal even yet that the gap will fill soon for any of the crops. In spite of this reality, plant breeders are being replaced by molecular geneticists whose primary motivation is to turn out articles for high-profile journals. It could be argued that the Green Revolution agricultural research agenda has little to offer because it cannot be expected to achieve the kind of yield gains experienced from the 1960s to the 1990s. The embracing of biotechnology is a quiet admission that the former emphasis is bankrupt.

As we scramble to meet the food demands of a still growing global population and given the ecological assault to our croplands over our long agricultural history, it is time to turn at least some of our attention to the other end of the biological spectrum, away from the emphasis on the molecules of life and see what the ecosystem concept has to offer. Nearly all of nature's ecosystems feature perennial mixtures. Most generally fix more carbon than our agricultural fields, even with all of the fossil carbon subsidy (for fertility, pest management, and traction). The efficiencies inherent within the natural integrities that have evolved over time are greater than what we come up with precisely because selection pressures have been at work up and down the hierarchy of life over millennia. Here the breeder becomes necessary again. He or she can go to work, exercising his or her cleverness, to change the harvest index to increase yields, but this time with an eye to maintaining the integrity of the most sustainable kind of system to date.