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Exploratory Modelling with Speculative Complex Biological Systems

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We present a specific performance with a speculative complex biological simulation in the terms of exploratory modelling in scientific practice. The simulation, which adapts a model of acellular slime mold *Physarum polycephalum*, challenges the locus of agency during the performance. This powerful performative agency arises from the persistence of state and feedback mechanisms of this complex network system. To understand how agency shifts, and how the performance relates to the underlying biological system being modeled, we use the *scribe-system-representation* framework. We motivate the use of scientific work as a rich, generative basis for creative coding projects, which we see as a vital mode of engagement with contemporary scientific work and process. This article provides conceptual tools and some practical examples to explore this avenue in artistic as well as pedagogic practice.

1. Introduction

Phenomena representable by complex networks are pervasive in the world today, from the smallest to the largest of scales. Notable examples include biological systems like slime mold, as used in this paper; the multi-scale movement and migration of humans; the structure of the internet; and the interlocking feedback systems that influence the global climate. The nonlinear dynamics of these systems make them notoriously difficult to understand. Coupled with the enormous existential importance of systems like climate and contagious disease, understanding these systems is a necessity. We argue that the deliberate use of scientific work on modelling complex systems to inform creative coding pedagogy and generative art is a valuable, emerging model of scientific engagement. This essay provides tools for pedagogy and practice by demonstrating relevant use of the creativity support index (Section 2) and exploratory exercises (Section 4).

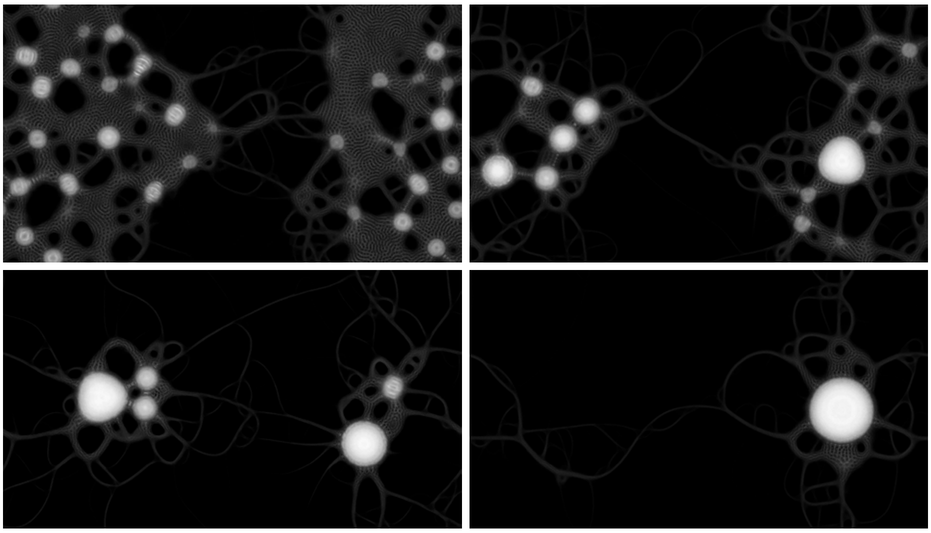

Fig. 1. The final movement of *Dismantling* (24:00–end[1]).

The essay is structured as follows. In Section 2, we introduce creativity support tools, which, in the context of art that involves writing code, has typically referred to the resulting code object. However, we motivate the use of this concept to understand not the code object but the paper on which it is based. We rely on a framework that distinguishes the (biological) system, the (simulated, performed) representation and the scribe (or performer) which highlights the shifting locus of agency in the live performance, "*Dismantling*" (Berlin, 2019; see Figure 1). In Section 3, we describe the performance and relate the artistic image-making to scientific image-making by drawing from Latour's concept of scientific inscriptions. In Section 4, we build on Gelfert's synthesis of exploratory modelling literature by translating it into a set of *Exercises for Performing with a Complex Network Simulation*. In Section 5, we consider the implications of exploring this relationship between scientific and artistic work in light of the inadequacy of the information deficit model in communication of climate change.

2. Scribe, System, and Representation

A major theme of *"Dismantling"* is the shifting locus of agency between the human performer and the simulation software used. In this section, we explain why viewing this software as a creativity support tool (CST) is inadequate. We introduce the *scribe-system-representation* framework that explains the relationship between software and performer. Then, we return to the CST framing, using it to describe not the software, but rather the scientific work that underpins the software. In this way, the CST evaluative framing becomes a generative tool for approaching scientific artifacts.

The simulation, which adapts a model of acellular slime mold *Physarum polycephalum* (Jones, 2010). The simulation is the *representation* of the biological *system*. The paper that describes this system is the means by which the representation-system relationship can be understood and validated. The performer, or *scribe*, influences the speculative *system*, by changing simulation parameters; and influences the simulated *representation*, by changing visual settings like color.

Because the aim of the performance is to explore a shifting locus of agency between the performer and a speculative biological system, the performance choreography focuses on ways that input can influence the system itself. Section 3 describes in further detail the controllability, in a complex dynamical systems sense, of the simulation, and its implications on the performance. Section 4 relates the choreography of the scribe's actions to exploratory modelling in scientific work, where researchers must resist "mistak[ing] their facility at exploring the 'world in the model' [*representation*] for an improved understanding of the *target system itself*" (emphasis original, Gelfert, 2016, p. 96). The exercises in Section 4 and pedagogical implications described in Section 5 maintain the distinction between *representation* and *system* as a means to relate the artistic work to the scientific work, and vice versa.

The Creativity Support Index (CSI) is "a psychometric survey... designed to assess the ability of a digital creativity support tools to support the creative process of its users" (Cherry and Latulipe, 2014). Here, the creativity support tool (CST) has a relatively inclusive definition: something which "be used by people in an open-ended creation of new artifacts... in the computing domain, CSTs are often software applications that are used to create digital artifacts or are used as part of the process of working toward the completion of an artifact" (Cherry and Latulipe, 2014).

The CSI asks the CST's user—in our case, the scribe—to assess the tool along six dimensions: Collaboration, Enjoyment, Exploration, Expressiveness, Immersion, Results Worth Effort. Although the simulation is the software, we view the underlying scientific object (the original *Physarum* paper) as the primary creativity support. The following two of the six dimensions of the CSI (explained below through descriptions quoted from the survey itself) especially underline the inapplicability of an analytic tool like the CSI to the simulation itself.

Immersion: "My attention was fully tuned to the activity, and I forgot about the system or tool that I was using" (Cherry and Latulipe, 2014). We interpret immersion here not as forgetting about the speculative biological *system* encoded in software, but rather as forgetting the mechanics of the *representation* and engaging with it as a view into the complex system with its own agency.
Results Worth Effort: "What I was able to produce was worth the effort I had to exert to produce it" (*ibid.*). As we describe in Section 4, the activities necessary to choreograph and perform map well onto the activities of exploratory modelling in the natural sciences (Gelfert, 2016). The production of compelling images is an important aim of the activity, but the "effort" of the activity itself offers additional results of elucidating the biological meaning of the system to the scribe and viewer. We discuss the implications of this in Section 5.

This particular paper is a rich CST because it describes a complex system with feedback loops and tipping points. The CSI framing helps reflect on complex systems epistemology as artistic medium:

Collaboration: "The system or tool allowed other people to work with me easily" (*ibid.*). The study of complex systems draws from physics, biology, and the social sciences both in method and the body of knowledge upon which it builds. (Thurner, Hanel, and Klimek, 2018).
Exploration: "The system or tool was helpful in allowing me to track different ideas, outcomes, or possibilities" (*ibid.*). The interactive elements of the representation, as described in Section 3, were designed to support the exploratory activities in Section 4.
Expressiveness: "The system or tool allowed me to be very expressive" (*ibid.*). This particular representation includes additional feedback loops, further delving into the speculative biology of the system. Limited controllability of a system where the topology of the network itself is a dynamical system (Liu 2016) expands the space of possibility of visuals and dynamics. The scribe is therefore not limited to deterministic logic (Figure 2).

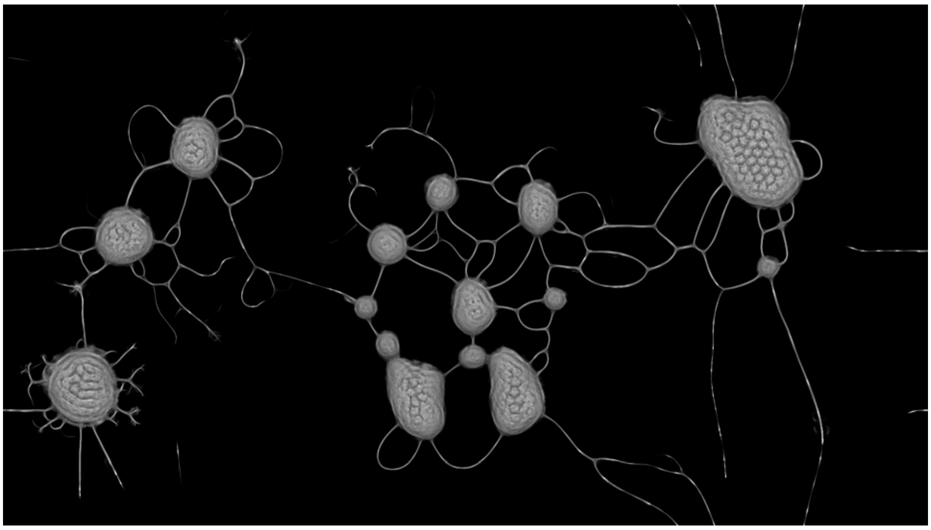

Fig. 2. Nonlinear behavior of the system allows a diversity of structures to arise from the same underlying simulation mechanics and parameterization.

The last of the six CSI dimensions, *Enjoyment* (“I enjoyed using the system or tool” (*ibid.*)) is omitted from the reflection above, though it is apparent from the description of the performance:

> “[...] reconstitutes fragments of scientific work. Using ink, tracing paper, video simulation, and tactile interaction, we hallucinate through complex networks that underpin biological and sociological systems. The viewer is invited to participate in the construction of meaning, as well as bask in the generative dismantling of the scientific face. [...] The images in science are the common thread and mediator, objects with meaning and agendas for both scientists (who produce them) and everyone else (who consume them). Through its human appendages, this face has the ability to materialize; often with dire social and environmental consequences. This exhibition reconfigures and scrambles the scientific face, collaboratively dismantling it piece-by-piece to reveal an expanded theater of operations, unexpected agency, and sensory lines of flight.”
> —*Dismantling* (2019) statement excerpt.

3. Inscriptions

In *Dismantling* (Berlin, 2019), we presented a live performance[1] using an interactive simulation. The *scribe* draws on a tablet, which relays the stylus position and pressure to an agent-based simulation (Figure 1). The behavior of the simulation itself is an adaptation of the behavior of the acellular slime mold *Physarum polycephalum* (Jones, 2010). Additional feedback loops were incorporated into the model to increase the heterogeneity of the patterns that were produced. The resulting *system* is therefore a speculative biological system that shares some, though not all, properties with the model it is based on. The *representation* entails the visual representation, as well as the interactive elements, especially the capacity of the *scribe* to alter the parameters of the underlying *system* as a way to induce particular behaviors in the representation (Figure 2).

1. A recording of the entire piece, recorded later, can be seen here: https://youtu.be/hEbbmJaYHAc.

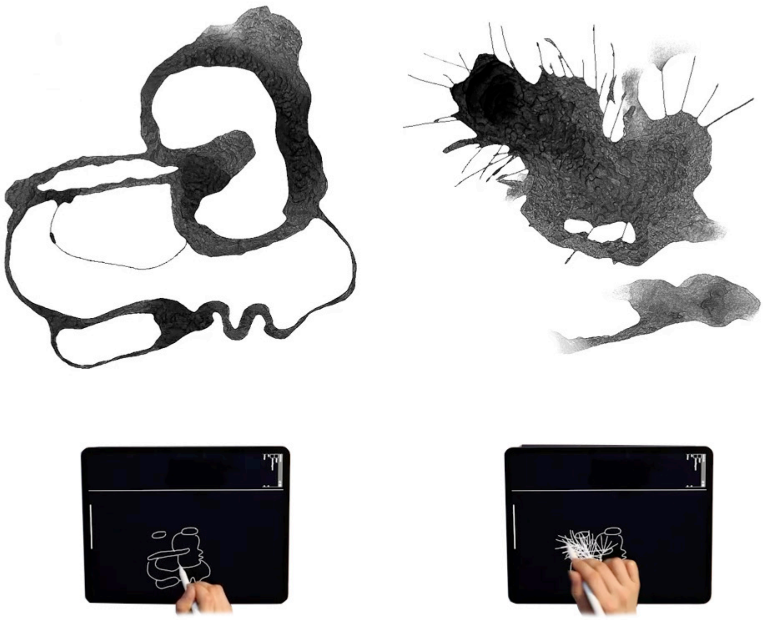

Fig. 3. Two frames showing how the scribe's input deliberately induces an accumulation of energy, which then flows in ways the scribe has no direct control over. (12:00–13:00 in the video[1]).

Figure 3 shows how building a concentration of particles leads to the simulation of those particles developing its own slow movement, demonstrating a shifting locus of agency. Prior to the shift, the system responds to the scribe (visually following the stylus), and after it, the scribe responds to the system, as the drawing can no longer significantly impact the macro-movement. The most striking difference in these two semi-stable states is a critical particulate density that alters the behavior of the simulation—a tipping point that, once reached, causes an explosive chain reaction through the connected components. The scribe has intentionally caused this state, ceding direct control of the flow of simulated matter.

This interactive simulation displays traits of a biological complex system—a co-evolving multilayer network. Experimentation with the simulation has demonstrated these traits: self-organization, nonlinear dynamics, phase transitions, and collapse and boom evolutionary dynamics. The interlocking feedback mechanisms and topological adaptability that drive the dynamics complicate its controllability—and thus the relationship between the scribe and the simulation. Controllability in this context means the ability to deliberately drive the system to a desired state at an intended pace. In contrast to abstractive digital text, the scribe retains a more limited level of control over the system, leaving a significant level of autonomy to the simulation itself. The controllability of this particular type of complex network (i.e. an adaptive transportation network, like acellular slime mold) remains an open problem, because the topology of the network itself is a dynamical system (Liu 2016). In spite of this, the scribe does have the ability to move the system between certain steady states—as demonstrated through the phase transition dynamics resulting from accretion of ink past a certain point— as well as guide the macro-scale behavior of the system.

Aside from the stylus spawning particulates, the scribe may change the parameters of the simulation: Figure 4 shows the aftermath of a parameter change alone. Changing parameters allows the scribe to redistribute the simulation's matter on the page, and change states, in an additional mechanism.

The role of the image, or visualization, in scientific practice helps to understand the relationship between the performance and the scientific work. Latour, investigating "what is specific to our modern scientific culture," considers breaking scientific practice "into many small, unexpected and practical sets of skills to produce images, and to read and write about them" (Latour, 1987). Although this "strategy of deflation" has major limitations, the analysis of inscriptions allows understanding scientific practice (Latour and Woolgar, 1979) and power (Latour, 1987). Inscriptions serve as record; basis for communication and rhetoric; and further investigation. We relate several properties of scientific inscriptions to the speculative simulation: recombination, scaling, and immutability.

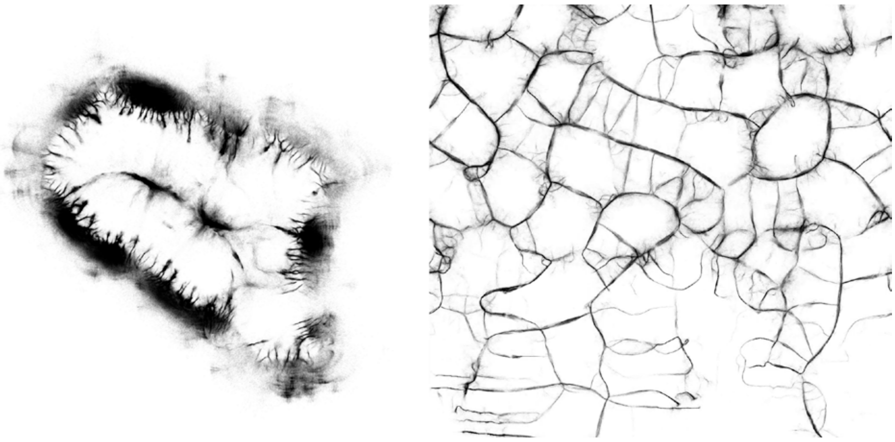

Fig. 4. Two frames showing how the scribe's input is affected by interaction between changing parameters of the system. Without any additional input from the scribe, the new parameter space reconfigures the visual field and invites different interactive input actions.

Recombination is enabled by "optical consistency" and its embeddedness in a shared visual culture, which "allows translation without corruption" (Latour, 1987). These inscriptions, including charts, tables, blots, and so on, depend on a domain's visual culture and shared socialization. Visualization is a meta-cognitive skill, including (1) familiarity with "the conventions of representation [one is] likely to encounter;" and (2) understanding of "the scope and limitations [i.e. what] aspects of a given model each can and cannot represent" (Gilbert, 2015). In the context of a performance, the scribe can support building a legible optical consistency through repetition and inclusion of familiar points of reference. *Dismantling* builds up each of the movements (Figure 6) to demonstrate the same actions resulting variously in either rupture or repair under different conditions.

The *scalability* of inscription is, in Latour's view, one of the sources of power of "scientists and engineers:" that "no one else deals only with phenomena that can be dominated with the eyes and held by hands" whether the phenomena be stars or atoms (Latour, 1987). As shown in Figure 5, the microscale simulation with which we perform mimics transportation networks. For Latour, the capacity to operate at radically different scales "following this theme of visualization and cognition in all its consequences" informs the "view of power" of scientific and engineering work:

> "There is not a history of engineers, then a history of capitalists, then one of scientists, then one of mathematicians, then one of economists. Rather, there is a single history of these centers of calculation. It is not only because they look exclusively at maps, account books, drawings, legal texts and files, that cartographers, merchants engineers, jurists, and civil servants get the edge on all others. It is because all these inscriptions can be superimposed, reshuffled, recombined, and summarized, and that totally new phenomena emerge, hidden from the other people from whom all these inscriptions have been exacted." (Latour, 1987)

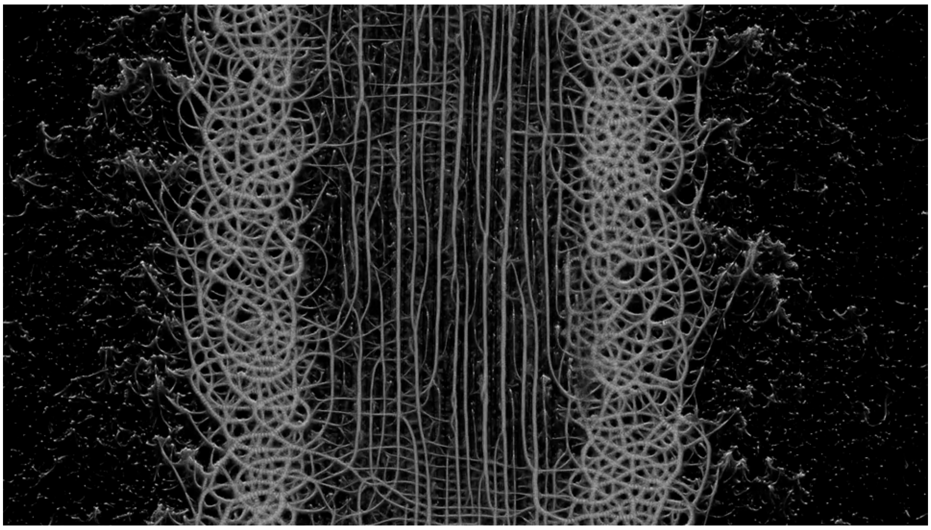

Fig. 5. Inscription of this microscale simulation mimics transportation network inscriptions, demonstrating the scalability and recombination of scientific inscription of complex networks.

By nature of work practices and contexts, they are *immutable*: "even exploding stars are kept on graph papers in each phase of their explosion" (Latour, 1987). This key property grants legitimacy, by means of legible record, to audiences outside of original investigators. A performance has a similar need: to create reproducible and legible images. The *immutable* inscription includes the simulation visual which inscribes dynamics of *Physarum* parameterizations (Figures 1–5, 7) and the abstract score (Figure 6) which inscribes the inscription. However, speculative simulation is unlike the field and lab-based examples Latour draws on, so in the next section, we relate it to exploratory modelling.

With scaling and recombination as means of power, and immutability and means of legitimacy, *inscriptions* are both tools by which science is done internally and communicated externally, as well as means to engage directly in scientific work. This performance is functionally a scientific act. Engaging with it is a form of direct participation, both on the part of the performer and the audience, depending on the content of the performance itself. Stylus input of the scribe made visible (included in Figures 1–5, 7) constitutes an insufficient record alone, but reveals the process of inscription construction, resisting hiding. In the next section, we draw from scientific exploratory modelling practice to inform performance exercises.

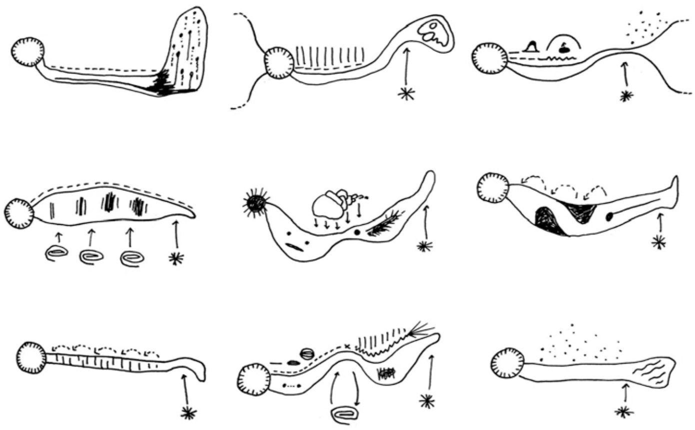

Fig. 6. Representation of each of the nine movements with enough detail to clearly distinguish between them, and to consistently achieve the desired state. The external "asterisk" notation refers to interpolation between parameter spaces; all other interactions are within particular parameterizations.

4. Exploratory Modelling

In this system, the scribe must develop an understanding of a complex system. The performance then uses that intuition with a particular set of parameters and their behavior in response to pen input in order to consistently induce emergent behaviors legible to an audience who does not possess that familiarity. Although the preparatory process described is active and exploratory, the scribe's task *during* the performance becomes focused on the consistently producing the inscription in cooperation with the *system*, through the *representation*.

The kind of hypothesis formulation and observation of the *system* through its *representation* can be seen as a form of exploratory modelling by the *scribe*. This section presents a detailed set of *Exercises for Performing with a Complex Network Simulation*, building on study of modelling in scientific work (Gelfert, 2016; Rosen, 1991). Writing about complex biological systems, Rosen recognises "essentially two ways [...] to obtain meaningful information regarding system behaviour and system activities. We can either passively watch the system in its autonomous condition and catalogue appropriate aspects of system activity, or else we can actively interfere with the system by perturbing it from its autonomous activity in various ways, and observe the response of the system to this interference" (Rosen, 1991). Both active interaction and passive observation of the result of a deliberate combination of initial conditions and parameters can be used in the performance (Fig. 7).

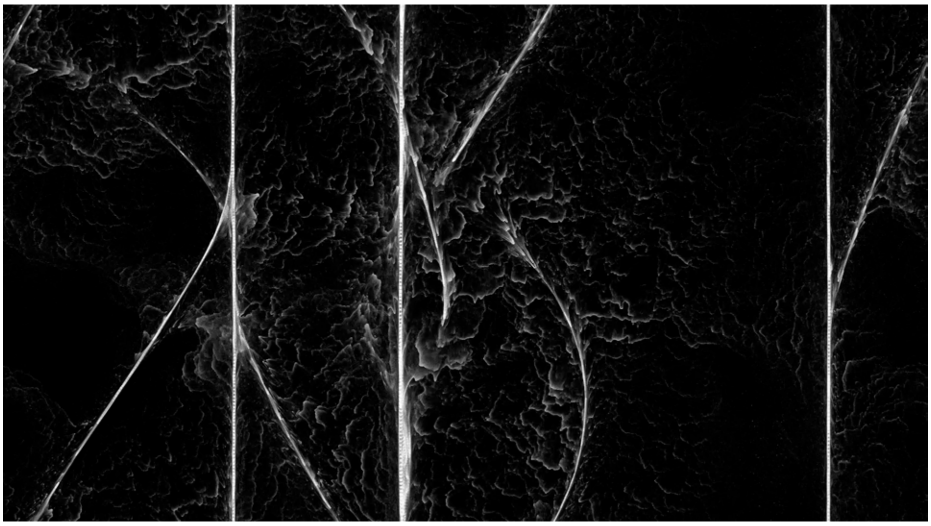

Fig. 7. The initial conditions and parameters lead to a tipping point, with a phase shift unfolding over the course of several minutes. In the video[1] the movement at 15:20-15:55 is followed by a change in parameters, and until 20:22 the remainder of this movement and the entirety of the next unfolds without any input from the scribe.

The actions that the scribe undertakes to *explore* the system through its representation can be seen as either (1) specific, "stimulus-oriented" behaviour which "*converges* upon a specific question, fact, detail, or 'missing link'", and (2) "divergent" exploration, which is "not directed at a specific object, question, or stimulus, but is response-oriented, in that the cognitive subject seeks novelty or surprise for its own sake" (p. 74–75, Gelfert, 2016). Gelfert writes that "manipulation [...] is a good way of deepening one's understanding of a model" (p. 73) further citing Mary Morgan's work that "representations only become models when they have the resources for manipulation." Projects like distill[2] and Complexity Explorables[3] specifically aim to create resources for manipulation as a way to make complex systems accessible to a wider audience.

2. https://distill.pub/2017/research-debt/.

3. complexity-explorables.org.

Referencing Steinle, Gelfert reviews some methodological guidelines for exploratory experimentation: (1) varying a large number of parameters; (2) determine which experimental conditions are indispensable, and which are only modifying; (3) look for stable empirical rules; and (4) find appropriate representations by means of which those rules can be formulated. These and the above two methodological guidelines can be further synthesized into the below exercises for developing a performance with a simulation that has both manipulation resources, and sufficient model complexity in the form of feedback loops and potential to create tipping points to enable deliberate shifting of the locus of agency. These exercises are shown in order of increasing need for developing an understanding and/or intuition of the system.

Exercises for Performing with a Complex Network Simulation

1. Find steady state(s);
2. Find a maximum density state;
3. Find a minimum density state;
4. Find pairs of states that demonstrate different scale of motion;
5. Practice creating tipping points to create a phase shift;

6. Practice finding a variety of states that consistently slowly converge back to steady state;
7. Determine some minimal parameter change that disrupts the steady state(s);
8. Find states in with a parameter space that are either difficult or impossible to achieve without certain starting conditions (which can be achieved in a different parameter space);
9. Document (as text, a sketch, or score) how overall impression of patterns and dynamics shifts (speed of movement, its structuredness or chaos, and so on) in response to manipulation.

In scientific work, models can "(1) function as a starting point for future inquire, (2) feature in proof-of-principle demonstration, (3) generate potential explanations of observed [...] phenomena, and may lead us to assessments of the suitability of the target" (Gelfert, 2016): "just as an experiment does not always serve the function of *testing* a theory, neither does a model always have to render an empirical phenomenon to subsumption of a pre-existing theory". Not only does choreography and performance require doing exploratory modelling, but the exploratory artistic practice can also become a form of scientific knowledge-building and synthesis.

5. Discussion and Implications

In previous sections, we presented exploratory modelling of speculative complex biological systems: a simulation that *represents* a *system*, controllable by a *scribe*'s actions, which can deliberately shift the locus of agency between the performer and the simulation. Our theoretical framing of this practice has implications for how creative coding pedagogy and science communication intersect.

When it comes to scientific communication, the presumed relationship between scientists and the general public remains informed by the information deficit model. This model suggests a one-way communication channel of scientists educating the public, despite having been shown to be inadequate and not reflecting reasons for lack of public engagement, particularly in the realm of anthropogenic climate change (Suldovsky, 2017). Suldovsky describes three alternatives to the information deficit model and their benefits, characteristic features in practice, and challenges:

Contextual model, as the information deficit model, "prioritizes one-way communication [but] does not assume that the mere presence of information will have a meaningful impact on audiences;" this is "most evident [in] attempts to segment audiences according to their level of concern about climate change." However, "it is not sufficient on its own as it fails to recognize [the many] goals in public engagement beyond the "selling" of climate change."
Dialogue model "rests on the assumption that greater public participation and engagement will lead to more effective policy" and is exemplified in

science museums. However, "while there is great enthusiasm [...] there is often little guidance on how to use [it] effectively or evaluate its benefits within the context of climate change." It is "time consuming and costly" to execute well; executed poorly, its drawbacks are as those in the information deficit model.

Lay expertise model is "most evident in approaches to climate change mitigation and adaptation" and "embraces non-scientific knowledge, or lay expertise, as equal to scientific expertise within the process of public engagement." Its utility is especially well-documented in natural resource management, although this model has also been criticized as contributing to anti-science sentiment, depending on the context and implementation.

The use of art objects or practices in science communication can be seen as a part of any of these communication strategies. However, we have seen continued and increasing interest among the general population to develop coding skills, combined with creative coding as offering accessible and low-barrier environments, as different expressive opportunities. Although the models Suldovsky presents have different drawbacks, they all struggle with relative lack of interest of engaging with scientific work directly. We see here an opportunity for channeling the interest of novice learners who search for appropriately challenging problems to fit their skill development interests.

As one example of a popular mobile app that attempted to raise awareness of sea-level rise due to anthropogenic climate change, After Ice[4] uses augmented reality to show water rising to fill the viewer's locale. While an engaging example of the contextual model, it is also an example of the drawbacks[5] of focusing on "selling": there is no climate model that makes the kind of precise claim with regard to a specific point and specific outcome (Lopez, et al, 2015). The uncertainty of climate models has been widely used to create doubt in the public sphere and showing precise numbers that directly contradict the epistemology of climate modelling arguably reduces the literacy of, and interest in, scientific information about climate change. The reality of climate change is not debatable, but the details are a subject of a wide range of ongoing research, and more—not less—enthusiastic, open-ended, multi-disciplinary public engagement with this research is needed. Perhaps in lieu of toy examples for creative coding, concepts from fascinating work on complex biological systems can be used in instruction, using the interest in creative coding as introduction not only to practical coding.

By creating a framing for incorporating scientific work into creative coding practice, we envision exploratory modelling practice within creative coding instruction. Gelfert (2016) delves into the uses of exploratory modelling "in situations where an underlying theory is unavailable" (p. 75) and introduces the notion of "minimal models [that are] not intended to be faithful representations of any target system in particular, but are meant to allow for the exploration of universal features of a large class of systems,

4. https://www.climatecentral.org/news/app-sea-level-rise-21374.

5. Critique of app based on discussion, in which one of the authors participated, at the Summer School on Simulation in Science. MECS Institute at Leuphana University in Lueneburg, Germany.

” such as in theoretical ecology (p. 80). In these situations, faced with (relative) “absence of comprehensive theoretical knowledge—determining where the target system begins and where it ends, reliably picking it out from the background noise, and arriving as a stable ‘research object’” requires recognizing that revision of any initial conception of target phenomenon is often necessary, and that exploratory modelling is a path to reconsideration of target systems.

Writing on the role of computers in creativity in 1967, Noll rejected the “portrayal of the computer as a powerful tool but one incapable of any true creativity… if creativity is restricted to mean the production of the unconventional or the unpredicted, then the computer should instead be portrayed as a creative medium – an active and creative collaborator with the artist” (Noll, 1967). In 2019, Hassine and Neeman highlight “a significant difference between early computer-generated art, from the 1960s-1970s, and this new type of [contemporary] generative art. Early computer art was undertaken in the spirit of open-ended experimentation, without a specific goal in mind. … In contrast, the projects … directed towards their predetermined [goal of replicating master works…] included substantial experimentation, yet this type of experimentation was most likely motivated by engineering rather than artistic purposes” (Hassine and Neeman, 2019). We see the use of scientific work as both structuring and providing fruitful creative constraints, especially in instruction, but also as actively supporting more open-ended, creative use of the powerful contemporary technical tools.

6. Conclusion

In this article, we describe a performance software that demonstrates a shifting locus of agency between the performer, the software, and the biological system that underpins the dynamics of the software. Although software is used, it does not constitute a “creativity support tool;” rather, we present a more generative perspective that hold the paper describing the biological system to the requirements of “creativity support” (Cherry and Latulipe, 2014). The *scribe-system-representation* framework helps to understand this performance as an interaction between speculative inscriptions of complex systems (Thurner, Hanel, and Klimek, 2018), drawing on Latour’s concept of inscriptions in science (Latour, 1987; Latour and Woolgar, 2013). We then bridge interactive visual art informed by models of natural or social phenomena, and exploratory scientific modelling (Gelfert, 2010).

Our synthesis of work from diverging areas allows us to envision a research and practice agenda for creative coding instruction, which we will explore in future work through workshops for novice and intermediate coders. Section 2 includes our own reflection of doing exploratory modelling in a complex speculative biological system, using the framing of the creativity support index (CSI). As we experiment with using scientific inscriptions, and the exploratory modelling exercises (Section 4) with learners, we will use the psychometric CSI instrument combined with qualitative methods (Maxwell, 2012) to understand learners' experience. Finally, in supporting learners presenting and sharing the outcome of creative coding, we hope to gain additional experience regarding ideas in Section 5 on the relationship of this artistic practice to scientific engagement.

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