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A Review of the Santa Fe Institute: Institutional and Individual Qualities of Expert Interdisciplinary Work

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Abstract

In the early 1980s, a group of senior scientists affiliated with Los Alamos National Laboratories set to the task of creating a Research Institute that would favor synthetic efforts across disciplines rather than specialization. Disenchanted with the shortsightedness resulting from increasing specialization in the hard sciences, and excited about the bursting fields of computer science and non linear dynamics, the scientists set up to create an institution that would reveal the complexity of the natural cultural and socials worlds we inhabit. The Santa Fe Institute --a center of complexity studies, now known world-wide, was born.

This paper portrays the Santa Fe Institute. In it the history of the institution frames the individual qualities of its interdisciplinary worker as well as the organizational features that support or hinder their work. A qualitative study of this institution revealed four central characteristics of successful interdisciplinary workers: (1) a reputation for scientific rigor and excellence; (2) inclination and excitement towards interdisciplinary work; (3) the ability to ask good questions and (4) the ability to teach. Unique to this institution's organizational structure is (1) its combination of permanent and visiting researchers body; (2) the combination of problem posing and problem solving approaches to interdisciplinary research; (3) a strong support for collaboration.

I. Introduction

For the past several years, members of the Project Zero research team have been engaged in studies of the scholarly disciplines. Our goal in this work was 1) to determine what constituted a thorough understanding in various disciplines and 2) to show how such an understanding could best be obtained. One of the basic findings of our studies is that disciplinary understanding is difficult to achieve; in order to attain it, an individual must discard common sense notions of the world and replace them with structured ways of thinking, which must be practiced repeatedly if they are to be assimilated. Though the disciplines are regularly featured in schools across the United States, many students fail to make the cognitive shifts necessary for disciplinary mastery.

The bar is set higher outside of schools: in today's research world, understanding one discipline does not seem to be enough. "Interdisciplinary," "multidisciplinary," and "cross-disciplinary" (in common discourse, each word is roughly synonymous with the others) are terms which, in recent years, have become increasingly popular descriptors of research by both individuals and institutions. Such labels may often be used inaccurately or at least lightly: it is doubtful that the bulk of institutions referred to as "interdisciplinary" are doing work that combines the philosophy and methodology of two or more disciplines in a deep and meaningful way. However, there are certainly some individuals and institutions whom it is appropriate to call interdisciplinary in the fullest sense. With respect to these people and places, two questions arise:

1. If mastery of one discipline is difficult to achieve, how hard is it to master and work with two?

2. Which components need to be in place (within individuals and organizations) in order for excellent interdisciplinary work to take place?

At Project Zero, we are trying to answer these questions by doing a two-pronged study of interdisciplinarity. One prong involves the study of excellent interdisciplinary programs and classes at the collegiate and pre-collegiate levels; the other is comprised of our investigations of outstanding interdisciplinary research institutions. Upon completion of these projects, we hope to be able to offer an analysis of the elements that contribute to quality interdisciplinary work: those things which are common to all (or nearly all) remarkable interdisciplinary workers and institutions.

This paper is related to our investigation of interdisciplinary institutions. Our team has investigated five such places thus far, each one doing work on a unique set of topics. Our team devised a simple set of four criteria which we used to select institutions for our study. Those criteria are:

1. The institution must have been in existence at least five years;
2. It must have clearly stated research/product goals and educational goals;
3. The institution (particularly its senior personnel) must exhibit continuity in direction;
4. It must utilize some measures (formal or informal) of success;

In addition, information about the output of permanent staff, visitors, and students, as well as about how the institution relates to standard university and professional schools, must be obtainable.

We began our project at MIT's Media Laboratory, perhaps the most famous interdisciplinary institution in the world. Background research and interviews with 13 key Media Lab personnel gave us valuable insights into the institution and interdisciplinary work in general, and our findings from that study will play an important role in our final analysis of interdisciplinarity[1]. However, the Media Lab is a particularly unusual institution, and we were eager to compare it with another entity. Therefore, we continued our study by going to a place that shares the Media Lab's reputation for boundary-breaking work but that has a different agenda and utilizes different methods: the Santa Fe Institute (SFI). In this piece I describe and analyze some of our findings from SFI. Before beginning, however, I provide a short history and brief overview of this institution.

II. History of the Santa Fe Institute[2]

In the early 1980s, a group of senior scientists affiliated with the Los Alamos National Laboratories (LANL) met regularly, in part to discuss their disenchantment with certain aspects of the scientific enterprise. One of the discussants, George Cowan, was particularly vocal. A chemist who had done graduate work with Eugene Wigner and was a key participant in the Manhattan Project, Cowan had become a researcher and administrator at Los Alamos and had also served on President Reagan's White House Science Council. In his positions at Los Alamos, Cowan witnessed the increased fractionation of the sciences: disciplines like physics spawned numerous sub-disciplines, each one set apart from the others. Students of various sub-disciplines addressed different topics, used different methods, and attended different conferences. This increasing specialization and the dearth of interaction between different groups of scientists was not solely the result of personal choices; in order to be successful, scientists in the late 20th century felt compelled to specialize. As Cowan once observed,

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[1] A paper describing our findings at the Media Lab (Interdisciplinary Research and Education: Preliminary Perspectives from the MIT Media Laboratory) may be downloaded at http://pzweb.harvard.edu/Research/GoodWork .

[2] Most of the information regarding the history of the Santa Fe Institute up until 1991, including all direct quotes, was obtained from Waldrop, M. Complexity : the emerging science at the edge of order and chaos. New York: Simon & Schuster, 1992.

“The royal road to the Nobel Prize has generally been through the reductionist approach.”

Cowan did not have a problem with reductionism, per se. Working on the Manhattan Project and at LANL, he had seen it used (and often used it himself) to great effect. However, things were beginning to seem a bit out of balance. Cowan’s experiences on the White House Science Council were occasionally unsettling: the board of distinguished scientists, of which he was a part, often had difficulty addressing the broad scientific and societal problems set before them. When doing reductionist science, Cowan noted, “You look for the solution of some more or less idealized set of problems, somewhat divorced from the real world, and constrained sufficiently so that you can find a solution. That leads to more and more fragmentation of science.” On the other hand, Cowan said, “The real world demands — though I hate the word — a more holistic approach.”

The existing practices in science and science education had created a body of specialists who were accomplished in their areas of expertise but who were disinclined (and maybe limited in their ability) to think, talk, and work outside of those areas. Cowan and his Los Alamos compatriots worried that if the trend towards specialization was not counterbalanced in some way, two things might happen:

1. the pace of innovation and discovery might slow to a trickle as scientists repeatedly revisited topics within their specialties;

2. important societal problems might go unsolved because of a shortage of thinkers broad-minded enough to tackle them successfully.

Even as these concerns surfaced, the group at Los Alamos noticed two new trends in science. First, there was increasing interest in non-linear dynamics: physicists and mathematicians were beginning to find and quantitatively describe regularities in systems which previously had seemed random or at least too complex for precise analysis. Second, and closely related, computer modeling was coming into widespread use, in part because computers' ability to process large amounts of data enabled scientists to find and describe the aforementioned regularities. Cowan and the other senior fellows saw the advances in non-linear dynamics and computer modeling as possible remedies to the problems of intense specialization and disciplinary isolation. Perhaps, via non-linear dynamics and computer models, the tools of math and physics might be brought to bear on complicated problems from various disciplines. This interdisciplinary work might spur new advances and lead to solutions of the problems which had bedeviled Cowan and his colleagues on the White House Science Council.

Frustration combined with a sense that there might be a way around the problems they had identified gave Cowan and the other Los Alamos scientists a sense of mission. They resolved themselves to create an institution which would be interdisciplinary in nature and which would make use of non-linear dynamics and computer modeling. The institution would favor synthetic efforts over specialization, it would de-emphasize disciplinary boundaries and bureaucracy, and it would be a haven for scientists in search of a broader view of their enterprise. Inspired, the Los Alamos fellows realized that before they began the practical work of putting the institution together, there was one last question: what would the scientists at this place study?

The decision to create a new kind of institution was followed by a long debate about what its focus should be. Nick Metropolis suggested that the discipline he had helped form, computer science, would be an excellent topic of investigation for the new institute, and some of the fellows agreed with him. Other members of the group disagreed and suggested other options, but nothing quite took hold. Entering the debate several months into its existence, Murray Gell-Mann (the Nobel Prize winning physicist and broad thinker *par excellence*) argued that the conceptions that had been put forth up to that point were simply not grand enough. For the proposed institute to really make an impact on people's imaginations and the course of science, Gell-Mann said, the topic of study had to be both broad and bold: computer science and the other options that had been proposed were too circumscribed and too well-established to have sufficient impact. Instead, Gell-Mann proposed more all-encompassing areas of inquiry. As he put it in an interview with us:

> I thought in terms of a grand synthesis like plate tectonics, like biological evolution, like elementary particles, like nucleosynthesis — generation of nuclei in the stars in the early universe, generation of chemical elements, the nuclei of chemical elements. All these things. Big.

Gell-Mann's notions held sway with the senior fellows: they agreed that a grand synthesis was what the new institution would need to create excitement and make an impact. However, they still were not clear about exactly what that grand synthesis would look like. In an attempt to clarify their thinking, attract new ideas, and get a sense of what topics would interest other researchers, the fellows held a pair of small conferences just as the institution was beginning to take shape. Renowned scientists from several disciplines attended, and many put forth their own ideas for the proposed institution. As the scientists spoke, Cowan, Gell-Mann, and the other fellows from Los Alamos detected a repeating theme: several of the researchers focused on how simple elements gave rise to complex phenomena, phenomena whose qualities could not easily be predicted from the nature of the constituent elements. The group from Los Alamos decided that their new institution would focus on "complexity," a term whose exact meaning was purposely left unclear: the founders wanted a wide range of scientific subjects to fit within the institute's purview.

By 1987, after some early bumps and bruises with respect to funding, space, and organizational infrastructure, the Santa Fe Institute was firmly established in an old Santa Fe building that had previously been a convent. Small in size, SFI was designed as a visiting institution, and the few residential faculty members were greeted regularly by researchers from other institutions who came to work for short periods of time (ranging in duration from a day to a few years).

Crucially, a few of the early workshops held at the Santa Fe Institute were quite successful. Particularly notable was a series of sessions that brought economists into contact with physical scientists. Stimulated by Citicorp CEO (and early SFI funder) John Reed's sense that the new institution's work might help produce a better understanding of the world's economy, a number of prominent economists traveled to the young Institute and shared their work. Almost every time an economist finished his or her presentation, the physicists in the audience let loose a barrage of questions and critiques concerning (among other things) the economists' somewhat extreme devotion to mathematical models and the notion of economic equilibrium. The ensuing exchanges were worthwhile (if not painless) for both groups: the economists were forced to re-evaluate their basic assumptions and methodologies, while the physicists were exposed to questions and issues that resided far outside their domain. Both groups realized that working together might prove fruitful, and in the late 1980s, several collaborations between economists and physicists associated with the Santa Fe Institute took place. Those collaborations have had an impact both on how economics is done[3] and on possible career paths for physicists.[4]

Early conferences like the ones mentioned above helped to legitimate the Santa Fe Institute and also served to create a stir in the intellectual community. The Institute's members did not try to divert this attention; as one subject told us, it is important to create a "fad" when you are trying to get a new enterprise off the ground. By the late

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[3] Roston, E. "Nature's Bottom Line." *Time.com* , May 28, 2001. (www.time.com/time/personal/article/0,9171,1101010528-127256,00.html)

[4] Farmer, J.D. "Physicists Attempt to Scale the Ivory Towers of Finance." *Computing in Science & Engineering (IEEE)*, November-December 1999, 26-39. (http://www.santafe.edu/sfi/publications/Working-Papers/99-10-073.pdf)

1980s, the Institute had begun to earn recognition as the nation's leader in the study of complexity and one of its foremost interdisciplinary institutions.

Success, however, can have its drawbacks[5]. When George Cowan stepped down from his position as the Santa Fe Institute's first president in 1991, SFI was beginning to receive widespread attention in the popular press. Over the next few years, several pieces about SFI appeared in various publications. Many of these articles were positive, but some authors had limited knowledge of the Institute's mission and overstated claims SFI researchers made about their work. Combined with, perhaps, a bit of over-enthusiasm on the part of some SFI personnel, these overstatements contributed to a perception among some that the Institute was more sizzle than substance. A handful of harsh critiques were put forth, and some of the Institute's most well-known and respected members had their efforts singled out for criticism. In short, the Santa Fe Institute had to deal with a spate of bad press in the mid-'90s.

The Institute's researchers soldiered on, and in 1995, SFI selected its third president, Ellen Goldberg, formerly the Associate Provost for Research and Dean of Graduate Studies at the University of New Mexico. It was an inspired choice. Goldberg told us that because she had not been associated with SFI since its inception, she was able to view the Institute with a distance unavailable to its first two presidents, George Cowan and Ed Knapp (a Los Alamos scientist and former Director of the National Science Foundation[6], who had been affiliated with SFI since its earliest days and led SFI from 1991 to 1995). Consequently, while Goldberg was impressed with many aspects of SFI and committed to pursuing the mission defined by the founders, she was also able to discern weaknesses that were holding back the Institute.

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[5] Information in this paragraph comes from interviews with SFI subjects, as well as from background reading. For a harsh article on SFI, see Horgan, J. "From Complexity to Perplexity." *Scientific American*, June, 1995 (www.sciam.com/explorations/0695trends.html)

[6] "Edward A. Knapp's Curriculum Vitae" (www.santafe.edu/sfi/People/eak/eak-vita.html)

One of the first issues Goldberg had to confront was the Santa Fe Institute's public relations problem. Goldberg told us that many of the accusations leveled at the Institute in the mid-'90s were off-base. However, she also said that as a newcomer to SFI, she could see how a journalist who did not fully understand the ideas being debated at SFI could become frustrated with occasional "hand-waving" by SFI scientists (fending off questions about the specifics of their research with vague statements and gesticulations).

Goldberg knew that the hand-waving did not stem from a fundamental weakness in the Institute's conception of complexity: the area of inquiry was promising and SFI researchers had already done valuable work within it. Furthermore, the researchers at SFI were (and still are) outstanding: the Institute has always been very selective in choosing new researchers. Consequently, Goldberg decided that the best way to deal with the Institute's public relations problem was simply to 1) re-emphasize the organization's commitment to rigorous science and 2) make sure that journalists who covered SFI left with a solid understanding of its mission. Today, Goldberg is satisfied that the "hand-waving" problem is solved, but she is vigilant about letting SFI's scientific results speak for the institution.

Another situation Goldberg decided to address early on concerned the Institute's organizational structure. Upon arriving at SFI, Goldberg was surprised to find that the institution famous for showing how complex behavior could emerge from a leaderless collection of simple entities was itself structured in a "top-down" fashion. According to Goldberg, when she arrived at SFI, the scientists were not involved in organizational decision-making, and the people in charge were removed from SFI's research (which may have contributed to the tendency of some SFI leaders to hand-wave and speak in generalities). Goldberg worked with members of the administration to remove bureaucratic obstacles that had arisen at SFI and tried to put more responsibility for the organization in the hands of individual researchers. For example, in the past, SFI's senior members wrote all the grants for the Institute; now researchers write their own grants. Changes like this have made a difference at the Institute: many of the administrators with whom we spoke said that SFI is more bottom-up than it was in the past, and that it now runs quite smoothly. Harry Owen, SFI's Chief Financial Officer, spoke to this:

> Ellen runs the organization in such a way that she allows you a tremendous amount of flexibility … . If I have a problem, I go to her, and we get it resolved and otherwise, I don't bother her. … she allows us to run our various … areas of responsibility with a pretty free hand. … I think it builds self-confidence for all of the individuals. The end result is it's really a team all going in the same direction … .

III. Brief overview of the Santa Fe Institute today

Today, the Santa Fe Institute is thriving. Housed in new, expansive quarters at the base of the Sangre de Cristo Mountains, the Institute is home to about 15 full-time scientists (researchers on multi-year appointments and post-docs). It has a vibrant external faculty (researchers who are affiliated with SFI and come back for repeated stays), and receives over 100 visitors yearly. SFI is run by president Goldberg and an administrative staff of 24 who handle the Institute's business relations, its publications, and its daily operational needs. SFI also has a Science Board (50 distinguished scientists charged with "oversee[ing] the general direction, integration, and quality of the Institute's research") and a Board of Trustees.

Research program

All of these people are attracted to the Institute's ambitious and evolving scientific agenda. True to Cowan and the co-founders' visions, SFI today does basic, integrative research, and there are "no formal programs or departments."[7] The environment at SFI is perhaps best described as *churning*: the overarching themes at the Institute are broad, scientists often work on various different topics simultaneously, and working groups form, dissolve, and re-form according to the interests of the researchers. This churn is augmented by SFI's constant stream of visitors: researchers come to the Institution, make a contribution to the effort, and then leave. SFI administrators hope that visitors will "spread the word" about SFI and complexity science by continuing to nurture investigations and collaborations started at the Institute when they return home.

While the Santa Fe Institute does strive to provide an integrative and synthetic environment for its researchers, there are still some overarching categories into which SFI research projects fit. Below, I have listed the categories currently in use at SFI, along with an extremely brief overview of the research in each area.[8] None of the overviews indicate the depth and scope of the projects included under each heading, but they at least give some feel for the general topics currently being studied.

1. <u>Computation in Physical and Biological Systems</u>

The Santa Fe Institute's Web site indicates that researchers in this area are "rethink[ing] what it means to compute and … ask[ing] what other systems in nature could be substrates for information processing."

2. <u>Economic and Social Interactions</u>

Researchers on projects falling under this heading are exploring the evolution of institutions, the formation of states and markets, and the dynamics of cultural change, among other topics.

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[7] www.santafe.edu/sfi/research/indexResearchAreas.html

[8] Research titles and descriptions taken from www.santafe.edu/sfi/research/indexResearchAreas.html

3. Evolutionary Dynamics

Here, effort is focused on developing models of the evolution of entities from their constituent parts, understanding the relationship between genotype and phenotype, and investigating "the extent to which evolutionary dynamics can assist in explaining human societal transformations."

4. Network Dynamics

The goal of researchers working in this area is to understand network structure and function. SFI scientists are working on biochemical networks, social networks, and the Internet.

5. Robustness

Measures of "robustness" correspond to the ability of an entity to withstand or adapt to insults. SFIers are studying the topic with reference to cells, organisms, computers, and societies.

Educational program

Though not degree-granting, the Santa Fe Institute supports a variety of educational initiatives.[9] First, at any given time, there are a number of post-docs present at SFI. These individuals are important contributors to the organization's research, but they also learn from SFI's more senior scientists. Second, a small number of graduate students, enrolled at other institutions and with their classroom requirements satisfied, visit the Institute to do their thesis research. Third, SFI hosts a very small number of undergraduate interns who visit and do research in the summertime. Finally, the Institute sponsors a number of educational workshops and conferences. Foremost among these is the Complex Systems Summer School (CSSS). Described as "the flagship

[9] Descriptions of educational programs taken from www.santafe.edu/sfi/indexEducation.html

of SFI's educational programs," the CSSS is "an intensive four-week introduction to complex behavior in mathematical, physical, and biological systems, intended for graduate students and postdoctoral fellows."

IV. Our methodology

Given the scope of the Santa Fe Institute's activities, my colleague Kaley Middlebrooks and I were ready to work when we arrived there for a one-week visit in the spring of 2001. Over five days, we toured the Institute's campus, attended a handful of afternoon teas with SFI researchers, and tried our best to soak up and understand the atmosphere in this unique environment. Most importantly, we also conducted one-and-a-half hour, semi-structured interviews with 12 SFI members (seven researchers and five administrators), in an attempt to answer three main questions:

1. Which kinds of people work in the SFI environment?

2. Which methods do those people use to do their work?

3. How do particular organizational structures and/or characteristics facilitate or impede interdisciplinary efforts?

Each interview was done in person and audio-taped, and quotes appearing in this paper come from transcripts of those interviews.

V. Characteristics of current SFI researchers

Perhaps the best way to begin to understand the "deep structure" of interdisciplinary work at the Santa Fe Institute is to take a closer look at the individuals there and the work that they do. George Cowan and Murray Gell-Mann are still a very important part of SFI, and Ellen Goldberg and her staff provide crucial leadership. Much of the Institute's scientific work, however, is carried out by younger researchers. Accordingly, the following section consists of brief introductions to three researchers who were at the Santa Fe Institute when we visited, and whose backgrounds and working styles are somewhat typical for the Santa Fe Institute. While it is impossible to make general statements that are accurate for all of the one hundred or more people who visit SFI in any given year, I believe that these three researchers can be used to illuminate themes broadly characteristic of the Institute.

VI. Profile of three SFI researchers: James Crutchfield, Mark Newman, and Ricard Solé

James Crutchfield

When we asked SFI Research Professor James Crutchfield about his youth, he told us he had been a "weird kid." He said he had always had a wide variety of interests, which he often tackled alone: he was ahead of his peers intellectually and became accustomed to solo exploration while growing up.

Crutchfield continued to investigate issues outside the norm during his undergraduate and graduate years at UC Santa Cruz. There, he became involved with a group of physics graduate students — Robert Shaw, Norman Packard, and J. Doyne Farmer (now also an SFI Research Professor).[10] The four were studying chaotic systems: systems whose behavior appears random, although it actually is not, and where small changes in initial conditions can lead to dramatically different outcomes. The group called themselves the Dynamical Systems Collective. When it came time to write their dissertations, the four relied on each other as advisors. By and large, the work of the Dynamical Systems Collective was not supported by UC Santa Cruz's faculty (Ralph

Abraham, a professor of mathematics, and Bill Burke, a physicist, were notable exceptions).

By the time he received his doctorate, Crutchfield had shown enough skill and ingenuity in mathematics and physics to be offered academic positions. He eventually became a professor in the physics department at the University of California, Berkeley, where he stayed for several years. Over a period of time, Crutchfield became increasingly interested in several topics outside of physics, especially biology and computer science. At Berkeley, he had difficulty pursuing these interests professionally for a couple of reasons. First, the multiple time commitments academia imposes made it difficult for Crutchfield to explore new disciplines and collaborate with faculty outside of the physics department. Speaking of the time crunch at Berkeley, Crutchfield said, "You know … your schedule is being compromised when the people you need to talk to at the University, you talk to them when you go to another coast for a conference … . SFI offered the possibility of, really, … full-time research." Second, Crutchfield's interests — particularly his desire to explore the ramifications of his theoretical work via computerized experiments — stood out as unusual in the Berkeley physics department. Again, Crutchfield did not quite fit in, and senior members of the department sought to keep him "on track." As Crutchfield put it:

> I wasn't studying high temperature superconductivity or particle physics … [and members of the physics department would say,] 'What's this weird stuff Crutchfield studies? He plays with video cameras and does video feedback and chemical reactions and electronic circuits, and then he does simulations and then proves theorems. What the hell is this all about? It doesn't make any sense. You either do experiments or you do theory.' I was told this a number of times by senior colleagues: 'Jim, come here. You really have to focus a little more. You're a little too broad. You either have to do experiments and get good at it, or you're going to do theory and get good at it.'

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[10] Gleick, J. Chaos: making a new science. New York: Viking Penguin Inc., 1987.

Therefore, when he visited the Santa Fe Institute in the late 1980s, Crutchfield was excited; here, at last, was a place where he could do more integrative research on a full-time basis. He soon accepted an offer to become an external faculty member affiliated with SFI. For several years, Crutchfield split his time between Berkeley and SFI; recently, he accepted a full-time position at the Institute.

Crutchfield is now a leader at the Santa Fe Institute. He is currently directing and working with groups studying topics like "Computational Mechanics" and "Evolving Cellular Automata," subject areas which combine biology, computer science, and theoretical physics. Each project is quite complex, but the overall goal of Crutchfield's work is easily digested: he wants to understand how humans and other complex, living systems discover patterns in the world and make sense of them. In other words, he is interested in exploring how organisms (and, in much of his work, computers) learn from their environment and adapt to it. He believes that an answer to this question can be found and documented.

Mark Newman

Like James Crutchfield, Research Professor Mark Newman was trained as a physicist: he earned his Ph.D. in theoretical physics from the University of Oxford in 1991. Newman then moved to the Cornell University, where he was first a post-doc and then a research associate at Cornell's Theory Center. In 1994, Newman — attracted by former SFI professor Stuart Kauffman's work on evolution — attended a conference at the Santa Fe Institute. Impressed with what he saw, Newman did his second post-doc at SFI from 1996-1998; when done, he stayed on at SFI as a Research Professor.

The similarity between Crutchfield and Newman extends to their work: though trained as physicists, neither has been content to stay put in his home discipline. Newman has applied the mathematical and physical tools he has learned to analyses of social networks and issues in paleobiology, exploring topics as diverse as the networks of collaboration amongst scientists[11] and patterns of extinction as seen in the fossil record.[12] When we asked him why he has strayed from physics' usual topics of study, Newman said:

> I don't know. Physics is an interesting subject intellectually. I find the mathematics interesting and the problems challenging. But which would you rather be thinking about: a lump of metal on your desktop or where the dinosaurs lay eggs? I guess I find those biology questions just intrinsically more interesting. Every kid is interested in dinosaurs when they are six. It takes people some decades before they develop an interest in mathematical physics.

Because of his skills and his diversity of interests, Newman (like Crutchfield) was an especially useful resource for us as we tried to understand interdisciplinary work at the Santa Fe Institute. In particular, his comments on the strategy he uses when planning and participating in an interdisciplinary collaboration, upon which I elaborate below, were invaluable to us.

Ricard Solé

Unlike Crutchfield and Newman, both residential faculty, Ricard Solé is one of the Santa Fe Institute's external faculty members. When he is not at SFI, Solé is usually at the Polytechnic University in Barcelona, where he is the head of the Complex Systems Research Group and an associate professor in the Department of Physics and Nuclear Engineering.[13] Like Crutchfield and Newman, Solé received his Ph.D. in physics; however, he also has a five year degree in biology.

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[11] See, for example, Newman, M. E. J. "The structure of scientific collaboration networks." *Proceedings of the National Academy of Sciences,* 98 (2001): 404-409.
[12] Solé, R. V. and Newman, M. E. J. "Patterns of extinction and biodiversity in the fossil record." In T. Munn (ed.), *The Encyclopedia of Global Environmental Change*. New York: John Wiley, 2001.
[13] Information taken from Solé's homepage: http://complex.upc.es/~ricard/

Solé's interests in biology stem in part from unusual experiences he had as a child. His father traveled the world and often brought home exotic animals for Solé and the rest of the family. For example, Solé and his siblings once went without a bath for a week — a small crocodile their father had brought home was occupying the tub. Today, biological questions continue to interest Solé, although he habitually addresses them using a physicist's tools. Solé works on problems in the SFI areas of Robustness and Network Dynamics; topics he has studied include ecological networks and the dynamics of the Internet.

VII. Keys to success at the Santa Fe Institute

Though these sketches have been brief, one can discern some similarities between Crutchfield, Newman, and Solé. Each man is a physicist, for example, and each is also interested in biology. However, with respect to these three men and other SFI researchers, there are commonalties at a deeper level: personal characteristics shared by almost all members of the Institute.

Several of our subjects quoted George Cowan as saying that the Santa Fe Institute has good "taste" in the researchers it selects. Associate Vice President Ginger Richardson explained that taste by citing four personal qualities SFI looks for in prospective researchers, and others with whom we spoke cited very similar qualities.

1. <u>A reputation for scientific rigor and excellence</u>

Since its inception, the Santa Fe Institute has recruited and attracted some of the best scientists in the world. For example, in addition to Cowan and Gell-Mann, early participants in Santa Fe Institute programs and workshops included Nobel laureates Phil Anderson (a physicist) and Kenneth Arrow (an economist). Young researchers at

SFI today are similarly impressive: the various positions Crutchfield, Newman, and Solé have held, as well as the professional opportunities they have enjoyed, indicate that these are talented scientists who would be able to work in many different environments.

Scientific excellence is crucial for SFI researchers for two reasons. First, the problems tackled at the Santa Fe Institute are very complex, and in order to have a chance at solving them, one must possess a sharp mind. Second, SFI's focus on interdisciplinary work is unusual, and a reputation for rigor is useful when a researcher (or an institution) is consistently probing new areas. The presence of Cowan, Gell-Mann, Anderson, Arrow, and others of similar stature helped to legitimate SFI in its early days, and men like Crutchfield may have an easier time both doing exploratory work and getting their efforts taken seriously than scientists who are less esteemed.

2. <u>Open-mindedness and excitement at the prospect of working in an interdisciplinary fashion</u>

Almost every Santa Fe Institute researcher with whom we spoke said that a fundamental openness to new perspectives and a sense of excitement with respect to interdisciplinary work are especially critical personality traits for SFI scientists. A representative quote comes from SFI Research Professor J. Doyne Farmer, who spoke to our team about reviewing applications at the Institute:

> Many of the people who apply are very narrow. So if we look at someone, and they just know about one little niche, then they are not going to be treated as favorably as somebody that's done several different things and seems to be broadly interested in a lot of different areas, because such a person is more likely to really interact with a broad group of people and create the synthetic view [and] actively participate in seminars.

One might reasonably ask: aren't open-mindedness and curiosity important traits for workers at *any* successful institution? Furthermore, wouldn't almost anyone, once they arrived at the Santa Fe Institute, at least appear excited about interdisciplinarity? Are these two traits really useful in distinguishing SFI personnel from researchers at any other institution?

While open-mindedness and excitement are prized widely, I think these two traits are especially critical at SFI — more so than elsewhere. Ellen Goldberg told us the Institute is looking for:

> The kind of person that can listen to another person's ideas and even have passionate arguments. I think passionate arguments are very important. So I don't think a person should necessarily concede. At least listen to the other person. Those are the people we look for, and those are the people we're finding. … Even though they may have big egos, they may have their own ideas about things, they listen. That really makes a difference.

Goldberg indicated, however, that firm resistance to others' points of view and a reluctance to collaborate is something that is seen from time to time at SFI. Many excellent scientists simply find it very hard to relax their grip on their own perspective, even for a short period of time. Working regularly as part of a dyad or a team can also be difficult for people whose careers have been made by their individual efforts. As reasonable as these stances are, researchers who burrow deeply into one problem, using one discipline, or who prefer to work behind closed doors, are generally not invited (or not invited back) to the Santa Fe Institute.

3. <u>An ability to ask good questions</u>

Open-mindedness and a willingness to do interdisciplinary work are important traits for those who work at the Santa Fe Institute, but if not well-channeled, they can cause researchers to run in circles — investigating several different problems but not actually achieving much. Disciplinary environments tend to emphasize repeated explorations of a few topics, so the minds of disciplinary researchers are, in a way, pre-channeled with reference to topic of study. By contrast, in order to make good use of their intellectual abilities in SFI's more free-form environment, researchers must exhibit (or quickly develop) an ability to chart a productive course of work by asking useful questions without much guidance. They must have, as SFI Associate Vice President Ginger Richardson put it, "an intuition about … important problems, important topics to pursue."

An interesting point to note is that as time has passed, a pattern has emerged at the Santa Fe Institute with respect to the types of questions asked by researchers. Ellen Goldberg pointed out that SFIers differ from most of their scientific brethren by choosing to work in two unusual ways:

1. SFI researchers focus on networks much more than on isolated entities;

2. Rather than disregarding statistically insignificant, aberrant results (in a computer model, for example), SFI researchers tend to hone in on just such outcomes, probing the 'noise' of their works for new insights.

Addressing the second point, Goldberg said:

> when I was sitting at a colloquium where someone was presenting something. They said, 'Well, it works 90 times out of 100.' At one point I'd say, "I'm convinced. That's the way it works." Now I say, "That's fine, but what about those ten that are not working? What is the difference?" …. That's what I would care about now. I would care about why that ten percent acted differently. … That was a direct influence with the Santa Fe Institute … I think it's the noise that gets very, very interesting.

These two modes of operation have served Santa Fe Institute researchers well. So well, in fact, that they may inadvertently become somewhat ingrained in the institution in the future. Perhaps in a few years, an individual's ability to ask good questions will become less important with respect to his or her suitability for work at SFI: standard types of questions may have become codified.

4. An ability to teach

Richardson emphasized to us that the Santa Fe Institute has chosen to emphasize education to a greater extent in recent years than it has in the past, and accordingly SFI is on the lookout for researchers who have some teaching ability. As Ginger Richardson put it, "We look at the ability of an individual to be a mentor, to be willing to work with students on an informal basis." It may also be that the Santa Fe Institute looks for researchers who are good at teaching colleagues. One of the Institute's hopes, after all, is that visitors will carry what they have learned at SFI with them when they leave and disseminate it to colleagues at their home institutions. Consequently, it would make sense for the Institute to at least be interested in attracting researchers who might also be good at "spreading the word."

Unfortunately, whatever the extent of the Institute's hopes with respect to education, we have very little data regarding what sorts of teaching qualities the Santa Fe Institute looks for in prospective researchers. Many techniques used by good teachers — for example, the ability to hold a learner's perspective and thus decide what topics to emphasize or explain — would seem to be of the utmost importance for those who would teach the interdisciplinary lessons SFI has to offer. We will have to analyze our data more deeply, and perhaps speak to more people, before we can accurately assess the validity of this hypothesis.

VIII. Organizational characteristics that affect interdisciplinary work at the Santa Fe Institute

The efforts of personnel are affected by the organizations in which they work. Below, I have described three qualities of the Santa Fe Institute which I believe play a large role in determining the way in which scientists there carry out their research.

1. A permanent visiting institution

The Santa Fe Institute is a unique combination of permanence and transience. The Institute's campus, the presence of Cowan, Gell-Mann, Goldberg, and long-time residential researchers like Crutchfield and Farmer, all suggest that the Santa Fe Institute is a stable institution with a core group of researchers and administrators. On the other hand, SFI has no tenured positions, receives over 100 visitors per year, and most residential researchers stay for at most a few years (Mark Newman, for example, has been at SFI for a reasonably long period of time — 5 years — and he lamented that his time is almost up.) Furthermore, despite its physical presence, the Santa Fe Institute describes itself as an "institute without walls":

> This means that although people come to visit, attend workshops, and collaborate, they return to their home institutions and research continues in a distributed fashion via e-mail, fax, phone, etc. among scholars in different places.[14]

Whether an institution is staffed with personnel who stay for long stretches or relies heavily on visitors makes a difference, especially with respect to interdisciplinary work. Below, I describe characteristics of SFI that illustrate its dual nature as part residential, part visiting institution, and that are related to its interdisciplinary mission.

[14] www.santafe.edu/sfi/research/indexResearchAreas.html)

Residential attributes, benefits, and concerns

At a residential interdisciplinary institution, the following realities become apparent:

a. Attention must be paid to the physical environment

At residential interdisciplinary institutions, crafting the environment so that it supports interdisciplinary work is often a concern, and SFI's physical reality is certainly important to its staff. The Institute's main building was built so as to facilitate interaction. Offices feature large windows which allow passersby to look inside, and most of them open out into large meeting areas. Furthermore, when we visited, the door of nearly every office was constantly open. The meeting areas tend to be large and inviting, and are furnished with movable couches, tables, and chairs.

Most people with whom we spoke indicated that the SFI environment is extremely conducive to personal interactions. Some lamented the Institute's move from its old home in the abandoned convent, saying that they preferred the physical intimacy that came with living in that crowded space. Either way, the point is that at an interdisciplinary institution where people come for extended stays, discerning ways to support productive mingling is an important issue.

b. Increased likelihood of long-term collaboration

Proximity is a determining factor in how often two people interact with each other. No matter how committed they are, two people in separate buildings are likely to meet less frequently than they would if they shared a common home. The Santa Fe Institute's building provides a common home for scientists, and the common areas at

SFI are used for informal gathering and discussion. For example, SFI's outdoor atrium and its large kitchen (where afternoon teas are held) provide scientists with space and the opportunity to meet with research partners regularly — a necessity for successful, long-term collaboration.

c. <u>More interdisciplinary researchers may mean broader thinking</u>

Interdisciplinary researchers working at a small residential institution benefit not only from seeing their collaborators frequently; they also have the opportunity to interact with others doing different types of interdisciplinary work. In fact, in the Santa Fe Institute's open environment, this type of extra-collaborative meeting is almost unavoidable. Such contact may promote broader thinking and a willingness to try new approaches.

Often, these meetings are a byproduct of one of the Institute's few policies: the two people who share an office must work on different problems at SFI, or at least be in different stages of their careers. One administrator described her "physical proximity" to her officemate as "remarkable," saying it leads to "tax-free communication": she and her officemate learn from each other almost through simple diffusion, by observing each other's actions and overhearing each other's conversations. As a result, she said, "we have become far more co-involved" on a common project. Other researchers indicated that they have derived similar benefits and inspiration from meeting individuals who do not work directly on their project(s).

The Santa Fe Institute as a visiting institution: one attribute, one question

Despite its constancy, the Santa Fe Institute is also a visiting institution. There are two issues associated with this aspect of SFI:

a. Increased churn

The Santa Fe Institute benefits from the constant stream of people coming through, as more people means more ideas, methods, and questions added to the interdisciplinary mix. Many of the ideas visitors bring in are well outside SFI's acknowledged areas of expertise. For example, Cormac McCarthy, author of *All the Pretty Horses* and several other notable novels, is currently on an extended visit to the Santa Fe Institute. McCarthy and people like him provide researchers with intellectual stimulation that would be difficult to obtain if SFI were a strictly residential institution with a "set" faculty and a few visitors a year.

b. The question of growth

The Santa Fe Institute has grown dramatically over the years. By inviting External Faculty members and visitors to communicate the problems and methodologies in use at the Institute to their colleagues back home, SFI has used this growth to spread its message rapidly and widely.

However, it should be pointed out that growth has presented some challenges. As SFI has become more successful, the number of visitors has increased and more residential faculty members have been added. Consequently, according to a few of the subjects with whom we spoke, some of the intimacy that existed in the past has been lost. In contrast to the situation a few years ago, it is no longer possible for researchers to know everyone else at the Institute at any one time. At a place where collaboration, discussion, and personal interactions are important, this loss of intimacy is no small thing. As James Crutchfield said:

> SFI has just grown by leaps and bounds relative to [its] early quiet period. … the resident research population now is 50, will soon be 60 and

probably this summer is going to be 70 or 80. Boy, the social dynamics is very different. Sometime about a year and a half ago the place had enough people in residence that I didn't know everyone around. Before that time, I always knew, I always chatted. And I am really concerned about that.

2. Innovation at SFI: part Freud, part Einstein

In his 1993 book *Creating Minds*, Howard Gardner compares and contrasts Sigmund Freud and Albert Einstein.[15] Both were supremely creative individuals, but Gardner notes that there are important differences in the nature and setting of their signal achievements. Freud essentially invented an entire discipline, psychoanalysis, and it is by no means clear that if Freud had not existed, someone else would have developed psychoanalysis around the time that he actually did. Einstein, on the other hand, provided a brilliant solution to problems about space and time that were "in the air." Obviously Einstein was more than a cog in the machine, but he himself suggested that if he had not offered his theory of relativity in the early 1900s, someone else (perhaps his colleague Paul Langevin) probably would have.

One might ask to what degree the Santa Fe Institute is like Freud--to what degree like Einstein. Do researchers there tend to develop drastically new approaches, new problems, even new disciplines? Or are they more inclined to offer creative and innovative solutions to problems that would be recognized by existing bodies of disciplinary specialists?

With respect to creativity, I view the Santa Fe Institute as roughly equal parts Freud and Einstein. SFI researchers work on topics, like robustness, which are not systematically studied elsewhere, using methods and tools (loosely organized under the heading of "complexity science") that are still rather unusual, despite their growing

[15] Gardner, H. Creating Minds. New York: Basic Books, 1993.

popularity. Certainly SFI is a pioneer with respect to complexity science in the United States, and the Institute as a whole can be seen as an important experiment in how science is done. However, most of the projects worked on at the Santa Fe Institute have clear ties to existing disciplines. While this in no way minimizes the creative acts required to formulate and work through these projects, they differ from efforts that are completely radical in their formulation.

Perhaps the Santa Fe Institute can best be seen as in balance between two poles: one being a completely wild, radical approach to science, and the other being the most conservative approach possible. By combining aspects of both poles and therefore staying somewhere in the middle, the Santa Fe Institute has managed to carry out important work and thrive institutionally for the past 17 years.

3. Achieving interdisciplinarity through collaboration (mostly)

There are many ways in which to do interdisciplinary work. For individuals, there are two obvious choices: become a disciplinary "hybrid" by learning two or more disciplines and combining them, or collaborate with a partner steeped in a discipline of interest. While the two categories are not mutually exclusive — hybrids can collaborate — and though both methods are used extensively at the Santa Fe Institute, the institution is generally disposed to a collaborative model (recall the "two to a room" policy, the focus on common meeting areas, and the Institute's reluctance to accept researchers who would work alone.) There are advantages and disadvantages to working within a collaborative model, detailed below.

Strengths and weaknesses of the collaborative model

a. <u>Advantage of collaboration: two researchers working together can inform and check each other</u>

Though Mark Newman was trained as a physicist, he has developed interests in other disciplines over the course of his career. When we interviewed him, Newman gave us a wonderful overview of how he works in those other disciplines (currently paleobiology and sociology). Newman told us he begins by reading extensively in a narrow area of the discipline he is interested. For example, when he became interested in social networks, Newman read the key sociological texts on that subject. Once he developed some expertise in social networks, he used that knowledge to attract a collaborator from sociology: someone who was knowledgeable in the discipline but also amenable to doing interdisciplinary work with a physicist. Working together, Newman and his partner were able to make advances in social network theory that they would not have been able to make on their own. Newman contributed mathematical insights and tools that are not usually used in sociology, while his collaborator offered a deep understanding of the history, methodology, and problems of sociology.

By working with a seasoned sociologist, Newman protected himself both from going down blind alleys in social network theory and from working on problems that had already been addressed in the past. This kind of spontaneous self-correction, present in a good collaboration between specialists, gives the work an excellent chance of being novel and valuable.

b. <u>Disadvantage of collaboration: working with researchers from other disciplines is often difficult</u>

Collaborative interdisciplinary work can be difficult to do well because people from different disciplines bring different training, perspectives, and modes of thinking to a particular problem. In order to bridge the gap between two disciplines and do valuable work, researchers must 1) develop appreciation and respect for each other's expertise and 2) find a common language.

Because most researchers at the Santa Fe Institute are convinced of the value of interdisciplinary work and actively seek out collaborations, fulfilling requirement #1 is relatively straightforward. Furthermore, even though the disciplines being explored at the Santa Fe Institute at any one time are varied, everyone at SFI seems to rely on non-linear dynamics or similar mathematical tools as they do their work. To the extent that this last statement is true (I am not knowledgeable enough about the range of projects affiliated with SFI to determine exactly how accurate a claim it is), requirement #2 is fulfilled. Even when both these needs have been met, however, collaborating effectively on an interdisciplinary venture can be a difficult task.

The Santa Fe Institute began as a place that put a great deal of emphasis on physics and mathematics. Recently, however, researchers at SFI have become increasingly interested in biology. Several subjects told us about the difficulties they have had putting physics and mathematics together with biology. In particular, James Crutchfield gave us insights into how difficult this process can be.

Crutchfield is a gifted physicist who uses his training to great advantage when he is doing interdisciplinary work. He uses mathematical tools to model processes in a number of different disciplines, including ones in which he has little to no formal training. Using this method, Crutchfield is able to gain a grasp on what is going on in those processes. As he put it:

> I feel sort of lucky that the kinds of mathematics I've learned as an undergraduate … is, in some ways, still underappreciated — how powerful it is. I sort of feel like I'm kind of cheating. I have a perspective that makes it very easy for me to look at problems in mathematical population genetics and re-represent those things fairly easily in my own language, which is this language of dynamics and mathematics. So that makes it easier.

This ability is very useful, but it has created some problems for Crutchfield as he has tried to develop his models in concert with biologists. First, Crutchfield's belief in the value of theory has sometimes been an issue, as most biologists do not share physicists' love for theoretical work. As Crutchfield told us:

> The work I'm doing in biology is very theoretical, mathematical. … the funny thing about this is that I have sort of an interest in those topics, but I go talk to a biologist about them, and the questions I'm asking just don't compute with them. They don't scan. … one reason for that is … . Biology is 80-90% experiment. In physics, there is this balance. You have this tension between the experimentalists, the theorists. … but there is actually — by comparison, I now appreciate a pretty healthy interaction between theory and experiment.

This difference in the belief about the value of theory means that Crutchfield's working style can be easily distinguished from that of most biologists. Crutchfield's first step in tackling a biological problem is to strip the system down to its most basic elements. He then studies the interactions between those elements in an effort to explain large-scale phenomena. The successful implementation of this method can put Crutchfield in an awkward position vis-à-vis biologists working in a more traditional, reductionist fashion. As Crutchfield told us, if he has developed a simple theory that can explain an important biological process — an aspect of evolution, for example — "and Fred here [a biologist] has been studying metabolic networks of one particular protein for twenty-five years of his career, and you say that mechanism isn't essential in evolution, he's not very happy about that."

To minimize this type of discomfort, Crutchfield selects his collaborators with care. He looks for biologists who are amenable to theoretical approaches and does not spend time trying to convert those who are not. Even when he is working with a theoretically-oriented biologist, however, Crutchfield can run into trouble. Many biologists are skittish about physicists' most basic tool — mathematics. Crutchfield believes that many of his collaborators from other disciplines have had "bad experiences with mathematics, and they feel slightly intimidated by it." Consequently:

> you can even imagine a very positive situation where you're the experimentalist, I am the theorist. I've got some idea we can actually start talking about. It looks like there's some real resonance. Then I go to the board, I start writing down my theory, it's like I just left you behind … . So there's a lot of time you've got to spend basically teaching people some more mathematics or, you know, rephrasing it so it is more accessible. Or you don't even mention it. You just tell the experimentalist what is relevant in their experiments. Forget the cool thing you found about solving this equation. Big deal. … So there can be antagonisms that develop. … and if you don't do it right, you end up alienating people.

Hybridization

Though nearly everyone at the Santa Fe Institute works in a collaborative fashion, most researchers are also disciplinary hybrids. The majority of SFI researchers — for example, Mark Newman — clearly have a "home" discipline (in Newman's case, physics) and make limited forays into other disciplines. Others, like Ricard Solé, combine two disciplines in more equal proportions. Researchers like Solé could do deep interdisciplinary work on there own, and at some institutions, they do. However, even within the collaborative environment of the Santa Fe Institute, there may be advantages to being a "true" hybrid.

One important advantage concerns the ability to spot holes in a collaborative effort. Suppose Mark Newman is working with a paleobiologist, as he has in the past. There may be an area of paleobiology which would greatly benefit from the mathematical tools Newman possesses, but of which he is unaware. Meanwhile, if Newman's collaborator does not understand the full extent of Newman's knowledge, he or she may not recognize the opportunity to apply Newman's skills and so may never bring the area to his attention. By contrast, because Solé has a lot of experience in biology, he may have an advantage when it comes to recognizing areas in which his physics skills would be put to good use.

That said, there are two distinct disadvantages to attempting to master two or more disciplines. The first is very simple: the time, energy, and skill needed to master more than one discipline is enormous. Advances in many disciplines come so quickly that it is very difficult for someone to split her time across two disciplines and still be a leading researcher. Collaboration between two specialists is easier to do and may be more efficient. The second disadvantage is closely related: when working alone in two disciplines, a hybrid scientist rarely has the benefit of a collaborator who can check whether the interdisciplinary connections being made are viable or not. A hybrid could waste a lot of time and effort investigating problems that a specialist could identify as unsolvable or unimportant. Again, however, because the Santa Fe Institute favors a collaborative model, neither of these problems seems prominent there.

Collaboration in general

Crutchfield provided us with two basic insights into the collaborative process. First, as mentioned earlier, he emphasized that he looks hard for people who are broad-minded and pre-disposed to collaborating; in his experience, trying to convert people into collaborative workers is not a good use of time. Second, Crutchfield told us that he makes an effort to watch out for smooth talkers. Some people seem like they would make good interdisciplinary partners because they are articulate and extroverted, but Crutchfield has found that when the time comes to do deep interdisciplinary thinking, the same people do not necessarily have much to offer: glibness and intellectual depth do not always go together.

A final point to make concerns the role of physics in interdisciplinary work. Many of the people to whom we spoke emphasized that physics is an excellent discipline with respect to interdisciplinary ventures. To some extent, this statement may reflect the particular historical character of the Santa Fe Institute, but several researchers, including Crutchfield and Newman, made a cogent argument for why physics is so useful. These researchers characterized the discipline of physics as a set of tools, rather than a body of questions or issues to be explored. Physics' emphasis on reductionism, theory, and mathematics, they explained, can be used on questions from any discipline, not just on traditional physics issues (other disciplines' methods are not so easily separated from the material.) One unfortunate, and perhaps unavoidable, side-effect of this fact is that some of the interdisciplinary projects underway at SFI may be one-sided. For example, Solé told us that he is able to put physics to great use when addressing biological issues, but that biology has not appreciably affected the way he does physics. Because of the focus on genomics and the promise of more underlying theory in the biology of the future, Solé expects this situation to change in time.

VIII. Questions for the future

The Santa Fe Institute is an evolving entity: administrators and researchers there are always making adjustments and trying to improve the institution. They have been successful: in addition to the work that has issued forth from SFI, all the people there with whom we spoke expressed happiness with the environment. There were incredibly few complaints.

However, one complaint did come up on several occasions. Several people, mostly administrators, mentioned internal communication as an aspect of SFI which could use improvement. Interestingly, SFI's weakness in this area seems to be a direct outgrowth of its particular mission and philosophy. Subjects lauded the lack of hierarchy at SFI, saying that they feel empowered to make decisions and are unencumbered by bureaucracy. At the same time, however, a few subjects observed that the lack of clearly defined roles means that some decisions go unmade for longer than necessary because it is not clear whose job it is to make them. On a related note, some subjects suggested that the lack of a clear decision-making process occasionally results in individuals being inadvertently left out of important conversations.

In addition to this current challenge, the Santa Fe Institute will be addressing a number of questions in the future. One issue that is often brought up at SFI relates to its nature as part permanent, part visiting institution: there is debate over whether or not the Institute should hire more residential researchers, as well as whether or not to offer tenured positions. Researchers who support these developments argue that the increased stability would mean better, more long-lasting collaborative efforts; researchers on the other side of the coin insist that it is the constant stream of visitors — the purposeful instability of SFI — that makes the institution so productive, and fear that too much stability would result in SFI's ossification.

Another major issue concerns the balance between theory and experiment at the Santa Fe Institute. SFI has always been an institute devoted to theoretical approaches. Some researchers have argued that while theory is useful, the Institute would do well to support some experimental work. Foremost among researchers holding this position is the Institute's president, Ellen Goldberg. A bench researcher for most of her academic career, Goldberg is committed to experimental approaches and believes they would be useful as a complement to the theoretical efforts now in place at SFI. Some disagree with her, and because of its size and nature as a visiting institution, SFI is unlikely to support large or long-term experiments in the near future. However, there may well be an increased emphasis on experimentation on SFI's horizon.

Finally, the most pressing issue is what the Santa Fe Institute will study in the future. In an interview with us, one senior member of SFI noted that almost all institutions harden over time. SFI, this scientist observed, has always worked hard to avoid such hardening. To continue to do so in the future, the Institute may have to change its topic of study: complexity may have to go. Other researchers and administrators with whom we spoke expressed similar opinions. Some of our subjects, on the other hand, see no need for the Santa Fe Institute to change its topic of study. In their minds, complexity is such a broad theme and shows up in so many areas that there will be plenty of original work to do on the topic for the foreseeable future. It will be interesting to see how this debate plays out over the next several years.

IX. Summary and conclusion

The Santa Fe Institute is a tremendously successful institution. By recruiting exceptionally bright, open-minded people and placing them in a boundary-free environment which supports collaboration and innovation, SFI has made important contributions to science and interdisciplinary work in particular. Furthermore, the Institute's openness to visiting scholars has allowed it to spread its philosophy and methodology around the world. Clearly there are some unanswered questions at SFI, but these will be addressed as the Institute continues to evolve.