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THE LANGUAGE OF GOD

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In choosing a topic for this landmark discussion, I took seriously the fact that we are here to talk not only about science, but how science interfaces with spiritual perspectives. I could have used my time to talk exclusively about genome science, because that field is undergoing enormous exponential growth right now. I will indeed talk about that, but I also would like to try to provide, from my own personal perspective, some comments about how these advances can be synthesized with belief in a Creator God. After all, the effort to explore such a synthesis is a major point of this meeting.

I often begin conversations about science and faith with a pair of images representing the two major worldviews that various peoples of the world are debating: one image is the rose window of a cathedral, with its beautiful radial pattern; the other is a view of DNA, a different one than you usually see, looking down the long axis of DNA and also showing quite a beautiful radial picture. There are many who argue at the present time that we have to make a choice between these two worldviews. Certainly, in my country, the USA, such shrill voices of opposition are heard much more commonly than those who argue for possible harmony.

Is it a mistake to try to discuss science and faith in the same room? I often reflect on the greatest commandment as spoken by Jesus, 'Love the Lord your God with all your heart, with all your soul, and with all your mind' (Matthew 22:37). Isn't doing science a way of loving God with all your mind? It certainly doesn't sound as if Jesus thought there was a conflict between faith and reason.

The Human Genome Project and the practice of medicine

The Human Genome Project, which I had the privilege of leading, had an audacious goal: to read out the entire DNA instruction book for *Homo*

sapiens, more than 3 billion base pairs. At the time of the beginning of this project the technology for doing this was clearly not in hand, so one could say this was a truly an ambitious objective. However, all of the goals of the Human Genome Project were achieved in April 2003. Throughout the course of the project, all of the DNA sequence from the human genome was made immediately available on the Internet every 24 hours, so that anyone who had ideas about how to use it for human benefit could begin work immediately.

The scientists who participated in the Human Genome Project hailed from six countries of the world. They, too, helped us identify where to go next. An iconic diagram featured in a *Nature* paper in April 2003 depicted a metaphorical building that we were now prepared to construct, resting upon the foundation of the Human Genome Project, but now applying that knowledge to biology, health and society.

Many of the 'Grand Challenges' outlined in that rather audacious publication have already been achieved, thanks to the rapid pace of genome research. Specifically, remarkable progress has been made in identifying variations in the human genome that are playing a role in risk of disease. Your genome and mine are about 99.6% the same. In that small percentage where we are dissimilar, most of those differences do not have medical consequences – but some of them do. For me, as a physician geneticist, a major goal was to try to identify what some of those genome glitches were that play a role in diabetes, heart disease, or cancer. While we had done a very good job of finding those glitches for diseases that were highly heritable, like cystic fibrosis and Huntington's Disease, until very recently we had not had much luck with the common diseases that fill up our hospitals and clinics. All that has changed in the last three years.

Building upon the success of the Genome Project, another project called HapMap provided a catalogue of human variation that made it possible in a comprehensive way – not based upon candidate genes, but looking at the entire genome – to scan and identify those variations associated with diseases that are non-Mendelian in their inheritance. The first success was age-related macular degeneration, mapped to chromosome 1 to a gene called 'complement factor H'. No one expected that gene to be involved in this disease, and yet a common variant in this gene is a major risk factor. Since that discovery, much has happened: in 2006 there were three more successes. With the full availability of the HapMap and the advent of very low-cost genotyping in 2007, discoveries really started to appear, and became a full-fledged deluge by 2008. As a result no less than 400 of these

well-validated genetic variations associated with common disease have emerged, mostly in the last two years, shedding dramatic new light on the causes of diabetes, heart disease, cancer, mental illness, autoimmune diseases, asthma, and many others.

These successes provide us with powerful new targets for therapeutics. They also present the opportunity to provide individuals with a refined estimate of their future risk of disease, depending on which of these variants they happen to carry. Already there are companies who offer you the chance to test your own genome for about a million different variants, for a cost as little as 400 US dollars. Whether that is premature or not is a matter of some debate; while the tests are scientifically based, most of the heritability of common diseases has not yet been uncovered, and there is limited evidence that knowing this information actually improves outcomes. But the era of personalized medicine is at hand.

As technology advances, we will soon be able to examine individual genomes in their entirety, identifying not only the common variants but the less common ones that play a critical role in disease risk. Professor Gojobori already presented information about the way in which DNA sequencing is advancing. This capability has made it possible to tackle problems in a comprehensive way that previously had not been feasible. An important area is cancer. Certainly we have known for a long time that cancer is quite literally a disease of the genome. It arises because of mutations in DNA. It takes an accumulation of several mutations over many generations of cell divisions to reach the point where that cell is truly malignant. If we really want to understand cancer, we need to develop a comprehensive catalogue of all the mutations in the cancer cell. Last year, the first paper describing the full sequencing of a cancer genome was published in *Nature*. It described the complete DNA sequence of a leukemia arising in a woman who had a very aggressive form of the disease. A number of new genes were found mutated in the cancer cells, and were not on anybody's previous list of oncogenes or tumor suppressors. From these findings it is clear that this comprehensive view is going to open up many new vistas in terms of the understanding of malignancy.

Another area that these sequencing advances now allow us to tackle is to look more closely at those non-human genomes that are on us or in us. There are hundreds of trillions of microbes on our skin, in our mouths, and in our gastrointestinal tracts. For the most part these organisms are synergistic with us and assist in maintaining our health. However, the balance between host and microbes can be deranged, and that can lead to illness.

The Human Microbiome Project is a new international program that aims to catalogue these microbial genomes, both in health and in disease. This has not really been possible in the past, as only a minority of these microbes are possible to culture in the laboratory. But they have DNA.

Technology promises even more disruptive advances for high-throughput, low-cost sequencing. An example mentioned by Professor Gojobori is a new approach from Pacific Biosciences that sequences single DNA molecules. I have recently seen a demonstration of this technology, which carries out DNA sequencing in real time using fluorescently labelled tags and massive parallelism. This promises to reduce the cost of sequencing another couple of orders of magnitude and bring it down to the point where a complete DNA sequence can be done for a thousand dollars or less, in a matter of a few hours.

So how will these advances play out in the practice of medicine? Discoveries about causes and treatment of each disease will move at a different pace, but I think we can expect things to happen pretty quickly. Already for some diseases, we are using the tools of genotyping and DNA sequencing to identify individuals at high risk. As just one example, those found to be at high risk for colon cancer can now be counseled to have annual colonoscopy beginning at age 30 (instead of the usual recommendation of age 50).

We also have the opportunity to use the tools of genetics to identify variations that will predict response to drug therapy. This is the field of pharmacogenomics, and promises to provide a better opportunity for a patient and physician to choose the right drug at the right dose.

I would predict, however, that the major, long term impact of the genomic revolution will be the discovery of new therapeutic opportunities, building on knowledge about biological pathways that are fundamental to disease pathogenesis. Some of these new treatments will be gene therapies, where the gene itself becomes the treatment. A recent exciting example of this is in the treatment of a particular type of blindness. But perhaps an even more widespread consequence of our new knowledge of the genome will be in the form of drug therapies, because of the new targets that are being discovered using the genomic approach.

It thus appears inescapable that medicine will undergo a major revolution in the course of the next ten years. Unfortunately, however, I do not think that the medical profession is currently well prepared to respond to this revolution, because of the disparity between the rapid nature of these discoveries and the relative slowness of the medical education system to incorporate them into training.

Evolution and the study of genomes

I would now like to turn to the evidence coming from these genome studies with regard to evolution, as that is a major topic of discussion at this meeting. If there have been legitimate doubts about whether Darwin's theory was correct, based upon so-called 'gaps' in the fossil record, those doubts have largely been swept away by the study of DNA. In fact, if Darwin had tried to imagine a compelling way to demonstrate the correctness of his theory, it is hard to see how anything outside of a time machine would have been better than comparative genomics.

Not only have we sequenced our own genome, but recent covers of *Nature* and *Science* magazines show successes for other genomes as well: the mouse, the chimpanzee, the dog, the honey bee, the sea urchin, the macaque, and the platypus. We have draft or complete genome sequences now for more than two dozen vertebrates. If you feed these genome sequences into a computer and ask it to create a relatedness tree between the organisms, it will produce a startlingly close match to evolutionary trees that have been generated from fossil data or from anatomical features.

But in my country, the USA, there are still many who reject the evidence that all of these organisms, including humans, are related by descent from a common ancestor. A recent poll shows that forty-five percent of Americans believe that the earth is less than 10,000 years old, and that humans were specially created by God. This view is in serious trouble, once one looks at the DNA evidence. Certainly, one could argue that God used the same motifs repeatedly to produce all of these organisms as acts of special creation, and that might explain the general relatedness at the DNA level. But when we look at the details, it is clear that this particular alternative view cannot be sustained. As an example, consider human chromosome 2. Chromosomes are the visible unit of heredity in a cell. We humans have 46 of them, made up in pairs. One can look under the microscope at a cell that is about to divide, and observe the chromosomes. It is noteworthy that human and chimpanzee chromosomes look a lot alike with regard to their size, their banding pattern and so on. The one exception, however, is that we have human chromosome 2 as our second largest chromosome, while chimps do not. They instead have two smaller ones. Gorilla chromosomes look similar to chimps; making us the outlier amongst primates.

There has been a prior supposition that perhaps in the lineage leading to humans there was a fusion of two smaller chromosomes giving rise to our chromosome 2. That finding has now been subjected to exquisitely

detailed analysis from the DNA sequence data. There are special sequences at the tips of all chromosomes. These are the telomeres; a particular sequence, TTAGGG, appears over and over again in order to prevent fraying as the cell divides. It is interesting to note that when you look at human chromosome 2, there are telomeric sequences in the middle, exactly in the position where you would predict such a DNA footprint would have been left by a fusion between two ancestral chromosomes.

Another revealing example of our common ancestry with other animals also explains why sailors contracted scurvy on those long sea journeys. If we look at the order of genes in multiple mammals around a particular gene called GULO, we will see the order of genes is the same in humans, cows and mice, as well as many other vertebrates. But this is an interesting example, because the gene GULO, which stands for gulonolactone oxidase, is a pseudogene in humans (and in other primates) – meaning that it has sustained a knockout blow, decapitating its front end completely so that it lacks the first part of the coding region. It is utterly nonfunctional. Well, the product of that gene normally catalyzes the final step in synthesizing ascorbic acid (vitamin C). Unable to make their own vitamin C because of the non-functional GULO gene, sailors developed scurvy when they did not have access to vitamin C. But the mice on the ship, possessed of a functional GULO gene, did just fine.

Looking at that data, it is extremely difficult to argue that we humans are created as a special separate lineage compared to other animals. One would have to infer that God intentionally inserted a non-functioning GULO gene in just the position to mislead us into thinking that descent from a common ancestor was correct. This model would put God in the position of being a DNA deceiver, which does not seem consistent with other basic tenets of religious belief.

Catholics are in general much more comfortable with the shared descent of humans and other animals, so I probably do not need to make this case so strongly to this particular audience. But for many protestant evangelical Christians in America, this is still not an easily accepted conclusion.

THE HARMONY OF SCIENCE AND FAITH

Let me turn now to another question. Simply stated, 'If evolution is true, does that leave any room for God?' Let me begin with a personal perspective. I was not raised in a religious tradition. Until my twenties, I con-

sidered myself an agnostic, and ultimately an atheist. It was actually my involvement in medicine that forced me to consider issues of life and death in more than hypothetical ways, and my involvement in science that convinced me that the purely materialistic approach can be unnecessarily limiting for the kinds of questions that we humans want to ask – such as why there is something instead of nothing. These intellectual explorations ultimately led me, to my great surprise, to Christianity.

It didn't take long for my colleagues to point out that they thought I was on a collision course between the scientific and spiritual worldviews. As a geneticist, evolution was fundamental to my understanding of biology. But didn't I know that evolution and faith were utterly incompatible? Certainly that case has been smoldering ever since 1859, and has been recently made rather loudly by some of my colleagues, such as Professor Dawkins.

In his book, *The God Delusion* (a rare book that does not require a subtitle), Dawkins uses evolution as one of his strongest arguments against the plausibility of God. He insists that once Darwin arrived at his theory of evolution the need to describe a Designer or Creator went out the window. But in my view and that of most thoughtful believers, Dawkins makes a category error by trying to use scientific arguments to weigh in on the existence of the supernatural.

Nearly two years ago, I engaged in a debate with Richard Dawkins for *Time* magazine. The exchange is still available on the Internet.[1] Ultimately at the end of it, Dawkins admitted this category error to a certain extent, recognizing that science cannot exclude the possibility of a supernatural God, even though he thought it highly unlikely. But he stated that if there was such a thing as a supernatural God, it would be much more grand than any of us could imagine. That's exactly the God believers are talking about, I said!

So we are back to the question, 'How can evolution and faith be reconciled?' If you will indulge me, I would like to provide a rather personal response. I understand the risk of doing so here, in front of esteemed scientific and theological colleagues. I am an amateur theologian and philosopher. But it seems to me that there is a readily-achieved synthesis that is entirely compatible both with what we know scientifically, and with what the basic Abrahamic principles say about God the Creator. Here it is: Almighty God, who is not limited in space or time (an Augustinian concept from 400 AD) created this universe with its parameters precisely tuned to

[1] See http://www.time.com/time/magazine/article/0,9171,1555132-1,00.html.

allow for the development of complexity over long periods of time. God thus endowed Creation with amazing potentialities. That plan included the mechanism of evolution to create the marvelous diversity of living things on our planet – and, most especially, human beings, with minds created in God's image. Evolution was sufficient to prepare the 'house' for all this, namely the human brain in all of its elegant complexity. But there was something missing until the additional spiritual component of humanity arrived. The story of the Garden of Eden is then a description of God's provision of additional gifts to humankind: free will, the soul, and – I know this will be controversial – the moral law. The moral law, the knowledge of right and wrong, is universal and unique to humanity, though its interpretation is strongly affected by culture. Biblically we learn in the story of Adam and Eve that we humans used our free will to break the moral law, leading to our estrangement from God. For me, as a Christian, it is Christ who provides the solution to that estrangement.

This synthesis of Biblical and scientific perspectives has traditionally been called 'theistic evolution'. But I don't think that is a great label. It turns a lot of people off because it sounds like evolution is the noun and theistic is the adjective, implying God is less important than Darwin. So, in my book *The Language of God*, I proposed an alternative term: *Bios*, meaning life, through the *Logos*, or the Word – or simply *BioLogos*, God speaking life into being.

As you may imagine, there are a variety of objections to this perspective. For instance, one often is asked: 'Didn't evolution take an awfully long time?' This question is a concern of many Evangelicals who cannot imagine why God would have taken so long to get to the point (humanity). They often ask, 'Why didn't God just snap his fingers and make it happen?' Well, again, if God is outside of time this is our problem, not God's problem. Another related objection is: 'Isn't evolution a purely random process?' This question seems to take God out of it. As one of several possible responses, I would posit that if God is outside of time, then randomness to us may not necessarily be randomness to God.

Intelligent Design proponents ask, 'Is evolution really sufficient?' In other words, aren't there biological structures, like the bacterial flagellum or the human eye, that are just too complicated for evolution alone to have produced? Each of these structures has many subunits, and when just one of them is knocked out, the whole thing stops working. So how could such complexity have arisen by natural selection alone? Well, those questions reveal a basic misunderstanding of the stepwise fashion by which such multiprotein complexes come into being. A recent paper from *Nature Reviews Microbiolo-*

gy points out how many of these intermediate steps are being discovered for the flagellum. Intelligent Design, in my view, is turning out to be a major misstep. It is both bad science, representing a God-of-the-gaps approach, and bad theology, portraying God as a rather inept Creator that had to keep intervening along the way to correct deficiencies in the original plan.

Proponents of evolutionary psychology have objected to my portrayal of the moral law as a signpost to God. Can't this be a consequence of evolution? Isn't altruism just a human behavior that has led to greater reproductive success of the species, and that's all? There are, to be sure, many aspects of altruistic behavior that are consistent with explanations provided by evolutionary psychology. They include: 'kin selection', which explains generosity to your relatives since you share your DNA with them, and if you help them be reproductively successful your own DNA is succeeding too; 'reciprocal altruism', which argues that our own altruism is often driven by a hope for some reciprocal benefit in the future from those we have shown kindness; and even 'group selection', which proposes that altruistic behavior of a group of individuals provides advantages to the whole group, even if it harms a few individuals' chances of reproductive success along the way. Martin Nowak at Harvard expounds on these models in his very interesting game theory studies. He concludes, however, that for group selection to work, one must be hostile to anyone who is not part of the group. But is that the kind of altruism we most admire in humans?

Imagine for a moment the person who, with great risk to themselves, reaches out to someone they do not know, someone who is part of another group. Evolution, ultimately, would predict hostility. But when we see this kind of radical altruism, we admire it. As an example from about a year ago, Wesley Autrey watched with horror as a young man standing on the subway platform in New York City went into an epileptic seizure and fell onto the tracks, with train No. 1 quickly approaching. Without hesitation, Wesley leaped onto the tracks. He covered the still seizing student with his own body and wedged them both between the tracks. The train rolled over them, and they both miraculously survived. Wesley was black. The student was white. They had never met. Stories like this one electrify us, and we are likely to point to such actions as representative of the best of human nobility. And yet, from an evolutionary perspective Wesley's action was a scandal, taking an enormous risk of sacrificing his own potential reproductive future to save someone he didn't even know.

A final objection to BioLogos, raised especially in my own Evangelical Christian circles, is the question about whether evolution conflicts with

Genesis 1 and 2. But as strongly as these concerns are raised, I see this as an unnecessary conflict. In this regard, I am greatly rewarded every time I open one of the four commentaries that St. Augustine wrote about Genesis. He was a theologian who thought deeply about this subject and who can hardly be accused of trying to retrofit his views into Darwin's theories – since St. Augustine wrote down his views on Genesis more than a thousand years before Darwin walked the earth. Augustine ultimately concludes that there is no way for any single interpretation of Genesis to be declared correct, and he provides a warning that ought to be heeded today by many churches, especially in my country. Augustine cautions, 'In matters that are so obscure and far beyond our vision, we find in Holy Scripture passages which can be interpreted in very different ways without prejudice to the faith we have received. In such cases we should not rush in headlong and so firmly take our stand on one side that if further progress in the search for truth justly undermines this position, we too fall with it'.

Finally, before concluding I would like to respond to Professor Zichichi's statements that took aim at the discipline of biology. Contrary to his view, I do believe that biology has arrived at a new phase of scientific rigor. The era of complete genomes, and the ability to understand life in a digital way, allows biology to take its rightful place as a truly quantitative science alongside physics and chemistry. Although this was not true a few decades ago, it is clearly true now. Evolution is at the core of these advances. I therefore associate myself with Theodosius Dobzhansky, one of the leading lights of evolutionary thought in the 20th century and a Russian Orthodox Christian, in his statement, 'Nothing in biology makes sense except in the light of evolution'. I do not know how we could do biological science at all without accepting the evolutionary paradigm. Nevertheless I agree that evolution does not have, and will never have, an answer to the 'why' question. That is a question that science cannot answer; it is a matter for faith to address.

Thank you, again, for the gracious invitation to join this distinguished group at the Pontifical Academy, and to spend time discussing these important worldview questions.