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THE SANTA FE INSTITUTE'S ECONOMIC AND GEOGRAPHICAL INFLUENCE ON THE COMPUTATIONAL BENT OF COMPLEXITY SCIENCES

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Abstract

Complexity sciences are a multidisciplinary and transnational field of study that aims at modeling natural, artificial, and social "complex systems." In most complexity institutes in the world, the only in-house infrastructures are computational in nature, while physical, chemical, biological, and behavioral science instrumentation is a rare exception. This article asks how complexity sciences became computational in the first place and offers three explanations. Firstly, the prevailing epistemic culture in complexity science is rooted in physics - a discipline characterized by its strong emphasis on mathematics, computational modeling, and reductionist approaches. Secondly, the economic dynamics of the institute influenced the founders' original funding goals and restricted their resources for facility budgets. Thirdly, the archives of the Santa Fe Institute - cradle of the complexity label - show that, as a consequence of budget constraints, the research center had to move its final headquarters in a residential area in the outskirts of the town. Before its installation there, the neighbors and the local administration opened up a public controversy and prevented the SFI from building potentially noxious experimental facilities. A diversity of material causes thus informed the computational identity of complexity sciences, which is reflected in SFI-like institutes around the world.

Keywords

Complex systems, simulations, interdisciplinarity, laboratories

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INTRODUCTION

Complexity sciences are a multidisciplinary and transnational field of study that aims at mathematically and digitally modeling natural, artificial, and social "complex systems" such as genes, ecosystems, computer viruses, energy grids, cities, markets, epidemics, and so forth. According to their representatives, systems become complex as they can be described as big ensembles of heterogeneous elements, which produce, through interaction, emergent properties that are not deductible from their microscopic level (Mitchell, 2009; Ladyman, Wiesner, 2020; Castellani, Gerrits, 2024). This article aims at tackling the historical origins of the computational specialization of complexity sciences. While dealing with living, social, and artificial systems, complexity scientists rely mainly upon digital simulations. Despite contributing to different disciplines, they end up mobilizing almost only mathematical-computational research tools (Li Vigni, 2020a, 2023). But nothing would in and by itself prevent them to couple their research with more empirical studies and facilities (and very few of them do it indeed). An enigma follows then: Why do most complexity scientists not lean on any other kind of inquiry instrument other than computer modeling? The Santa Fe Institute (SFI) was at the origins of the complexity label which federated isolated complex systems researchers and sparked the project of a "science of complexity" (Li Vigni, 2020b, 2021).[2] As a consequence, the institutes getting inspiration from the SFI employ more or less the same methods and facilities, host the same specialties, and have similar institutional settings as the ancestor of the field. However, the limited historical literature addressing complexity sciences tends to offer simplistic explanations for this state of affairs, either by relying on the historical generalization of the computer or by invoking the nonlinear, macroscopic nature of complex systems.

On the contrary, the central argument of this paper is that three related factors played a significant role in shaping the identity of complexity sciences. Firstly, the prevailing epistemic culture in complexity science is rooted in physics - a discipline characterized by its strong emphasis on mathematics, computational modeling, and reductionist approaches.

[2] Concurrently with the establishment of the SFI, other research centers in the US and Europe emerged, prominently featuring the term "complexity" in their names and operative keywords. Examples include Stephen Wolfram's "Center for Complex Systems Research," founded in 1986 at the University of Illinois, and the "Interdisciplinary Center of Non-linear Phenomena and Complex Systems," established in 1991 by Grégoire Nicolis at the Free University of Brussels in collaboration with Nobel laureate Ilya Prigogine.

Secondly, the economic dynamics of the institute influenced the founders' original funding goals and restricted their resources for facility budgets. Thirdly and as a consequence, geographical factors contributed to the identity of the field, particularly in terms of the decision to forego traditional "wet" lab facilities. Analysis of the SFI archives reveals that, during the institute's relocation to its final headquarters in the outskirts of Santa Fe in the 1990s, local residents and the town administration opposed the installation of potentially hazardous instrumentation. The choice of a small building in a residential area is a direct effect of the budget limitations, because the initial ambitions of the founders turned toward a gigantic campus somewhere between Los Alamos and Santa Fe. This case serves as an illustrative example of how epistemic objects can be influenced or co-produced by more broad social factors and considerations (Jasanoff, 2004). Following the pioneering Science and Technology Studies (STS) works on the ethnography of scientific laboratories, which already focused on the material locality of sciences (Latour, Woolgar, 1979; Lynch, 1985; Knorr-Cetina, 1999), several authors quickly moved beyond the confines of research institutions to broaden the scope of their social analysis of knowledge. These scholars examined how both proximate and distant factors interact with science and technology, shaping their development by enabling certain affordances while closing off other possibilities. This literature spans both the Global North and the Global South and encompasses historical and contemporary case studies (Ophir, Shapin, 1991; Livingstone, 2013; Henke, Gieryn, 2008; Kaşdoğan, Okune, 2023; Edgerton, 2011; Raj, 2007). This paper contributes to such literature, particularly to the subset that focuses on the ways in which technoscientific facilities' localities contest their presence within their territories (Hermann et al., 1987). While the literature on conflicts surrounding the siting of private or public technological facilities such as radioactive waste or windmills is abundant across various disciplines beyond the history and sociology of technosciences (Borell, Westermark, 2018; Kasperson, Golding, Tuler, 1992; Burningham, 2000; Chung, Kim, Rho, 2008; Luloff, Albrecht, Bourke, 1998; Carissa, 2007; Wolfe et al., 2002; Gusterson, 2000; Delicado et al., 2014; O'hare, Bacow, Sanderson, 1983), there is a notable gap in research concerning conflicts related to scientific laboratories. Now, the role that geography plays in the fabrication of science is equally important as that of economic, political, or other material factors (Gieryn, 2006). Focusing on place is indeed another way to denaturalize technosciences by dis-entrenching them from the purely cognitive endeavor they are often reduced to and by challenging idealized narratives of their evolution. Against classical historical and philosophical accounts, this paper demonstrates that the socio-epistemic features of complexity sciences were not predetermined by any natural or technological order, but rather emerged through a complex interplay of social and material factors.

To show how complexity sciences became essentially computational, I utilize various sources, including SFI's outreach materials, archives, secondary literature, and interviews. First, I engage with existing accounts about complexity sciences' history as well as with the oral history of some of their representatives so to assess the limits of their explanations. Subsequently, I demonstrate how the founders of SFI envisioned a sprawling campus equipped with facilities for all disciplines and emphasize the significance of location in the transformation of complexity sciences into predominantly computational endeavors. The conclusion resumes the key points of the paper.

1. THE COMPUTER AT THE SFI

Complexity sciences were launched in the mid-1980s by a group of senior physicists from the Los Alamos National Laboratory and other American research institutions, with the aim of applying computational power and interdisciplinarity to life, social, and computer sciences, in addition to the classical topics of chaos and nonlinear studies.[3] In 1984, after two years of meetings and discussions, the group established a small private research center called the "Rio Grande Institute," later on renamed the Santa Fe Institute (SFI). Even if historically the SFI is not the first center to profess the study of complex systems, it made the organizing of "a general science of complexity" its core mission (SFI, 1990: 3). Thanks to the prestige of the Senior Fellows who founded the institute, to its external faculty program (which led many associates to bring complexity back to their countries and sometimes to found new institutes), to its educational devices (i.e. the Complex Systems Summer Schools) and to its efforts in bringing them to other countries,[4] as well

[3] The founders were Edward Knapp, Herbert Anderson, Peter Carruthers, George Cowan, Stirling Colgate, Darragh Nagle, Nicholas Metropolis, Louis Rosen, Richard Slansky, Alwyn C. Scott, David Campbell from the Los Alamos National Laboratory; Gian-Carlo Rota from MIT, David Pines from the University of Illinois, Anthony Turkevich from the University of Chicago, Murray Gell-Mann from Caltech, and John Rubel from the Department of Defense.

[4] The success of the first summer schools (which started in 1988) led the institute to organize a winter version in January 1992 in Tucson, Arizona (SFI, 1991: 16-17). This one was the first of many. In the early 2000s, the Academic Affairs Department set itself a new goal: to

as to several popular books (Waldrop, 1992; Lewin, 1992),[5] the SFI succeeded in establishing an international standard for complexity sciences and generated many vocations around the world that took it as an inspiring model. Until 2012, there were more than sixty complexity institutes in the world, which were present on all continents except Africa, with a particular concentration in the US, in the UK, and in France.[6] While not all of them inscribe into the field of "complexity sciences," many of them explicitly connect to the tradition initiated by the SFI - hence the focus of this paper on this particular center.

My central argument is that SFI's influence largely stems from its inquiry tools "package" and its "lean" institutional model. During my visits to various laboratories across Europe and the United States, I observed that these institutes, like the SFI, often bring together physicists, mathematicians, and computer scientists who repurpose their traditional tools to explore other fields of knowledge. In some cases, they collaborate with life and social scientists, though these remain a minority within such institutions. This claim is supported by interviews in which I asked whether these labs were aware of or influenced by SFI, as well as by an analysis of literature and archival materials to assess whether they employed similar methodologies and referenced the same intellectual frameworks as their New Mexican predecessor. As the rest of this section will illustrate, SFI's scientific influence has spread internationally through multiple channels, but one practical factor has been particularly significant: Establishing a complexity institute is relatively straightforward, even in times of austerity. These institutes typically function as visiting centers with only a small number of permanent members, serving as hubs for collaboration across institutions and disciplines. Unlike traditional laboratories, they do not require heavy machinery, operating instead with little more than office space. Furthermore, in some cases - such as the New England Complex Systems Institute, founded in Cambridge, MA, in 1996 - SFI's funding model has also been replicated.[7] This includes a significant reliance on private funding, such as founda-

expand its influence internationally (SFI, 2000: 28; SFI, 2001: 27; SFI, 2005: 12; SFI, 2008: 17).

[5] For more titles, see (Williams, 2012: 194).

[6] As physicist and entrepreneur Stephen Wolfram shows, complexity institutes exist only in the Americas, in Europe, in China, in Japan and in Australia: Stephen Wolfram, "It's Been 10 Years: What's Happened with *A New Kind of Science*?" 7 May 2012, http://blog.stephenwolfram.com/2012/05/its-been-10-years-whats-happened-with-a-new-kind-of-science/.

[7] Interview with physicist Yaneer Bar-Yam, 13 September 2016.

tions and donors', alongside governmental support.
As the sociology and history of science has shown, the formation of a school of thought in the scientific realm relies on strategies of influence (Lenoir, 1997; Schut, Delalandre, 2015). One such strategy is integrating researchers into the SFI so they can later introduce its approaches within their own institutions. For instance, Michel Morvan, director of the Lyon Complex Systems Institute, served as an external professor at SFI from 2004 to 2013,[8] while Ricard Solé, founder and director of the Barcelona Complex Systems Lab, has held the position since 1997.[9]

A second key influence strategy is scientific collaboration through international research projects. Timoteo Carletti, who served as founder and director of the Namur Institute for Complex Systems in Belgium from 2010 to 2014, collaborated with former SFI members in a European research project based in Venice in the early 2000s.[10]

Publications also serve as a major tool for influence. For instance, Paul Bourgine, founder and director of the Parisian Complex Systems Institute, which began in 2003, had closely followed SFI's activities since its inception and had previously attempted, unsuccessfully, to establish a French equivalent in the 1990s.[11] Similarly, readers of SFI's books and papers, such as Ali Cinar and Fouad Teymour, founders of the Center for Complex Systems and Dynamics at the Illinois Institute of Technology in Chicago, have drawn inspiration from SFI's methodologies and research directions, applying them to engineering and biomedical sciences.[12]

Another significant instrument of influence has been the Complex Systems Summer Schools. First launched in 1988, these schools played a crucial role in defining the field's research standards, including the scope of complexity sciences (broad enough to encompass multiple disciplines), the key analytical tools (such as agent-based models, network theory, and statistical physics), and research priorities (e.g., financial markets, immune systems, cities, etc.). Additionally, these summer schools helped establish SFI as the leading institution in complexity science by standardizing and disseminating its frameworks through both educational programs and related publications. They also provided a social environment that fostered future collaborations among participants. Between 1988 and 2010, more than a thousand students attended

[8] Interview with computer scientist Michel Morvan, 3 October 2016.
[9] Interview with biomathematician Ricard Solé, 16 June 2015.
[10] Interview with physicist and mathematician Timoteo Carletti, 15 March 2016.
[11] Interview with engineer Paul Bourgine, 27 March 2017.
[12] Interview with chemical engineers Ali Cinar and Fouad Teymour, 16 September 2016.

these summer schools (SFI, 2010: 14), including PhD and postdoctoral researchers from the institutions I visited, who had participated during their master's or doctoral studies.

Conversely, institutions such as the Max Planck Institute for the Physics of Complex Systems in Dresden, Germany,[13] and the Matter and Complex Systems Laboratory at Diderot University in Paris,[14] make no reference to SFI. Their researchers often remain unaware of - or even dismiss - SFI's influence. In these public research centers, complexity is primarily understood through the lens of statistical and condensed matter physics, where the concept has been in use since the 1970s without being tied to a discipline-building project.

For all these reasons, SFI can be regarded as the cradle of complexity sciences, having provided the field with a coherent global intellectual and institutional identity. Understanding the role of computation at SFI, therefore, requires tracing the history of this institution.

The SFI's founders - as well as complexity specialists in general - promise, theorize, and practice interdisciplinarity. This is the only way, according to them, to tackle their study objects. Formally, it is true that research institutes, publications, conferences, and individuals availing themselves of this label participate in basically all fields of knowledge - physics, computer science, chemistry, biology, ecology, health studies, engineering, as well as sociology, anthropology, and economics among others. At first sight, complexity may thus look like an all-encompassing research community, on the disciplinary, methodological, and sociological levels. One would therefore expect to find different kinds of scientific tools, approaches, and facilities - quantitative and qualitative methods, small and big instruments, wet and dry laboratories, indoor and outdoor experimental equipment, etc. Nevertheless, this is not the case. Surprisingly, among the SFI-like complexity institutes that exist in the world, almost no-one has physical, chemical, biological, or behavioral science instrumentation in-house. Although interdisciplinarity is the watchword of complexity specialists, their institutions - apart from very few exceptions - do not host benches, centrifuges, microscopes, MRIs, cameras, or any other instrument that would allow them to manipulate real systems, from which to collect data and on which to test theories. In most complexity institutes, the only infrastructures present are PCs and servers.

The SFI's initial biographer, *Science* journalist Mitchell Waldrop,

[13] https://www.pks.mpg.de/institute/.
[14] http://www.msc.univ-paris-diderot.fr.

recalls that the founders intended to place computers at the core of their scientific endeavors right from the beginning. This emphasis on computing was closely intertwined with their personal intellectual and professional careers. In his 1992 bestseller *Complexity*, Waldrop wrote:

> By the beginning of the 1980s, says George Cowan, such numerical experiments had become almost commonplace. The behavior of a new aircraft design in flight, the turbulent flow of interstellar gas into the maw of a black hole, the formation of galaxies in the aftermath of the Big Bang - at least among physical scientists, he says, the whole idea of computer simulation was becoming more and more accepted. [It is then, according to Cowan, that] "you could begin to think about tackling *very* complex systems" (Waldrop, 1992: 64).

In Cowan's interpretation, "*very* complex systems" specifically refers to nonlinear systems, although nonlinearity is not the sole indicator of complexity. Chaotic systems, which serve as a prime example of nonlinear systems, have a remarkable characteristic: The output's change is not mathematically comparable to the change in the input. Even slight variations in the system dynamics upstream can result in significant downstream effects, a phenomenon famously known as the "butterfly effect" or "sensitivity to initial conditions." Complexity scientists emphasize that numerical and digital methods are typically necessary when studying nonlinear systems, whether they are chaotic or organized. As Waldrop explains:

> Nonlinear equations are notoriously difficult to solve by hand, which is why scientists tried to avoid them for so long. But that is precisely where computers came in. As soon as scientists started playing with these machines back in the 1950s and 1960s, they realized that a computer couldn't care less about linear versus nonlinear. It would just grind out the solution either way. And as they started to take advantage of that fact, applying that computer power to more and more kinds of nonlinear equations, they began to find strange, wonderful behaviors that their experience with linear systems had never prepared them for (Ivi: 65).

According to Waldrop's account, physicist Nicholas Metropolis "liked the idea [of the SFI] because of Cowan's emphasis on computation," and "Metropolis was pretty much Mr. Computer at Los Alamos. It was he who had supervised the construction of the laboratory's first computer back in the late 1940s" (Ivi: 70). Along with mathematician Stanislaw Ulam and polymath John von Neumann, he was also one of the developers of the famous Monte Carlo simulations (SFI, 2000: 26; Galison, 1997: 692). In the 1994 SFI bulletin - which celebrated the first ten years of the institute - one could read the following passage:

> [Physicist Darragh] Nagle recounts the first few meetings of the Senior Fellows. "The question was, 'What new initiative could we as the Senior Fellows take that would lead to a new science?'" he says. "In the initial discussions people were thinking supercomputers because at that time parallel computers were a hot idea" (SFI, 1994: 30).

Some of the SFI's founders had firsthand experience with the increasing power of computers in their nuclear research through Monte Carlo simulations. They believed that this tool could significantly contribute to the "emerging syntheses" they aimed to foster or generate (Pines, 1988). The initial cohort of visiting professors and post-doctoral students at the SFI included physicists, biologists, and economists who possessed computational skills or were eager to collaborate with computer scientists, demonstrating a strong interest in interdisciplinary research. Their early projects paved the way for the development of simulation software, such as Christopher Langton's agent-based models, and John Holland's genetic algorithms. These tools were employed to simulate social and biological systems, as well as to enhance industrial optimization within big enterprises, and eased the first private fundings coming from Citibank for the study of financial markets from a different standpoint than neoclassical economics (Helmreich, 1998; Waldrop, 1992: 260; SFI, 1992: 27; Baker, 2022). All this shows that the computational tropism was embedded into the SFI almost by design.

As STS highlight the significance of materiality and infrastructures in shaping the outcomes of a given scientific practice (Slota, Bowker, 2017; Edwards, 2010), it is essential to also explore the history of SFI's facilities to reveal how this interest in the computer as a research tool was technically and concretely implemented. Back in 1988, the center provided every fellow of its faculty with a Macintosh, and its associates with IBM and Sun machines. The institute also implemented two network connections: one to the New Mexico Technet in order to be in contact with the LANL and with four other universities in the State; and the other to the ARPANET with the aim of connecting with several supercomputers that were distributed over the United States (SFI, 1988). A little later, in 1995 the SFI was one of the first scientific enterprises to be equipped with an institutional website, www.santafe.edu, still active today (SFI, 1995-1996: 22). The current SFI Director of Technology relates that a first cluster of servers was constituted at the institute in

2001, when he managed to acquire twenty-four computers, assembled together in a room without special cooling.15 Because the SFI fellows have limited CPU needs for occasional simulations, the Board of Trustees and Scientific Advisory opted for an in-house conglomerate to avoid an expensive rental of calculation time from external grids. In 2013, the Director of Technology oversaw the renovation of the computing cluster, which was replaced with four machines equipped with 256 cores, costing $50,000. This infrastructure is housed in a secure enclosure at the entrance of the institute's campus and features appropriate cooling systems. By 2019 and 2020, the annual expenses for "Technology" (which likely include more than just the cluster) ranged between $220,000 and $250,000, accounting for approximately 2% of SFI's general $12 million budget (SFI, 2021). Beyond reading, discussing, writing, calculating, and coding, complexity researchers frequently conduct hundreds of thousands, or even millions, of simulation runs on such clusters and computational grids. These simulations are critical for statistically analyzing, testing, and refining their models with data. This reliance on computational infrastructure has led other complexity institutes worldwide to adopt similar setups, either maintaining in-house clusters or renting computing power from public or private providers such as the European Grid Infrastructure, Google, or Amazon's clouds. This material setup highlights the predominantly computational nature of complexity research practices, which often replicate the SFI's model. Unlike researchers who conduct experiments at laboratory benches (e.g., chemists, embryologists), work with large-scale infrastructures (e.g., physicists, astronomers), or gather first-hand data in the field (e.g., zoologists, anthropologists), complexity scientists more closely resemble computer scientists or theoretical physicists working at their desks rather than a blend of these other research profiles.

On the disciplinary level, there is also a predominance of individuals with backgrounds in physics and computation. This can be observed in the founders, who were physicists or chemists. The very first active fellows of the institute consisted of computer scientists, computational biologists, and computational economists. While there have been a few social scientists affiliated with the SFI throughout its existence, it is worth noting that some of them were not trained in social sciences but were physicists or mathematicians working on social networks (think of Duncan Watts and Steven Strogatz). Observations made at different points in the center's history confirm this trend. In 1992, for example, the list of new members of the scientific council included an economist,

[15] Interview with SFI's technical director Nathan Metheny, 27 September 2016.

a computer scientist, an anthropologist, a molecular biologist, a bioinformatician, two mathematicians, and five physicists (SFI, 1992: 32-33). In 2001, most undergraduate students, as well as the majority of temporary and permanent researchers, came from physics (11), computer science and/or mathematics (8), then from life sciences (4), economics (2), and socio-informatics (1) (SFI, 2001: 22-24). Regardless of the time period or the complexity institute considered, this sociological pattern is consistently observed.

It is important to note that when trained behavioral or social scientists are present, they may experience symbolic violence from physicists, mathematicians, and computer scientists or protest against their imperialistic tendency. For example, as declared by a psychologist associated with SFI, Mirta Galesic: "I have a sympathy for physicists, who say let's look at humans as particles, who are just following simple rules like imitating a random person around."16 She also admits that for a long time, she felt uncomfortable due to her "soft" discipline, but regained confidence when she realized that studying humans is more challenging than engineering sciences:

> I have to admit that for a long time […] I felt a bit embarrassed to be a psychologist because we seem like softie. Probably people still think that we're mainly using mouth. But then now I'm not embarrassed anymore because I realized this is the most difficult part studying […] humans. That's more difficult than rocket science.[17]

At the same time, resistance to the imperialistic attitude of SFI's founders and early members may serve as a blueprint for the very epistemic foundation of complexity sciences. After an initial interdisciplinary workshop, archaeologist George Gumerman, an expert on the American Southwest and Oceania, addressed Murray Gell-Mann in a letter published in the 1993 bulletin, in which he questioned the operation of conquest and appropriation by physicists over other disciplines:

> My problems concern what I think might be some misunderstandings between the SFI complexity folk (mainly Stu Kauffman, Chris Langton, and perhaps yourself) and the collected Southwest archaeologists; on a more pessimistic note, I'm worried about one of the assumptions of the conference: if Southwest archaeologists can only learn about 'complexity' from the SFI experts, they will become better archaeologists. I write this memo,

[16] Interview with psychologist Mirta Galesic, 6 October 2016.
[17] Ibid.

> then, presuming that you'll tell me where I'm off base on how the SFI investigates 'complexity' and also whether my own notions of complexity in archaeology are of any interest to the gurus at the SFI (SFI, 1993: 21).

As a consequence of their epistemic project, complexity researchers have tended, since the establishment of the SFI, to identify themselves as "modelers" and distinguish themselves from "experimenters" (SFI, 1989:14). While modelers may possess only an approximate understanding of the properties of real systems, they aim to bring valuable computer skills to simulate these systems. On the other hand, experimenters may have limited expertise in computing, but they contribute their disciplinary knowledge to analyze the simulated systems. Essentially, complexity specialists do not conduct experiments directly on real-world objects; if they do, they typically delegate such experiments to colleagues in other institutions, as it has been the case at the SFI. Regardless, their core identity lies in utilizing mathematical and computational models and tools. Through an analysis of the institutes' archives, books, web pages, summer school flyers, and conference titles dedicated to complex systems in both the United States and Europe, these tools include dynamical, fractal and chaos systems, cellular automata, statistical physics, network theory, agent-based models, and genetic algorithms.

The computational dimension of complexity sciences is also visible in the ontological view their representatives have of their study objects. In this view, the world of simulation and the world of target systems do not share the same material cause but do share the same formal one. In this overarching viewpoint, causality and the identity of a system are determined by its organization, form, or code, rather than its physical matter. One of the clearest illustrations of this ontology comes from a computational epidemiologist based in France:

> [The simulation] is an abstraction of the form. If a real form exists, the form of the simulation is an abstraction of the real form. […] What I capture with [my model] is the set of ingredients I believe have an important role within the epidemic propagation phenomenon, and they are real ingredients […] we write [mobility, gravity, diffusion] laws […] and the starting hypothesis is that these laws […] are a precise and reliable description of what's going on in reality. […] When [the simulation] works, it means that the phenomena I have captured within it are the real ones.[18]

Materiality is considered secondary because in their dualistic view the

[18] Interview with physicist and computational epidemiologist Vittoria Colizza, 9 May 2017.

crucial factors are the structural properties of systems, regardless of their ontological domain. Therefore, if a system is structured as a network, information assumes a central role in both the internal functioning of systems and their description and modeling. For most complexity specialists, indeed, "all complex, adaptive systems are designed to process information. They are equipped to gather information from their external environments and to react to it or store it internally in a compressed form and to retrieve it when necessary" (SFI, 1989: 2).

The previous elements unambiguously lead us to the following analysis. From a sociology of science perspective, a key reason why complexity sciences became predominantly computational lies in the dominance of a physical-computational "epistemic culture" (Knorr-Cetina, 1999) and its expansionist or "imperialistic" ambitions (Cat, 1998). As the Italian philosopher Giorgio Israel observed, "The success of physics is due to the fact of having chosen as its guiding principle the Galilean approach of 'pruning the impediments' […] that is the belief in the fact that there is a mathematical order underlying nature which is simpler than it appears, and that represents the essence of phenomena" (Israel, 2005: 479-509). If the fundamental layers of reality are simple, then the messy, macroscopic complexity of the world can be overlooked in favor of identifying the elegant, underlying structures common across systems. This attitude underpins what might be termed the "unifying tendency" of physicists - and, by extension, many complexity scholars. Just as theoretical physicists have long sought overarching, general theories, the early ambition of institutions like the SFI and other centers for complexity studies - especially up until the mid-1990s - was to develop a general unified theory of complex systems. Tied to this ambition was a second, more ideological objective: the desire to make the so-called "soft sciences" more "scientific" by way of numerical formalization. Consequently, the ascendancy of physics, computer science, and mathematics over other disciplines led to an extension of deterministic reasoning into fields where it may be epistemologically inappropriate (Li Vigni, 2023). Living and human systems were reinterpreted through the lens of computational networks, reducing their multidimensional nature in the process. Holism, once a critical alternative to analytical fragmentation, was paradoxically brought back under the wing of an analytical framework. This entire intellectual operation corresponds to what Israel defined as reductionism, that is, "the attempt to subordinate every aspect of reality to the same interpretative key" (Israel, 2005: 505). In other words, SFI's founders' project has never meant to foster a bidirectional exchange between disciplines but rather consisted of an infantilizing operation of conquest of new territories of knowledge considered as nonscientific.

Facing these realities, historians and philosophers of complexity sciences have instead tended to explain the computational bent of this field in another way. They attribute it to the rise of digital tools within academia and society in general. For instance, historians Sam Schweber and Matthias Wächter argue that the advent of computers brought about a "Hacking-type revolution" in the sciences (Schweber, Wächter, 2000). They assert that such revolutions surpass Thomas Kuhn's paradigm shifts as they entail radical modifications on multiple levels. Firstly, they transform the research practices of various disciplines. Secondly, they give rise to new institutions to support the emerging science. And thirdly, they bring about a new worldview and ontology. In their piece, Schweber and Wächter focus on one aspect of what they term the "complex systems computer modeling and simulation revolution." They contend that "complexity has become one of our buzzwords and *mathematical* modeling and simulation *on computers* constitute […] its style of reasoning" (Ivi: 585; emphasis in the original). In their view, "The Santa Fe Institute is perhaps the paradigmatic institutional manifestation of this viewpoint" (Ivi: 588). They trace the origins of this revolution to the digital boom itself:

> That the computer has similarly generated a sweeping transformation of the social, material, economic and cultural context is evident - think only of the transformation of the workplace and the novel routinisations that the computer has introduced, of e-commerce, of the new classes of professionals, etc. (Ivi: 585)

Referring again to the historical digital context, French historian and philosopher of science Franck Varenne proposed a comparable hypothesis in a text examining the emergence of complexity sciences. He characterizes their rise as a bumpy evolution with historical ups and downs, wherein computers played a pivotal role in their consolidation:

> The science of complexity has known multiple births during the 20th century. It has known many historical reconstructions too. But it is only in the 1980's that it began to be a well recognized academic domain. At that time, interdisciplinary research programs became more systematic. There are many reasons for this long maturation. According to me, one of the main factors is quite prosaic. But simultaneously […] this factor reveals a relative continuity in epistemological positions, contrasting with what is often said about the paradigm shift from simplicity to complexity. This factor is the brutal and large diffusion of PC's in all types of labs all over the world in those years. (Varenne, 2009: 7)

Coincidentally, this kind of explanations for the emergence of complexity is not dissimilar from the narrative put forth by complexity institutes' founders - both in the US and in Europe - in their historical and strategic accounts. For example, physicist Daniel Stein, one of the early students and ambassadors of the SFI, explicitly stated that "you wouldn't have had complex systems sciences without computers."[19] Biologist Harold Morowitz, an active figure at the beginnings of the SFI, wrote in a book review of Waldrop's book that "The new approach [of complexity sciences] is made possible, indeed it is mandated by computers" (SFI, 1992: 7). Guillaume Beslon, a French bioinformatician at CNRS and former director of the Lyon Complex Systems Institute, shares a similar explanation for the success of the complexity wave in the 2000s:

> Santa Fe was founded in 1984, first cybernetics in the 1940s, Varela and the like were active in the 1970s […] Huxley in 1890. Complexity [à la SFI] is nothing new […] The only novelty in history is that we have a tool to do automatically and quickly all the calculations that underpin those methods. […] So somehow there was a vocation, a possibility to re-found all this at the beginning of 2000s - because the computational power had been democratized and so we had the means to do something out of it.[20]

Such an explanation is problematic for at least two reasons. First, it relies on technical determinism: While the rise of computers was indeed a prerequisite for digital simulation (Ryan, 2010; Campbell-Kelly, Garcia-Swartz, 2013), computational availability alone cannot fully account for what is fundamentally a sociotechnical endeavor (Wyatt, 2007). Historians and philosophers of complexity sciences often fail to critically analyze the narratives of complexity scientists and rather tend to confirm and naturalize them. When these scientists assert that computational tools are "mandatory" because "the nature of the systems requires computer modeling," they are effectively constructing a retrospective justification. More than one argument can be given to question it. If we follow complexity scientists' definition, virtually any object of study in any discipline could be considered a complex system, yet other fields have long studied these systems without relying solely on computational

[19] Interview with physicist Daniel Stein, 8 September 2016.
[20] Interview with Guillaume Beslon, 15 September 2015. Contrarily to what Beslon claims, first and second cybernetics does not actually have any direct link to complexity sciences *à la* Santa Fe. See: (Li Vigni, 2022: 17-44).

approaches and have not waited for complexity sciences to tackle them. Furthermore, the SFI's efforts to foster collaborations with experimentalists underscore the importance of real-world facilities and their compatibility with computational tools according to the institute's leaders themselves. The institute's Bulletins repeatedly document examples of collaborations between SFI modelers and external experimentalists, such as immunologists or neurophysiologists conducting lab experiments (SFI, 2012: 31; SFI, 2000: H). Following a 1995 article by John Horgan in *Scientific American* entitled "From Complexity to Perplexity" in which the journalist accused the SFI of engaging in "flaky" science (Horgan, 1995), the institute's leadership, under microbiologist Ellen Goldberg (president from 1996 to 2003), along with vice presidents of academic affairs mathematician Eric Jen and microbiologist Tom Kepler, actively emphasized the importance of collaboration between theoreticians and experimentalists (SFI, 1996-1997: 8; SFI, 2000: 33). This commitment was reflected in both programmatic statements and institutional policies. For instance, the 1996 postdoctoral call stated: "Special consideration will be given to those applicants who propose, as an integral part of their research at SFI, a project involving experimental work or data collection at locations other than SFI" (SFI, 1996-1997: 1). While many complexity institutes focus almost exclusively on computational modeling, there are exceptions besides the SFI that demonstrate the potential of integrating experimental and theoretical approaches. A notable example is the French laboratory BioEmergences, located in the outskirts of Paris.[21] This lab specializes in developing cutting-edge methodologies and tools for the *in vivo* and *in silico* multiscale and multimodal observation, quantification, and theoretical modeling of biological processes. Their research combines advanced imaging techniques - such as multiphoton point laser scanning microscopy and light sheet microscopy for long-term 3D+time imaging of developing organisms - with automated image processing workflows and interactive visualization tools for reconstructing cellular dynamics. In addition, they employ computer simulations, such as agent-based modeling, to integrate and interpret their findings.

These examples underscore that some complexity scientists recognize the value and feasibility of bridging experimental and theoretical approaches. However, historians and philosophers of complexity sciences who claim that the study of complex systems "inherently" requires computational methods - arguing, for instance, that simulation is indispensable for modeling an entire city - often overlook the possibility

[21] http://bioemergences.eu/bioemergences/index.php

of complementing such simulations with qualitative approaches, such as surveys, ethnographies, focus groups, and in-depth interviews with smaller segments of the population under study. From the STS perspective, the role of social scientists in analyzing scientific practices should be to contextualize the narratives of scientific actors, critically examine their ontologies, and denaturalize their epistemologies, rather than uncritically reinforcing the dominant "winners' narrative" that validates and perpetuates their accounts.

Another relevant issue with relying on the digital rise as an explanation of complexity sciences' emergence is that it neglects important questions, such as: Were other kinds of facilities considered at the beginning of the history of the field? To what extent was the computational identity of complexity sciences a deliberate choice of its founders and representatives, and to what extent was it influenced by other social elements? Could complexity institutes have included experimental laboratories as well? The following section delves into these matters, revealing that the SFI's founders indeed aspire to establish experimental facilities. However, budget constraints and subsequent siting conflict with the future neighborhood of the institute ultimately prevented this, leading to the consolidation of the "lean" model now characteristic of many complexity institutes. Most of these complexity institutes function with relatively low costs as visiting institutions, resulting in a relatively small number of resident researchers, often focusing on coding and sometimes the development of digital platforms for larger communities of researchers. Moreover, the majority of their fellows are temporary associates who either have brief stays and then depart or are formally affiliated for an extended period but only spend a few weeks per year at the institute.

2. THE SANTA FE INSTITUTE'S BUDGET CONSTRAINTS AND SITTING CONFLICT

While the SFI's founders shared a consensus on the importance of computers in interdisciplinarity, the institute's archives reveal an aspect that has been overlooked in existing literature on complexity sciences. Specifically, certain documents indicate that the Senior Fellows initially intended to establish various types of laboratory facilities within the research center. However, due to unfavorable circumstances, this objective was not realized. Before summarizing the reasons behind this, let us provide an overview of the history of the SFI's headquarters to give some elements of context.

When the Senior Fellows officially established their research center as a legal entity, they discovered that the name "Santa Fe Institute" was already being used by a therapeutic service in the area. As a temporary solution, they adopted the name "Rio Grande Institute" (SFI, 1994: 16). However, in 1985, when the therapeutic center ceased its operations, the founders amended the bylaws to officially name the institute the way they wished (SFI, 2013). During this period, the SFI possessed neither a staff nor a physical headquarters. As physicist Edward Knapp later recounted: "We joke that our early home was a desk drawer in Trustee Art Spiegel's office in Albuquerque, and we progressed to a Santa Fe post office box before we had a place of substance" (SFI, 1994: 0). In 1985, the SFI secured a rental office space in a building in Santa Fe to accommodate its two employees, namely the secretary Ginger Richardson and the development director Ron Zee.[22] In 1987, the SFI relocated to 1120 Canyon Road, in the Cristo Rey Convent (Ivi: 16). This move was significant as it marked the period when the institute started gaining recognition, initially within the United States and subsequently expanding to Europe and other parts of the world. The convent served as an inspiring setting for scientists, journalists, and the general public, contributing to the institute's growing visibility. However, in July 1991, the SFI temporarily moved to 1660 Old Pecos Trail while awaiting the necessary fundraising, acquisition, and renovation for its permanent home (Ivi: 17). With the contribution of George Cowan, who donated funds to purchase a mansion in the Santa Fe hills, the SFI finally acquired its permanent headquarters at 1399 Hyde Park Road in July 1994. The subsequent details discussed in the text pertain to this final location; however, this recall highlights the material realities of the institute, whose reputation is inversely proportional to its modest material conditions.

The hills of Santa Fe primarily consist of a residential area populated by upper middle-class individuals, predominantly white, many of whom are retired professionals from various fields such as science, business, art, and culture. It is within this socio-cultural context that a controversy arose between the city of Santa Fe and the SFI regarding the institute's potential facilities, among other matters. Referring to the founding bylaws of the institute, it states that:

> The primary charitable, educational and scientific purposes for which the corporation is formed are: a) To engage in, carry on and conduct scientific

[22] Interview with Ginger Richardson, March 5, 2017.

> research, experiments, investigations, analyses and studies in the physical and social sciences; […] and c) To establish, maintain and operate laboratories, plants and any and all other establishments for the purposes aforesaid. (SFI, 1984a).

From this excerpt, it is evident that the founders of the institute envisioned a more ambitious plan than what was actually implemented afterwards. According to Waldrop's account, the Senior Fellows initially aimed to raise up to $100 million dollars, which is ten times the current budget of the SFI at its peak (Waldrop, 1992: 90). However, an archival document suggests an even higher target of $230 million (SFI, 1984a). The Senior Fellows wished to allocate $80 million for the establishment of forty chairs, $60 million for hiring a hundred scientists, $20 million for laboratory facilities, offices, and seminar classes, and the remaining funds for other operational needs. With this substantial amount of funding, the founders intended for the institute to function as a research center, a university, and a think tank. Their vision was to create an institution capable of nurturing the scientific and technocratic elite of the future, positioning it alongside prominent American organizations such as the RAND Corporation and the Brookings Institution, organizations with which the Senior Fellows were familiar for having collaborated with them. During one of the SFI's founding meetings, Murray Gell-Mann emphasized that "[a]lthough the Institute will have, especially initially, an important emphasis on theory, there will be experimental and observational work" (SFI, 1984b). During that same period, he expressed his views even more explicitly, stating the following:

> The research program of the Institute would include both experimental and theoretical work, which complement and reinforce each other. We would differ fundamentally, therefore, from the Institute for Advanced Study in Princeton, for example, which has no experimental work, does not award degrees (although I believe it is allowed to), and does not have very much collaboration among different kinds of scholars. Experimental and observational work of very expensive kinds, such as high energy physics, astronomy, and oceanography, should probably not be undertaken, while use is made of cooperative arrangements with nearby observatories, laboratories, museums, industrial enterprises, and so forth. (Gell-Mann, 1988: 12)

According to this excerpt, the vision for the SFI entailed conducting some aspects of experimental research in collaboration with external laboratories, as is presently the case. However, it was also intended for the institute to possess in-house experimental facilities, with the exception of prohibitively expensive equipment in the realm of natural sciences. During the seminal conference that marked the institute's establishment, George Cowan articulated the overarching intellectual objective behind this dual alliance: to bridge the gap between theoretical and experimental work, as well as to foster collaboration between the natural and social sciences. The ultimate goal was to transcend the division between the "two cultures" (Snow, 1959) and ignite a profound cultural and scientific revolution of historical significance:

> Looking to the longer term, the Institute will plan to develop a campus which is large enough to provide sites for nearby, independent academic organizations representing social, political, and behavioral sciences and parts of the humanities. As experimental, computational, and mathematical tools grow in capacity, it is possible to envision a time, not far off, when the rigor of the hard sciences and elements of human experience and wisdom will be joined more effectively together so that we can better model and hope to understand the most complex and interactive systems of all, those which govern our bodies and brains and those developed within past and present societies which shape and govern much of our lives. […] With wisdom, the diffusion of the hard sciences into what are now considered the soft sciences may well become the most important achievement of the twenty-first century. To help insure that the next generations can rise to this challenge, the Institute must strive to promote a unity of knowledge and a recognition of shared responsibility that will stand in sharp contrast to the present growing polarization of intellectual cultures perceived so well by C. P. Snow nearly a generation ago. (Cowan, 1988: 236-237)

This passage highlights the clear and ambitious aspirations of the founders during the early 1980s, a time when the future was still open. Doctor and theoretical biologist Stuart Kauffman, a witness of that period and one of the institute's original fellows, reveals that the pioneering group had contemplated the possibility of relocating the institute to an area where the establishment of laboratories could be feasible:

> in the earliest SFI years, we went to the west out of town and considered a beautiful site where a larger institute could be built. Most of us liked the idea, and thought a building there would be lovely and accurate value. It never happened, but it might have been possible to have laboratories there.[23]

However, to this day, the SFI and the majority of its followers noticeably lack any substantial experimental and observational research. The questions that arise thus are: What are the reasons behind this absence?

[23] E-mail by Stuart Kauffman, 23 October 2021.

Were there certain factors that hindered the SFI founders from realizing their initial ambitions and that led them to a shift in perspective? 1980 SFI's postdoctoral student physicist Daniel Stein succinctly outlines the two primary concerns that will be elaborated upon in the remainder of the article:

> Creating an active experimental program from scratch requires a massive financial investment. […] the required outlay to create an experimental program at SFI far surpassed what the institute founders were able to raise. Then the Hurley residence (now the Cowan campus) was acquired, and I suspect that pretty much put an end to the whole debate. That acquisition was already controversial with the surrounding community (which I don't think has fully died down to this day), and agreements with the city (and probably zoning laws) likely killed off any last possibility that experimental facilities could be constructed.[24]

As evidenced by this interview quote, the downsizing of the SFI can be attributed primarily to economic factors. While initial fundraising efforts succeeded in launching the institute, they fell short of establishing the new, technoscientific, and politically influential institution that the Senior Fellows had envisioned. This financial setback significantly undermined the founders' lofty aspirations. The SFI's bulletins and annual reports reveal the progression of its budget over the years. In its first year, the budget amounted to approximately one hundred thousand dollars, which grew to over one million by 1988, and eventually stabilized at around twelve million in the early 2000s. One could argue that the likelihood of raising hundreds of millions of dollars for a still-undefined, allegedly groundbreaking scientific endeavor was understandably low. However, this only accounts for half of the story. The ultimate obstacle that thwarted the realization of experimental facilities within the SFI's premises was a problem of interaction with the neighbors of the final headquarters of the institute. Since the latter's limited budget necessitated its relocation to a residential area, this led to negotiations with local residents over the permitted activities and scope of the institute's operations.

An internal report from the SFI reveals that the acquisition of the "Hurley Residence," now known as the "Cowan Campus," sparked considerable controversy both within and outside the institute's circle (SFI, 1993a). Internal discussions revolved around the role of architecture in facilitating the desired scientific interactions, while external

[24] E-mail by Daniel Stein, 23 October 2021.

conflict emerged when a group of residents from the Santa Fe hills began sending open letters to the local press. The neighbors of the "Hurley Residence" voiced concerns primarily centered around three issues. Firstly, they feared that the arrival of the SFI would lead to increased car traffic on Hyde Park Road, suggesting that the institute should be situated in commercial areas instead (SFI, ca. 1993a). Secondly, they expressed apprehension about the potential resale of the building, in the event of the SFI's financial difficulties, to an entity that might disregard the surrounding regulations (SFI, ca. 1993b). Lastly, there were worries about the architectural development of the institute compromising the "greenbelt effect" in the area (SFI, ca. 1993c). Some residents even suspected the SFI of being a government-backed think tank that would rapidly expand and introduce spin-off activities (SFI, ca. 1993d). The situation gained public attention, and local authorities became involved in the ensuing debate. Ultimately, a compromise was reached at the administrative level.

During the debate, the SFI presented a series of arguments aimed at reassuring its prospective neighborhood. Firstly, they assured that major events such as summer schools and general audience conferences would be organized at locations other than 1399 Hyde Park Road. Secondly, the researchers emphasized their desire for tranquility and serenity, which made a suburban area more appealing to them than a commercial one: "SFI got the experience of what worked and not worked at the convent. So, it was searching for more a residential area, more meditative place;" "People are happy to have that amazing view and to be in a place where they can concentrate on their research."[25] Thirdly, the SFI emphasized its strong economic position, ensuring that there were no signs of impending financial collapse. Fourthly, they argued that the institute's architectural expansion would have been significantly less intrusive compared to the potential construction of twenty-two houses by a real estate company. Finally, they pointed out that local regulations prohibited certain types of property usage in the hills of the town (SFI, ca. 1993e).

In subsequent documents, the SFI, which had a university-like structure outlined in its bylaws, sought to strengthen its arguments by asserting that "student 'pollution'" would be minor: "Some serious students participate at SFI, but the number is small. Up to a dozen undergraduates during the summer, working under the mentorship of senior scientists" (SFI, 1993b). Additionally, they highlighted the institute fellows' environmentally conscious nature by emphasizing their "green thumb:" "SFI scientists have strong environmental, preservationist concerns"

[25] Interview with Ronda Butler-Villa, 3 November 2016.

(Ibid.). These points conveyed the message that the activities of building construction and hustle and bustle would be kept at a moderate level.

Such organizational and legislative arguments effectively convinced a significant portion of the residents in Santa Fe. Amidst the controversy, a group of citizens emerged in support of the institute, expressing their endorsement through letters sent to local newspapers and the town's mayor (SFI, 1993c). These individuals passionately defended the reputation and prestige of the SFI, drawing attention to the minimal architectural impact it would have on the area. They also underscored the societal value of the "community lectures" organized by the institute since 1987, which were open and free events aimed at enhancing "the general public's understanding of the nature of the sciences of complexity and their relevance to today's society" (SFI, 1987: 10). As the debate concluded, the majority of letters addressed to the mayor expressed favorable sentiments toward the SFI. This sentiment was also reflected in the votes cast by the town council and the Board of Adjustment.[26] Consequently, the SFI was granted permission to purchase the Hurley Residence and establish its presence within it.

Nevertheless, the inclusion of the institute within the leafy residential region came at a price. Several limitations were imposed, including the prohibition of student dormitories, restrictions on alterations to the local architectural style known as "pueblo" and "adobe"… *and, most significantly, the strict ban of laboratories* (SFI, 1993d). Furthermore, the town's code explicitly forbade any hazardous activities for an organization classified as a "private club" (SFI, ca. 1993f):

> Any use or structure not specifically or provisionally permitted herein and any use or structure which the board of adjustment, on appeal and after investigation of similar uses or structures elsewhere, shall determine to be potentially noxious, dangerous or offensive to residents of the district or those who pass on public ways, by reason of odor, smoke, noise, glare, fumes, gas, vibration, threat of fire or explosion, emission of particulate matter, interference with audio or television reception, or radiation, or likely for other reasons to be incompatible with the character of the district. (SFI, ca. 1993g)

Therefore, contrary to the initial intentions outlined in the institute's first bylaws and founding meetings, the institute's leadership assured the town of Santa Fe that no experimental infrastructure would ever be established within the premises of the SFI. As stated in their declaration:

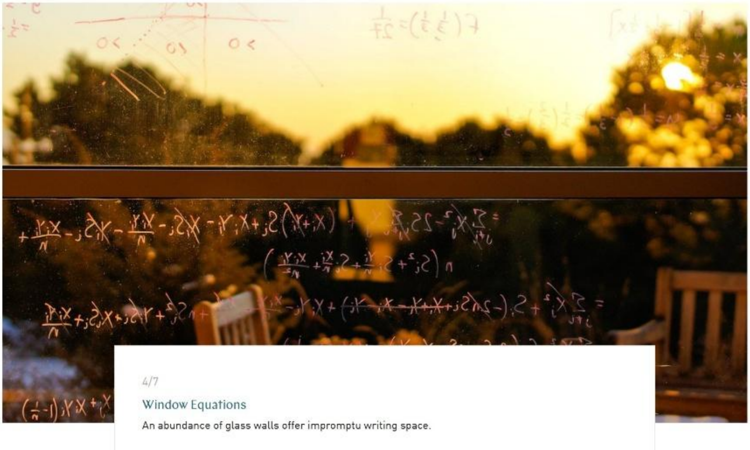
[26] A citizen civil tribunal that resolves local urban zoning quarrels.

"No laboratory work involving chemicals or biological facilities nor any laboratories using radioactive or other hazardous materials shall be permitted on the Property" (SFI, 1993e). During the proceedings before the Board of Adjustment, the then-vice president of the SFI, Bruce Abell, went even further to clarify the situation, affirming: "There are no laboratories at SFI nor any contemplated. Research is theoretical - the only experiments are conducted on whiteboards and computers. No chemicals. Nothing radioactive. No heavy equipment, no high-power machines" (SFI, 1993f).

Clearly, the restriction on installing equipment such as wet labs was a result of both legal requirements and the concerns of the surrounding neighborhood. One could hypothesize that if the SFI had succeeded in its original plan to raise $100-230 million to build an expansive campus, the social, epistemic, and material character of complexity sciences might look very different today - perhaps involving different disciplines or a different balance between them; perhaps employing a broader range of tools in active combination rather than relying predominantly on computational methods; perhaps embracing a more pluralistic, multi-level ontology rather than a primarily computational and reductionist one; and perhaps featuring more diverse physical facilities. This story highlights the fact that the identity of scientific domains is molded by various factors that some might perceive as "external" to science, but that from an STS perspective appear as constitutively intertwined with scientific practices: rhetorical persuasion, funding requests, resolution of conflicts with local communities, and political negotiations with authorities and institutions all come and interact with scientific questions, theories, tools, and results. As the controversy came to a close, the SFI had successfully established itself as a renowned center for theoretical research, based on simulations and mathematics. This achievement in shaping public perception likely facilitated the acceptance of relinquishing wet labs and similar facilities.

When examining the history of the institute's narrative, it becomes apparent that the SFI successfully turned its economic and geographical constraints into a positive aspect of its communication efforts. Figure 1, an image prominently featured on the institute's website and in various outreach publications (the bulletin, the annual report, the mailing list, etc.), exemplifies this approach. The photo showcases the institute's extensive use of glass surfaces, allowing for visual contact and serving as blackboards, facilitating interaction among researchers (SFI, 1996-1997: 24-25).

Figure 1. Window equations.



Source: https://www.santafe.edu/about/overview (retrieved the 5th June 2021).

Figures 2 and 3 depict the architectural layout of the institute, organized in pods where communal spaces are more substantial than individual offices. This design concept draws inspiration from the "caves and commons" method pioneered by cognitivist scientist Marvin Minsky at MIT in the 1960s, subsequently adopted by digital enterprises and now utilized in numerous research centers and universities (Brand, 1995). In line with this architectural philosophy, the common areas were designed to be spacious, comfortable, and well-equipped with blackboards, sofas, desks, and libraries, encouraging residents to remain and engage with one another. In summary, despite being unable to achieve the original goals set by the Senior Fellows, the SFI successfully transformed a potential weakness into a strength. The institute's purely theoretical nature became one of its most renowned features.

Figure 2. Fig. 2. Cowan Campus main pod's planimetry.

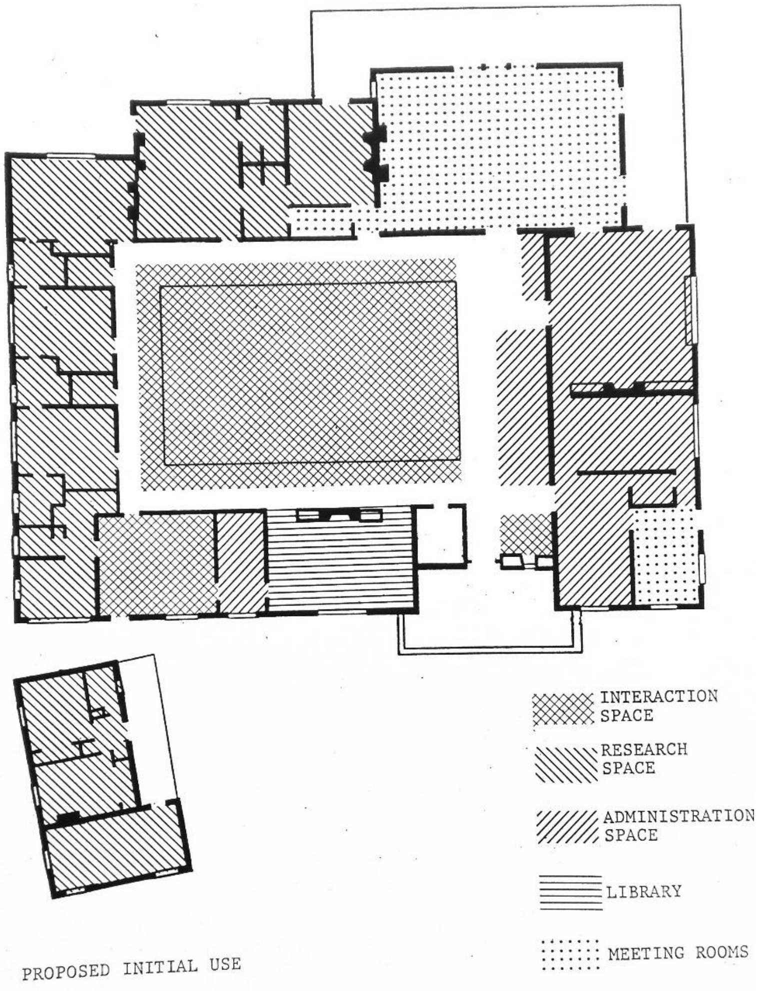
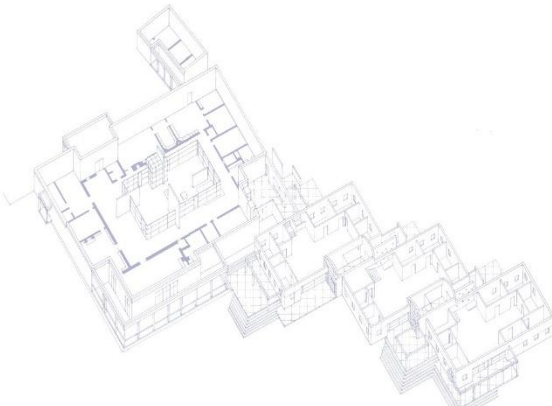


Figure 3. The SFI's complete planimetry after 1996–1997 interventions on the "Cowan Campus."



However, the initial acclaim received by the SFI did not shield it from criticism, as evidenced by the above-mentioned article written by John Horgan. Therein, while some SFI fellows declared that "[t]here [was] a lot to be proud of" about the institute, Horgan ironically remarked that "[t]here certainly [was], at least from a public-relations standpoint:" despite its small size, "the institute [had] enjoyed much favorable attention from the press, including *Scientific American*, and [had] been celebrated in several popular books" (Horgan, 1995: 104). Yet, Horgan revealed that "even some scientists associated with the institute [were] beginning to fret over the gap between such rhetoric and reality" (Ibid.). One example he took was that of Jack Cowan, a mathematical biologist and an SFI's founder, who declared that "some Santa Fe theorists exhibit[ed] too high a 'mouth-to-brain ratio' for his taste" and that "[t]here [had] been tremendous hype". Horgan attributed this discrepancy to the institute's focus on computational approaches, particularly exemplified by Christopher Langton's field of "Artificial Life" - aimed at exploring the organization principles of living beings. Horgan compared the situation to the field pioneered by Turing, Minsky, and Papert: "just as artificial intelligence [had] generated more portentous rhetoric than tangible results, so [had] artificial life" (Ivi: 106). To support this view, Horgan cited British evolutionary biologist John Maynard Smith, who had been invited to the institute by theoretical biologist Stuart Kauffman:

> Smith, who pioneered the use of mathematics in biology, took an early interest in work at the Santa Fe Institute and [had] twice spent a week visiting there. But he [had] concluded that artificial life [was] "basically a fact-free science." During his last visit, he recall[ed], "the only time a fact was mentioned was when I mentioned it, and that was considered to be in rather bad taste." (Ivi: 107)

Interestingly, following Horgan's article, the institute underwent a notable transformation. In 1996, as mentioned earlier, a new phase began with the appointment of microbiologist Ellen Goldberg as the institute's president. Her primary objective was to restore and enhance the SFI's public image by "putting theory into practice" (SFI, 2000: 33). However, by that time, it was already too late to consider conducting such collaborations within the institute's walls.

3. CONCLUSION

According to Schweber and Wachter, modeling and simulation of complex systems represents a "Hacking-type revolution" - defined as a transformation of research practices of several disciplines, triggering the foundation of new institutions, and carrying a new worldview - but do not explain how complexity sciences became computational in the first place (Schweber, Wächter, 2000). In the present day, the computational nature of complexity sciences is widely recognized and accepted. Comparing the SFI with other complexity institutes in the US and Europe, it becomes evident that the ancestor's approach to architecture and scientific instrumentation for studying complex systems has forged a distinctive identity and influenced its followers (Li Vigni, 2021). While there are exceptions where wet labs and complex machinery are employed for direct data collection in or outside the institutes, in most cases laboratories are disregarded altogether.

The origins of this computational identity in complexity sciences are often attributed to intrinsic characteristics of complex systems or to contextual technological advancements. However, this article sheds light on the original intentions of the SFI founders, who had envisioned incorporating laboratory facilities within the research center. Archival evidence from the 1980s reveals that the future of complexity sciences was still uncertain and open at that time. Two factors intervened to prevent the institute from becoming what its founders wished it to be.

While the economic factors were not unfamiliar to the literature about this research field, the local controversy and compromises with the neighborhood that followed the budget constraints, presented here for the first time, played a role in closing down the door to experimentation within the institute. More generally, this article emphasizes that scientific communities and the knowledge they generate are shaped through a process involving scientific ambitions, theoretical frameworks, material resources, economic considerations, and socio-geographical dynamics at one and the same time.

REFERENCES

BAKER, E. (2022). The Ultimate Think Tank: The Rise of the Santa Fe Institute Libertarian. *History of the Human Sciences*. 35(3–4): 32–57.

BORELL, K., WESTERMARK, Å. (2018). Siting of Human Services Facilities and the NIMBY Phenomenon: A Critical Research Review. *Community Development Journal*. 53(2): 246–262.

BRAND, S. (1995). *How Buildings Learn: What Happens to Them After They're Built*. London: Penguin.

BURNINGHAM, K. (2000). Using the Language of NIMBY: A Topic for Research, Not an Activity for Researchers. *Local Environment*. 5(1): 55–67.

CAMPBELL-KELLY, M., D. D. GARCIA-SWARTZ (2013). The History of the Internet: The Missing Narratives. *Journal of Information Technology*. 28: 18–33.

CASTELLANI, B., GERRITS, L. (2024). *The Atlas of Social Complexity*. Cheltenham: Edward Elgar Publishing.

CAT, J. (1998). The Physicists' Debates on Unification in Physics at the End of the 20th Century. *Historical Studies in the Physical and Biological Sciences*. 28(2): 253–299.

CHUNG, J. B., KIM, H.-K., RHO, S. K. (2008). Analysis of Local Acceptance of a Radioactive Waste Disposal Facility. *Risk Analysis*. 28(4): 1021–1032.

COWAN, G. (1988). Plans for the Future. In D. Pines (ed.), *Emerging Syntheses in Science: Proceedings of the Founding Workshops of the Santa Fe Institute*, Santa Fe, New Mexico. Volume I (pp. 235–237). New York: Perseus Books.

DELICADO, A., L. JUNQUEIRA, S. FONSECA, M. TRUNINGER, L. SILVA (2014). Not in Anyone's Backyard? Civil Society Attitudes towards Wind Power at the National and Local Levels in Portugal. *Science &*

Technology Studies. 27(2): 49–71.

EDGERTON, D. (2011). *The Shock of the Old: Technology and Global History since 1900*. Oxford: Oxford University Press.

EDWARDS, P. N. (2010). *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming*. Cambridge, MA: MIT Press.

GALISON, P. (1997). *Image and Logic: A Material Culture of Microphysics*. Chicago and London: University of Chicago Press.

GELL-MANN, M. (1988). The Concept of the Institute. In D. Pines (ed.), *Emerging Syntheses in Science: Proceedings of the Founding Workshops of the Santa Fe Institute*, Santa Fe, New Mexico. Volume I (pp. 1–15). New York: Perseus Books.

GIERYN, T. F. (2006). City as Truth-Spot: Laboratories and Field-Sites in Urban Studies. *Social Studies of Science*. 36(1): 5–38.

GUSTERSON, H. (2000). How Not to Construct a Radioactive Waste Incinerator. *Science, Technology, & Human Values*. 25(3): 332–351.

HELMREICH, S. (1998). *Silicon Second Nature: Constructing Artificial Life in a Digital World*. Berkeley and Los Angeles: University of California Press.

HENKE, C. R., GIERYN, T. F. (2008). Sites of Scientific Practice: The Enduring Importance of Place. In E. J. Hackett, O. Amsterdamska, M. Lynch, J. Wajcman (eds), *The Handbook of Science and Technology Studies* (pp. 353–376). Cambridge, MA: MIT Press.

HERMANN, A., KRIGE, J., MERSITS, U., PESTRE, D. (1987). *History of CERN. Volume I: Launching the European Organization for Nuclear Research*. Amsterdam and New York: North-Holland.

HORGAN, J. (1995). From Complexity to Perplexity. *Scientific American*. 272(6): 74–79.

ISRAEL, G. (2005). The Science of Complexity: Epistemological Problems and Perspectives. *Science in Context*. 18(3): 479–509.

JASANOFF, S. (ed.) (2004). *States of Knowledge: The Co-Production of Science and Social Order*. London: Routledge.

KASPERSON, R. E., GOLDING, D., TULER, S (1992). Social Distrust as a Factor in Siting Hazardous Facilities and Communicating Risks. *Journal of Social Issues*. 48(4): 161–187.

KAȘDOĞAN, D., OKUNE, A. (2023). TRANSnationalizing STS: Places, Spaces, and Politics. *Engaging Science, Technology, and Society*. 9(1): 50–62.

KNORR-CETINA, K. (1999). *Epistemic Cultures: How the Sciences Make Knowledge*. Cambridge, MA: Harvard University Press.

LADYMAN, J., WIESNER, K. (2020). *What Is a Complex System?* New

Haven: Yale University Press.
LENOIR, T. (1997). *Instituting Science: The Cultural Production of Scientific Disciplines*. Stanford: Stanford University Press.
LEWIN, R. (1992). *Complexity: Life at the Edge of Chaos*. New York: Macmillan Publishing Company.
LI VIGNI, F. (2020a). Le projet épistémique des sciences des systèmes complexes. *Philosophia scientiæ*. 241(1): 181–200.
LI VIGNI, F. (2020b). The Failed Institutionalization of "Complexity Science": A Focus on the Santa Fe Institute's Legitimization Strategy. *History of Science*. 59(3): 344–369.
LI VIGNI, F. (2021). Complexity Sciences: A Scientific Platform. *Science & Technology Studies*. 34(4): 30–55.
LI VIGNI, F. (2022). *Histoire et sociologie des sciences de la complexité*. Paris: Éditions Matériologiques.
LI VIGNI, F. (2023). The Promises of Complexity Sciences: A Critique. *Perspectives on Science*. 31(4): 465–502.
LIVINGSTONE, D. N. (2013). *Putting Science in Its Place: Geographies of Scientific Knowledge*. Chicago: University of Chicago Press.
LULOFF, A. E., ALBRECHT, S. L., BOURKE, L. (1998). NIMBY and the Hazardous and Toxic Waste Siting Dilemma: The Need for Concept Clarification. *Society & Natural Resources*. 11(1): 81–89.
LYNCH, M. (1985). *Art and Artifact in Laboratory Science: A Study of Shop Work and Shop Talk in a Research Laboratory*. London and Boston: Routledge & Kegan Paul.
MITCHELL, M. (2009). *Complexity: A Guided Tour*. Oxford and New York: Oxford University Press.
OPHIR, A., SHAPIN, S. (1991). The Place of Knowledge: A Methodological Survey. *Science in Context*. 4(1): 3–22.
O'HARE, M., BACOW, L. S., SANDERSON, D. (1983). *Facility Siting and Public Opposition*. New York: Van Nostrand Reinhold Company.
PINES, D. (ed.) (1988). *Emerging Syntheses in Science: Proceedings of the Founding Workshops of the Santa Fe Institute*, Santa Fe, New Mexico. Volume I. New York: Perseus Books.
RAJ, K. (2007). *Relocating Modern Science: Circulation and the Construction of Knowledge in South Asia and Europe, 1650–1900*. Dordrecht: Springer.
RYAN, J. (2010). *A History of the Internet and the Digital Future*. London: Reaktion Books.
SCHIVELY, C. (2007). Understanding the NIMBY and LULU Phenomena: Reassessing Our Knowledge Base and Informing Future Research. *Journal of Planning Literature*. 21(3): 255–266.

SCHUT, P.-O., DELALANDRE, M. (2015). L'échec d'une discipline: montée et déclin de la spéléologie en France (1888–1978). *Revue d'histoire des sciences*. 68(1): 81–107.

SCHWEBER, S., WÄCHTER, M. (2000). Complex Systems, Modelling and Simulation. *Studies in History and Philosophy of Modern Physics*. 31(4): 583–609.

SFI (1984a). Articles of Incorporation of Rio Grande Institute. May 22, 1984.

SFI (1984b). Concluding Comments, October Workshop. Board Meetings September 9, 1984–March 9, 1986.

SFI (1987). *The Bulletin of the Santa Fe Institute*. 2(1).

SFI (1988). Report of the Computational Resources Committee to the Annual Meeting of the Science Board of the Santa Fe Institute. March 11, 1988.

SFI (1989). *The Bulletin of the Santa Fe Institute*. 4(2).

SFI (1990). A Proposal to the National Science Foundation for a Broad Research Program on the Sciences of Complexity at the Santa Fe Institute, Santa Fe, New Mexico. July 1, 1990.

SFI (1991). *The Bulletin of the Santa Fe Institute*. 6(2).

SFI (1992a). *The Bulletin of the Santa Fe Institute*. 7(1).

SFI (1992b). *The Bulletin of the Santa Fe Institute*. 7(2).

SFI (1993a). Facilities Program. Santa Fe Institute. Prepared by Laban Wingert Associates. Santa Fe, New Mexico. November 1993.

SFI (1993b). Informational Report. Santa Fe Institute Request for Special Exception. March 22, 1993.

SFI (1993c). Santa Fe Institute's Proposal; Case #S.E. 1993–5. Patty J. Johnston to Mayor Sam Pick.

SFI (1993d). S.F. Institute's Plan Worries Neighbors. Bob Quick, The New Mexican.

SFI (1993e). Abell Presentation to Board of Adjustment.

SFI (1993f). City OKs Institute's Hyde Park Relocation. Michelle Melendez.

SFI (1993g). Santa Fe City Code: Land Development.

SFI (ca. 1993a). S.F. Institute's Plan Worries Neighbors. Bob Quick, The New Mexican. Box "Santa Fe Institute Archival Materials Relating to Acquisition of The Hyde Park Road Campus."

SFI (ca. 1993b). Abell Presentation to Board of Adjustment. Box "Santa Fe Institute Archival Materials Relating to Acquisition of The Hyde Park Road Campus."

SFI (ca. 1993c). Santa Fe Institute's Proposal. Box "Santa Fe Institute Archival Materials Relating to Acquisition of The Hyde Park Road

Campus."
SFI (ca. 1993d). Appeals Delay Institute Closing. Tom Sharpe. Box "Santa Fe Institute Archival Materials Relating to Acquisition of The Hyde Park Road Campus."
SFI (ca. 1993e). Abell Presentation to Board of Adjustment. Box "Santa Fe Institute Archival Materials Relating to Acquisition of The Hyde Park Road Campus."
SFI (ca. 1993f). City OKs Institute's Hyde Park Relocation. Michelle Melendez. Box "Santa Fe Institute Archival Materials Relating to Acquisition of The Hyde Park Road Campus."
SFI (ca. 1993g). Santa Fe City Code: Land Development. Box "Santa Fe Institute Archival Materials Relating to Acquisition of The Hyde Park Road Campus."
SFI (1994). *The Bulletin of the Santa Fe Institute*. 9(2).
SFI (1995–1996). *The Bulletin of the Santa Fe Institute*. 11(1).
SFI (1996–1997). *The Bulletin of the Santa Fe Institute*. 12(1).
SFI (2000). *The Bulletin of the Santa Fe Institute*. 15(2).
SFI (2001). *The Bulletin of the Santa Fe Institute*. 16(1).
SFI (2005). *The Bulletin of the Santa Fe Institute*. 20(1).
SFI (2008). Santa Fe Institute Annual Report. Santa Fe.
SFI (2010). Santa Fe Institute Annual Report. Santa Fe.
SFI (2012). *The Bulletin of the Santa Fe Institute*. 26: 31.
SFI (2013). Bylaws of the Santa Fe Institute. Santa Fe, New Mexico. As amended on November 3, 2013.
SFI (2021). Financial Statements and Supplementary Information. Years ended December 31, 2020 and 2019. Albuquerque: CliftonLarsonAllen LLP.
SLOTA, S. C., BOWKER, G. C. (2017). How Infrastructures Matter. In U. Felt, R. Fouché, C. A. Miller, L. Smith-Doerr (eds), *The Handbook of Science and Technology Studies* (pp. 529–554). Cambridge, MA: MIT Press.
SNOW, C. P. (2001 [1959]). *The Two Cultures*. London: Cambridge University Press.
VARENNE, F. (2009). Models and Simulations in the Historical Emergence of the Science of Complexity. In M. A. Aziz-Alaoui, C. Bertelle (eds), *From System Complexity to Emergent Properties. Understanding Complex Systems* (pp. 3–21). Berlin and Heidelberg: Springer.
WALDROP, M. M. (1992). *Complexity: The Emerging Science at the Edge of Order and Chaos*. New York: Simon & Schuster Paperbacks.
WILLIAMS, L. (2012). *Modeling, Building, Writing: A History of Nonlinear Dynamics and Complex Systems (PhD thesis)*. Cambridge, MA: Har-

vard University.

WOLFE, A. K., BJORNSTAD, D. J., RUSSELL, M., KERCHNER, N. D. (2002). A Framework for Analyzing Dialogues over the Acceptability of Controversial Technologies. *Science, Technology, & Human Values*. 27(1): 134–159.

WYATT, S. (2007). Technological Determinism Is Dead; Long Live Technological Determinism. In E. J. Hackett, O. Amsterdamska, M. Lynch, J. Wajcman (eds), *The Handbook of Science and Technology Studies* (3rd ed., pp. 165–180). Cambridge, MA: MIT Press.