HOW TO OBSERVE THE INNER SPACE OF A COMPLEX BIOLOGICAL SYSTEM THROUGH SPECULATIVE SIMULATION

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ABSTRACT

We present an approach for composition and performance with speculative complex biological systems. The goal of this approach is to incorporate not only the content of scientific work but the activities of scientific practice, specifically exploratory modelling with a computer simulation. We present the method, a conceptual framework and a list of exercises, and demonstrate its application in two generative art works. The framework distinguishes a system, its representation, and the human observers; this helps to clarify influences, material artifacts, and sources of tension. In *Dismantling*, a live performance using a simulation based on a model of the acellular slime mold *Physarum polycephalum*, we explore a shifting locus of agency during the performance between the observer and the representation.

In *Feed*, a visual and sound installation representing addiction as a multi-scale process, we explore the generative tension of representation re-use to engage with different systems. The model specifications of biological phenomena are used as bases for interactive complex network simulations.

Keywords: Generative art; Performance; Creativity; Creativity support tools; Complex networks; Exploratory modelling; Philosophy of science.

1. INTRODUCTION

Phenomena representable by complex networks are pervasive in the world today: biological systems like slime mold; multi-scale processes of drug addiction; 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. Because of their enormous existential importance, understanding such systems is as necessary as it is difficult. Referring to the role of art in human engagement with this complexity, Morton writes in *Hyperobjects*: “We need art that does not make people think … but rather walks them through an inner space that is hard to traverse.” (Morton, 2013, p.184)

The works described in this article aim to engage the human observers in a process of building intuition for specific complex biological systems. This is done by incorporating not only the content of a scientific article as inspiration for a visual work, but also practices, particularly exploratory modelling and visual representation that is applicable at multiple scales and across domains. We draw on existing literature regarding the roles of these practices in scientific work, and then describe how we have combined these concepts into a method and applied them in practice.

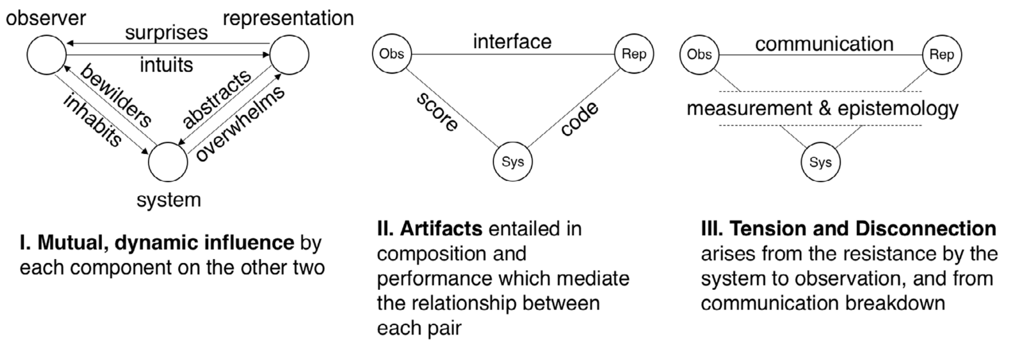

Figure 1: The relationship between each component (system, its representation, and the human observer(s)) entails (I) mutual, dynamic influence, (II) the iterative construction of artifacts, and (III) distinct sources of tension.

The motivation of each of the two works described is to iteratively deepen the connection with the underlying scientific work during both composition and performance. We consider how observers take on different roles (composer, performer, viewer); and how the artwork may combine aspects of multiple biological systems, depending on the expressive and communicative aim. We contribute a method for creating generative art through computational means, which relies on, but does not centre, computational tools. As shown in Figure 1, distinguishing the system, its representation, and the human observer allows us to clarify the influences, material artifacts, and sources of tension; any of which can entail a computational component.

This article is organized as follows. In Section 2, we motivate the use of exploratory modelling in generative art as a more engaging method for work that aims to communicate science to the general public. In Section

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3, we translate the activities of exploratory modelling in science to the choreography and performance with an interactive simulation through *Exercises for Performing with a Complex Network Simulation*. In Section 4, we offer example criteria for selecting a scientific paper as a model specification. In Section 5, we consider re-use of code and visuals across projects and for multi-scale representation, reflecting on visualizations' properties of recombination and scalability.

Two works are used as examples: *Dismantling* (2019), a live performance using a simulation adapted from a model of acellular slime mold *Physarum polycephalum*; and *Feed* (in progress), a visual and sound installation regarding addiction as a multi-scale process. In both cases, the biological phenomena of interest can be viewed as complex networks with performative potential that arises from the persistence of state and feedback mechanisms, and multi-scale behaviours.

2. BACKGROUND

Our motivation is to create engaging artworks that allow interested members of the public to better engage with scientific work. In this section, we first summarize some approaches and challenges in the communication of science to the public. Then, we introduce exploratory modelling as a practice in scientific work. The method we propose arises from the following observations in these two different fields. First, one-way communication (the "information deficit model") is both common and ineffective in communicating science to the public. Second, the practice of exploratory modelling is an iterative, speculative, and highly interactive method that is appropriate especially in the study of complex system or systems about which there is limited existing knowledge. In the rest of the article, we translate aspects of the exploratory modelling practice into a visual art practice that aims is to be interesting to a non-scientific audience, and to be legibly related to the phenomena it is based on.

2.1 PUBLIC COMMUNICATION OF SCIENCE

Under the information deficit model, which continues to inform the typical relationship between scientific work and the public, the root cause of misunderstanding, mistrust, or disinterest is a lack of information; and the aim of communication of science is to offer the information from scientific expertise, to a mostly passive public audience. This approach can be ineffective, but is used widely (Suldovsky, 2017). Suldovsky describes three alternatives, their benefits, characteristic features in practice, and challenges:

1. 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

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level of concern about climate change." However, the contextual model "is not sufficient on its own as it fails to recognize [the many] goals in public engagement beyond the 'selling' of climate change."

2. 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 similar to those in the information deficit model.

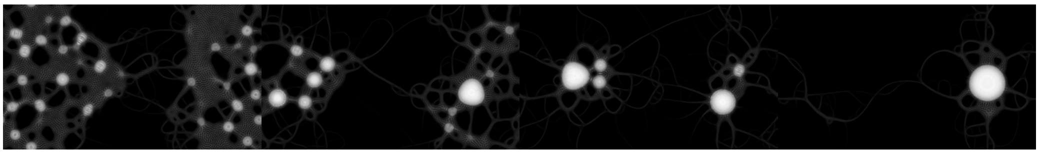

Figure 2: The final movement of *Dismantling* (24:00-end).

3. 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 for contributing to anti-science sentiment, depending on the context and implementation.

As one example of a popular mobile app that attempted to raise awareness of sea-level rise due to anthropogenic climate change, *After Ice*[1] 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 of focusing on "selling": there is no climate model that makes the kind of precise claim with regard to a specific location and impact (e.g., 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 that arguably reduces the literacy of, and interest in, scientific information about climate change. The reality of climate change is not debatable, but the details remain the subject of a wide range of ongoing research. Next, we consider the practice of exploratory modelling, which inspires an additional pathway for engagement that makes use of the expressive potential of simulation, rather than attempting to simplify it for legibility.

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

2.2 EXPLORATORY MODELLING

Exploratory modelling takes place in the natural and social sciences "in situations where an underlying theory is unavailable" (Gelfert, 2016, p. 75) and introduces the notion of "minimal models [that are] not intended to be

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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", such as in theoretical ecology (Gelfert, 2016, p. 80). These situations entail a (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 at a stable 'research object'". Exploratory modelling is a path for the necessary revision of initial conception of target phenomena.

Models play different roles, and offer different opportunities for interaction: "(1) function as a starting point for future inquiry, (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". 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, p. 610).

Both active interaction and passive observation of the result of a deliberate combination of initial conditions and parameters are used for choreography and performance in *Dismantling* (Figure 3). Through the lens of exploratory modelling, we can consider the interactive simulation as the site of inquiry. In scientific practice, that inquiry is the underlying phenomenon of study; whereas in artistic practice it can be related to the legible communication of some aspect of the biological system. In our case, the works attempt to represent the counter-intuitive non-linear dynamics of complex network systems.

The actions that the observer 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'",
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" (Gelfert, 2016, p. 74-75).

Gelfert writes that "manipulation … is a good way of deepening one's understanding of a model" (Gelfert, 2016, p. 73) further citing Mary Morgan's work that "representations only become models when they have the resources for manipulation."

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Scientific literacy and education benefits from helping learners to develop “metavisual capability” with respect to visualization and visual representation (Gilbert, 2015). Projects like *Distill* (http://distill.pub) and *Complexity Explorables* (http://complexity-explorables.org) use manipulation as a method for making complex systems accessible to a wider audience. Direct engagement with minimal models is an existing, effective way to educate and communicate, and it has a lot in common with Suldovsky’s dialogue model, which includes the interactive exhibits in science museums, and whose main drawback is cost. Simulations are useful not only for the study of phenomena, but also for communication of those phenomena to non-experts.

3. HOW TO OBSERVE: AGENCY

A simulation, used either for research or for communication, can be highly interactive: a researcher or performer can change parameters, adjust internal dynamics, and influence the starting conditions or boundary behaviours. In this section, we translate the activities of exploratory modelling to the space of visual performance and its choreography. We consider the role of the observer: both the more active observer taking part in the development of code or composition of a score; and the more passive audience. Based on our experience with a live performance we reflect on how the locus of agency shifts from the human observer to the simulated representation of a biological system.

In *Dismantling* (Berlin, 2019), we presented a live performance (https://youtu.be/wXB0Gv4Rf64, Figure 2) using an interactive simulation. The performer draws on a tablet, which relays the stylus position and pressure to an agent-based simulation (Figure 3). The behaviour of the simulation itself builds on the behaviour of the acellular slime mold *Physarum polycephalum* (Jones, 2010). During development, we incorporated additional feedback loops into the model to increase the heterogeneity of the visual patterns 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 interface, especially the capacity of the performer to alter the parameters of the underlying *system* as a way to induce particular behaviours in the representation. Aside from the stylus spawning particulates, the performer may change the parameters of the simulation.

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 performer (visually following the stylus), and after it, the performer 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 behaviour of the simulation—a tipping point that, once reached, causes an explosive chain reaction

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through the connected components. The performer has intentionally caused this state, ceding direct control of the flow of simulated matter. Referencing Steinle, Gelfert reviews 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;
4. find appropriate representations by means of which those rules can be formulated.

These methodological guidelines inform 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 listed starting with requiring the least intuition for 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 locating 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 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.

The performer engages in interaction with a simulation as medium. The resulting 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 observer and the simulation.

Controllability in this context means the ability to deliberately drive the system to a desired state at an intended pace. The performer retains a more limited level of control over the system, leaving a significant level

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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 performer 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 behaviour of the system. In the next section, we more directly address the relationship between the system (here, the articulation of the model) and its representation (here, the code).

4. THE SYSTEM AND ITS REPRESENTATION

To create artwork with speculative simulation, code is required, but so it is the model specification, such as from a scientific publication. In this section, we relate an existing set of criteria for evaluating the effectiveness of computational creativity support tools (CST) to this situation. We apply these criteria to describe not the code, but rather the scientific work that underpins the software ("System" in Figure 1). Using examples from our own perspective, we demonstrate how a practitioner can apply this framework to select paper(s) using which to build an interactive simulation artwork.

The Creativity Support Index (CSI) is "a psychometric survey … designed to assess the ability of a digital creativity support tool to support the creative process of its users" (Cherry & Latulipe, 2014). Here, the creativity support tool (CST) has a relatively inclusive definition: something which can "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 & Latulipe, 2014).

The CSI asks a CST's user (here, choreographer or performer) to assess a tool along six dimensions: Collaboration, Enjoyment, Exploration, Expressiveness, Immersion, Results Worth Effort. We view the underlying scientific object (the original *Physarum* paper) as the primary creativity support, mediated by code. 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 & 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" (Cherry & Latulipe, 2014). In the observer's multiple possible roles (composer; performer or scribe; and observer) the activity results in different intuitions. The intuitions

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demanded by choreography and performance map well onto the activities of exploratory modelling in the natural sciences (Gelfert, 2016, see section 2.2). 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 even a passive observer.

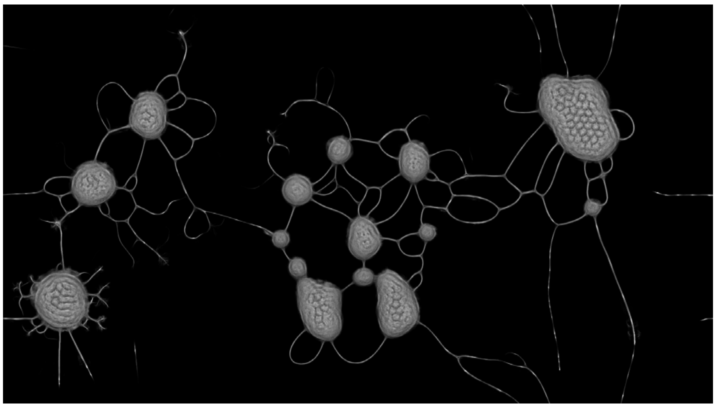
The paper on which *Dismantling* builds, (Jones, 2010), is a rich CST because it describes a complex system with feedback loops and tipping points. The CSI framing helps reflect on complex systems as artistic medium:

Collaboration: "The system or tool allowed other people to work with me easily" (Jones, 2010). 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 (e.g., Thurner, Hanel & Klimek, 2018), and we found interdisciplinary publications to be relatively approachable, as well as researchers open to offering feedback and critique. One danger of all the models of communicating science to the public is misleading or erroneous representation; working with scientific concepts, it is therefore important to select a well-explored and well-explained model, which is accessible and widely accepted enough that it is possible for an artist to become sufficiently familiar with it, and to connect with relevant scientists for feedback.

Expressiveness: "The system or tool allowed me to be very expressive" (Cherry & Latulipe, 2014). 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 observer is therefore not limited to deterministic logic (Figure 3).

The next section presents experiences with a different system and focuses on iteration while maintaining a persistent connection to the scientific basis of the work, which is enabled and encouraged by consistently articulating the artifacts produced in each of the relations.

(a)



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(b)

(c)

Figure 3. (a) Nonlinear behaviour of the system allows a diversity of structures to arise from the same underlying simulation mechanics and parameterization (b) 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) (c) Two frames showing how the scribe's input is affected by interaction between changing parameters of the system. Without additional input from the scribe, the new parameter space reconfigures the visual field and invites different interactive actions.

5. MULTI-SCALE INSCRIPTION

Motivated by communication of science through interactive simulation artworks, we described how to incorporate into the artistic process elements of scientific practice; specifically, exploratory modelling. In this section, we consider another aspect of how practices within science can be included in such artworks. We turn to Latour's writing on how images are used in communication within scientific fields and describe how understanding the relationship between system and representation supports the iterative development of a different piece, *Feed*.

The biological subject of *Feed* is different (addiction) than that of *Dismantling* (slime mold), but *Feed* begins with some reusable visual and code components of *Dismantling*. We use Latour's notion of inscription devices to understand reuse and recombination. When it comes to exploratory modelling in scientific practice, 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). This is particularly applicable when the same representation is re-used for exploring different systems (Figure 4).

The role of the image (here including visualization and visual representation in simulation) 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

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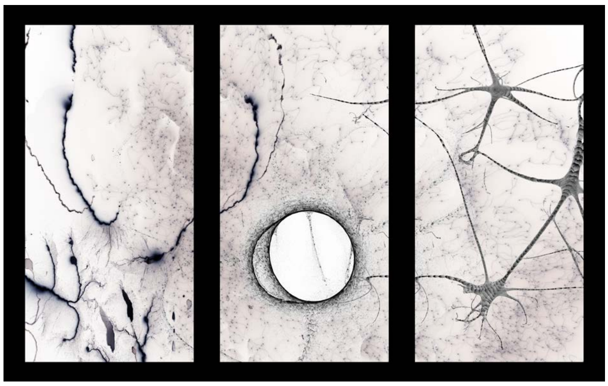
sets of skills to produce images, and to read and write about them" (Latour, 1987). Although this "strategy of deflation" has major limitations, the analysis of inscriptions allows understanding scientific practice (Latour & Woolgar, 1979) and power (Latour, 1987). Inscriptions serve as record; basis for communication and rhetoric; and further investigation. We relate several properties of scientific inscriptions to the speculative simulation: recombination, scaling, and immutability.

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;"
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 performer can build 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.

(a)



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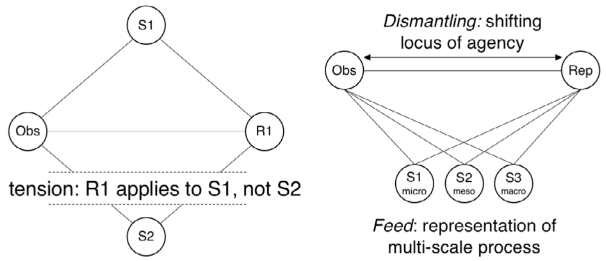

Figure 4. Whereas *Dismantling* explored the shifting locus of agency between the observer and the representation, *Feed* requires representation of a multi-scale process in a cohering representation (a, mockup). Engaging with an unfamiliar system with a familiar representation (reusing code or interface) may introduce epistemological tension that must be resolved (b).

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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). For example, 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.

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 as means of legitimacy, *inscriptions* are both tools by which science is done internally and communicated externally. Engaging with an unfamiliar system through a familiar representation (reusing code or interface) demonstrates the power of that representation, but may introduce epistemological tension that must be resolved by ensuring that the representation ultimately matches the model specification (Figure 4, b).

There are many possible representations besides simulation, and the representation of a complex system is necessarily an abstraction with the potential for expressivity: mathematical formulae describing the system; code implementation; simulation of the emergent visual processes; drawings, sketches, or schematics; photographs of the visible parts of the process. All of these may act as artefacts produced in any of the interactions between observer, system, and representation (Figure 1). When the artifacts mediating the system-representation relationship strive to maintain an accurate connection to that research in the final work, they gain the power to not only to place different systems into conversation, but also to communicate in greater depth to the observer.

Feed is an audio-visual simulation that overlays three scales of time and space into a shared environment to reveal parallels and speculate on imagined interactions. The project extracts motifs from the scientific literature on addiction, and fuses these patterns into real-time, never-repeating heterogeneous motion. The neural structure of an addicted brain embodies interconnected forces. Addiction is a process that operates over many levels of space and time, ranging from nearly instantaneous molecular dynamics to social forces over a human lifetime. Multi-scale analysis that embraces the interplay between these levels is a valuable avenue towards understanding the process of addiction, as exemplified by

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such work as (Lytton et al., 2017, p. 220; Gutkin & Ahmed, 2012), which informs this piece.

Feed models addiction at 3 scales:

1. cellular: the synaptic cleft, or the space between neurons, as the site of a drug's effect on the brain via dopamine molecules;Find a maximum density state
2. brain: connectivity between brain areas, the reward circuit;
3. society: marketplace interactions, rehab/recovery loops, epidemic models of spread.

At mesoscale (2), the interaction at microscale (1) is abstracted as likelihood of activation given neighbourhood activation. The explorations shown in Figure 5 relate to the mesoscale (2), and start with the slime mold *Physarum polycephalum*. In this example, the visual substrate will be replaced by a three-dimensional sculpt of the brain. Its current utility is visual similarity to neuron-like structures (Figure 6), and intuition of the choreographer.

The use of a familiar and intuitive representation allows starting quickly with a different work, but requires that the representation is updated: the controllable aspects of the simulation, like its internal function, parameter space, and initial and boundary conditions must match the intended model specification. Then, the observer can work on shifting agency toward the representation, which in turn allows more passive observers to engage with the organic unfolding patterns of the system, as it is represented. Importantly, this iteration allows the continual shifting of agency by the composer or choreographer even during construction of the representation-related artifacts to encounter emergent forms and be moved by them in a fluid way. Whereas the *Exercises for Performing with a Complex Network Simulation* focus on the shifting locus of agency, and continue to be vital for developing performability, *Feed* introduces the new challenge of integrating representations of multiple different systems in an iterative manner.

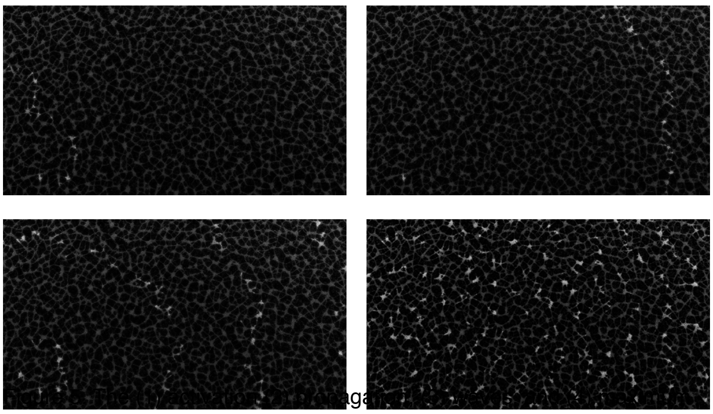

Figure 5: The (1) activation, (2) propagation, [illegible] activity in a *Feed* sketch that uses a *Physarum polycephalum* simulation as a substrate, to focus on the activation mechanism. This builds on the model from *Dismantling* (2019), adding the layer of activation and shown through the brightness of points, in an unchanging landscape.

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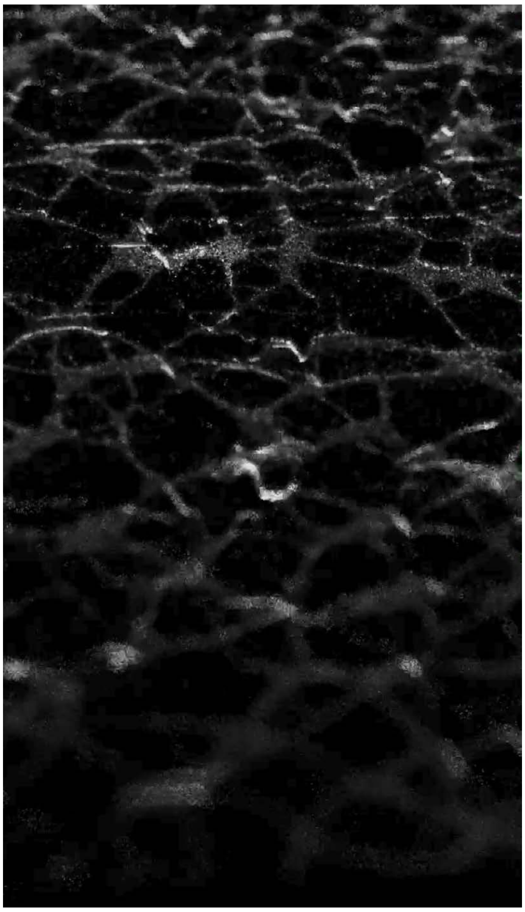

Figure 6: A parameterization of the *Physarum polycephalum* simulation results in what visually resembles neuron-like structures. The use of this visual substrate as a starting point for *Feed* enables fluid iteration on a work that synthesizes multiple systems in one representation. By adapting the representation over time, the composer can address the epistemological tensions that arise early in the process. Balance is achieved over time, and supports not only the aesthetic sensibilities and performance capacities, but the demand of accurate representation in relevant aspects of the work.

Non-linearity must be built in to enable the kind of performability we described in Section 3, where it is possible to choreograph a shift from more control by the performer's interaction, to more control by the simulation's unfolding of a post-tipping-point, cascade dynamic without need for interference beyond setting up the choreographed parameters and conditions. In the example in Figure 5, higher-density regions are non-linearly more active than lower-density regions: meaning, they are ready to fire sooner following decay, with continuous (not binary) activation/firing. This enables expressivity and smoothly-shifting agency with neither the performer nor the representation wholly in control.

The performability we aim for requires also building in element that can be influenced through interaction:

1. topology structure;
2. timing for reactivation of neurons: when they fire and how long it takes to become active again;
3. initial site of ignition.

It is at this point in the iterative process that the *Exercises for Performing with a Complex Network Simulation* become relevant. In the case of *Feed*, our future work includes also practicing this approach in sonification, in addition to generative visual art.

6. CONCLUSION

The goal of our generative art is to render observable the inner space of complex biological systems that are pervasive in the world, vital to understand, and difficult to grasp. We present two case studies of an approach to speculative simulation that distinguishes the human observer, the system, and its representation (Figure 1). Although software is used, it does not alone constitute a “creativity support tool;” rather, we evaluate the scientific paper describing the biological system using the requirements of “creativity support” (Cherry & Latulipe, 2014) to articulate the criteria for an effective model to use as a basis for this type of artwork. Our approach frames performance as an interaction between speculative inscriptions of complex systems (Thurner, Hanel, & Klimek, 2018), drawing on Latour’s concept of inscriptions in science (Latour, 1987; Latour & Woolgar, 2013). We build the practice of exploratory scientific modelling (Gelfert, 2010) into our interactive visual art about natural or social phenomena, explicitly outlined in the *Exercises for Performing with a Complex Network Simulation* (Section 3).

Not only does choreography and performance require doing exploratory modelling but, we envision, the exploratory artistic practice can support developing metavisual capability; an important skill in scientific education (Gilbert, 2015). Manipulable simulations have successful (if costly) precedent in existing effort to improve the communication of science to the public. Typical examples use minimal models for education purposes. We take a similar motivation, and apply it to massive, real-time, interactive simulations of complex network systems.

The method we describe has been successfully applied in two projects. First, in *Dismantling*, we explored the shifting locus of agency between the observer and the representation. Second, in *Feed*, we presented the opportunity and the challenge of re-use of a representation for other systems, both as a creative iteration, and as means to explore multi-scale representations. In both cases, engagement with scientists in relevant fields was sought throughout the lifetime of the work, from initial experimentation, to later performances and installations. The live performance of *Dismantling* was engaging to a varied audience. Formal theorizing of the relationship between artistic and scientific practice; and validation of the effectiveness of the outcome of this process on the communication of scientific concepts to the public remains a subject for future work. The current work offers a concrete set of practices, which build on several different bodies of research, on how, as an artist, to observe a complex biological system through speculative simulation.

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