Faith and the Human Genome

Francis S. Collins

Despite the best efforts of the American Scientific Affiliation to bridge the gap between science and faith, few gatherings of scientists involved in biology include any meaningful discussion about the spiritual significance of the current revolution in genetics and genomics. Most biologists and geneticists seem to have concluded that science and faith are incompatible, but few who embrace that conclusion seem to have seriously considered the evidence.

From my perspective as director of the Human Genome Project, the scientific and religious world views are not only compatible but also inherently complementary. Hence the profound polarization of the scientific and religious perspectives, now glaringly apparent in the fields of biology and genetics, is a source of great distress. Hard-liners in either camp paint increasingly uncompromising pictures that force sincere seekers to choose one view over the other. How all of this must break God's heart! The elegance and complexity of the human genome is a source of profound wonder. That wonder only strengthens my faith, as it provides glimpses of aspects of humanity, which God has known all along, but which we are just now beginning to discover.

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We are just on the edge of a whole host of developments spurred on by genetics that are going to require careful and deliberative thought. Those of us who are blessed enough to have a foundation for how we decide what direction to go, namely our faith, will need to be deeply engaged, if the outcome is going to be one that Almighty God would be proud of. Psalm 8 refers to the interface between science and faith.

> *"O Lord, our Lord, how majestic is your name in all the earth! You have set your glory above the heavens. From the lips of children and infants you have ordained praise because of your enemies, to silence the foe and the avenger. When I consider your heavens, the work of your fingers, the moon and the stars, which you have set in place, what is man, that you are mindful of him, the son of man, that you care for him? You made him a little lower than the heavenly beings and crowned him with glory and honor. You made him ruler over the works of your hands; you put everything under his feet: all flocks and herds, and the beasts of the field, the birds of the air, and the fish of the sea, all that swim the paths of the seas. O Lord, our Lord, how majestic is your name in all the earth!" Ps. 8:1–9 (NIV).*

As a scientist I love that Psalm because it really does speak from David's heart and describes the glories of the heavens, the amazing features of biology, and yet presents the real message, "How majestic is your name in all the earth!"

For almost twenty years, I have been a member of ASA. This is the first time I have been able to come to an annual meeting. I confess that I am humbled to speak about the interface between science and faith, because many of you have written in very eloquent terms about the intricacies of how we synthesize those components. My own understanding is still a work in progress. You may find places where you would like to challenge me, and I hope you will. This organization has been a constant source of

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The audio presentation is available on the ASA web site: www.asa3.org

encouragement to me over the course of those nearly twenty years.

Let's look at two very thought-provoking images that look very similar: the Rose Window from York Minster Cathedral, a beautiful stained glass window; and an unusual view of DNA, where you look at it, not from the side, but "down the barrel" so that the double helix in its spiral form is shown in a particularly beautiful aspect (see Figure 1). These images can represent two world views, which most people imagine are incompatible—the spiritual view and the scientific view. Alternatively, having those two world views synthesized within is a wonderful opportunity to appreciate each in a special way.

My Upbringing

I grew up in a home in the Shenandoah Valley of Virginia, where faith was not regularly practiced. My parents were very creative people, particularly in theater and the arts. They taught me at home until the sixth grade but not because of the desire to instill religious beliefs in me—as is now often the case in home schooling—but just to keep me out of hands of the county schools, whose teachers were perceived as being a little less than encouraging to the creative instincts of my mother's four boys. She inspired in me a desire to learn things. But I did not learn much about faith or gain a belief in God. I was sent to church at the age of six, for a very specific reason—to join the boys' choir in order to learn music. I remember an exhortation from my father, saying, "You're there to learn the music. There's going to be this other puzzling stuff about theology. Don't pay any attention to that. It will just confuse you." So I followed those instructions, and I learned a lot about music, but I had no clue what was going on in terms of the rest of those services.

When my friends in the dormitory at college quizzed me about what I believed, I realized I had absolutely no idea. It was fairly easy for me to decide I did not believe any of this stuff that some of the people were talking about—about Christ or other forms of religious faith. I assumed that it was all superstition. I had gotten along quite well without it and did not feel any particular need to embrace it.

I finished my undergraduate degree in chemistry and went on to work on a Ph.D. in chemical physics at Yale. After delving into that particular field and concluding that the only real truths were second-order differential equations, there seemed to be even less need for God. God did not seem to me like he would be a second-order differential equation. So I became a rather obnoxious atheist in graduate school. If you had gone to lunch with me, you would not have enjoyed the experience. I had absolutely no interest in matters of the spiritual life, because I did not think there was such a thing.

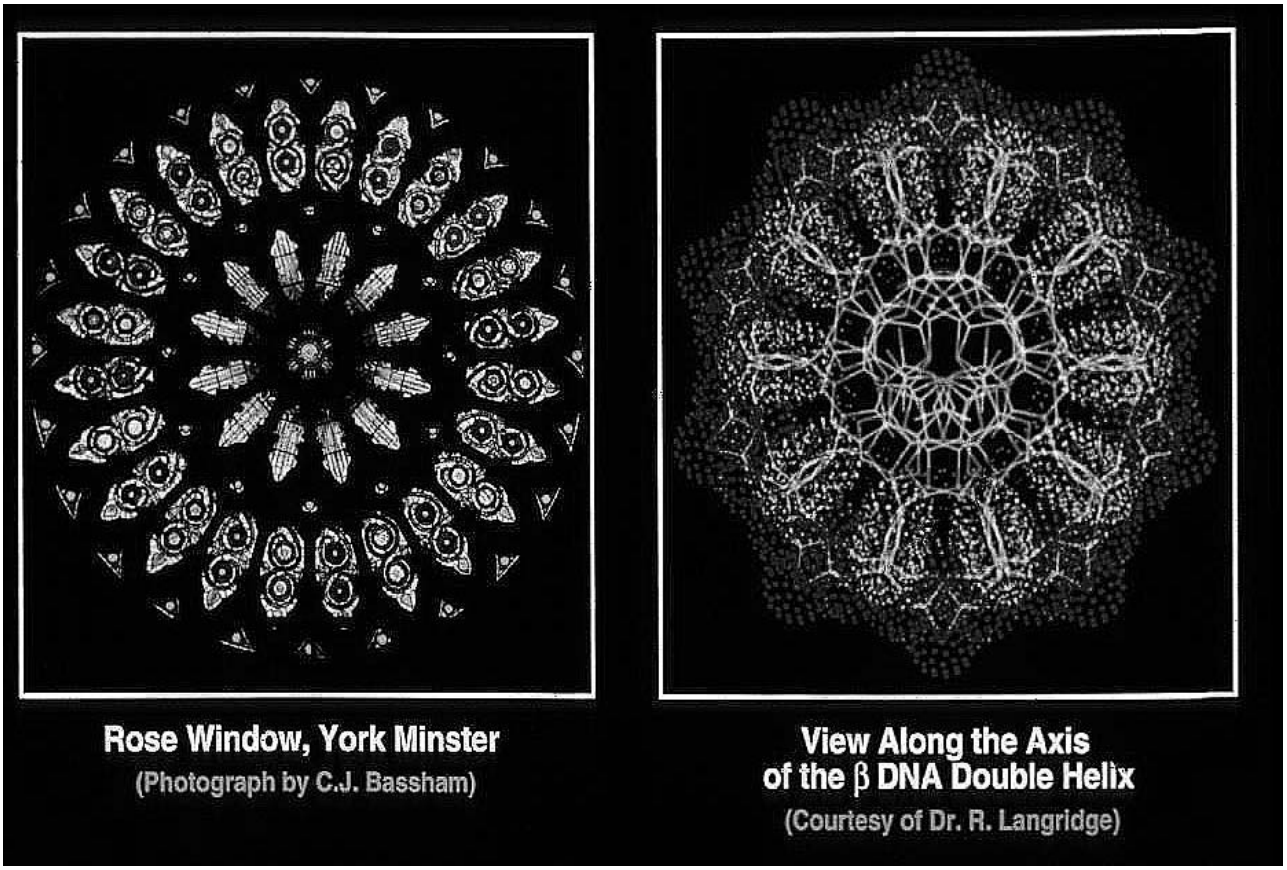

Figure 1.

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As a scientist, I had always insisted on collecting rigorous data before drawing a conclusion. And yet, in matters of faith, I had never collected any data at all. I did not know what I had rejected. So I decided I had better be a little better grounded in my atheism. I had better find out what this is all about.

But then, I changed directions. Deciding that biology was a lot more interesting than I had earlier thought, I determined to go to medical school. I wanted to learn that particular discipline in order to apply my scientific instincts in a human health direction. As a medical student, I encountered many people going through terrible suffering, stricken down with diseases not of their own making. Yet I could not help but note that some of these people appeared to have incredible faith. They were not angry with God, which I thought they should have been. If they believed in a God and he let them get cancer, why weren't they shaking their fist at him? Instead, they seemed to derive this remarkable sense of comfort from their faith, even at a time of great adversity. That response really puzzled me. A few of my patients asked what I believed; I stammered and stuttered and realized I was too embarrassed to say, "I don't know."

Then something came to me. As a scientist, I had always insisted on collecting rigorous data before drawing a conclusion. And yet, in matters of faith, I had never collected any data at all. I did not know what I had rejected. So I decided I should be a little better grounded in my atheism. I had better find out what this is all about. I challenged a patient Methodist minister down the street. After listening to my questions and realizing I was not dealing with a very full deck of information, he suggested that I read the Gospel of John, which I did. I found that Scripture to be interesting and puzzling and not at all what I had thought faith was about. But still I was not ready to consider the plausibility of faith; I needed more of an intellectual basis to get past my own arguments about why this was just superstition. For that purpose, he turned me to the writings of C. S. Lewis in his classic book, *Mere Christianity*. (Even today *Mere Christianity* seems to be the very best book to put in the hands of a young seeker who is trying to figure out if there is rationality for faith.) So I read *Mere Christianity,* and my materialist view was quickly laid to ruins. Particularly compelling for me was Lewis' argument about the law of human nature: Why is it there? Why is it universal? Also his argument: Would not this be the place to look for evidence of a personal, perfect, and holy God if there was one?

Sociobiologists will argue that human nature is all, in some way, an evolutionary consequence. That just never seemed particularly compelling to me as an explanation for the moral law: that we know somehow intrinsically, and yet often do not obey. Here is a wonderful sentence from Lewis:

> We find out more about God from the moral law than from the universe in general, just as you find out more about a man by listening to his conversation than by looking at a house he has built.

I realized that my scientific life was looking at the house, while I had never considered the conversation (the moral law) as evidence of God. I needed to study the Creator. After struggling many months, I realized that if there was a God, he was holy and I was not. I realized for the first time just how flawed a person I was. I then recognized what Christ did by providing a bridge between God and all his holiness and me and all my unholiness. Finally I gave in and surrendered—not perhaps, like Lewis, the most dejected and reluctant convert in all England, which is how he described his conversion. A rush of warm emotion did certainly not afflict me either. Rather, it was very much like walking into a complete unknown. God is good, and over the course of many more years of learning—and I am still on that road—my faith has become the guiding light of my life.

My scientific world view began earlier. I got excited about science as a high school student. I then got excited about chemistry, went on to medicine, and ultimately got excited about genetics as a way to unravel all the difficult mysteries of medical illness. I certainly never imagined that a call would come, where I would be asked to move to the National Institutes of Health (NIH) and become, of all things, a federal employee, and to direct a project aimed at mapping and sequencing all of the letters of the human instruction book. It has been a truly remarkable moment in history, and a moment that we have essentially now just passed through. It has been nine years since I came to NIH. I have had an incredible ride, and it ain't over yet! In many ways, we are at the end of the beginning. Where we are going next, I think, will have even more profound impacts on medicine and on our society. As Christians,

we bring a special perspective on how to usher in this new revolution in a fashion that has the maximum benefits and is done in the most benevolent way.

The Future of the Human Genome Project

The Human Genome Project (HGP) has now been going on for twelve years. All of the original goals of this project have been achieved three years ahead of the projected deadline of 2005. I am happy to say (and this plays very well inside the Beltway) that the HGP has all been done for substantially less money than originally had been projected. The HGP is one federally funded project that is ahead of schedule and under budget!

The applications of the HGP are going to be across the board, in virtually every area of medicine, because virtually every disease has some genetic component. Scientists have tended to emphasize those disorders that are inherited in very strong genetic ways, like cystic fibrosis, Huntington's disease or sickle cell disease. But virtually everything, except maybe a few cases of trauma, has some genetic component—diabetes, heart disease, mental illness, asthma, high blood pressure, and cancer. All of these tend to run in families, which means there are glitches in the DNA sequence that predispose people to be at risk.

Furthermore, we realize that there are no perfect specimens. This is the biological equivalent of original sin. We are all flawed; we have all fallen genetically short of perfection. There is no perfect DNA sequence; there is error in all of us. We all have probably dozens of places in our DNA sequence where you wish you had a T (thymine) but you really have a C (cytosine). Consequently that change makes you at risk for some disease. You may never be bothered by many of those risks because you will not encounter the environmental trigger required to cause the disease or you will not have the mix of susceptibilities to push you over a certain threshold. However, we all have stuff in our genome that is lurking and we carry the probability that our specific genome is going to cause us some trouble. We are on the brink in the next ten years or so, of being able to find out what those probabilities are for each one of us. The enormity of that potential is really serious to contemplate.

Now fifty years since Watson and Crick unraveled the structure of the double helix, I think it is amazing to contemplate the elegance of DNA carrying information—this language that is shared by all life forms. This digital code allows, in a very easily copyable form, such a massive amount of information to be carried inside each cell of the human body. This double helix DNA is made up of base pair letters. The whole human genome consists of three

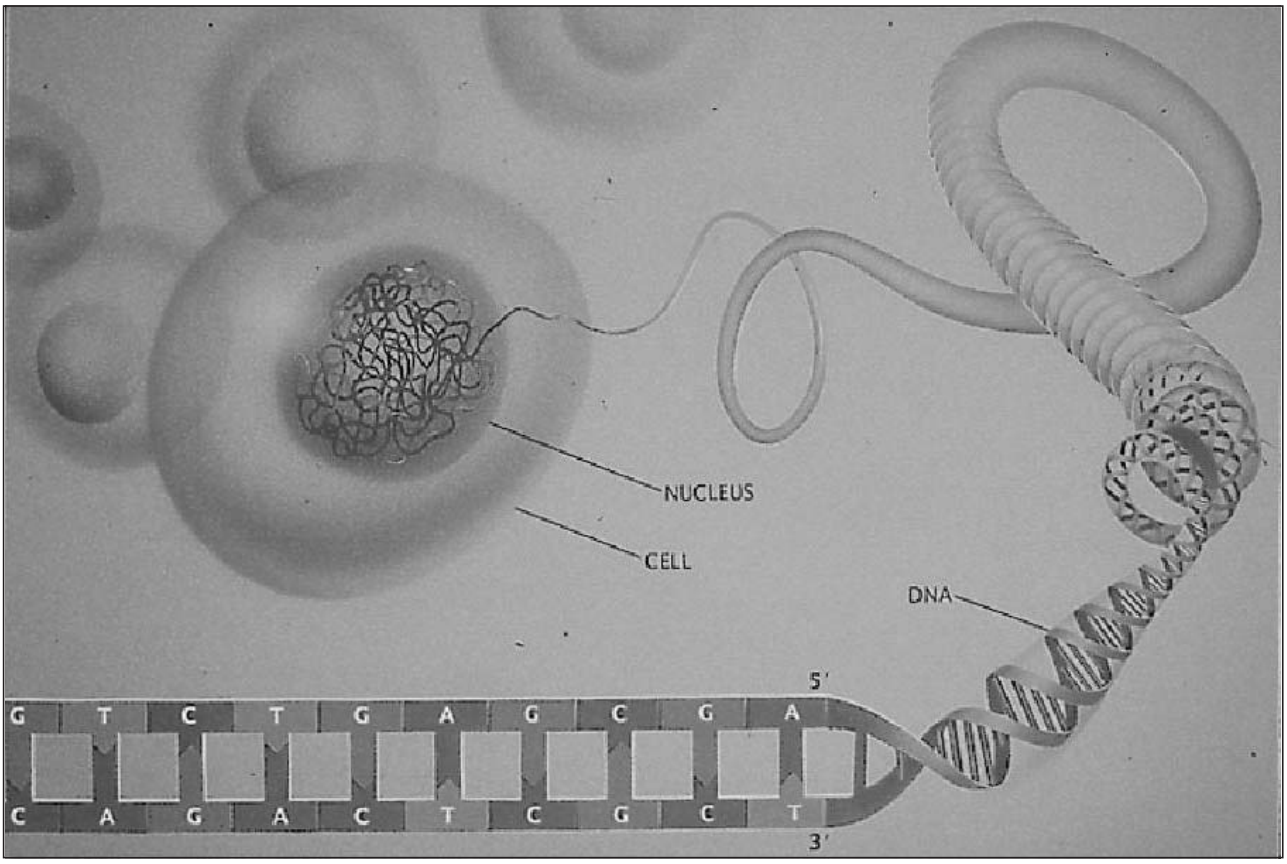

Figure 2. Double helix DNA is made up of base pair letters. The whole human genome consists of three billion of these base pairs all packaged inside of the cell's nucleus.

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billion of these base pairs all packaged inside the cell's nucleus (see Figure 2). While that is a huge number, it still seems surprising to me that it is a finite number. The three billion letters are able to direct all of the biological properties of a human being. Although there are a lot of biological properties in a human being, especially when you consider the complexities of development, yet this structure is sufficient.

The HGP aimed to read out all those letters and to develop techniques to enable us to understand what this language is all about—because otherwise it would all be gibberish. Thus while part of the success of the project has been reading out the letters, a major part has been developing other methods of understanding what's encoded within them.

We reached a significant milestone in 2001 with the publication in *Nature* of the longest paper it has ever published—over sixty pages of fine print, describing what we had learned with a first reading of a draft of the human genome sequence.[1] This was an exhilarating experience. I and about four dozen of my colleagues spent about six months doing almost nothing else but trying to figure out what we could learn from reading the human genome sequence. It is like reading the world's most incredible literature classic that no one else had ever read before, and getting to write the first critical review. Out of this we learned an incredible amount of things that were surprises! By the way, all of these data are available on the Internet. That availability of information was a cardinal principle of the international consortium that I had the privilege to lead. We wanted every bit of information released on the Internet. History will look back on the availability of information as a defining characteristic of the HGP. The release of this information enabled anyone with a good idea to begin working with the information immediately, rather than waiting for a long time or being required to put up large amounts of money in order to gain access to the information.

We discovered some pretty surprising things in reading out the human genome sequence. Here are four highlights.

1. *Humans have fewer genes than expected.*
My definition of a gene here—because different people use different terminology—is a stretch of DNA that codes for a particular protein. There are probably stretches of DNA that code for RNAs that do not go on to make proteins. That understanding is only now beginning to emerge and may be fairly complicated. But the standard definition of "a segment of DNA that codes for a protein" gives one a surprisingly small number of about 30,000 for the number of human genes. Considering that we've been talking about 100,000 genes for the last fifteen years (that's what most of the textbooks still say), this was a bit of a shock. In fact, some people took it quite personally. I think they were particularly distressed because the gene count for some other simpler organisms had been previously determined. After all, a roundworm has 19,000 genes, and mustard weed has 25,000 genes, and we only have 30,000? Does that seem fair? Even worse, when they decoded the genome of the rice, it looks as if rice has about 55,000 genes. So you need to have more respect for dinner tonight! What does that mean? Surely, an alien coming from outer space looking at a human being and looking at a rice plant would say the human being is biologically more complex. I don't think there's much doubt about that. So gene count must not be the whole story. So what is going on?

2. *Human genes make more proteins than those of other critters.*
One of the things going on is that we begin to realize that one gene does not just make one protein in humans and other mammals. On the average, it makes about three, using the phenomenon of alternative splicing to create proteins with different architectures. One is beginning to recover some sense of pride here in our genome, which was briefly under attack, because now we can say, "Well, we don't have very many genes but boy are they *clever* genes. Look what they can do!"

3. *The male mutation rate is twice that of females.*
We also discovered that simply by looking at the Y chromosome and comparing it to the rest of the genome—of course, the Y chromosome only passes from fathers to sons, so it only travels through males—you can get a fix on the mutation rate in males compared to females. This was not particularly good news for the boys in this project because it seems that we make mistakes about twice as often as the women do in passing our DNA to the next generation. That means, guys, we have

to take responsibility for the majority of genetic disease. It has to start somewhere; the majority of the time, it starts in us. If you are feeling depressed about that, let me also point out we can take credit for the majority of evolutionary progress, which after all is the same phenomenon.

4. *"Junk" DNA may not be junk after all.*

I have been troubled for a long time about the way in which we dismissed about 95% of the genome as being junk because we didn't know what its function was. We did not think it had one because we had not discovered one yet. I found it quite gratifying to discover that when you have the whole genome in front of you, it is pretty clear that a lot of the stuff we call "junk" has the fingerprints of being a DNA sequence that is actually doing something, at least, judging by the way evolution has treated it. So I think we should probably remove the term "junk" from the genome. At least most of it looks like it may very well have some kind of function.

Where do we go from this? In April 2003, which conveniently happened to be the fiftieth anniversary of Watson and Crick's DNA paper, we completed the whole human genome sequence. Talk about a milestone! The first draft was interesting but having the final sequence is of course the real point of the whole exercise.

For several years, we have been thinking about where to go next. Four areas of research are already under way and are going to expand considerably as we move into the next phase of genome research. These four areas are medical genomics, functional genomics, comparative genomics, and proteomics. Much work is now focused toward the medical applications and trying to make those happen. Although I do not have time to discuss each of these areas, proteomics is certainly a compelling opportunity that describes studying proteins on a global scale instead of one at a time just as we have been doing so successfully now for DNA and RNA in genomics. Functional genomics has many facets, for example, the use of DNA microarrays or DNA chips will give us the ability to understand how genes turn on or off as well as defining the pathways and networks that regulate gene expression.

Comparative genomics is both scientifically fascinating and highly relevant for the contentious discussions about evolution and faith. We have, in fact, not only sequenced the human genome; we also have sequenced a number of other organisms and a lot more are coming along very quickly. For instance, we now have a very advanced draft of the sequence of the laboratory mouse, the organism that is most extensively used by researchers in trying to understand human disease. Evolution tells us that humans and mice diverged about 80 million years ago. And yet, when you line up their sequences of the same homologous gene, you see very interesting evidences of similarity. Figure 3 is a complicated diagram showing this relationship. At the bottom is a schematic of part of chromosome 7 (CFTR is, by the way, is the gene for cystic fibrosis) but 500 kilobases away from that is a gene called CAPZA2 which is chosen at random. Across the top is a schematic of part of that CAPZA2 gene in the human. Each one of those funny looking symbols is one of these repetitive sequences. You need not concern yourself much about those; they are just different types of transposable elements and other types of repeats.

Now underneath there, what we are plotting is the similarity in the mouse homologue of this same region. How close is the sequence of the mouse to the human? Note that the scale goes from 50% to 100%. We are not bothering with things that are less conserved than that. So basically, this analysis allows you to look across and find a stretch where there is identity or close to identity over a stretch of 100 base pairs or so. Notice that each place there is an exon (numbered 2, 3, and 4), which is a protein encoding region

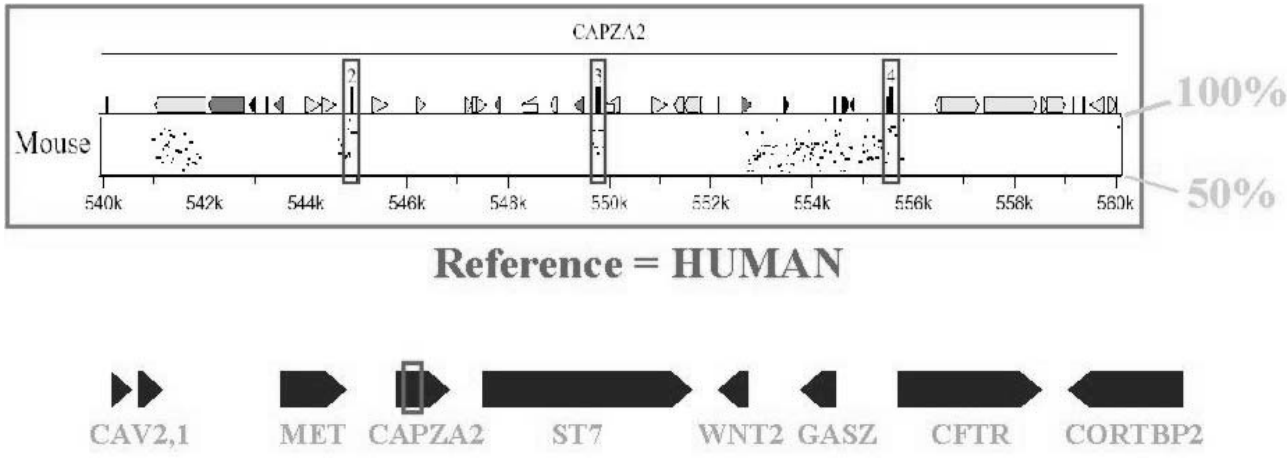

Figure 3 is a complicated diagram showing the relationship between humans and mice. At the bottom is a schematic of a small part of chromosome 7 (CFTR is, by the way, the gene for cystic fibrosis). About 500 kilobases away from that is a gene called CAPZA2. Across the top is a schematic of part of that gene in the human. The numbered boxes are the protein-coding exons.
Diagram courtesy of Dr. Eric Green.

Based on our current trajectory and on our understanding of the genome and its variations, we should be able to uncover the major contributing genes for common diseases in the next five to seven years.

of this gene, there is a little blip in the analysis that says the mouse region is strongly similar. Whereas in the introns, which lie between protein coding regions, there is less going on. But there are other interesting clouds of similarity that suggest maybe some other functional elements might be coding something important that we have not discovered yet. Certainly this kind of evidence is strongly in support of the evolutionary theory. I will come back to that in a bit.

It is not just a human/mouse comparison one can do. Eric Green at the Genome Institute has looked at this same region in many other species and, in fact, you can find this same CAPZA2 gene in everything from chimps down to zebra fishes and a lot of things in between (see Figure 4). Notice the pattern. The chimpanzee is almost 100% identical to the human, except the chimp has a deletion just before exon 2 that we do not have. Otherwise the match-up, as in most cases of human and chimp comparison, is about 98.5% to 99%. You can see that the baboon is starting to diverge. The cat and the dog and the cow all look a lot alike, and again if you look at the CAPZA2 exons, you will see that every one of those species has a nice conserved little segment there. But as you get further away to rats, mouse, chicken, two different kinds of pufferfish and then a zebra fish, about the only thing you see is the protein encoding regions, while the rest of the scattered noise goes away. Again, this is a very compelling kind of pattern in terms of what one would expect from evolution.

If you compare human and mouse regions where there are not close similarities, the matching is still above the statistical norm. One can identify lots of examples of transposable elements that are in the same place in the human and in the mouse, yet those transposers have been nonfunctional for more than 80 million years essentially as DNA fossils. It is very hard to see how that is *not* a very strong bit of evidence for a common ancestor for humans and mice.

In regards to medical genomics, I am going to make a prediction. Based on our current trajectory and on our understanding of the genome and its variations, we should be able to uncover the major contributing genes for common diseases in the next five to seven years. We have done really well finding the genes for diseases that are strongly inherited but we have not done so well for other conditions. That will change with the tools that the genome project has produced. Then the clinical implications will kick in. We will find the genes involved in susceptibility, those in turn will give us the ability to make predictions about who is at risk. For many of those conditions, a preventive medicine strategy of diet, lifestyle, and medical surveillance can be implemented to reduce risk.

Pharmacogenomics, another consequence of the HGP, is the ability to make a prediction about whether a particular drug is the right drug for you before you take it, or whether you are the one in one hundred people for whom the drug is going to give a side effect. Much of that variability in drug response is going to turn out to be DNA encoded. We are going to figure out how that works. So don't be surprised in five years if your physician will ask for a blood sample and do a DNA test before she writes the drug prescription. Ultimately, the goal of all this is to develop therapies that are more effective, with fewer side effects, then the often empirically derived therapies on which we now depend.

Therapeutics will be the ultimate medical payoff of our understanding of the genome—either as gene therapy or gene-based drug therapy. While gene therapy has gone through a pretty bumpy road over the course of the last three or four years, it is now looking more promising in at least a couple of conditions, mainly immune deficiencies and hemophilia.

My own view is that the greatest impact of this whole process is when genetic information is used to understand, at the most molecular level, the basic biological defect and then that information is used to develop a designer drug. One can already see that happening in a few instances, particularly for cancer. A most dramatic example is the drug Gleevec® (imatinib mesylate) that was recently approved by the FDA for leukemia. Gleevec's development resulted from this rational approach; as a drug, it puts almost all patients in remission with very few side effects.

That all sounds great. Where is it going to take us? Let me guess at that. If this all happens the way it is supposed to, by 2010, I think we will have an opportunity to individualize preventive medicine based on

DNA-based predictions of genetic risk. With available interventions for perhaps a dozen conditions to reduce the risk, that should be a really good thing. It will allow us to focus more of our energies on keeping people healthy instead of spending lots of money after people are already at death's door in the ICU, which seems to be largely what our medical care system is focused on at the moment.

Pharmacogenomics should be able to ensure that a drug is chosen appropriately for a patient, resulting in a reduction of adverse outcomes. However this raises some issues. Who is going to have access to this kind of new technology? Our current medical care system seems to turn a blind eye to those who do not have access. I see no evidence at the moment that that is changing. So will we be happy with an outcome where only those with financial resources and Ph.D.s have the ability to benefit from the new treatments? That should make all of us troubled. Will we solve the very vexing problem of genetic discrimination? Maybe you will find out that you are at risk for colon cancer, so you are the one who ought to have colonoscopy every year starting at age 45. However, suppose your health insurance agent says, "Well, you don't sound like a good risk any more. I am sorry, your policy has been canceled." That is happening right now. We need effective federal legislation to prevent that. There is major movement in that regard in the Senate, a little less in the House. The President of the United States has made public statements about the need for such legislation. This might be the year where it gets done. But the longer we go on without that protection, the more trouble we are going to be in.

Let's go another ten years. I think that by 2020 the therapeutic consequences of this revolution are going to be in full swing. We will have designer drugs available for diabetes, for Alzheimer's, for Parkinson's, for high blood pressure, and other conditions. You will probably get your entire genome sequenced, save it on a CD-ROM, and put it in your medical care record. That information could be incorporated into the decision making whether a particular drug is the right choice for you or what kind of preventive medicine strategy you should follow.

But there will be many debates about the ethical questions. What of the nonmedical uses of genetics? A paper in *Science* described a group from New Zealand who identi-

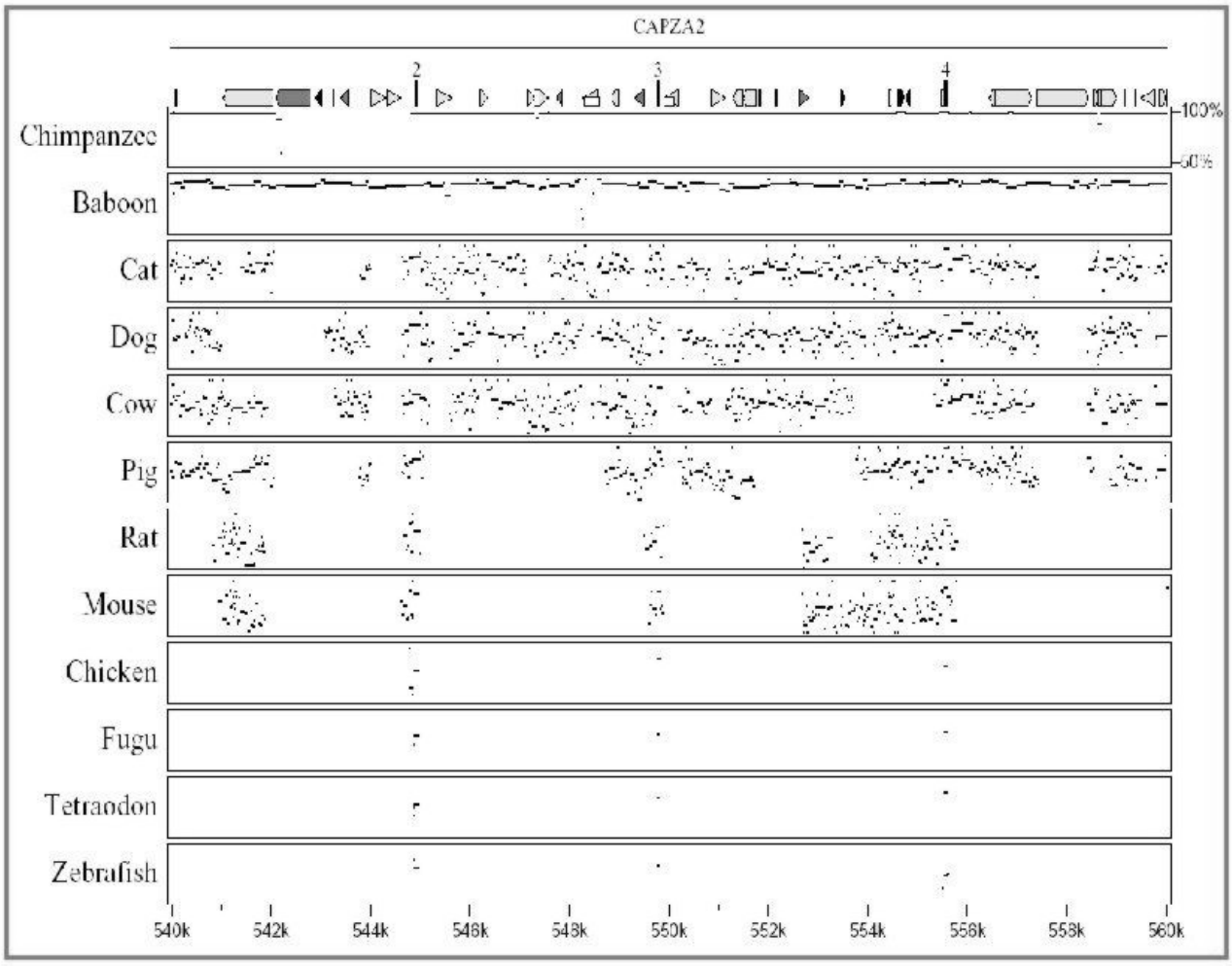

Figure 4. CAPZA2 gene in different species. *Diagram courtesy of Dr. Eric Green.*

A faith perspective is going to be needed more than ever. In fact, the bioethicists who debate these issues are all smart people, but many of them are not standing upon a foundation that has a solid sense of what is right and what is wrong. Christians are incredibly blessed to have that Rock upon which one can stand …

fied a variant in a gene on the X chromosome that they claimed plays a major role in whether boys who are subjected to childhood abuse end up growing up to be criminals.[2] In their particular study, over 30% of those who had been subjected to childhood abuse and had this particular variant in the monoamine oxidase gene were convicted of criminal activities. This was a much higher risk than the abuse alone or the gene alone, but if you put the two together, then the risk goes way up. Can you imagine how that is going to get folded into our criminal justice system? Will that be a defense against criminal activity—"my genes made me do it," plus I had a bad childhood so I am not responsible? Or will this get used in a way to try to deny opportunities for those who have that high risk version of the monoamine oxidase gene because they might behave badly later on? These are serious issues lurking in the future—and not the very distant future.

A faith perspective is going to be needed more than ever. In fact, the bioethicists who debate these issues are all smart people, but many of them are not standing upon a foundation that has a solid sense of what is right and what is wrong. Christians are incredibly blessed to have that Rock upon which one can stand when you are trying to make a judgment about a complicated ethical issue. Certainly while that particular Rock makes some of our postmodern colleagues nervous, it should from our perspective put us in a special position to contribute to those debates in a highly meaningful way.

What is the Interface between Science and Faith?

I want to briefly turn to a question I have touched on a couple of times. Is there potential harmony between science and Christian faith? As ASA members and scientists who have a strong personal faith, how do we put these two things together? I will give you a bit of a personal view. After all, genetics is perceived by many as perhaps the area of science that is least compatible with faith. Regretfully a very polarized division separates the extremists: those who look at the science of the genome as a particularly dangerous way of misunderstanding God's providence, and those who by studying genetics have decided that there is no more need for God because they have discovered everything that matters in DNA.

Is this an irreconcilable conflict? Many of our colleagues seem to think so. But I do not have to tell you that this conflict does not make sense. Science explores the natural world. Faith explores the supernatural world. If I want to study genetics, I am going to use science. If I want to understand God's love, then that is where the faith world comes in. Does that make them separate and impossible to integrate into one person, one experience, one thought? Is Stephen Jay Gould right when he calls these "the non-overlapping magisteria"? No, from my perspective these two world views coexist in me, and in many of you, right now. We are not torn apart by that; we are not forced into contradictions. Rather, I believe that we are enriched and blessed. We have an opportunity to practice science as a form of worship. We have a chance to see God as the greatest scientist. As we discover things about the world, we can appreciate the wonders of God's creation. What a gift it is to be a scientist and be able to do that.

Why is the conflict then perceived to be so severe? Science and Christianity do not have a pretty history. Certainly conflicts tend to arise when science tries to comment on the supernatural—usually to say it does not exist—or when Christians attempt to read the Bible as a science textbook. Here I find it useful to recall that this is not a new debate, and I often refer back to the wisdom of St. Augustine. Augustine in 400 AD had no reason to be apologetic about Genesis, because Darwin had not come along. Augustine was blessed with the ability to look at Gen. 1:1 without having to fit it into some sort of scientific discovery of the day. Yet, if you read Augustine's interpretation of Gen. 1:1, it is a lot like mine. In fact, Augustine makes the point how dangerous it is for us to take the Bible and try to turn it into a science text. He wrote:

> It is a disgraceful and dangerous thing for an infidel [unbeliever] to hear a Christian, presumably giving the meaning of Holy Scripture, talking nonsense on these topics; and we should take all means to prevent such an embarrassing situation in which people show up vast ignorance in a Christian and laugh it to scorn … If

> they find a Christian mistaken in a field which they themselves know well, and hear him maintaining his foolish opinions about our books [Scriptures], how are they going to believe those books in matters concerning the resurrection of the dead, the hope of eternal life and the kingdom of heaven, when they think their pages are full of falsehoods on facts which they themselves have learnt from experience and the light of reason?[3]

These are very strong and effective words. But the past century has not been a good one in terms of the polarization between the more evangelical wing of the church and the scientific community. We seem to be engaged in contentious, destructive, and wholly unnecessary debate about evolution and creation. From my perspective as a scientist working on the genome, the evidence in favor of evolution is overwhelming.

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What are the arguments in favor of evolution? Let me quickly describe two arguments. (1) The fossil record. Macroevolution has growing and compelling evidence to support it. Elephants, turtles, whales, birds often have been cited as species where transitional species have not been identified. That is no longer true. We have gained more in the fossil record in the last ten years than in almost the entire previous history of science. (2) The DNA evidence for evolution. I mentioned the ancient repeats we share with mice in the same location showing no conceivable evidence of function, diverging at a constant rate just as predicted by neutral evolution. One could only conclude that this is compelling evidence of a common ancestor or else that God has placed these functionless DNA fossils in the genome of all living organisms in order to test our faith. I do not find that second alternative very credible. After all God is the greatest scientist. Would he play this kind of game?

Arguments against macroevolution, based on so-called gaps in the fossil records, are also profoundly weakened by the much more detailed and digital information revealed from the study of genomes. Outside of a time machine, Darwin could hardly have imagined a more powerful data set than comparative genomics to confirm his theory.

So what are the objections then to evolution? Well, obviously, the major objection in many Christians' minds is that it is not consistent with Genesis. I find Gen. 1:1–2:4 powerful, but admittedly complex and at times difficult to understand with its seemingly two different versions of the creation of humans. Problematically, a literal translation of Gen. 1:1–2:4 brings one in direct conflict with the fundamental conclusions of geology, cosmology, and biology.

Professor Darrel Falk has recently pointed out that one should not take the view that young-earth creationism is simply tinkering around the edges of science. If the tenets of young earth creationism were true, basically all of the sciences of geology, cosmology, and biology would utterly collapse. It would be the same as saying 2 plus 2 is actually 5. The tragedy of young-earth creationism is that it takes a relatively recent and extreme view of Genesis, applies to it an unjustified scientific gloss, and then asks sincere and well-meaning seekers to swallow this whole, despite the massive discordance with decades of scientific evidence from multiple disciplines. Is it any wonder that many sadly turn away from faith concluding that they cannot believe in a God who asks for an abandonment of logic and reason? Again from Augustine:

> In matters that are obscure and far beyond our vision, even in such as we may find treated in Holy Scripture, different Interpretations are sometimes possible without prejudice to the faith we have received. In such a case, we should not rush in headlong and so firmly take our stand on one side that, if further progress in the search of truth justly undermines this position, we too fall with it.[4]

Again, written over 1600 years ago but right on target today!

What about Intelligent Design?

Here is an area where I think that probably some of you in the audience will disagree with me. The past ten years have seen the emergence of a new theory of how God has intervened in the development of living organisms. Intelligent Design proponents point to the complexity of multicomponent molecular machines as unlikely products of a random evolutionary process. The argument about irreducible complexity is an interesting one. And yet I must say, the more one looks at these supposedly complex and irreducibly complex structures (whether it is the flagella, the eye, or the clotting cascade), the more one begins to see some evidence of intermediate forms that could have had some selective advantage. While not offering strong evidence against Intelligent Design, the study of genomes offers absolutely no support either. In fact, I would say—and many others have said it better—a major problem with the Intelligent Design theory is its lack of a plan for experimental verification. I view Intelligent Design ideas as an intriguing set of proposals, but I certainly do not view them as the kind of threat to evolution that its most vocal proponents imply. Again, let us be careful of the "God-of-the-gaps" problem that Augustine was referring to. The disproof of an unnecessary theory like ID can shake

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the faith of those who are asked to equate their belief in God with their belief in the theory.

Another issue, however—one where I am very puzzled about what the answer will be—is the origin of life. Four billion years ago, the conditions on this planet were completely inhospitable to life as we know it; 3.85 billion years ago, life was teeming. That is a very short period—150 million years—for the assembly of macromolecules into a self-replicating form. I think even the most bold and optimistic proposals for the origin of life fall well short of achieving any real probability for that kind of event having occurred. Is this where God entered? Is this how life got started? I am happy to accept that model, but it will not shake my faith if somebody comes up with a model that explains how that the first cells formed without divine intervention. Again, watch out for the God-of-the-gaps. However, I think it is noteworthy that this particular area of evolution, the earliest step, is still very much in disarray.

How Do We Put These World Views Together?

I arrived at my synthesis of this before I knew of the ASA and before I read some of the wonderful articles in its journal that advanced the view, which we generally call theistic evolution. God who is not limited in space or time, who created the universe, chose the remarkable mechanism of evolution to create plants and animals of all sorts. (By the way, notice in Genesis how plants appear before animals and fish before birds—which is precisely what science tells us.) Most importantly God chose this means in full knowledge that it would ultimately give rise to creatures with whom he could have fellowship and relationship, whom he would imbue with the moral law and a longing to seek him, to whom he would ultimately reach out to by himself becoming flesh and walking amongst us. Furthermore, as God is not limited by natural laws, he on occasion has performed miracles which science is unable to judge, since they fall outside the natural realm. Those miracles include many signs and wonders in Old Testament days. But most importantly to my Christian faith is the literal and historical resurrection of Jesus Christ from the dead, which is the absolute cornerstone of what I believe.

I find that synthesis completely satisfying. It brings together what I know about Christ from reading about him, from my prayer life, and what I know as a scientist about the natural world. Furthermore evolution is not a stumbling block in any way as long as one reads Genesis as Augustine did, and does not insist upon reading this as a science textbook.

Where We Are Going in the Future?

Let me finish with a quick glimpse of where we are going in the future as we contemplate our own instruction book and dream of what we might be able to do with that to alleviate suffering and to better the lot of humankind. There are a number of ethical issues that are raised by this. Is this a treasure chest or Pandora's box?

One message that this raises comes from Prov. 19:2: "It is not good to have zeal without knowledge." Some observers are getting pretty worked up about genetics and the dangers of it, but are worrying about the wrong things. As scientists we have a great obligation to explain ourselves, what our science is about, and what it can and cannot do. The time for a geneticist or in fact any scientist to go into the lab and close the door and let somebody else worry about the consequences of scientific advancement has passed.

Advances in genomics raise serious ethical issues, but offer potential solutions. (1) Genetic discrimination can be solved with effective policy implementation. (2) Unequal access to new advances needs to be addressed by a change in the U.S. health care system. (3) Genetics and race brings potential prejudices. We are learning that we are 99.9% identical at the DNA level. Most of our differences pre-existed in the founder population from which we are all descended. The notion that you can draw a precise boundary around any particular group and say, "They are different" is not supported by science. That understanding ought to be a very strong argument in the contentious debates about genetics and race, while also diminishing the opportunity for prejudice. (4) Genetic technology brings a major ques-

tion, "Where are we going to draw the boundaries between treating terrible diseases and enhancing character traits of the next generation?"

You have probably all seen "designer baby" scenarios presented on prime time TV or in Hollywood movies. Most of those are not very realistic, since the environment heavily influences the enhanced characteristics portrayed in those scenarios—intelligence, athletic ability, physical attractiveness, or musical talent. While genetics may change the odds a little bit, genetics alone is not going to determine the outcome. Thus the wealthy couple that decides to spend tens of thousands of dollars in taking advantage of an embryo selection program in order to have a son whose going to play first violin in the orchestra, score touchdowns for the football team, and get A+ in math is likely to experience a disappointing outcome, when their sixteen-year-old is up in his room listening to heavy metal music and smoking pot. Because the parents forgot that environment is important also, they are going to wonder, "What happened here?"

It may be our saving grace that while many of those enhancement scenarios are not stopped because of ethical concerns; they are stopped because they do not work. Meanwhile, we really do have to watch out for genetic determinism. I recently saw an article in the religious literature suggesting that spirituality might be in your genes and consequently the people who go to church are those who are somehow hard-wired to seek after God and those who lack those genes, do not. I do not think that idea is supported by the data!

Scientists who are Christians have a critical role to play in this genomic revolution both as scientists and as contributors to the ethical discussions. I hope the ASA and other organizations like it will step up to that challenge. In that regard, I would like to read another quotation written about one hundred years ago by the Princeton conservative theologian Benjamin Warfield. It is a wonderful exhortation to Christians; it could well be the motto of ASA.

> We must not then as Christians assume an attitude of antagonism toward the truths of reason or to the truths of philosophy or the truths of science or the truths of history or the truths of criticism. As children of the Light, we must be careful to keep ourselves open to every ray of light. Let us then cultivate an attitude of courage as over against the investigations of the day. None should be more zealous in them than we. None should be more quick to discern truth in every field, more hospitable to receive it, more loyal to follow it whithersoever it leads. It is not for Christians to be lukewarm in regard to the investigations and discoveries of the time. Rather, as followers of the Truth, indeed we can have no safety in science or in philosophy save in the arms of Truth. It is for us, therefore, as Christians to push investigation into the utmost, to be leaders in every science, to stand in the band of criticism, to be the first to catch in every field the voice of the Revealer of Truth who is also our Redeemer. All truth belongs to us as followers of Christ, the Truth. Let us at length enter into our inheritance.[5]

I think scientist-believers are the most fortunate. We have the opportunity to explore the natural world at a time in history where mysteries are being revealed almost on a daily basis. We have the opportunity to perceive the unraveling of those mysteries in a special perspective that is an uncovering of God's grandeur. This is a particularly wonderful form of worship. ✹

Notes

[1]"Initial sequencing and analysis of the human genome," *Nature* 409, no. 6822 (2001 Feb 15): 860–921.
[2]Avshalom Caspi, et al., "Role of Genotype in the Cycle of Violence in Maltreated Children," *Science* 297, no. 5582 (2002): 851.
[3]St. Augustine, *The Literal Meaning of Genesis*, Book 1, Chapter 19.
[4]St. Augustine, *The Literal Meaning of Genesis,* Book 1, chap. 18, in *Ancient Christian Writers* 41, translated and annotated by John Hammond Taylor, S.J. (New York: Paulist Press, 1982).
[5]Benjamin Warfield, *Selected Shorter Writings* (Phillipsburg, NJ: P & R Publishing, 1970), 463–5.