Complexity Science and 21st Century Issues
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"Future Directions in Complexity Science at the Santa Fe Institute"

During the last two decades, the essential role of complex interactions in science, government, business and other human social interaction has become widely appreciated. Dr Eisenstein charts the progress made in developing analytical and computational tools and outlines some potential new directions for the scientific program at the Santa Fe Institute. Among other things, he discusses the connections of fundamental scientific concepts to the understanding of aspects of human behaviour and decisions regarding social policy.

The SFI is 20 years old this year and is a non-profit private institution and if there's one thing that describes us above everything else is that the SFI is all about boundaries, edges and frontiers. Our founders have included some extremely prominent scientists and we focus entirely on theoretical research and do mostly mathematical and computational modelling of systems.

We have very strong connections to the business community and almost 55 companies belong to our Business Network. We also have a board of trustees, mostly business people and philanthropists, a science board of about 40 people including 5 Nobel Laureates and an external faculty of about 7 people who come for short periods of time. We also have 15 resident faculties, 15 post doctorates, 6 students and about 100 research visitors every year.

Our work includes everything from medicine to physics to social science and we have a significant international program with many connections not only in what I might call the First World but also in the developing world as well. SFI is unusual in the United States in that only 25% of our money comes from the federal government and the rest from private sources. We emphasise interdisciplinary science often based on complex systems analysis and try to attract visionary scientists and students from all over the world.

I like to start with a simple diagram in which there is a progression from objects we like to think of as being simple, though probably they're not so simple, ascending through more and more complex entities; atoms to molecules, amino acids, simple life forms, fish, mammals, early man, mind conscientious, language and human social behaviour. The traditional modality of science for most of human existence has been to try to simplify all the time and it's a very valuable thing to do and still very valuable, but what's happened over the last 20 or 25 years has been a realisation that we can learn a lot by turning that approach on its head. My favourite example from the physics world is that if you think of an ideal gas with each of its point particles moving according to Newtonian laws then those laws are time reversal invariant. On the other hand when you put Avogadro's number of particles together in a container then all of a sudden the system does not obey irreversible physics. It's not time reversal invariant and that emergence of the Second Law of Thermodynamics largely out of reasoned combinatorial processes is a very good example of an emergent behaviour. That's one where we do understand the dynamics, but there are many other cases which we want to talk about where we don't understand the dynamics of what's going on. If I were being philosophical about it I would try to quote a famous Western explorer John Muir who said that when one tugs at a single thing in nature you find it hitched to the rest of the universe.

There is a great deal of information out there if you know how to get your hands on it. And that's sort of what SFI is trying to do; bring people together so the computer scientists might learn something from the physicists and physicists might learn something from the biologists that changes the way they do research. These are some of the impacts on science over the years and although we may not have had an exclusive credit or right to these ideas we played a role in germinating and propagating them. You will hear from Geoff West about scaling as a way to understand complex behaviour and many aspects of non-linear dynamics and network dynamics. Agent-based modelling is not something I'll discuss much, nor will I talk much about theoretical biology because you'll hear some of that from Geoff. The SFI has also done a lot of work on the origin of language and modelling social and economic interactions, the economy as a complex system and ideas about innovation, evolution and clusters.

So I'm not going to say much about scaling but the basic notion in Geoff West's talk will be to try to account for a remarkable phenomenon that has been known for about 100years; that if you plot the metabolic rate of all the mammals in the world you find the metabolic rate scales against the mass of the animal to 3/4 power. You can make a sort of naïve argument that will generate mass to the 2/3 power using surface area to volume as the measure but that's not the way it goes. It's to the 3/4 power and it's clear that that's the case, and I'll leave it to Geoff to tell you why that's true. I'll just take a moment to show you the data that he will talk about. This is a $\log_n/\log_n$ plot and you can see the known mammals from the sperm whale to the shrew as points on a line as a 3/4 power line. Mammals have a circulatory system which Geoff will describe to some extent and if you go into the cellular world where the circulatory system is not so clear you still see the same relationship even though there's some offset between the two lines. It turns out we can understand what's going on here with networks. The ideas seem simple but of course only in retrospect. At all scales, life is sustained by hierarchical fractal-like branching network systems; circulatory, respiratory, neural, mitochondrial networks. The networks are space filling in that they reach all the cells in the organism. Their terminal branch units, for example capillaries, are the same size within a given taxonomic group and natural selection has optimised these networks. In other words cardiac output is minimised. So like in these rather simple ideas you can talk about scaling in lots of other domains. This further graph shows how scaling behaviour starts at the molecular level and extends all the way up through the biosphere.

Networks are everywhere particularly in our work and we're very proud of the fact that Duncan Watts as a young investigator learned some of the ideas that he put into two books very well known in the United States: *Small Worlds* and *Six Degrees*, the notion that networks are not as you might think, random. I can't really say more than Chris Barrett gave us yesterday in his talk about network theory being applied to social systems but I will say a little about contacts in epidemiological research. Again this work has been carried out by Lauren Myers and her colleagues. What we would like to do is to predict the size and demographics of disease outbreaks before things get out of control. This is not limited to human diseases but is also important in the agricultural framework. We like to understand how we can develop control strategies and it's important to remember that we can't experiment with people. It's usually unethical so we need a mathematical model to help. But you have to do it in a useful way. Predicting the obvious is a good thing to do to check you're on the right track, but if at the end of the day that's all you do, you haven't made much progress. So we want models that are both reliable and usefully predictive.

The traditional approach is to compartmentalise the problem in an abstract and not very realistic way, into groups of 'susceptibles', 'infecteds' and 'recovereds' and the traditional approach in epidemiology has been to use differential equation analysis to map the change. There's nothing wrong with that except that it glosses over all of the subtleties or details and only describes gross behaviour. A much more realistic approach is the notion of using contact networks in which you divide the world again into susceptibles, infected and recovereds but you can spread these nodes all over a topological map, load data into the nodes and based on the strength of the interaction between the nodes you can build a realistic model of what's going on. So you build a realistic network and try to predict the spread of disease through it and then quantify the impact of various intervention schemes. That can be as complicated and as detailed as you want it to be. The trick is to avoid being overwhelmed by combinatorics; you can't take all possible solutions there are just too many, so you have to have filters in place that allow you to make reasonable selections. These models can be extremely important from a sociological point of view. You can understand when a disease outbreak becomes an epidemic; you can try to determine what the possibility is that it will turn into a large epidemic; you can try to understand the risk of an epidemic depending on how many cases there are initially and so on. But you can't do that with a normal differential equation set. You have to have the microscopic model

I'll just mention about explaining the regularities in the financial market using the methods of physics and ecology, but I won't say very much because my colleague Doyne Farmer will speak to you later. The basic idea is you look at the behaviour of financial data which display rather striking statistical properties and one example is clustered volatility; that is the sizes of prices on one day are much stronger than on the previous day, which is a bit like looking out of the window and saying the weather is not what it was yesterday. Most of the price changes are not driven by news arrival as people tend to think, and a good example of that was on October 19, 1987 when the US stock market lost 25% of its value. The conventional wisdom at the time given by The New York Times and other publications, involved all sorts of not very convincing reasons and the point is that these things are sometimes internally generated by the statistics.

SFI takes a different approach to these kinds of problems. Most economic models assume that all investors are rational and that the Market behaves in an ideal fashion. Doyne and his collaborators assume that individuals make their own choices on what they perceive locally as the rational thing to do. On the other hand with so many investors the behaviour ends up essentially random, behaving like moving particles with zero intelligence. Models can be set up simulating this and then you can try turning on intelligence in small ways and seeing what happens and you can use these strategies to predict what markets might do. What's interesting about this is not so much that people want to make money, but to provide guidance to the markets so that when they see trends moving in certain ways they can take corrective action to prevent excessive market swings. Doyne and his colleagues are using an enormous data set from the London Stock Exchange (350 million records) to try to retrospectively understand what's going on over the time the data was accumulated. Future work is going to be on agent based simulation rather than zero intelligence models and a bigger agenda later on is to try to extend these studies into work on social evolution.

The last example I'd like to give you is something we have not heard much about and that is the work of the Santa Fe Institute Consortium (SFIC) which is a multidisciplinary multi-site program to try to understand how children learn and whether or not that learning process can be described in a quantitative way. Basically the idea is to bring physical scientists and modellers and mathematicians and statisticians into contact with what amounts to a very powerful suite of instruments, Magnetic Resonance Imaging, Electron and Magneto Encephalography, PET scanning and all kinds of wonderful instruments that exist today to try to see whether with children we can begin to understand how brains develop. There will be two cohorts of kids, one from six months to five years and another from ten years to fifteen years and basic testing will be on linguistic, cognitive and social functions.

OK, so just a bit more on the future of SFI. Last October we had a scientific retreat where we all got together and talked about what might be interesting frontiers for the future. We hope to get our science board to validate what we've come up with in May. One area we want to concentrate on is the fundamental laws of biology. There are fundamental laws of physics which would take a number of pages to write down and they do a very good job, so the question is: 'are there fundamental laws of biology? Geoff will tell you about one possible fundamental law of biology concerning networks and scaling. There are other candidates we can think of such as the polymer principle in chemistry which determines how an adder is built from chemicals which interact with each other, but there are others. Is there a reason for example why the Krebs citric acid cycle is the way it is, and are there similar acid cycles in other forms of life?

A second question is how do biological systems store, retrieve and use information? In other words how should we think about how a cell computes? One thing a cell does not do is compute numbers. It may not even mimic a Turing machine very well. What a cell does is to sit there and do information processing on its metabolism, reproduction protein folding and all the things that go on in the cell driven by information. In addition cells do this in a very reproducible way. The errors in molecular biology are really quite small, or if they're large the cells know how to cope with that. How does all this go on?

The third question is how do ideas about complexity, entropy and the physics of information interact with each other? The SFI held a couple of workshops about this in the late 1980s and early 1990s but a lot has happened since then and it really foreshadows the notion that ideas about information and about computation are maybe even more fundamental than we realise. In my particular area of cosmology and particle physics there is now a lot of discussion about what happens to the information that falls into a black hole. Suppose you throw a phone book into a black hole. A phone book has a lot of information in it. What happens to it? That's an interesting conversation.

The fourth question is can we model innovation? Or robustness? Or evolution? I spent eleven years in federal government in the United States and a lot of the time was spent with congressmen, representatives and staffers and they're very smart people but they do not understand notions of innovation. Making an argument about why we should invest in science when we cannot predict the outcome is a hard sell. And I've many times wished that I had a convincing explanation about how it's impossible to predict innovation. We won't be able to predict innovation either but we might be able understand its impact if we study when it occurs in a quantitative way.

I've just mentioned the question of how we can understand or not, how the human brain develops in a quantitative way and that research will be ongoing.

One of the things we are thinking about these days at SFI is whether we can usefully simulate the interaction between the earth's physical systems, the oceans or the environment and human systems. This is taking the kind of work Chris Barrett describes and moving it to even larger scale, trying to understand whether we can be predictive about this. For example, the United States government will not sign the Kyoto Protocol because the science behind it is not very well understood. So what would it take in terms of understanding the science to induce governments like the United States and Russia to sign?

The last thing I'll talk about briefly is whether one can ameliorate civil conflict through the study of model systems. One of the regular members of the Santa Fe Institute is Elizabeth Wood and she's a professor of politics at Yale though she was at NYU until recently. She studies civil conflicts that occur in places like Columbia to try to understand why certain civil conflicts are resolved more or less amicably and remain robust and resistant to breakdown and others such as the Middle East of the conflict in Northern Ireland are much more difficult to resolve. It would be hard to conceive of a more important thing to understand, at least in the realm of politics.

So, as you can see, there is a lot going on at the Santa Fe Institute. Thank you for your attention, and I look forward to speaking with you during the rest of the meeting.