THE SIMPLE AND THE COMPLEX Part II: THE SCIENCE OF COMPLEXITY with MURRAY GELL-MANN, Ph.D.

JEFFREY MISHLOVE, Ph.D.: Hello and welcome. I'm Jeffrey Mishlove. Today we're continuing our discussion on "The Simple and the Complex" with Professor Murray Gell-Mann. Professor Gell-Mann received the Nobel Prize in 1969 for his theoretical work which led up to the idea of the quark. He is on the faculty of the Santa Fe Institute in Santa Fe, New Mexico, where he is also the founding chairman. In addition he has been a professor of physics for 38 years at Cal Tech in Pasadena, California. He is the author of a book called *The Quark and the Jaguar*. Welcome back again, Professor Gell-Mann.

MURRAY GELL-MANN, Ph.D.: Very nice to be here, Jeffrey.

MISHLOVE: Nice to be with you. We really need to talk more about complexity itself. It's a term which is becoming very courant, and I don't think people always understand what is meant by complexity.

GELL-MANN: Well, it probably takes several definitions to cover the various meanings that we attribute to complexity and simplicity, but we can try to examine a couple and see the virtues and flaws in them. Something that we might call crude complexity would be the length of a message describing the system, but then we have to qualify that.

MISHLOVE: You mean the longer it takes me to describe some system, the more complex it would be?

GELL-MANN: Something like that. But then we have to put in a lot of qualifications.

MISHLOVE: Like the use of language.

GELL-MANN: For instance, right. It depends somewhat on the language; We mustn't allow you to invent a special pet name for the thing you're talking about. A system, no matter how complex, could be called Sam or Judy, and then the length of the description of course wouldn't mean anything. So it should be in a language previously agreed upon. And you shouldn't be able to point to it either, because that's also cheating. So it should be described to a distant correspondent, or something like that. And of course it also depends on the shared knowledge and understanding of the world, how long the description has to be. Furthermore it depends on the level of detail at which the system is being described. Suppose you're talking about a natural community, like a forest. Ecological scientists have argued for a long time about whether up to a point it's the simpler or the more complex forest that's more robust with respect to natural or artificial changes in the environment.

MISHLOVE: A more complex forest might have more species in it.

GELL-MANN: Well, exactly. If you ask, "What do you mean by a more complex forest?" for one thing it would have more species. A tropical forest might have several hundred species of trees, whereas the kind of coniferous forest you see from a ski lift in North America might have only five or six. The number of mammals would be much smaller; the number of insects would be much smaller, and so on, so you would have a simpler forest. But what do you count when you measure the complexity of a forest? Do you count just mammals and trees and flowering plants? What about microorganisms? And of course ecologists would count the interactions among species -- predator-prey, pollinator-pollinated, host-parasite, and so on. Do you count very obscure interactions? So it depends on the coarse graining, on the level of detail at which the system is being described.

MISHLOVE: I suppose if one attempted a quantum physical description they'd all be equal.

GELL-MANN: In any case, clearly, complexity is not an intrinsic property of the thing being described, but depends also on who or what is doing the describing.

MISHLOVE: Yes.

GELL-MANN: Now, crude complexity, with all those qualifications, would be the length of a message describing the system. It doesn't really correspond to what we normally mean by complexity, for the following reason. Suppose we compare the works of Shakespeare with a passage of equal length typed by the proverbial monkeys, supposed to be typing at random and producing mostly gibberish. The work of the monkeys would be largely random, and would have therefore a longer description, because the work of Shakespeare could be compressed using some of the regularities of language, the regularities of images, and so on and so forth.

MISHLOVE: Some of the compression techniques that are used all the time in computers could apply to Shakespeare, but not to the monkeys.

GELL-MANN: Exactly. And therefore by the definition of crude complexity the work of the monkeys would be more complex, which is certainly not what we usually mean.

MISHLOVE: That's right.

GELL-MANN: So I would use rather what I call effective complexity, which is something like the length of the message describing the regularities of the system. So whoever or whatever is doing the describing picks out perceived regularities and then compresses the description of those regularities into a brief message or model or schema, and the length of that is the effective complexity of the thing being described. Now suppose we compare the two quantities. When you have complete order, then both of them are very small; the system is certainly simple, if it's completely orderly. For instance, a string of ones -- 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 -- or a crystal at absolute zero temperature, something like that, completely orderly, would have essentially no crude complexity, and essentially no effective complexity. At the other end, let's look at a sequence that's completely random, or a gas at very, very high temperature. That has very high crude complexity, but again almost no effective complexity. So effective complexity can be large in the region in between order and disorder.

MISHLOVE: This seems to be very crucial, because it has something to do, I'm sure, with living systems. We live in this middle region ourselves.

GELL-MANN: Absolutely right. Complex adaptive systems flourish in that middle region, and cannot exist at the ends. For example, life can't exist in a crystal at absolute zero, and life doesn't exist in the middle of the sun either.

MISLOVE: So it's something about our intelligence as well. That use of effective complexity is often the way our minds work.

GELL: Exactly so. That perception of regularities, and then compression of those regularities into a brief schema or model or theory, that's what characterizes what I call complex adaptive systems, including living things. A complex adaptive system receives a stream of data, and it picks out regularities in that data stream, perceived regularities, compresses their description into a very brief message of some kind which I call a schema, and then it uses that schema for description or prediction, or for prescription of behavior for itself. And that description or prediction or behavior has consequences in the real world, and those consequences feed back to competition among alternative schemata. The schema, while it's robust, can be transformed into another schema, or replaced by another schema, and the competition among the schemata is affected by the real-world consequences of the prediction or the description or the behavior. You might say that there's a feedback loop in which effects in the real world feed back to influence the competition among schemata. For example, science, the scientific enterprise, is a wonderful example of a complex adaptive system.

MISHLOVE: Of a complex adaptive system.

GELL-MANN: The scientific enterprise -- the schemata or theories. The scientific enterprise generates theories which are very brief, concise descriptions of the regularities of phenomena. Those theories then can be modified or replaced by other theories, but the theories have predictive value, and they predict behavior in the real world, behavior of nature. They predict how nature works, and if observation confirms the results of the theory, that feeds back to promote or establish the theory. If observation -- experiment, for example -- shows that the predictions of the theory are wrong, that has a negative effect on the survival of the theory. Another example would be biological evolution, in which the schemata are genotypes -- DNA of organisms. There the genome, acting together with a whole lot of events in development and early life of the organism, lead up to an adult organism. The adult organism is codetermined by the genome, the DNA, and by all the events occurring in development and in early life. And then in adulthood there's a test, namely, sexual selection, if you're dealing with a sexual species like ours -- sexual selection, procreation, the survival of the offspring. And those determine whether the genotype, or something like the genotype, is passed on.

MISHLOVE: You've used the term complex adaptive systems to describe the whole of science and also the whole of biology.

GELL-MANN: The whole of biological evolution.

MISHLOVE: And at the same time I see it could apply equally well to a single organism, or perhaps even to a robot.

GELL-MANN: It could apply to a robot if the robot is adaptive, if the robot has the characteristics we just described. And computer systems have already been designed that act as complex adaptive systems. It can also apply to a part of an organism. For example, the immune system in mammals, including human beings, is a complex adaptive system. It acts very much like biological evolution, but on a much, much shorter time scale. Instead of hundreds of thousands of years, or millions of years for a major adaptation, it takes hours or days, and it has to in order to cope with invaders of the body.

MISHLOVE: What I'm getting from this discussion is the notion of emergence -- that at a certain level of complexity these systems emerge.

GELL-MANN: Complex adaptive systems can evolve, and when they do they explore, they create and fill niches, they try things, and they have a great tendency in the course of that to spawn other complex adaptive systems -- the way biological evolution has given rise to organisms and to ecological communities, but also to parts of organisms like the immune system, and also to learning and thinking. And then with human language it's given rise to sophisticated human enterprises like the scientific enterprise, like markets, societies, and then to the invention of computers which can be designed or programmed to be themselves complex adaptive systems -- for instance, to evolve strategies for playing games, strategies that no person ever thought of.

MISHLOVE: In Part 1 of our discussion you referred to one of the goals of quantum mechanics would be to have a theory of the whole universe, not just a special theory.

GELL-MANN: Well, those of us who are constructing what I call the modern interpretation of quantum mechanics would like it to apply to the whole universe.

MISHLOVE: Would you say the whole universe, then, is a complex adaptive system?

GELL-MANN: One or two people speculate about that, but I don't. I haven't dealt with that speculation myself. As far as I'm concerned, there's no evidence of that, and there's no evidence that galaxies or stars or planets or rocks are complex adaptive systems. They all undergo evolution, but it's not, as far as we know, the kind of evolution that we were discussing, where the experience of the system is separated into perceived regularities and perceived randomness, and then the perceived regularities are compressed into a brief message or schema, and then the schema is one of many alternative schemata related by mutation and variation, and then the competition among the schemata is affected by their consequences in the real world. We don't have evidence that galaxies do that, or stars or planets or rocks, and I don't think we have evidence that the universe does it either.

MISHLOVE: Now, in Part 1 of our discussion we refer to the M word and to the C word -- mind and consciousness. I think what you're saying when you refer to these schemata and the way they interact, it seems like perhaps a more operational discussion of what might otherwise be called consciousness.

GELL-MANN: No, not necessarily. All of these things that we were just discussing can exist even when there is minimal consciousness.

MISHLOVE: As that robot.

GELL-MANN: A robot, or organisms that are less sophisticated than human beings, much less sophisticated than human beings. You probably wouldn't ascribe a great deal of consciousness to a paramecium or a worm or something, but they are complex adaptive systems.

MISHLOVE: You're willing to consider that there might be some consciousness at that level.

GELL-MANN: There might, but probably -- I mean, we haven't defined it very well, but however we define it, there probably isn't very much. However, in many parts of the universe, as we were saying, complex adaptive systems presumably have evolved and will evolve, and I would guess that in the course of poking around, exploring possibilities, spawning new systems that are complex adaptive systems, and so on, that they give rise to consciousness here and there -- that it's not a unique phenomenon here on earth. Presumably it exists in very many places, and in very many forms, which it would be fascinating to know about.

MISHLOVE: I gather that you're suggesting then that consciousness emerges at a certain level of complexity, much the way chemistry emerges, or biology emerges.

GELL-MANN: That's what I would guess.

MISHLOVE: Rather than that it's, say, fundamental to the elementary level of physics that you've explored all your life.

GELL-MANN: There is no evidence of that whatsoever, as far as I know.

MISHLOVE: Well, there is the theory, I think put forth by Wigner and von Neumann, that consciousness is somehow involved in -- I'm not a physicist, but I believe they would say the collapse of the wave function.

GELL-MANN: Yes, but in the modern interpretation of quantum mechanics, one tries to describe that process differently, and it becomes, I think, much less mystical, much more comprehensible, and generally more satisfactory. Namely, as we were discussing in our earlier incarnation, the alternative outcomes of a quantum event have to be described in sufficiently coarse-grained fashion that they decohere from one another, they don't interfere. Only those non-interfering, coarse-grained histories can be assigned probabilities that have any meaning in quantum mechanics. That means that if you can divide the world into a system and its environment -- which you can't always do, but let's suppose for simplicity you can -- that the interaction with the environment, which is then averaged over, destroys the phase relations among the different outcomes. In that case the outcomes are just like very familiar outcomes -- outcomes of a horse race, or outcomes of any other probabilistic event. And in that case you don't have to worry about this -- this so-called collapse of the wave function, when the alternatives are decoherent, is no different from the collapse that occurs when you're at the races and in the first race there are a lot of horses with different probabilities of winning, but at the end of the race one of them has won, and do you say the wave function has collapsed to the victory of that one horse, and it's very mysterious and paradoxical? No, you say there were various possibilities, one of them happened, and the rest of them no longer have anything but zero probability because they didn't happen. That's all it is. It's no more complicated than that.

MISHLOVE: In other words, you're saying, if I understand you, that the quantum world is no more complicated than a horse race.

GELL-MANN: Once it is coarse-grained to the point where the alternatives decohere, and that's the only level at which it can be utilized. Only at that level can it be utilized. Once that's done, then it's no different from a horse race, and there's nothing peculiar about it anymore. That's, I think, quite a useful observation that those of us who are constructing the modern interpretation of quantum mechanics make.

MISHLOVE: And if this interpretation succeeds, then you will in effect have proved Niels Bohr wrong when he said you have to be dizzy if you contemplate quantum mechanics.

GELL-MANN: I'm afraid there is still some dizziness left. We haven't gotten rid of it all yet, but we try. We would like to get rid of it. We would like to demystify quantum mechanics as much as possible. Now, there is still the point that if quantum mechanics gives only probabilities, that's useful only if there is something around to bet on those probabilities. So it is still true that a complex adaptive system is an interesting system, because it is the thing that can utilize the quantum mechanical probability. So to have a complex adaptive system around, watching what happens, observing that this happened and not that, is still interesting; but it doesn't play the central role that it played in the standard Copenhagen interpretation.

MISHLOVE: Earlier you said that whether you choose to look at the system from a fine-grained perspective or a coarse-grained perspective, that's always a decision of the observer.

GELL-MANN: Not necessarily a decision, no. I think to talk about it as a decision is not a very good way. It's perhaps a more old-fashioned way to talk. I would say simply that there exist coarse grainings, and that those coarse grainings can lead to a quasi-classical world.

MISHLOVE: Quasi-classical.

GELL-MANN: Quasi-classical, because there's always the branching, the quantum-mechanical branching; but a quasi-classical world which obeys roughly classical laws, subject to very frequent small fluctuations and occasional very large branchings. And this quasi-classical world, then, is what is actually dealt with, and in the quasi-classical world there are then no more paradoxes, no more difficulties. But complex adaptive systems then evolve to exploit such a quasi-classical world, and they need the regularity that comes from the quasi-classicality in order to find regularities -- in order to behave like complex adaptive systems, in order to find patterns, they need the regularity associated with the quasi-classical domain, as we call it. And of course there's always plenty of indeterminacy to supply the disorder.

MISHLOVE: Now, in the branching that occurs in the many-worlds interpretation, you've speculated, I think, referring to some of the Russian science fiction writers, about the idea of gremlin universes that interact with each other.

GELL-MANN: Something like that. Let's try and get it clear. The idea there is that such a quasi-classical domain as we were talking about is based on simple, familiar variables, in practice. The one that we have evolved to exploit, everything that we know about has evolved to exploit, is a particular quasi-classical domain involving electric charge densities and momentum densities and energy densities and things of that kind, variables like that, taken over small volumes which are large enough for certain criteria to apply, and small enough for other criteria to apply. Those are sometimes called hydrodynamic variables. They're very familiar variables, things like the amount of energy contained in a little volume, things of that kind. You follow those through time at certain intervals, frequent intervals of time. Those are your coarse-grained histories. We have evolved to exploit that kind of coarse-grained history, that kind of quasi-classical domain. Then we raise, not completely with tongue in cheek, the question of whether there might be other, very different quasi-classical domains with which we are not familiar, and whether complex adaptive systems might then evolve to exploit those. We don't know if there is such a thing. We don't know if there are these alternative quasi-classical domains, very different from the one we are familiar with, and so we don't know whether complex adaptive systems evolve to exploit it. But we just ask whether that might be possible. If so, what would be the relationship between the complex adaptive systems in one quasi-classical domain, and those in another quasi-classical domain skew, so to speak, to the first one?

MISHLOVE: Right.

GELL-MANN: It's a kind of weird question, but we ask it. And a Russian theorist told us that he believes that in science fiction such domains would be referred to as goblin domains, but I have no idea whether that's true. It's something we were told.

MISHLOVE: It's something one would find in mythology as well, not just science fiction.

GELL-MANN: Well, I don't know, but anyway it's amusing. Jim Hartle, my collaborator, and I -- Jim Hartle is a very distinguished quantum cosmologist; in fact he and Stephen Hawking founded the field of quantum cosmology with their famous paper, "The Wave Function of the Universe" -- Jim and I worked together on these things for a number of years, seven or eight years. And he and I speculate about whether there might be these additional quasi-classical domains, skew to ours, and maybe complex adaptive systems in each, and if so, how they would relate to each other. And to one system the other would be accessible, perhaps by some shared variables, or if there are no shared variables, they might be accessible only by making a quantum mechanical calculation or a quantum mechanical measurement. In other words, one kind of thing would appreciate what the other kind of thing can see and work with only by a complex calculation or measurement. You might argue that that's something like the relation between men and women.

MISHLOVE: Like ships passing in the night. Sometimes we can make a quantum mechanical measurement and get together.

GELL-MANN: Anyway, that's not the most serious part of our work.

MISHLOVE: Indeed, but I guess it does suggest that even yet quantum mechanics still has a few mysteries.

GELL-MANN: It has some. Certainly it has some mysteries.

MISHLOVE: Professor Murray Gell-Mann, it's been such a pleasure discussing the issues of simplicity and complexity with you. At the end of our first program I was sort of feeling that the simple is really complex, and the complex is really quite simple. But I think you've really clarified this time how simple the simple can be, and how complex the complex can be. So we've covered the entire spectrum.

GELL-MANN: Thank you very much. It's been a pleasure.

MISHLOVE: Thanks so much for being with me.