SCIENCE IS NOT ABOUT CERTAINTY: A PHILOSOPHY OF PHYSICS

A Conversation with

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[CARLO ROVELLI:] We teach our students: we say that we have some theories about science. Science is about hypothetico-deductive methods, we have observations, we have data, data require to be organized in theories. So then we have theories. These theories are suggested or produced from the data somehow, then checked in terms of the data. Then time passes, we have more data, theories evolve, we throw away a theory, and we find another theory which is better, a better understanding of the data, and so on and so forth.

This is a standard idea of how science works, which implies that science is about empirical content, the true interesting relevant content of science is its empirical content. Since theories change, the empirical content is the solid part of what science is. Now, there's something disturbing, for me as a theoretical scientist, in all this. I feel that something is missing. Something of the story is missing. I've been asking to myself what is this thing missing? I'm not sure I have the answer, but I want to present some ideas on something else which science is.

This is particularly relevant today in science, and particularly in physics, because if I'm allowed to be polemical, in my field, in fundamental theoretical physics, it is 30 years that we fail. There hasn't been a major success in theoretical physics in the last few decades, after the standard model, somehow. Of course there are ideas. These ideas might turn out to be right. Loop quantum gravity might turn out to be right, or not. String theory might turn out to be right, or not. But we don't know, and for the moment, nature has not said yes in any sense.

I suspect that this might be in part because of the wrong ideas we have about science, and because methodologically we are doing something wrong, at least in theoretical physics, and perhaps also in other sciences.

Let me tell you a story to explain what I mean. The story is an old story about my latest, greatest passion outside theoretical physics: an ancient scientist, or so I would say, even if often je is called a philosopher: Anaximander. I am fascinated by this character, Anaximander. I went into understanding what he did, and to me he's a scientist. He did something that is very typical of science, and which shows some aspect of what science is. So what is the story with Anaximander? It's the following, in brief:

Until him, all the civilizations of the planet, everybody around the world, thought that the structure of the world was: the sky over our heads and the earth under our feet. There's an up and a down, heavy things fall from the up to the down, and that's reality. Reality is oriented up and down, heaven's up and earth is down. Then comes Anaximander and says: no, is something else. 'The earth is a finite body that floats in space, without falling, and the sky is not just over our head; it is all around.'

How he gets it? Well obviously he looks at the sky, you see things going around, the stars, the heavens, the moon, the planets, everything moves around and keeps turning around us. It's sort of reasonable to think that below us is nothing, so it seems simple to get to this conclusion. Except that nobody else got to this conclusion. In centuries and centuries of ancient civilizations, nobody got there. The Chinese didn't get there until the 17th century, when Matteo Ricci andthe Jesuits went to China and told them. In spite of centuries of Imperial Astronomical Institute which was studying the sky. The Indians only learned this when the Greeks arrived to tell them. The Africans, in America, in Australia… nobody else got to this simple realization that the sky is not just over our head, it's also under our feet. Why?

Because obviously it's easy to suggest that the earth sort of floats in nothing, but then you have to answer the question: why doesn't it fall? The genius of Anaximander was to answer this question. We know his answer, from Aristotle, from other people. He doesn't answer this question, in fact. He questions this question. He says why should it fall? Things fall toward the earth. Why the earth itself should fall? In other words, he realizes that the obvious generalization from every small heavy object falling, to the earth itself falling, might be wrong. He proposes an alternative, which is that objects fall towards the earth, which means that the direction of falling changes around the earth.

This means that up and down become notions relative to the earth. Which is rather simple to figure out for us now: we've learned this idea. But if you think of the difficulty when we were children, to understand how people in Sydney could live upside-down, clearly requires some changing in something structural in our basic language in terms of which we understand the world. In other words, up and down means something different before and after Anaximander's revolution.

He understands something about reality, essentially by changing something in the conceptual structure that we have in grasping reality. In doing so, he is not doing a theory; he understands something which in some precise sense is forever. It's some uncovered truth, which to a large extent is a negative truth. He frees ourselves from prejudice, a prejudice that was ingrained in the conceptual structure we had for thinking about space.

Why I think this is interesting? Because I think that this is what happens at every major step, at least in physics; in fact, I think this is what happened at every step, even not major. When I give a thesis to students, most of the time the problem I give for a thesis is not solved. It's not solved because the solution of the question, most of the time, is not solving in the question, it's just questioning the question itself. Is realizing that in the way the problem was formulated, there was some implicit prejudice assumption that was the one to be dropped.

If this is so, the idea that we have data and theories, and then we have a rational agent that constructs theories from the data using his rationality, his mind, his intelligence, his conceptual structure, and juggles theories and data, doesn't make any sense, because what is being challenged at every step is not the theory, it's the conceptual structure used in constructing theories and interpreting the data. In other words, it's not changing theories that we go ahead, but changing the way we think about the world.

The prototype of this way of thinking, I think the example that makes it more clear, is Einstein's discovery of special relativity. On the one hand there was Newtonian mechanics, which was extremely successful with its empirical content. On te other hand there was Maxwell's theory, with its empirical content, which was extremely successful, too. But there was a contradiction between the two.

If Einstein had gone to school to learn what science is, if he had read Kuhn, and the philosopher explaining what science is, if he was any one of my colleagues today who are looking for a solution of the big problem of physics today, what would he do?

He would say, okay, the empirical content is the strong part of the theory. The idea in classical mechanics that velocity is relative: forget about it. The Maxwell equations, forget about them. Because this is a volatile part of our knowledge. The theories themselves have to be changed, okay? What we keep solid is the data, and we modify the theory so that it makes sense coherently, and coherently with the data.

That's not at all what Einstein does. Einstein does the contrary. He takes the theories very seriously. He believes the theory. He says, look, classical mechanics is so successful that when it says that velocity is relative, we should take it seriously, and we should believe it. And the Maxwell equations are so successful that we should believe the Maxwell equations. He has so much trust in the theory itself, in the qualitative content of the theory, that qualitative content that Kuhn says changes all the time, that we learned not to take too seriously, and so much faith in this, confidence in that, that he's ready to do what? To force coherence between these two, the two theories, by challenging something completely different, which is something that is in our head, which is how we think about time.

He's changing something in common sense, something about the elementary structure in terms of which we think of the world, on the basis of the trust of the past results in physics. This is exactly the opposite of what is done today in physics. If you read *Physical Review* today, it's all about theories that challenge completely and deeply the content of previous theories: so theories in which there is no Lorentz invariance, which are not relativistic, which are not general covariant, quantum mechanics might be wrong…

Every physicist today is immediately ready to say, okay, all of our past knowledge about the world is wrong. Let's randomly pick some new idea. I suspect that this is not a small component of the long-term lack of success of theoretical physics. You understand something new about the world, either from new data that arrive, or from thinking deeply on what we have already learned about the world. But thinking means also accepting what we've learned, challenging what we think, and knowing that in some of the things that we think, there may be something to modify and to change.

What are then the aspects of doing science that I think are under-evaluated, and should come up-front? First, science is about constructing visions of the world, about rearranging our conceptual structure, about creating new concepts which were not there before, and even more, about changing, challenging the a-priori that we have. So it's nothing to do about the assembly of data and the way of organizing the assembly of data. It has everything to do about the way we think, and about our mental vision of the world. Science is a process in which we keep exploring ways of thinking, and changing our image of the world, our vision of the world, to find new ones that work a little bit better.

In doing that, what we have learned in the past is our main ingredient, especially the negative things we have learned. If we have learned that the earth is not flat, there will be no theory in the future in which the earth is 'flat.' If we have learned that the earth is not at the center of the universe, that's forever. We're not going to go back on this. If you have learned that simultaneity is relative, with Einstein, we're not going back to absolute simultaneity, like many people think. This means that when an experiment measures neutrinos going faster than light, we should be very suspicious, and of course check and see whether there is something very deep that is happening. But it is absurd that everybody jumps and says okay, Einstein was wrong, just for a little anomaly that shows so. It never works like that in science.

The past knowledge is always with us, and it's our main ingredient for understanding. The theoretical ideas which are based on 'let's imagine that this may happen because why not' are not taking us anywhere.

I seem to be saying two things that contradict each other. On the one hand, we trust the knowledge, and on the other hand, we are always ready to modify in-depth part of our conceptual structure about the world. There is no contradiction between the two, because the idea of the contradiction comes from what I see as the deepest misunderstanding about science, which is the idea that science is about certainty.

Science is not about certainty. Science is about finding the most reliable way of thinking, at the present level of knowledge. Science is extremely reliable; it's not certain. In fact, not only it's not certain, but it's the lack of certainty that grounds it. Scientific ideas are credible not because they are sure, but because they are the ones that have survived all the possible past critiques, and they are the most credible because they were put on the table for everybody's criticism.

The very expression 'scientifically proven' is a contradiction in terms. There is nothing that is scientifically proven. The core of science is the deep awareness that we have wrong ideas, we have prejudices. We have ingrained prejudices. In our conceptual structure for grasping reality there might be something not appropriate, something we may have to revise to understand better. So at any moment, we have a vision of reality that is effective, it's good, it's the best we have found so far. It's the most credible we have found so far, its mostly correct.

But at the same time it's not taken for certain, and any element of it is a priori open for revision. Why do we have this continuous…? On the one hand, we have this brain, and it has evolved for millions of years. It has evolved for us, for basically running the savannah and run after and eat deer and try not to be eaten by the lions. We have a brain that is tuned to meters and hours, which is not particularly well-tuned to think about atoms and galaxies. So we have to get out of that.

At the same time I think we have been selected for going out of the forest, perhaps, going out of Africa, for being as smart as possible, as animals that escape lions. This continuous effort that is part of us to change our own way of thinking, to readapt, is a very part of our nature. We are not changing our mind away from nature; it is our natural history that continues to change that.

If I can make a final comment about this way of thinking about science, or two final comments: One is that science is not about the data. The empirical content of scientific theory is not what is relevant. The data serves to suggest the theory, to confirm the theory, to disconfirm the theory, to prove the theory wrong. But these are the tools that we use. What interests us is the content of the theory. What interests us is what the theory says about the world. General relativity says space-time is curved. The data of general relativity are that Mercury perihelion moves 43 degrees per century, with respect to that computed with Newtonian mechanics.

Who cares? Who cares about these details? If that was the content of general relativity, general relativity would be boring. General relativity is interesting not because of its data, but because it tells us that as far as we know today, the best way of conceptualizing space-time is as a curved object. It gives us a better way of grasping reality than Newtonian mechanics, because it tells us that there can be black holes, because it tells us there's a Big Bang. This is the content of the scientific theory.

All living beings on earth have common ancestors. This is a content of scientific theory, not the specific data used to check the theory. So the focus of scientific thinking, I believe, should be on the content of the theory, the past theory, the previous theories, try to see what they hold concretely and what they suggest to us for changing in our conceptual frame themselves.

The final consideration regards just one comment about this understanding of science and this long conflict that has crossed the centuries between scientific thinking and religious thinking. I think often it is misunderstood. The question is, why can't we live happily together, and why can't people pray to their gods and study the universe without this continuous clash? I think that this continuous clash is a little bit unavoidable, for the opposite reason from the one often presented. It's unavoidable not because science pretends to know the answers. But it's the other way around, because if scientific thinking is this, then it is a constant reminder to ourselves that we don't know the answers.

In religious thinking, often this is unacceptable. What is unacceptable is not a scientist that says I know, but it's a scientist that says I don't know, and how could you know? Based, at least in many religions, in some religions, or in some ways of being religious, an idea that there should be truth that one can hold and not be questioned. This way of thinking is naturally disturbed by a way of thinking which is based on continuous revision, not of the theories, of even the core ground of the way in which we think.

So summarizing, I think science is not about data; it's not about the empirical content, about our vision of the world. It's about overcoming our own ideas, and about going beyond common sense continuously. Science is a continuous challenge of common sense, and the core of science is not certainty, it's continuous uncertainty. I would even say the joy of taking what we think, being aware that in everything we think, there are probably still an enormous amount of prejudices and mistakes, and try to learn to look a little bit larger, knowing that there is always a larger point of view that we'll expect in the future.

We are very far from the final theory of the world, in my field, in physics, I think extremely far. Every hope of saying, well we are almost there, we've solved all the problems, is nonsense. And we are very wrong when we discard the value of theories like quantum mechanics, general relativity or special relativity, for that matter. And throw them away, trying something else randomly. On the basis of what we know, we should learn something more, and at the same time we should somehow take our vision for what it is, a vision that is the best vision that we have, but then continuous evolving the vision.

If this is science, if science works or in part works in the way I've described, if this which I've described, it's some relevant aspect of the way science works, this is strongly tied to the kind of physics I do. The way I view the present situation in fundamental physics is there are different problems in fundamental physics. One is the problem of unification; it's providing a big theory of everything. The more specific problem, which is a problem in which I work, is quantum gravity. Quantum gravity means simply doing the quantum theory of gravity, how things fall, i.e. the gravitational field.

It's a remarkable problem because of general relativity; gravity is space-time; that's what we have learned with Einstein. Doing quantum gravity means understanding what is quantum space-time. And quantum space-time precisely requires some key change in the way we think about space and time. Now, with respect to quantum gravity, in my opinion there are two major research directions today. Which is the one in which I work, loops, and strings. There are not just two different set of equations, but they are based on different philosophies of science, in a sense.

The ones in which I work is very much based on the philosophy I just described, and that's somehow what forced me to think about the philosophy of science. Why? Because the idea is the following: the best we know about space-time is what we know from general relativity. The best we know about mechanics is what we know from quantum mechanics. There seems to be a difficulty in attaching the two pieces of the puzzle together: turn them around, and they don't fit well. But the difficulty might be in the way we face the problem. The best information we have about the world is still contained in these two theories, so let's take quantum mechanics as seriously as possible, so believe it as much as possible. Maybe enlarging a little bit to make it general relativistic, or whatever.

Let's take general relativity as serious as possible. General relativity has peculiar features, specific symmetries, specific characteristics. Let's try to understand them deeply and see wether as they are, or maybe just a little bit enlarged, a little bit adapted, can fit with quantum mechanics to give a theory. Even if the theory that comes out then contradicts something that is the way we think.

That's the way quantum gravity, in the way of the loops, the way I work in, and the way other people work in, is being developed. This takes us in one specific direction of research, a set of equations, a way of putting up the theory. String theory has gone in the opposite direction. In a sense it says, well, let's not take too seriously general relativity as an indication of how the universe works. Even quantum mechanics has been questioned to some extent. Let's maybe imagine that quantum mechanics has to be replaced by something very different. Let's try to guess something completely new, which is some big theory out of which somehow the same empirical content of general relativity and quantum mechanics comes out in some limit.

I am distrustful of this huge ambition because we don't have the tools to guess this immensite theory. String theory's a beautiful theory. It might work, but I suspect it's not going to work. I suspect it's not going to work because it's not sufficiently grounded in everything we know so far about the world, and especially in what I think or perceive as the main physical content of general relativity.

String theory's a big guesswork. I think physics has never been a guesswork; it has been a way of unlearning how to think about something, and learning about how to think a little bit different by reading the novelty into the details of what we already know. Copernicus didn't have any new data, any major new idea, he just took Ptolemy, in the details of Ptolemy, and he read in the details of Ptolemy the fact that the equants, the epicycles, the deferents were in certain proportions between them, the way to look at the same construction from a slightly different perspective and discover the earth is not the center of the universe.

Einstein, as I said, took seriously Maxwell's theory and classical mechanics to get special relativity. So loop quantum gravity is an attempt to do the same thing: take seriously general relativity, take seriously quantum mechanics, and out of that, bring them together, even if this means a theory where there's no time, no fundamental time, so we have rethink the world without basic time. The theory, on the one hand, is very conservative, because it's based on what we know. But it's totally radical because it forces us to change something big in our way of thinking.

String theorists think differently. They say well, let’s go out to infinity, where somehow the full covariance of general relativity is not there. There we know what is time, we know what is space, because we're at asymptotic distances, at large distances. The theory's wilder, more different, more new, but in my opinion, it's more based on the old conceptual structure. It's attached to the old conceptual structure, and not attached to the novel content of the theories that have proven empirically successful. That's how my way of reading science matches with the specifics of the research work that I do, and specifically of loop quantum gravity.

Of course we don't know. I want to be very clear. I think that string theory's a great attempt to go ahead, done by great people. My only polemical attitude with string theory is when I hear, but I hear less and less now, when I hear 'oh, we know the solution already, certain it's string theory.' That's certainly wrong and false. What is true is that that's a good set of ideas; loop quantum gravity is another good set of ideas. We have to wait and see which one of the theories turns out to work, and ultimately to be empirically confirmed.

This may take me to another point, which is should a scientist think about philosophy, or not? It's sort of the fashion today to discard philosophy, to say now we have science, we don't need philosophy. I find this attitude very naïve for two reasons. One is historical. Just look back. Heisenberg would have never done quantum mechanics without being full of philosophy. Einstein would have never done relativity without having read all the philosophers and have a head full of philosophy. Galileo would never have done what he had done without having a head full of Plato. Newton thought of himself as a philosopher, and started by discussing this with Descartes, and had strong philosophical ideas.

But even Maxwell, Boltzmann, I mean, all the major steps of science in the past were done by people who were very aware of methodological, fundamental, even metaphysical questions being posed. When Heisenberg does quantum mechanics, he is in a completely philosophical mind. He says in classical mechanics there's something philosophically wrong, there's not enough emphasis on empiricism. It is exactly this philosophical reading of him that allows him to construct this fantastically new physical theory, scientific theory, which is quantum mechanics.

The divorce between this strict dialogue between philosophers and scientists is very recent, and somehow it's after the war, in the second half of the 20th century. It has worked because in the first half of the 20thcentury, people were so smart. Einstein and Heisenberg and Dirac and company put together relativity and quantum theory and did all the conceptual work. The physics of the second half of the century has been, in a sense, a physics of application of the great ideas of the people of the '30s, of the Einsteins and the Heisenbergs.

When you want to apply thes ideas, when you do atomic physics, you need less conceptual thinking. But now we are back to the basics, in a sense. When we do quantum gravity it's not just application. I think that the scientists who say I don't care about philosophy, it's not true they don't care about philosophy, because they have a philosophy. They are using a philosophy of science. They are applying a methodology. They have a head full of ideas about what is the philosophy they're using; just they're not aware of them, and they take them for granted, as if this was obvious and clear. When it's far from obvious and clear. They are just taking a position without knowing that there are many other possibilities around that might work much better, and might be more interesting for them.

I think there is narrow-mindedness, if I might say so, in many of my colleague scientists that don't want to learn what is being said in the philosophy of science. There is also a narrow-mindedness in a lot of probably areas of philosophy and the humanities in which they don't want to learn about science, which is even more narrow-minded. Somehow cultures reach, enlarge. I'm throwing down an open door if I say it here, but restricting our vision of reality today on just the core content of science or the core content of humanities is just being blind to the complexity of reality that we can grasp from a number of points of view, which talk to one another enormously, and which I believe can teach one another enormously.