Vital Networks:
The Biological Turn in Computation, Communication, and Control

By

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Abstract

Networks, such as the Internet, are comprised of dense information flows with expansive, multi-directional reach that continuously change—and this changeability is what keeps the network active, relative, and vital. I call the form of network exhibiting those dynamic features the *vital network*. This form of network is not simply the outcome of connectivity and communication between diverse affiliative objects and actors such as cell phones and humans that together convey a sense or feeling of ‘aliveness;’ it is the outcome of deliberate software programming goals for communication systems inspired by nonhuman, self-organizing biological life. The biological turn in computation produces an organizing logic for the vital network that self-propagates connections and disconnections, services, collectives, and structures proximal to forms that feel vital and dynamic. The vital network can *do* things, it has capacities to *act*, and different material consequences emerge out of the organization and coordination of communication with particular implications for human privacy, autonomy, and network transparency.

In this dissertation, I examine the biological turn in computing as a crucial feature within a development program for the design of digital network control systems that rely on self-regulation and autonomous communication processes intentionally constructed to be non-transparent—to be unseen. I explore nonhuman models of control as a response to this requirement considered through three objects: microbe, simulation, and control, each understood in process terms that disclose what these things *do* and how they *act*. It is appropriate to the concerns of this dissertation to think of these as *object-processes*
occurring within three moments or transverse becomings: first, in terms of Gilles
Deleuze’s notion of differentiation from the one to the many; secondly, from organism to
simulation through the use of models to describe microbial processes in informatic terms;
and finally, from description to control through the progression in computing from an
emphasis on structure and descriptive procedures, to processes of control.

Given that so much of contemporary life is structured by communication
technology, my study points to the need for an ethics of control to imagine how much and
how deep control should go when considering the organization appropriate to our shared,
technically enabled, sphere of communication.
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Chapter One: Introduction

Networks and digital systems are all around us: we connect to them throughout our day, sometimes very consciously, such as when we call another person on our cell phone, or simply in the act of swiping an access card to gain entry to a building. We use applications programmed to run on networks, from those that enable social communications, to those that provide transactions in finance, education, employment, and consumer activities. Communication and information technology and networks feel present through those activities, yet are unseen; we sense them through our devices such as the cell phone, that mediate our network experience alongside software applications such as Facebook or Google, which enable us to interact and to communicate. The network we think we know and experience has become an “internet of things” (Ashton [1999] 2009). Scott Lash argues that this ‘internet of things’ is reflective of an era of information intensity defined by information flows carrying all kinds of information such as capital, people, products, genetic codes, and media content circulating in networks governed by a computational logic or sensibility that has become the organizing principle through which more and more of life is converted to information (Lash 2002; see Castells 1996). The computational logic within information flows extends network capacities, but through an increasingly complex form of control, making it difficult to gain insight into the functionality of these opaque control features organizing network processes. For social science, a heterogeneous network that seems to do things, that has capacities to act, and out of which different material consequences unfold confronts us with a challenge: how might we ‘see’ and understand this new, complex network and its consequences for
our social world? How can we uncover its capacities for control, for action and organization, given its propensity for self-regulation obscured beneath the applications we use?

This problem of knowing and seeing into a complex technical system, a ‘black box’ that operates behind a layer of opacity shielding us from its detailed workings, is reflected in Joseph Kosinski’s science fiction film TRON: Legacy (2012). In the opening scene, the main character, Flynn, relates his long quest to see into an informatic network or grid of connections:

The grid: a digital frontier. I tried to picture clusters of information as they moved through the computer. What did they look like: ships... motorcycles? Were the circuits like freeways? I kept dreaming of a world I thought I’d never see. And then one day, I got in.

The film’s lead character, Flynn (Jeff Bridges), ‘gets in’ when he is transported into a mainframe computer through a dematerialization process and gains the ability to be part of the system—to finally gain sight into its interior environment. What he finds, what he sees, is a highly complex system of autonomous processes: self-regulating software that requires no human oversight, in a contest for control over the mainframe system. The autonomous processes are biologically inspired ‘isomorphic algorithms’ (coded instruction sets called ISOs in the film), programmed to emulate behaviour found in human and nonhuman life forms including decision-making, self-replication, and self-organization.¹ Their behaviour is isomorphic to their biological antecedents, but their

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¹ An algorithm is a form of computation in which a number of inputs can be analyzed to produce an output and the outputs can be weighted for relevance and ranked according to variables such as search term frequency, page relevance, trending topics, geographic location of the searcher, and more (Gurevich 2011). Algorithms will be detailed in Chapter Six.
world-making is not. These algorithmic processes operate through dynamic relation, from the one to the many, whereby many local interactions in the system, in TRON, produce a self-organized aggregate capable of emergent or unpredictable behaviour; and, as Flynn says, “the conditions were right and [the ‘ISOs’] came into being. Everything I had expected to find in the system—control, order, perfection—none of it meant a thing.”

While there are several strands that could be followed in this film concerning worries and fears about autonomous machines and their potential for mastery over the human (and see Winner 1977; Winograd 1991), it points to a key issue in my project: the role of biological inspiration in computational development and the shift in control it produces.

The biological turn in computation amplifies the relation between system complexity and obscurity, and when nonhuman life forms provide the inspiration for control, what emerges is a radically different arrangement of forces not organized around a centre, or a human, but dispersed across the system. If the ‘black-box’ of a complex system remains closed, it solidifies mysterious actions of unknown and unknowable communication and information technology and it ensures that the processes of communication remain “isolated, protected, and simultaneously obscured” (Kember and Zylinska 2012, 2). The TRON example gestures toward the privileging of sight as a way to ‘know’ the grid and the role of simulation to bring features and behaviour from one register into another: from the human physical world to the silicon cosmos of TRON. Flynn’s curiosity about the grid also shows our reliance on metaphor, using things he understand from his human world to explain what an unknown space may look like; and
that no matter how different a complex system is, we only have our human vocabulary to describe the new and different.

For the most part, when we do think about communication technology, we think about human-centred machines: those computers and communication systems organized through hierarchical control governed by a human logic and enabling human engagement, interaction, and intervention; this was the logic organizing the development of machines, from computers to networks, until very recently. My dissertation links the obscurity of control to a shift in the form of control being developed for our increasingly complex digital systems and networked communications—a shift from those human-centred systems to one in which the idea of control is drawn from nonhuman biological life systems. Networks, such as the Internet, are comprised of dense information flows with expansive, multi-directional reach that continuously change—and this changeability is what keeps the network active, relative, and vital. I call the form of network exhibiting those dynamic features the vital network. This form of network is not simply the outcome of connectivity and communication between diverse affiliative objects and actors such as cell phones and humans, that together convey a sense or feeling of ‘aliveness;’ it is the outcome of deliberate software programming goals for communication systems inspired by nonhuman, self-organizing biological life.

My project traces the genealogy of biological inspiration from mid-twentieth century cybernetics and early computer science research centred on replicating human-animal forms of cognition in self-regulating machines, to a close examination of nonhuman communication processes that serve as inspiration for the development of
contemporary digital system and network control. The concept for machines that are self-regulating, or autonomous, has been a central preoccupation within computer science and engineering (together known as the artificial sciences) throughout the last 70 years, and it is connected to the idea that systems of organization in nature can provide inspiration for human social, political, and technological organization (Brooks 1999; Froese 2007; Hayles 1999; Johnston 2008; Keller 2002; Parikka 2010; Rodgers 2008; Wiener 1950).

The centralized control systems required for those earlier machines were inflexible structures—they literally required considerable physical electric circuitry and careful linear programming to enable self-regulation—and the resulting machine was inflexible and unreliable. The current interest in self-regulation maintains at least one original assumption of mid-twentieth century investigation into what Norbert Wiener designated as cybernetics, or “the scientific study of control and communication in the animal and the machine,” in that “some aspect of a living organism’s behaviour can be accounted for [and] modeled by a machine” (Wiener 1948; see also Johnston 2008, 31). What has shifted is where in nature the inspiration is located, and it is more often looked for in the control and communication of nonhuman organisms that furnish a quite different model of control and self-organization.

Within sociology (and anthropology), the emphasis in studies of emerging or new technologies has been to examine the outcomes of the adaptation and application of a particular technology within society, such as Lucy Suchman’s (with Blomberg, Orr and Trigg 1999) pioneering work at the Xerox Palo Alto Research Center (PARC), examining interactivity and reliability in research and design work across a range of technical
products and computer systems (and see also Suchman, Blomberg and Trigg 2002). That research is considered as part of science and technology studies (STS) which focuses on the mingling of materials, culture, and practice in a technical collective and the subsequent success or failure of scientific and technological innovation diffusion and adoption in society (and see Bijker 1995; MacKenzie and Wajcman 1999). STS that explicitly looks to communication and information technology proceeds along a similar vein to explore the materiality of communication and information technology in terms of human-computer interaction and software engineering practice (Mackenzie 2006, 14; see also Helmreich 2001; Boczkowski and Lievrouw 2008; Lievrouw and Livingstone 2006; Suchman 2002). These studies place emphasis on both the objects and technical artifacts of science and technology, and the social and cultural milieu of practice and technique, but remain human-centric in so far as they “depend upon a knowing human subject that … ‘brings forth a world’” (Hird 2009, 14, 16-17; cf. Maturana and Varela 1980).

There is a wide range of sociological research exploring the materiality of communication: in network culture (Kember 2003; Lash 2002; Terranova 2004), political economy (Bell 2007; Castells 1996; Mosco 1996), social media use (Beer and Burrows 2007; Trottier 2012), and surveillance, privacy and data security (Haggerty and Ericson 2000; Koops 2013; Lyon 2002). Other disciplines have engaged with aspects of control within and over the Internet including in media and communication studies (Galloway 2004; Galloway and Thacker 2007; Parikka 2010; Packer and Wiley 2010), and through legal studies examining Internet regulation (Lessig 2006; Reidenberg 1998) and
autonomous systems (Hildebrandt 2011; Kerr 2012; Kerr and Bornfreund 2005; Koops 2013).

Yet, these approaches have left out the role of processes of control that operate within the Internet’s subsystems to automatically organize human and machine, and machine-to-machine, communication. They do not address the development of control nor what biological inspiration assumes in shaping the form of control. My purpose is to address that gap as a contribution to scholarship that examines the materiality of communication. My project traces the role of nonhuman biological inspiration as a crucial feature within a development program for the design of digital control systems that rely on self-regulation and autonomous communication processes intentionally constructed to be non-transparent—to be unseen. These autonomous communication processes underwrite the surface arrangements of networks, the application level programs and practices that human network clients interact with, and perform as the primary organizational logic enabling humans and machines to navigate the dense web of information (and see Chun 2011; Galloway 2010, 2004). At the same time, however, these obscure control processes hide system complexity beneath the simplified user interface convenient for human network clients, producing a distancing effect that amplifies the opacity of the very processes that organize and control the bulk of our communication and transactions of daily life (Galloway 2010; Hildebrandt 2011). What is emerging is a radically different mode of control that is not organized from the human-centred vantage point; rather, it is nonhuman control enabled by communication and self-
organization and characterized by a complexity of behaviour found in life systems and emulated in a machine.

John Johnston, in his comprehensive genealogy of artificial life, argues the ‘life’ that manifests in contemporary complex systems is a mélange of machines (computers), programs, and processes that produce a vital, self-organizing system that he calls “machinic life” (2008). The system may be software, a coded application that has a particular function such as searching for information, or it may be a physical robot that performs a simple task, but in either case Johnston suggests any system that can operate without centralized control, and self-organize, mirroring the purposeful action of organic life, is a ‘liminal machine’ hovering on the boundary between the living and non-living producing ‘machinic life.’ While I do not characterize the vital network as ‘machinic life,’ and I will expand on the vital network in Chapter Six, I am congenial to Johnston’s notion that there is a vital quality to the features and capacities of self-organizing systems out of which behaviours emerge as a matter of interaction between machines, programs, and processes. The notion of vitality describes the collection of traits and processes simulated in a complex system that enables life-like behaviour to emerge as part of a synthetic system. We may recognize the synthetic behaviour and name it after another form of life, but I argue it is only life-like.

Johnston makes a strong argument for a wider program of research within the social sciences and humanities into autonomous systems and self-organization, noting that before “speculating about the cultural implications of these new kinds of life and intelligence, we need to know precisely how they come about and operate as well as how
they are already changing” (2008, xi). Johnston’s book, *The Allure of Machinic Life: Cybernetics, Artificial Life, and the New AI* is to a large extent historical, but when he moves into the contemporary moment it is to examine artificial life research and robotics, and not the features and processes of control in contemporary networks. My project responds to his invocation to examine systems that are self-regulating, and indeed I argue it is necessary to do so in the case of uncovering opaque processes of control governing our communication and information technology, but also an explicit effort to interrogate what is not in his study, and that is control itself: to understand how biologically inspired processes of control ‘come about’ by looking to their inception within biological life and tracing the movement from there to the computational milieu.

To understand the intensity of this biological turn in computing and control, I closely examine the biochemical processes of communication necessary to the self-organization and differentiation of two unicellular microbial life forms. These two organisms serve as a model of self-organization and show the process whereby organisms become inspiration. Bacteria and slime molds self-organize into large multi-cellular, highly differentiated, super-organisms or swarms, as part of their lifecycle (Adamtzky 2010; Bassler 1999, 2002; Bebber et al. 2007; Diggle et al. 2008; Peysakhov et al. 2006), and this form of self-organization and communication presents researchers in both computer science and systems engineering with a biological model for self-organization and self-assembly, and of non-hierarchical communication and control that effectively distributes control across a multitude or population of communicating entities (see Balasubramanian et al. 2008; Dove 2011; Dressler 2005). The biochemical
communication circuits that coordinate this activity in microorganisms are modeled mathematically and then emulated on a computational platform as a computer simulation. What emerges is a vital network, an assemblage conjoining bacterial syntax and slime mold rational calculus with human-constructed technical networks enabling life-like behaviours to emerge dynamically in response to changes within the network. Under this model of control, the vital network breaks from the older cybernetic model of unidirectional flow, from sender to receiver, for something more diffuse and multiple.

My conceptual framework for the project draws from the philosophy and theory of Gilles Deleuze, and those in dialogue with his philosophical program, to explore the meeting of biological life and computational simulation in the “machinic phylum” through the interface between human and nonhuman, organic life and artificial life, and combinations of both (Deleuze and Guattari 1987, 409; and see Johnston 2008, 107). Deleuze’s philosophy (alone and with Guattari) puts an emphasis on matter (materiality) and process and steers away from understanding reality as only socially constructed or as only relations between objects; rather, its construction is that and more—it is reality as a becoming. Deleuze’s philosophy bears the imprint of Henri Bergson, among others, and Deleuze identifies processes rather than objects as the main feature of the real, wherein an object is understood by what it does and not what it is (K. Robinson 2009; Stengers 2009, 2011). Deleuze contributes a different vocabulary which relies less on human social terms to describe inhuman systems, processes, and action—his is the world not of individuals but of populations, multitudes, packs, swarms, colonies, and collectives. Even so, there remain many instances in the dissertation where I fall back on language that is
situated in humanist terms enrolled to describe quite different, nonhuman processes.

Biologists and computer scientists rely on human social terms to describe their systems, whether organismal or artificial, whereby bacteria ‘decide’ or machines ‘think’ (and see Chapter Five and Six).

My conceptual approach is also indebted to assemblage theory, a Deleuzian construct developed by Manuel De Landa. Assemblages are wholes comprised of heterogeneous parts that arise out of processes of becoming and can include institutions, organisms, or, as in my project, the objects, processes and events that congeal in a vital network. To understand an assemblage in spatial and dimensional terms, De Landa adapts a concept from mathematics known as the space of possibility. A space of possibility encompasses the possible ways an assemblage may change, understood through its capacities, such as the capacity for control, and its tendencies, such as the tendency toward emergent and unpredictable behaviour on the network (De Landa 2011, 186).

Simulations are crucial to defining the space of possibility: through simulation all the possibilities for the space can be mapped by changing variables, time, entities, and the rules that emulate biological behaviour.

This dissertation begins in a review of the theories, debates, and conceptual ideas relevant to the vital network and the biological turn in computation, communication, and control expanding on the outline provided in the foregoing. In the next chapter, I organize my discussion around four themes: control, autonomy, self-organization, and life. Each of those themes highlights important aspects of the vital network across different disciplines and through ideas as diverse as biological self-organization and complexity, to
cybernetics and the artificial sciences, and posthumanism. This chapter locates my project in a particular history, the history of cybernetics and the capture of ‘life’ as information, and situates it within a sociology of communication that is more and more attuned to the role of information flows, whereby communication is the central unit of analysis.

In Chapter Three I explore specific themes, including vitalism, communication, simulation, and assemblage theory, which emerge out of the debates and ideas within the multidisciplinary theory and scholarship discussed in Chapter Two. Methodologically, I engaged a three-stage research method organized around the substantives in my dissertation which track three key moments that will explain how biological inspiration is incorporated into the digital domain: first, thinking in terms of Deleuze’s notion of differentiation from the one to the many; secondly, from organism to simulation through the use of models to describe microbial processes in informatic terms that can then be simulated on a computational platform; and finally, from description to control through the progression in computing from an emphasis on structure and descriptive procedures, to processes of control. As I proceeded through the research phase, I consulted with researchers as subject matter experts to ensure I understood the communication processes and self-organization in microbial life systems and the subsequent simulation of biologically-inspired models in computer science and systems engineering as applied to the design and development of network control and functionality.

In this dissertation, my purpose is to locate and interrogate the role of nonhuman biological inspiration as a crucial feature within a development program for the design of
digital control systems that rely on self-regulation and autonomous communication processes intentionally constructed to be non-transparent—to be unseen. I argue that the growing lack of transparency within our communication systems and networks presents particular challenges: first, for analysts who are attempting to disassemble the processes of control operating on information flows; second, to develop an understanding of the new configurations of power realized through a system of control that operates at a distance from its target; and third, in managing individual privacy, autonomy, and control over personal communication in view of the self-regulating capacities of the vital network. The vital network that enables the best of Internet engagement, through interactivity, participation, and engaged communication, also extends surveillance capacity and erodes privacy. While my dissertation does not examine those problems in detail, it suggests that an ethics of control may be required as a response to the growing obscurity of control over communication systems so crucial in contemporary life.

A vital network is more than just a sense of aliveness within a population of networked machines, processes, and things. Its vitality, its dynamism, is a matter of coding, but that code is grounded in organismal communication and self-organization and produces a particular decentered, non-anthropomorphic control—a nonhuman mode of control. Specific biologically inspired design goals cohere around, and as part of, processes of control and communication intended to be complex, obscure, and self-regulating. I return throughout the dissertation to the crucial role of communication processes that instigate organizational change and differentiation both in organismal life and within computational systems programmed to be ‘life-like;’ this is because vital
networks are ceaselessly changing as objects and entities are added and dropped or join and leave the network, and as processes are continuously started and stopped, interrupted and augmented.

As this dissertation proceeds, the processes of communication significant to a vital network replay over and again among ideas of control, life, self-organization, and autonomy for both biological life and ‘liminally life-like’ machines. Drawing on Deleuze’s biophilosophical program to understand the vital network means remaining open to the possibility that this new space is vital, agential, active, life-like and self-regulating. To grasp the implications of the vital network, analysts must reach back to the models and simulations that shape its development to understand how it functions, because once deployed, the biologically inspired processes of communication and control are designed to be unseen; to sink deeper into the matrix of hardware and software setting human network clients and our simple user interfaces at a distance from the growing complexity of action within the network.
Chapter Two

The Literature Review: Outlines, Edges, and Spaces

Introduction

In this chapter I examine scholarship that contends, often in unique ways, with themes of control, autonomy, self-organization, and life, and the theoretical significance for the vital network. In the first section, I examine control as it has been conceived within sociology in the context of digital systems and networks. I then review cybernetics as the first coordinated response to the problem of communication and control in machines in the mid-twentieth century and its relation to contemporary computer science. In the second part of the chapter I address ideas of self-organization and autonomy in biological life that feature significantly as inspiration for the artificial sciences (computing), and in particular, as a model of control within contemporary complex digital systems and networks.

There is a shift underway from computation-based control models that historically relied on the human-animal model of cognition to govern communication and control, to a decentred, nonhuman model of control over digital systems and networks. Throughout the substantive ideas and disciplines encountered in this chapter that touch on control, autonomy, and self-organization, the idea of life and living systems as inspiration for digital system design and control surfaces. In the encounters between the biological and artificial sciences, life has come to mean ‘life-like’ when simulated in digital systems that
have dynamic and adaptive properties and capacities—most particularly in the context of self-organization.

Manuel De Landa considers self-organization central to a “space of possibility,” because many different potentials emerge when systems respond to an organizing logic that is non-hierarchical, open, and dynamic (2011, 5-6). While I will explore De Landa’s spatial theory in the next chapter, the literature reviewed in this chapter examines ideas and debates that trace the edge, or outline, of such a possibility space, which defines the tendencies and capacities of the assemblage I call the vital network. The vital network can be understood as a diagram of relations expressed as processes that enable connections between points (and see, for an illustration, Figures 1 and 2 below), at once topological and spatial, in which the connectivity and exchange of flows is not static, but dynamic and changeable. This chapter starts at the intersection of sociology and communication, and proceeds through influences as diverse as cybernetics, artificial intelligence, and biological self-organization, and finally to the posthuman, the nonhuman, and more, directly engaging with ideas of control, self-organization, autonomy, and life itself. It traces the genealogy of inspiration through the particular human-animal model of control evident in mid-twentieth century cybernetics and early computer science and communication research, toward the burgeoning field of research into nonhuman, self-organizing control in which the nonhuman organism has become a key source of inspiration.
The concept of an electronic network—of what a network is—has shifted in recent years away from the notion of a specific grid of connections such as the Internet, or a phone line, to the network as a “hypernetwork, a meshwork potentially connecting every point to every other point” (Terranova 2004, 41; see also Lash 2002). What we experience through our connected devices and online practices as a contiguous and seamless Internet, is a more complex unity: it is a heterogeneous milieu of objects and processes constituting many networks and sub-networks in a communicative assemblage. This shift extends Manuel Castells’ view of the late twentieth and early twenty-first century period as a “network society” in which the “power of flows takes precedence over the flows of power” through the proliferation of multiple, autonomous networks powered by digital technologies as a “space of flows” (1996, 469). The flows Castells refers to are the streams of data, of information, that circulate on global informatic networks gathered from millions of collection points, human and nonhuman, object and enterprise. The “hypernetwork” intensifies the local to global connections furnished by telecommunication service providers (TSPs), enabling its commercial and consumer subscribers to connect to the network through a variety of digital devices—from cell phones to computers to on board vehicle computers. The result is a meshwork of data, devices, network infrastructure, and software requiring seamless control to coordinate the information flows and network processes.
Castells is but one of several sociologists who have examined the growing prominence of communication and information technologies for society, including Daniel Bell (1973), who asserts that a post-industrial society would coalesce around information and services, James Beniger (1986), who examines the centralizing powers of twentieth century information control, Scott Lash (2002), who critiques the information age, and Tiziana Terranova, who examines network culture in the information society (2004). For sociologists such as Bell (1973), specialized firms in the latter part of the twentieth century, including those in the semiconductor industry and software and hardware developers such as IBM, focused on communication and information processing and heralded a new information society. In this society, Bell argued, manufacturing had declined and information and knowledge as capital was on the rise within a services-based economy (1973; Lash 2002). Later information theorists within sociology and geography emphasized the hegemony of flows of information as circulation and this opened up a new critical approach to understanding the growth of networks (Castells 1996; Harvey 1989). The hegemony of flows has re-oriented the sociology of communication, such that “communication and perhaps no longer the ‘social act’ [has] become the contemporary unit of analysis,” meaning “in the information order, the social relation is displaced by the communication” (Lash 2002, 206, emphasis in original).

The successive movements in our understanding of communication and information technology over the last 30 years thus identify a shift from the “logic of structures to a logic of flows” (Lash 2002, 208; cf. Castells 1996). Control for analog systems and pre-digital networks in the nineteenth and part of the twentieth centuries was
mechanical, structural, and institutional, organized hierarchically to interface with and between humans and machines. Its goals were human-centric and humans were positioned to intervene in an exercise of control over machines that functioned to extend human capability and productivity (Lash 2002). In the twenty-first century, control is digital and nonhierarchical and no longer about structures, but about processes distributed across networks of heterogeneous entities, and the human does not reside in the centre of this new apparatus of control. Contemporary information flows require robust processes of control to ensure their continuous circulation on global networks, and Terranova argues that the biological turn in computing is a response to the growing multitude of entities, processes, data, and parts of networks that must be able to exercise control from within and between the flows and their waypoints on the network (2004, 116-117; see also Galloway and Thacker 2007). I concur with her appraisal and will return to biological inspiration in Chapter Five, but despite her claim and the other contemporary theories located around communication and information technologies, such approaches lack detailed analysis of the design and configuration of technical control processes that organize flows of information and networks.

Alongside the foregoing, Gilles Deleuze theorized “societies of control” in an oft-cited postscript that has taken on significance for network analysis by at least the suggestion that control figures importantly within any reading of network or information intensive social organization (1995; and see also Negri 1990). In Deleuze’s view, control targets individuals through codes and passwords that have become a crucial feature within communication technology in which control is “continuous and unbounded,”
without limit, and thus in “continuous variation” within the network (Deleuze 1995, 179, 181; Negri 1990, 3-4). Yet, in spite of the suggestion of specific control in his designation for a new form of society, Deleuze barely hints at what that control is, or what is required of/from control in contemporary digital systems and networks. Deleuze alludes to codes of information and control as “numerical language,” presumably computational logics, but he never comments on the codes (software) that provide the control features and capabilities, the “programming and activation,” of contemporary networks and digital systems (Bogard 2009, 19).

More recently, computational control was detailed in Alexander Galloway’s analysis of the data transmission protocols or hierarchical traffic rules that govern how information flows circulate on the Internet (2004). Galloway investigated such rules as a political technology and as a new form of biopolitical management based in the procedural logics of network infrastructure. For Galloway, protocols are a biopolitical technology precisely because they provide digital control over social and communicative aspects of life at the individual and population level; they are the technological rules that govern networks, providing a “management style for distributed masses of autonomous agents,” human or not, connected on networks (2004, 87). This biopolitical stance is taken further in his 2007 book, The Exploit (with Eugene Thacker), in which the authors argue that biopolitics creates and manages the contemporary network as a ‘living network’ operating through a new “set of technologies through which populations may be organized and governed” (71). Yet, for all the work Galloway does to elevate
protocological, or rule-bound control, even understood through biopolitics, here too the analysis leaves control, as an object itself, under-exposed and under-theorized.

Galloway ultimately turns to Deleuze’s control thesis to explain protocols as part of the continuously changeable apparatus of distributed control that operates through “pattern and code” within the network (2004, 18; cf. 1996). Galloway’s work is a critical precursor to the explorations underway in my dissertation and he makes a case for a “material understanding of technology [wherein] computer code is always enacted [as] a set of procedures, actions, and practices” that do something (ibid., xii; see also Chun 2011). While Galloway examines control on networks as a “virtual bureaucracy” necessary for extensive global networks to function, he does not look to the sources of inspiration for new models of control; rather, he is concerned as much with how protocol is conceived and documented in technical requirement specifications (see Galloway 2004). When in later work he tackles the notion of self-organizing networks, he passes over the specifics of design and development referring only broadly to nonhuman swarms and multitudes as a metaphor for organization, leaving the question of how such self-organization is coded and operates on/in networks (2010; Galloway and Thacker 2007). My sense is that for all the important effort in recent examinations of network organization and of network culture (and see Chun 2011; Lash 2002; Terranova 2004; Parikka 2010; Thacker 2008), the very object of control, even when it is recognized to be shifting away from structured, hierarchical centres, is not ‘pulled apart’ enough to disclose the shift itself. The shift in control is, as I argue in my dissertation, a radical
move away from the conservative, rational mode of control originally conceived for networks in the twentieth century.

As the preceding discussion demonstrates, while control has become more central to analysis among sociologists and among media and communication theorists, they do not delve into how and why control itself is shifting and the response within computer and network science to address the demands for network control. The requirements for network control have intensified the search for models that address system-wide organization for contemporary networks. These requirements, for issues such as system robustness, redundancy, self-capability, and even self-repair, exceed many of the foundational control models historically deployed in computing based in command and control organized through hierarchical, linear or step-by-step coding common from the 1940s to the early 1970s (see Adam 1998; Haraway 2004; Hayles 1999; Wiener 1948, 1950). Even as the requirement for and of control is changing and as much as contemporary digital systems and networks are highly advanced when compared to earlier systems, the requirements for control can be understood in relation to the development of information theory and communication technology in the mid-twentieth century and linked to early models of computing and machine learning that were popular at the time.

**Cybernetics**

In the 1930s and 1940s several American scientists and mathematicians including Warren McCulloch, Claude Shannon, R.V. Hartley, John Von Neumann, and Norbert Wiener, studied aspects of communication and control and the problem of information
organization and transmission (Clarke and Hansen 2009; Johnston 2008). These researchers were at first interested in what Wiener defined as the “study of messages, and in particular of the effective messages of control” and of system behaviour as part of information theory (1950, 8). The interest in information theory had developed through research at Bell Laboratories in the United States in the 1920s and was greatly expanded in the Second World War through developments in cryptography and radar (Peters 1999; Hayles 1999). This effort coincided with the development of early analog computational machines (analog computers) and communication systems such as radio, telephone, and telex. For scientists such as Wiener and Shannon, information was defined as a statistical probability that calculated random noise, or interference, in electronic communications, rendering information (and communication) a mathematical quantity, a disembodied and immaterial signal distribution transmitted from sender to receiver (Hayles 1999; Johnston 2008; and see Clarke 2010).

Between 1943 and 1954 a series of interdisciplinary conferences, known as the Macy Conferences, brought together researchers in neuroscience and artificial cognition, biology, mathematics, systems theory, social science, and information theory (Hayles 1999; Johnston 2008). The Macy Conferences introduced debate around theories of information and communication with an emphasis on control and organization alongside a heightened interest in human-animal neural networks and the role of systems-oriented cognitive processes (Clarke and Hansen 2009, 2-6; Hayles 1999, 50-67, 90-91; and see Johnston 2008; Wilson 2010). For several researchers, discourse converged around the idea of a ‘thinking machine’ that could perform calculations through human-like problem
solving understood to be a central cognition module which would provide control over a complex autonomic or self-regulating system (Hamilton 2009; Johnston 2008). Thus the programmed intelligence of such a machine was predicated on mimicking the processing power of a disembodied human or animal brain and replicating the brain’s neural network in a model of intelligence that would be a top-down, hierarchical center of control in a computational machine. This combination of information theory, neural processing, and computation, whereby humans became understood as “information processing entities” whose processes of cognition could be replicated in a ‘thinking machine,’ solidified control, communication, and information as the synthetic triad to bridge the gulf between the organic and the machinic (and see Hayles 1999, 7-8; Froese 2007). Friedrich Kittler echoes this point, noting that “if data makes possible the operation of storage, addresses that of transmission and commands that of data processing, then every communication system, as the alliance of these three operations, is an information system,” in which algorithms provide the control over the processes of communication (1996, under Introduction). An algorithm is a form of computation in which a number of inputs can be analyzed to produce an output and the outputs can be weighted for relevance and ranked according to variables such as frequency, relevance, time, geographic location of the searcher, and more (Gurevich 2011). Algorithms are usually sequential processes that can incorporate the output of other algorithms and be assembled in cascades of processes, which together produce the complexity of systems such as Google’s search capacities and Facebook’s friend-linking algorithm (and see Bucher 2012).
One early version of a machine that could ‘think’ was proposed by Alan Turing in the ‘imitation game,’ a game that unfolds as a conversation between several entities: a man and a woman are in one room and an interrogator of either sex is in another. In the first version the man attempts to pass himself off as the woman in response to questions posed by the interrogator, and in the second Turing suggested a machine would take the woman’s place (Johnston 2008, 425n37). The ‘game’ is intended to prove that machines can think-like-a-human if the interrogator cannot distinguish between the human responses and the computer.²

While Turing’s machine was not actually constructed, three autonomous machines were built: William Grey Walter’s mobile self-regulating battery-run ‘tortoises,’ Shannon’s maze-finding mouse, and Ross Ashby’s homeostat (Johnston 2008, 43-53). Walter was another scientist involved in cybernetics who, between 1948-49, designed a pair of mechanical tortoises with rudimentary circuitry and a light sensor attached to the steering mechanism. The tortoise interacted with light sources in its environment in sometimes complex and unpredictable ways, even returning to its battery charging station when its power drained (Johnston 2008, 48-51).³ First built in 1948, Ashby’s homeostat was a machine that could respond to changing conditions and in turn adjust itself through negative feedback loops until it reached stasis. If this failed, it would re-order the system using a secondary set of feedback until it stabilized. In both machines self-regulation

² There is a gender problem in this test: first the man attempts to answer questions as though a woman, and then the woman is outright replaced by the machine (and see Adam 1998; Johnston 2008). The ‘thinking game’ continues to be played, in various chess matches between human players and IBM’s supercomputers, and recently in a televised Jeopardy contest that pitted IBM’s Watson computer against human contestants of the popular quiz show (Hamilton 2009; IBM 2012).

³ There is no question that this simple model, and that of Shannon’s, influenced robotics research. Rodney Brooks’ design of his commercialized autonomous vacuum cleaner, the iRobot, which is simply designed with ‘insect intelligence’ and returns to home base to charge its battery after cleaning (iRobot 2012; Brooks 1999).
featured as a form of “autonomous, self-organizing behavior [and] the crucial property of these systems … lay in the relations between components” out of which “functionality or purpose would emerge,” and the relations were facilitated through the communication unfolding within its subsystems that enabled self-regulation (Keller 2005, 1070-1071; Johnston 2008, 42-44). Shannon’s mouse, designed around 1950, was rather more spectacular in some ways: it was an electro-mechanical mouse that would explore a maze in its first outing, and then find its way perfectly to the end point on its second and subsequent ‘runs.’ Theseus, as it was known, had a computationally primitive learning or memory function that would ‘learn’ through exploring its environment and ‘remember’ where it had been.

These rudimentary systems are significant for two reasons. In the first instance, they demonstrated that self-organization and self-regulation, whether expressed as ‘learning,’ adjustment, or ‘remembering,’ were not only found in organisms and nature, as Immanuel Kant had first philosophized in *The Critique of Judgement* (1914, s.65), but could be emulated in purposive human-made machines. In the second, if self-organization is not exclusively biological, then the boundary between organisms (nature) and machines appears tenuous (Keller 2005, 1071; see also Haraway 2004).

Even as Turing’s machine could not be built at that time, his work is crucial in the development of the modern computational paradigm. As early as the 1930s, he postulated that a set of instructions expressed as an algorithm could address a problem of computability with a number of variables to be calculated to solve a mathematical problem (Johnston 2008, 69; Adam 1998). This has become known as the Turing
machine, a finite-state machine capable of one set of procedural calculations based on logical instructions (and it only calculates, it cannot store information), but Turing subsequently postulated a universal machine (the universal Turing machine) that would be programmable by emulating the set of instructions of a Turing machine (Johnston 2008, 69-70). In essence, the Turing machine provides the set of instructions or programming (software) to the universal machine (computer), which can then perform many different calculations (ibid.; and see Goujon 2006). Nowadays, these instructions are known as stored programs or software stored in computer memory.

The first era or wave of cybernetics, with a clear mathematical foundation for computation provided by Turing and others, launched what would become a long project in the artificial sciences exploring human-like intelligence or ‘smartness,’ and setting out foundational mathematical logic and algorithmic expressions crucial to computing and computer networking (see for discussion Clarke and Hansen 2009; Hamilton 2009; Hayles 1999; Johnston 2008; Wilson 2010; cf. Turing). The hardware and programming limitations in the 1950s meant that many of the theories could not be fully tested. Turing and later Alonso Church had only postulated software, the stored program, and the notion of computer memory, and the mathematical properties of information control and communication that Wiener, Shannon, McCulloch, and von Neumann experimented with could not be made fully operational within a network (Johnston 2008).

In spite of the limitations to hardware, cybernetics did set in motion foundational concepts that inform the contemporary computational paradigm and also provided a fundamental understanding of the transmission and control of information between
machines. But Wiener and his contemporaries went farther than this initiation into communication as a science and engineering discipline—their research heralded a new era of research, which would trouble the organism-machine divide that Kant had carefully laid down, suggesting that “the newer study of automata, whether in the metal or in the flesh, is a branch of communication engineering” that encompasses “computing machines and the [animal] nervous system” (Wiener 1948, 42). Wiener was keenly interested in information feedback and the notion that a cybernetic system possesses “balance, self-regulation, circularity, and control” much as in living organisms (Galloway 2004, 59; Johnston 2008, 26-27; Wiener 1948, 1950). Wiener imagined information and communication systems that were dynamic, autonomous and self-regulating, and could maintain balance (homeostasis) through constant feedback, yet envisioned each as a small closed system. While cybernetic feedback systems would go on to influence theories of the organism and theories of machine communication and control, as discussed below and in later chapters, the idea of absolute closure within such systems would not become part of contemporary networks that flourish through openness (Galloway 2004; Walrand and Parekh 2010).

**From Cybernetics to the Artificial Sciences**

Significant research projects in artificial intelligence and artificial life grew out of the Macy Conferences. Artificial intelligence (AI) and artificial life are entwined branches of computing, to which I refer to collectively as the artificial sciences, and it is difficult to view them as separate research programs for reasons I discuss here. Artificial life research in relation to computational machines began in earnest through cybernetics
instigated in part by Von Neumann's theory of a self-reproducing (and self-assembling in his original description) computational form known as cellular automata (Helmreich 1991; Johnston 2008). Von Neumann was keenly interested in how biological system organization functioned, in particular the human brain and neuronal network, and its suitability as inspiration for self-regulating artificial systems. In his work, Von Neumann considered the high degree of fault tolerance and organization in the human-animal brain when, as neurons fail, the nervous system continues to function. For Von Neumann this was suggestive of a complex structure that could be emulated in machines with “an ability of the automaton to watch itself and reorganize itself” (Von Neumann cited in Johnston 2008, 38). Von Neumann imagined an apparatus or automaton that had instructions for self-assembly; and these instructions would be passed on to its ‘offspring’ to continue self-production (Johnston 2008, 168). Cellular automata, as a theoretical simulation of artificial life, can now be programmed to run on a computer creating self-reproducing automata in which each cycle, or generation, makes copies of itself—each with a self-description to keep on reproducing (Helmreich 1991, 387; Johnston 2008). In this model, the calculus is not situated around solving a problem or task, as with more formal computational approaches, but simply with coding the automaton for self-production over successive generations to produce dynamic behavior, which in turn generates unpredictable complexity, or the emergence of unanticipated system behaviour (ibid.). The purpose here is to observe how simulated populations replicate and differentiate over time through self-organization.
The mathematically derived model of cellular automata continues to influence development in the artificial sciences, having set in motion key ideas about self-regulating systems including networks. Importantly, in the instance of artificial life computation based on cellular automata, control is not a programmed rule to govern system expansion: control emerges as the artificial population undergoes continuous change and differentiation following simple instructions for self-replication. In this way, control dynamically emerges from within the population determined by the interaction of the system and its agents (Helmreich 1991). In principle, Von Neumann’s notion that an artificial system should be able to watch itself and reorganize itself is the basis for current programming goals for self-capability across most digital systems and networks, and forms a central part of contemporary simulation software, which I detail in Chapter Five and Six.

Artificial life research uses a computational approach to construct simulations of life systems and population growth and change for the purposes of exploring synthetic or artificial (digital) life forms, whereas early artificial intelligence programs were situated around computational reasoning using a defined rule-set programmed to search for the answer to a specific problem (Johnston 2008; see Adam 1998). As interest in human-animal neural nets and brain cognitive mapping expanded, a biologically inspired connectionist approach to computation developed. This connectionism, as it was known, followed the model of the human-animal neural network, in which a computer system is

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4 In the later twentieth century, computer programming has moved on from the classical, linear programming model of lists and variables, symbols and formal rules, to object-oriented programming emphasizing objects and actors (Turkle 1991, 237; see also Adam 1998).
programmed with a set of rules that enable it to learn from each successive operation: it responds to a problem through pattern matching and weighted answers or ‘best of’ alternatives, through which the system grows smarter over time and with use (Johnston 2008, 337-338; see also Adam 1998; Brooks 1999; Kember 2003; Shackelton et al. 2006; Winograd 1991).

In current development and practice it is difficult to separate AI research from artificial life because the above approaches merge in some instances. Contemporary research on AI designates intelligence as a property, or collection of properties, constituted through computational structures in which are said to reside ‘smart’ capabilities that can ‘learn,’ self-organize and propagate routines without centralized control (Brooks 1999; Maes 1995; Wright and Steventon 2006; Woolridge and Jennings 1995). This approach combines research in artificial life and self-organization using cellular automata theory, as discussed above, alongside the embodied interactions displayed by physical robotics (Brooks 1999; Langton 1995). Robotics research has demonstrated that physical robots with simple coding can produce unanticipated behaviour through local interaction of the units in their environment: no central control governs the robots’ actions; rather, it is the combination of carefully constructed algorithms that enable the robots to self-organize in response to each other and to their environment, much like Grey Walter’s tortoises (Brooks 1999). There are several hallmark projects that dot the history of artificial intelligence and robotics: Thomas Ray’s Tierra software program for creating artificial life populations (1996); Craig Reynolds’ Boids program, which simulates bird flocking and aggregation (1987); Luc Steels (1995)

This combination of ideas discussed above, of self-capability and local interactivity between units absent of any centralized control, has become a model for complex networks and digital systems wherein self-organization and self-regulation are realized through software programming to coordinate many communicating objects and entities such as across cellular telephone networks (Galloway 2004, 2010; Galloway and Thacker 2007; Schmeck 2005). Self-capability in biological systems is what so intrigues computer scientists and engineers searching for more flexible network control, a flexibility of the kind found in nonhuman organisms that have a capacity to self-organize using complex communication processes.

**Self-organization**

Self-organization has featured as an object of analysis in philosophy, science, computing and the artificial sciences, and within social science drawing scholarly attention around both technologically-enabled networks and biological networks, from the fascination with Grey Walter and Ashby’s machines, to self-organizing organisms, and to more recent investigations into self-organizing digital systems (Camazine *et al.* 2001; Feltz, Crommelinck and Goujon 2006; Galloway and Thacker 2007; Langton 1995). Self-organization occurs through a multiplicity of interactions within what is initially a dispersed or disordered complex system, biological, physical, or digital, when under certain conditions the interactions of system elements may give rise to global or system-wide behaviour. System-wide change is contingent on the cumulative interactions
of local entities, molecules, or organisms, such that global “pattern formation occurs ... internal to the system, without intervention through external directing influences,” a ‘bottom-up’ organizational capacity as opposed to a hierarchical or top-down organization control process (Camazine et al. 2001, 7; see also Beekman, Sword and Simpson 1998). Control is thus a distributed process occurring across and within the system. Out of this process of self-organization an emerging pattern, feature, or behaviour arises unexpectedly from the interaction of system units (Camazine et al. 2001, 7). This emergence, the creation of higher order behaviour, demonstrates functionality, purpose and adaptation within a complex, dynamic system displaying a “distinctive quality of growing smarter over time” in response to environmental and system cues, biological or digital (Johnson 2001, 20).\(^5\)

Self-organization and emergence can together be comprehended through complexity theory or complexity science, which “investigates emergent, dynamic and self-organizing systems that coevolve and adapt in ways that heavily influence the probabilities of later events” (Urry 2005, 113; see also 2006). Complexity projects a system view onto worlds, collects, pattern-forming physical phenomena, and social life in order to locate interdependences and synergies between collective phenomena (see Lewin 1993; Kauffman 1995). Complexity talk has influenced research agendas in social

\(^5\) For this reason, the literature on self-organization and emergence also references chaos theory, which suggests an explanation of system behaviour sensitive to initial conditions. The classic example of such sensitivity is often drawn from the “butterfly effect,” which posits that a subtle change in a nonlinear system will effect monumental change over time due to a sensitivity in initial conditions within the system (the graphic modeling of such a system looks somewhat like butterfly wings) (Lorenz 1963; Ditto and Munakata 1995; Bradley 2007). It became part of popular imagination when it was invoked by Edward Lorenz to explain how the flapping of a butterfly's wings could, in theory, alter the initial conditions of a weather system and result in a tornado geographically distant from the origin of the system (1963). Emergence is an outcome of the interacting units and is susceptible to bifurcation or the “sudden transition from one pattern to another following even a small change in a parameter of the system” (Camazine et al. 2001, 32; Kauffman and Clayton 2006).

**The Self-organizing Organism**

*Ants*

Science has often turned to nonhuman species as model organisms for the study of self-organizational capacities, functionality, and processes in life systems, to glean wider understanding of issues in medical science, biology, theoretical biology, and computation. What scientists refer to as a model organism is often chosen for a particular feature that can accelerate laboratory analysis in some way, such as in the case of the fruit
fly, which has a very short lifecycle making it ideal for genetic research; or in the case of ant colonies, which exhibit colony self-organization; or the highly adaptive *Escherichia coli* bacteria, which responds well to laboratory cultivation for studies of proto-sociality, molecular communication, and disease resistance (Dorigo and Stützle 2004; Spradling et al. 2006; West et al. 2007; Williams et al. 2007). Ants, and social insects more generally, have often been preferred as case studies for biologically inspired technological organization (networks) and computation (ant colony optimization, swarm intelligence, and self-organization) (Dorigo and Stützle 2004; Parikka 2008; Thacker 2004a; 2004b; 2008), and as social and political models of organization (see Maeterlinck 1927; Rodgers 2008; Wheeler 1911).

Social insects display local to global coordination for foraging, colonization, and swarming (swarming is a self-organizing collective behaviour based in the local interactions of the many to induce a particular behaviour or action in the population as a whole) (Gordon 2007; Hölldobler and Wilson 1990). This self-organization has served as inspiration to several generations of scholars in computer science, biology, sociology, and media studies. In the late nineteenth century and early twentieth, studies of insect self-organization inspired theories about human social and political organization, suggesting that rational, hierarchical order was ‘natural’ in nature, as evidenced by bee hives and their self-organized activity, and thus by extension human life (Maeterlinck 1927; Parikka 2008). The insect ‘body politic’ represented the kind of order and economic

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6 I will explore the notion of a model in more detail in Chapter Three.
efficiency attractive to a burgeoning Fordist, technological human society of the early twentieth century (De Landa 2006, 9; Kosek 2010; Parikka 2010; Rodgers 2008).

In recent work, Jussi Parikka examines social insects as a way to approach media theory, noting that these nonhumans reveal “a whole new world of sensations, perceptions, movements, stratagems, and patterns of organization,” which lead to a “non-discursive media construction” reflecting the coupling of insect behaviour, such as swarming, with media technologies (2010, ix, xiii-xv). His archaeological approach reveals a long history of entanglement between biology, technology, and human social and political life, which he argues, results in an insect theory of media. Parikka examines how social insects became entwined within technological discourses, standing as inspiration for, among other things, software agents and web spiders (search-capable programming on the Internet).

However, while it would be tempting to posit a *microbe media* as the next affective organism suited to contemporary communication and information technology, I argue that the design and programming of software that underwrite networks and their control features, and that lie ‘beneath’ media streams, are a more powerful constitutive force for the vital network. Therefore, this dissertation investigates what constitutes the systems that provide control over our critical communicative practices, human and machine, enabled through sophisticated communication technology and networks. I focus on the materiality of the vital network, such that “[a]ttention to media infrastructure—its technical capacities, temporalities, and spatial distributions—moves us beyond the
narrow focus on audiovisual media that has characterized the field of media studies” (Packer and Wiley 2012, 109).

In the ant example, scientists have studied their swarm ‘intelligence,’ revealing that chemical signaling is key to their display of self-organization and coordination out of which mass organism movements occur collectively in a massive swarm or group (Gordon 2007; Hölldobler and Wilson 1990). Pheromones exuded by individual ants are essential chemical markers, which convey information about the environment, food location, foraging patterns, and colony member identification. Ants do not demonstrate a keen individual sense of geographically useful information in terms of spatial and directional awareness, but the local communication with other ants, through interactive contact of their antennae as they pass each other, leads to more complex global behavior, which benefits the entire colony by ordering the movements of ants at the global level (Gordon 2007; 2000). Swarm intelligence is a product of the collective action of the whole population acting as a ‘super-organism’ whereby the emergent behaviour is more complex than that of the solitary organism (ant). The swarm is better at solving environmental, metabolic, and population survival issues. Self-organizing behaviours that result from this swarm intelligence exhibit impressive efficiencies in finding the shortest path to food sources or a new colony site, or coordinating threat avoidance. In the ant colony, there is no decisive, orchestrated effort to lead hierarchically; there is no governing ant queen (see Johnson 2001, 29-32; Gordon 2000).

The eloquence of this ant behaviour attracted researchers in computer and network science struggling to find solutions to human network problems of traffic
routing, scheduling, load balancing, and searching in high population scenarios. This network puzzle or logistical problem is known in mathematics as the traveling salesman problem or the Hamiltonian path problem (Ramos et al. 2005). The networks or ‘traveling path’ can be digital, such as the Internet or electricity grid, or physical, such as roads and highways connecting shipping and receiving points (Miller 2007). The ant colony optimization (ACO) routine seeks the best possible solution, or shortest path, between points to solve this problem within a system with other constraints such as time, unit quantities, and potential courses of action, all of which require advanced mathematical computation to arrive at the most optimized solution (Ramos et al. 2005; Dorigo and Stützle 2004). In this model, it is the actions between nodes, or the lines or edges that run between them, that are described and coded in the ACO routine of significance for shipping, logistics, and efficient route planning for delivery services (Ramos et al. 2005; Dorigo and Stützle 2004; and see for related Galloway and Thacker 2007). In each instance, the algorithm filters a plethora of information about the number of units that must travel on the network, time to travel, distance between points, traffic along the route, and available options that provide the most efficient route given all the variables (Ramos et al. 2005; Dorigo and Stützle 2004). This biologically inspired algorithm is an important precursor to current investigation into network path-finding among Physarum slime molds, discussed in Chapter Five.

**Microbes**

Sherry Turkle has recently pointed to the importance of “evocative objects” that serve as “provocations to thought” and problem solving across disciplines (2007, 5). As
the above discussion highlights, social insects have certainly served many scientists and social scientists as ‘things to think with.’ Ants, as biological inspiration, are pivotal in the solution to a human logistical and computational problem through the ant-inspired ACO algorithm; and social insects have expanded knowledge of how self-organization occurs in large populations that exhibit collective swarm intelligence (Dorigo and Stützle 2004; Camazine et al. 2001). Following this example, microbes, in particular bacteria and slime molds, have proven similarly inspirational to a generation of scientists examining nonhuman self-organization and communication in life systems, and for this reason they make fascinating objects to think with in biology (Bassler 1999; 2002; Bebber et al. 2007; Ben-Jacob 2008; Bonner 1999; Carreras et al. 2005; Crespi 2001; Keller 1985, 2007;), sociology (Hird 2009), and computational science as a model of complex, self-organizing control (Peysakhov et al. 2006; Li and Knickerbocker 2007; Ramos et al. 2005; West et al. 2007a, 2007b).

Bacteria and slime molds provide a particular form of social self-capability, and self-regulation, of millions of colony members through chemical communication and signaling (see Bassler 1999; Ben-Jacob, 2003, 2008; Crespi 2001; Dussutour et al. 2010). In the mid-twentieth century slime molds were studied with regard to their ability to self-organize multi-amoeboid aggregations to form a multicellular ‘slug’ to search for new food sources (Bonner 1999, 9). Many researchers were convinced, even in the absence of direct evidence, that there must be a central, directing unit in the slime that coordinated collective organization and behaviour of the aggregation. Evelyn Fox Keller and Lee Segel’s (1970) study of slime molds established that aggregation and self-organization
occurred *without* a central, directing ‘pacemaker’ cell or unit (and see also Keller 1985). In effect, slime molds can exist as single cells or aggregate and navigate their environment in a now classic example of local to global action dictated through cellular chemical interactions and communication from the one to the many (see also Adamatzky 2010; Tero *et al.* 2010).

Bacteria exhibit complex chemical and electrochemical signal processing to self-organize and self-regulate their networks of communication (Bassler 1999; Carreras *et al.* 2005). In this regard, microbiologists sometimes define bacteria as a “biotic autonomous system” with capabilities that include “storage, processing and interpretation of information,” which enable it to initiate and respond to other bacterium signaling mechanisms (Ben-Jacob, Aharonov, and Shapira 2004, 1). Microbial life in this example displays a fascinating capacity toward coordination, indicating parallel processing of information and communication from bacterium to its near neighbours, to the whole colony itself, and beyond to other colonies and species (*ibid.*; see also Hellingwerf 2005). As with the slime mold and ant examples this is the classic flow of self-organization, from the local to global scale, which gives rise to emergent properties. It is this microbial self-capability that serves as a model of organization for complex digital systems and multi-entity networks (Carreras *et al.* 2005; Peysakhov *et al.* 2006).

There has been considerable research in microbiology on bacterial communication, and in particular around the process known as ‘quorum sensing,’ including from Bonnie Bassler (1999, 2002), Bassler and Richard Losick (2006), Eshel Ben-Jacob (2003, 2008), Ben-Jacob and Herbert Levine (2006), Klaas Hellingwerf
(2005), and Ian Joint, Allan Downie, and Paul Williams (2007). Quorum sensing occurs at “high cell population densities,” and is a mode of cell-to-cell communication that offers a sort of ‘census-taking’ from which the bacterial colony can determine cell numbers and, after a ‘voting exercise,’ coordinate activities to permit the bacteria to synchronize global behaviours (Bassler 2009). Quorum sensing is emerging as one model for technologists designing different types of sensor networks whereby individual units must operate as a “symmetric, cooperative and self-organising” global entity in which each sensor node is at a distance from each other and without central control, but must be able to account for, or calculate, nearby nodes to communicate with (Sacks et al. 2003, 1). Systems installed in remote environments are an example of this type of system with a requirement for monitoring via distributed sensors that measure, track, analyze, and communicate data such as weather conditions, seismic activity, or border integrity (see Peysakhov 2006).

Microbial self-organization demonstrates a many-to-one communication system wherein the ‘one’ is comprised of the ‘many’ operating in unison without direct, centralized control reaching “univocity-through-assemblages” on the network (Thacker 2008, 140). This is the bacterial or slime mold aggregate of many hundreds to millions of individual cells joined together to function as a multi-cellular organism instigated by communicative processes that produce self-organization. As will be detailed in Chapter Five, the combination of specific molecular communication and self-organization capacities within such a large population of organisms provides an example to computer scientists and network engineers as to how to program these particular life-like qualities.
into a digital system or network consisting of many thousands of communicating objects and processes.

**Life-Like and Like Life**

In much of the contemporary literature on biological organization the description of flows of communication among and between organisms and cells is ‘informationalized’ in a seamless merger that enrolls the language of cybernetics to describe biologics, meaning that biological self-organization has also become a standard to describe autonomous networks and digital systems (Bassler 1999, 2002; Bassler and 2006; Ben-Jacob 2003, 2008; Ben-Jacob and Levine 2006; Galloway and Thacker 2007; Keller 2005, 2007; Thacker 2005, 2010; see also Rose 2007). Self-organization is now the descriptive context for any complex digital system and network that displays life-like, or vital qualities in its self-regulation, a consequence of cybernetic discourses about self-regulation in humans and machines that influenced artificial life research (Galloway and Thacker 2007; Johnston 2008; Keller 2007; Parikka 2010; Thacker 2010).

The problem of how to define life and its qualities was a preoccupation for the early Greek philosophers and continues to be debated across interdisciplinary fields today among philosophers, scientists, and social science and humanities scholars (Ansell Pearson 1997, 1999; Bennett 2010; Colebrook 2010; Keller 2002, 2007; Kember 2005; Langton 1995; Lash 2002, 2006; Protevi 2012; Thacker 2010a, 2010b; West et al. 2007). There is, as Eugene Thacker notes, the “pervasive anthropomorphism of the concept of ‘life’” in that “only human beings … worry about the definition of life—the rest of the world simply lives it” (2010a, xv). Discussions of life are often enmeshed with vitalism,
and in particular a vitalism contained in recent discussions of self-organization in biological and digital systems (Protevi 2012; Thacker 2010a, xiii; see also Keller 2005). I will revisit vitalism in the forthcoming chapter, but the vitalism relevant to points made in this dissertation about the vital network is not that of nineteenth century classical vitalism, which sought to locate and explain a hidden and mercurial cosmic force to explain all of life and causation. Rather, it “concerns the capacity for novel emergent properties in the self-organization of material systems” that are life-like even if they are not alive in the sense of an animal, a tree, or slime mold (Protevi 2012, 7; Lash 2006, 323; and see Thacker 2010a). This point, then, links the definition of life closely to self-organization as a principle defining ‘aliveness,’ and as Keller notes Kant proposed that purposiveness in nature and in organisms relies wholly on the “internal dynamics of being” and of being alive (2005, 1070). This is a self-regulated and self-organized autonomous being (a point I expand on below) with a capacity for self-generation.

Life can be considered as comprised of “heterogeneous domains of the living” and of being alive within and as part of such domains consisting of assemblages of the technological, biological, social, political, linguistic, and so on (Thacker 2010a, 17-18; 2010b, 128). Life in this sense is understood as a composite: it is composed of assemblages across domains from human to nonhuman, elements to atoms, and words to things. But is one part of the assemblage more alive than another? On the one hand, I can make a distinction between the aliveness of matter within and as part of our biosphere, and on the other the ‘life-likeness’ within artificial and simulated systems rendered through computation, but there are also instances where the biological and technological
touch very closely, such as cultured animal brain cells joined with mobile robotics or human-implantable radio frequency identification chips (and see Warwick 2010). The self-organization and vital communication of digital systems and networks are at best life-like in my view—they can be coded to simulate behaviours we understand as similar to biological systems such as bacteria and slime molds. Life-like conveys a certain vitality in the sense of being dynamic and changeable, autonomous, and ‘like,’ or similar to, a life system, but as above, best considered through the “role of the biological within the technological, the material within the informational [and] the actual within the possible” (Kember 2005, 154). This echoes how Gilles Deleuze and Felix Guattari see life: it is both life understood through the self-organization of biological matter (what we may also call organic life) including the organism, and a non-organic life comprised of assemblages that combine the organic and non-organic (Deleuze and Guattari 1987; Protevi 2012).

In the philosophy of biology there is a persistent bifurcation between life and the living, and an emphasis on clear boundaries of articulation that delineate the living from the non-living (Thacker 2010a, 24). For biophilosophers such as Deleuze and Guattari (1987), Manuel De Landa (2006), Keith Ansell Pearson (1997), and Thacker (2010a, 2010b, 2008) life is not defined by ‘or’ as in alive or not, but by ‘and,’ such that life and the living are seen as biological and technical, words and things, alive and not. Life from this perspective is an all-inclusive thing: in spite of its seeming finitude and “constraints of corporeality [and] temporality” for some entities, life is affirmed when seen as part of a process that is “generous, productive, proliferative, and germinal” and unlimited; life as
both creative and destructive (Thacker 2010, 26-27; see also Ansell Pearson 1997; Bergson 1922; Deleuze and Guattari 1987; Protevi 2012). This is in some ways an alternate biological cosmology that stands in opposition to mainstream biology organized around species classification (and see Chapter Five for further discussion on this point) (see also Ansell Pearson 1999; Deleuze 1990; Deleuze and Guattari 1987; Van der Vijver, Speybroeck and Vandevyver 2003; Wolsey and Wolsey 1992). The intent here is to suggest that what we consider life is problematized in new ways by developments in the artificial sciences that produce artifacts and processes that have vital, or life-like, qualities, much as Grey Walter’s tortoise displayed rudimentary self-organization (Thacker 2010b, 128).

Until the era of cybernetics, the organism (as a creature of nature) and self-organization as the description of its propensity for self-regulation were tightly entwined, but the introduction of self-regulating, cybernetic machines troubled this distinction (Hayles 1999; Keller 2005). Cybernetic machines demonstrated that not only could human-built machines self-regulate, but that aspects of a life system could be emulated through computation as information: self-organization became reduced to a series of mathematical and computational puzzles to be solved by machines as a program or plan that executed in a distributed fashion across a system (and see De Landa 2011; Keller 2007; Van der Vijver, Speybroeck and Vandevyver 2003). This formally initiated the field of artificial life and artificial intelligence research discussed above, and with it the primacy of ‘life as information’ as an idea that has been amplified through the science of
genetics and later bioinformatics (the capture of biological systems and processes as information) (Kay 2000; Keller 2002, 2007).

While metaphors of life as information are evident in descriptions of genetics, such as genes as the basis for ‘the book of life’ or ‘codes of life,’ other non-genetic attributes of life such as self-organization, metabolism, and biochemical communication processes in life systems are not metaphorical. In the context of ideas under discussion in this dissertation, self-organization is not so much a metaphor used by scientists and technologists to mobilize knowledge across disciplines, as a template that provides a developmental approach for software system design and control processes for networks (Thacker 2010b; Kauffman et al. 2008; Keller 2007). As Keller has noted, in the biological sciences processes of replication, communication, metabolism, and differentiation are often understood as programmatic—framing life systems as information in terms that convey a set of proceedings or programs that unfold in relation to the life cycle (2007, 303-304; 2002; see also Doyle 1997; Thacker 2010b; Turkle 2009). Thus whether it is the specifics of genetic replication or through other life processes described in informatic ways, information has come to be equated with a life ‘program’ for the living in which the program provides instructions integral to life itself (Keller 2007; see Goujon 2006; Keedwell and Narayanan 2005). This maneuver reduces organisms of all kinds to informational entities, whether single-celled bacteria or multi-celled animals, all are autonomous entities furnished with the instructions necessary for a life. Information becomes a common language through which to describe and explain life.
and life-like as merely a set of instructions operating in different registers, the biological and the technological.

This logic has two implications for the exercise of translating nonhuman biological behaviours understood as information into mathematical models that can be simulated computationally, as discussed in later chapters. Firstly, while this maneuver simplifies and facilitates a non-metaphorical pathway for organismal behaviour to be used as inspiration in technological development as for network design and control, it brings along its particular nonhuman model of autonomous or self-capable control. Secondly, as I touched on in Chapter One and will argue in Chapter Six, this particular model of control has a distancing effect; it widens the gap between the human user and the control apparatus within the digital system and network by disrupting the notion of human agency over, and in relation to, a hierarchically controlled technological system (see Chun 2011). Autonomy, then, becomes a feature to describe contemporary networks and systems perhaps even more than the capacities for action of its human users. This was the concern Wiener disclosed when he first imagined self-regulating machinery: that machines would weaken liberal humanism’s staunch defense of the autonomous individual, the human, at the centre of life rather than simply machines made “alike in the image of an autonomous, self-directed individual” (Hayles 1999, 7; Johnston 2008; cf Wiener 1950).

**Autonomy**

My discussion of autonomy signals the crucial role of the description of self-organization in both biological and technological systems and highlights the profoundly
human-like notion of autonomy that informs these descriptions. The idea of autonomous selves and systems has deep roots within western philosophical thought and tradition, and in many ways autonomy has become harmonized in meaning in both biology and technology (Hayles 1999; Johnston 2008; Thacker 2010a, 2010b; Van der Vijver 2006). The word autonomy, and variants such as autonomic and autonomous, feature in explanations of biological organisms and life systems that are said to function in an independent and self-organizing manner, and, particularly following the era of cybernetics, the term autonomy features in descriptions of biologically-inspired technological systems that have life-like functionality (see Bongard 2009; IBM 2012; Maes 1995; Peysakhov et al. 2006). Kant, in his contemplations on nature, understood the organism to be autonomous “because it is an organised and self-organising being” with a clear purpose (1914, s.65). In Gertrudis Van der Vijver’s examination of Kant’s contribution to the idea of biological self-organization, she emphasizes Kant’s belief that “organisms present themselves as systems that hold within them the principle of their organization ...[and] present themselves to us as unified entities, as autonomous totalities” (2006, 145).

In the century following Kant, liberal humanism cultivated a concept of autonomy attached to human agency and self-determination, predicated upon an “inward domain of consciousness” that produces ‘properly’ purposeful, rational, autonomous (human) agents in society (Mill 1993). This ‘properly produced’ self, the self of liberal humanism, is autonomous, agential, and self-aware, coherently arranged around relations of interiority (consciousness) that convey a unity of purpose. It has a profound influence over the
concept of self that appears in cybernetics, attached to properties intended to render the self-regulating machine as autonomous and purposive. Contemporary computing research and development continue to deploy the same language within the goals and requirements for artificial intelligence intended as self-capable, even as the mode of cognition oriented around the human-animal brain has shifted to the nonhuman organism.

The humanist ‘self’ is how biology has come to see the living organism—a bounded entity that, as Evan Thompson argues, “continually re-creates the difference between itself and everything else” (2007, 99). The “circular interdependence” this self requires, that is, to re-generate and self-propagate as part of its organization, is similar in principle to the self of cybernetics as for a self-regulating machine (Thompson 2007, 101; Johnston 2008). It is also the self of a theory intended to explain the “organization of the living:” autopoiesis (Maturana and Varela 1980).

**Autonomy in Biological Systems: Autopoiesis**

The model of life systems offered by Humberto Maturana and Francisco Varela ([1972] 1980; Varela 1979), known as autopoiesis, turns on an understanding of life in the abstract as a self-producing, self-contained autonomous system strongly correlated with Kant’s perspective on the organism (Van der Vijver 2006). I want to engage briefly with some of the thinking around autopoiesis because the approach troubles the computational aspect of describing life in terms of information processing and brings together the preceding discussions on control, life, self-organization, and autonomy in one framework, which presents a quite different concept for autonomous systems based in organization, but which insists on operational closure as a means to its ongoing self-production. Yet, as
I show, it maintains strong ties to a sense of the organism as a bounded, integral self closely aligned with liberal humanism. Maturana was involved in the Macy Conferences and cybernetic thinking had a profound influence on how he understood the life of the organism as a system. The concept of autopoiesis also signals the second wave of cybernetics. This is the shift within cybernetics toward explicit systems thinking, whereby life is considered as a whole ‘living system’ and as “self-organizing biochemical machines” maintaining their own identity and persisting independent of any observer (Johnston 2008, 167). This is a system that thrives not on information processing, nor signals and messages passing between an organism and its environment, but on “constitutive interactions” between system components (Hayles 1999, 10-11).

Maturana and Varela thus set out their theory of living systems constructed as a response to, and in opposition to, informational and computational descriptions of life that early cybernetics championed. Autopoiesis is defined as a “network of processes of production” that describe living systems in terms of a self-referential and self-producing organizational apparatus that exists within an organism only so that it can produce and maintain itself (1980, 78; and see for discussion Clarke and Hansen 2009; Johnston 2008; Thompson 2007). There are three postulates within autopoiesis: first, the theory itself is a mechanistic explanation of life systems wherein life is described as an autopoetic machine; second, openness through closure; and finally, the eschewal of computational explanations for the functions of living systems in favour of self-maintaining organizational form (Maturana and Varela 1980).
In the first instance, autopoesis turns on a mechanistic view of life systems as autonomous machines that produce and maintain themselves through a dialectic of regeneration and destruction. This occurs within a network of “component parts and processes” acting in relation only to itself (Johnston 2008, 191; see Thompson 2007). This seeming contradiction means that although there is an emphasis on the processes of self-production and self-propagation, this is facilitated through a distinctively mechanical apparatus (structure) that does not require information to pass between the organism and the environment. This leads to the second point of a closed-onto-itself system (it has a certain bounded integrity as a self) that is open in the sense of a continuous exchange with the environment to meet its matter and energy needs, but not for informatic exchanges. An autopoetic machine (the organism-as-autonomous system) has no inputs and outputs in terms of structural or organizational contact with an environment or other organisms or cells that result in a fundamental state change within the organism itself, and can be considered a stable or homeostatic system (see Johnston 2008, 193; Maturana and Varela 1980; Varela 1979). Finally, Maturana and Varela’s insistence that autopoesis is not explainable through computational logics that render life as information refutes informational descriptions of life in favour of a more nuanced theoretical engagement with what life is by theorizing a system of organization and self-production. In part this may be so, yet autopoesis has strong similarities to Von Neumann’s computational theory of cellular automata.

As with mid-century cyberneticians (and see above), throughout the work of Maturana and Varela the spectre of liberal humanism persists to organize their vision of
the organism as a bounded self, and in Varela’s later work (without Maturana) he expands on this notion in the context of autonomous systems (1979; Varela and Bourgine 1992). Varela describes autopoietic systems in recursive terms and he turns to cellular automata to model the systems—both computational frameworks deployed in the artificial sciences of autonomous digital systems at large (Varela 1979; Johnston 2008). The issue here, in the context of a vital network, is that autopoiesis might have provided a model of living systems through its organization and processes with implications for modeling digital autonomous systems also organized around processes (such as I propose in my dissertation). However, both the mechanistic fixation of autopoiesis as mere clockwork and its reliance on the notion of closure leave it hanging awkwardly beyond reach as a model for biologically inspired computing in my view. Maturana and Varela’s organism is analog, solitary, conformist, rigidly structured, and a fixture of humanistic individuality. The organismal model of twenty-first century life is a creature of information; it is digital, multiple, differentiating, organized by processes of communication, and decidedly nonhuman, eschewing structure for process. The nonhuman constituent of a vital network is the intelligent search agent, web-crawling ‘spider,’ viral botnet, and friend-linking Facebook algorithm.

**Systems and Second-order Cybernetics**

As a preface to the subsequent section on posthumanism, it is worth noting the role of systems theory in neocybernetics, or what I call late second-order cybernetics in direct dialogue with autopoiesis. Neocybernetics takes hold from within a strong radical constructivist epistemology that turns against ontology by emphasizing
phenomenological accounts of life through experience, resulting in an autological, self-creating theory of form (Clarke and Hansen 2009, 4; and see Thompson 2007). Bruce Clarke and Mark Hansen argue strenuously for this position, proposing that the operative axiom of autopoesis, openness-through-closure, is what in neocybernetics is the ‘real’ source of complexity and emergence, and this flows directly from autopoesis: in this view, complexity arises through recursion, that act of the organism doubling back on itself that ensures an autopoietic system self-produces (2009, 7-9; Wolfe 2010, xxi). Again, they stress that autopoetic systems are both “environmentally open to energetic exchange and operationally closed to informatic transfer,” meaning they remain metabolically open, but informatically closed (Clarke and Hansen 2009, 9-10). By extension, neocyberneticists such as Clarke and Hansen do not see complexity arising from simple local actions leading to more complex behaviour, but rather a shift from the “chaotically complex to the manageably complex” (ibid., 11). This is a significant disjuncture between how I conceive the vital network and the role of self-organization in biological and digital systems.7

My argument is that there is something ‘there’ in self-organizing, networked relations; the actions and processes are material, vital (as in life-like), and agential—all attributes that neo-cyberneticians reject. Far from being able to solve this disjuncture here, I argue that vital networks are invariably within the tradition marked by computational logics, which may manage chaos in relation to a dynamic self-organizing

7 The sociologist Niklas Luhmann also features within this debate because his systems theory is explicitly linked to neocybernetics and autopoesis and the notion of operational closure (2009). Luhmann’s dialogue with autopoesis turns on his understanding of systems through communication, and importantly, the simplified interiority of a system is contrasted with an overly complex exterior environment. Communication was, in his model, selective and worked to reduce the complexity of the external environment (ibid.; and seen Wolfe 2010).
digital system, but which are modeled upon organismal self-organization as an assemblage of events, actions, and processes of control (and see for discussion Chapters Four and Five). This is not necessarily beyond critique because it leverages the ‘life as information’ and ‘information as life’ equation, which erodes important distinctions between biological life and machinic life, and out of which a nonhuman, decentered mode of control arises as a standard for contemporary digital systems and networks. In any case, it ought to be troubled because the notion of nonhuman autonomy and control, as it is expressed in biological self-organization, has also become tethered to a central feature of autonomy in digital systems that grounds itself in the idea of submerging complexity and its distributed control features within the system in a manner that is not visible to human network clients (see for example IBM 2012; Steventon and Wright 2006).

**Autonomy in Digital Systems**

The conception of a self located within the liberal humanist tradition explains how computer science historically configured systems and networks, engaging the model of control and communication that imagined cognition as computation housed in a central processing unit—most often the model of autonomous control in the human-animal brain and autonomic function. The shift away from this human-animal model of control over digital systems to a nonhuman (and non-mammal) model is a radical departure because it ensures a flattened, non-hierarchical control distributed across and within the digital system or network imposing no fixed control structure to govern the system (Galloway and Thacker 2007; and see Lash 2002). Therefore, the locus of control is neither
centralized nor particularly human-centric or human-like, and breaks with the computational model based on human intervention and interaction, shifting to one in which the system ‘decides’ on the best course of action out of several alternatives (Riva et al. 2005; Wright and Steventon 2006). Thus, digital systems designed to be autonomous are then also designed to have decision-making capacities (see Hamar and Dove 2012; IBM 2012; Kallinikos 2011; Riva et al. 2005; Shackleton et al. 2006; Winner 1977; Winograd 1991; Woolridge and Jennings 1995; Wright and Steventon 2006).

IBM has championed smart computing and autonomic computing intended to leverage the processing power of today’s microchips and increasingly sophisticated software programmed with artificial intelligence capabilities (2012). The IBM approach follows Mark Weiser’s landmark publication describing digital systems that would be autonomous or self-regulating and embedded in the environment of everyday life and “vanish into the background” ([1991] 1999, 3). IBM has established a baseline of eight parts for autonomous system functionality, detailed in Table 1. These systems must include the capacity to be self-knowing (knows what is part of the system and what is not), self-configuring, self-protecting, self-healing, and context-aware (2012; see also Riva et al. 2005; Shackleton et al. 2006, 323). The characteristics are influenced by biologically inspired models alongside the engineering goal of pervasive computing that relies on information and communications technology composed of “self-contained autonomous processes” connected over a network (Power 1992, 2).

Table 1 shows the features IBM has assembled to describe an autonomic or autonomous system. In this table and down the list through the eight features, each one is
biologically-inspired and the template clearly incorporates cybernetic features linked to Wiener and his Macy Conference associates’ vision for self-regulating machines that draw on functionality based in biological self-organization. A key difference is that many of the features are not strictly drawn from the human-animal model. In the first instance, the system must be able to self-identify and be able to distinguish its own singular boundary and location in terms of its local connections. This first feature is crucial to all the other features within the system, and is similar to the immunological understanding of a self. Here, the self resides in the knowledge that there is a unitary, autonomous entity that recognizes, at the unit level (or what would be the molecular level in a biological system), what it ‘is’ and what it ‘is not,’ distinguishing between the self and the non-self to defend against disease and predation in biological worlds or a digital system (Pradeu and Carosella 2006). In the context of the autonomous system IBM seeks to describe, the machinic self is a stable construct created in code and around which engineers program specific capacities such as self-healing, yet it reflects the persistence of the humanist subject position as a solitary, bounded entity, even within what is a radically different system composed of decentred, distributed processes.

Features two through eight build on various capacities for the machinic self. Each capacity furnishes functionality that enables the system to be dynamic, responsive, adaptive, and highly complex. The last feature explicitly directs system developers to work toward hiding or submerging the complexity of systems and network control to minimize human-machine interaction and intervention (IBM 2012; see also Wright and Shackelton 2006; Riva et al. 2005). When taken together these eight features enable
control to be distributed across the system or network, devoid of any hierarchical control
console or centrally located cognition module.

Table 1: Features of autonomic computing: The eight key features for autonomic computing
relevant to adaptive, autonomous digital systems development (adapted from IBM Research,
Autonomic Computing 2012; see also Wright and Shackelton 2006; Riva et al. 2005).

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. System must self-identify</td>
<td>System must distinguish or ‘know itself’ and have a self-identity; to be able to recognize its own system components, status, connections, shared/owned system resources, and so on</td>
</tr>
<tr>
<td>2. Automatic system self-configuration</td>
<td>System must self-capably configure and reconfigure its system state dynamically according to environment or network conditions</td>
</tr>
<tr>
<td>3. Continual self-optimization</td>
<td>System persistently fine-tunes to improve operational capacity and meet system goals</td>
</tr>
<tr>
<td>4. Self-repair</td>
<td>System must have programmed self-healing capacity; respond automatically to system failures, diagnose, and repair problems, or invoke alternate solution (re-route tasks to working systems)</td>
</tr>
<tr>
<td>5. System integrity and security: self-protection</td>
<td>Persistently monitor for system threats (e.g. virus or malware) and defend the system</td>
</tr>
<tr>
<td>6. Context-awareness</td>
<td>System must remain self-aware and aware of other entities, nodes, and information of its near neighbours</td>
</tr>
<tr>
<td>7. Open system</td>
<td>An autonomic system must be open to its environment and non proprietary; able to dynamically communicate with multiple systems within its own network and to others</td>
</tr>
<tr>
<td>8. Hidden complexity</td>
<td>An autonomic system must submerge complex machine code to minimize human user interaction and intervention</td>
</tr>
</tbody>
</table>

The lack of visibility in complex digital systems is a problem for a sociology of communication, insofar as we can only examine what we know is there and what we can see, but as system complexity slides deeper into the programming of contemporary digital systems and networks, it becomes ever more difficult to know how such systems operate. To focus on the materiality of networks—their processes of communication and control, components, and actions—ensures that analysts can contend with this infrastructure and its “technical capacities, temporalities, and spatial distributions” even
as they are changing, both in design and in functionality (Packer and Wiley 2012, 109). The guidelines for autonomous functionality contribute to system obscurity not only by hiding complexity behind a simplified human client interface, but through the expression of system requirements in human social terms. This expression ensures that human clients of the system understand the functionality through a long-standing usability model for software interfacing that mimics aspects of our human material world and embodied actions, from notions of a desktop on our computer, to computer icons showing a camera, file folder, or calendar (see Bodker 1989; Suchman 2000). We are compelled to relate to the technology as if we understand what it does in spite of the clever 'black-boxing' that locates complexity within parts of the system we do not make contact with. In this way, a highly complex and new form of control is masked behind the simple encounters between human users and the software interface, arguably reducing, or at least managing, anxieties about complex digital systems (and see Winner 1977).

The systems being contemplated are self-knowing, context aware, ‘defensive,’ ‘neighbourly,’ and capable of invoking the right ‘decisions’ and solutions for itself and the collective entity. IBM is deploying the language of cybernetics and self-regulation to describe a radically different sort of system intended to simulate nonhuman self-organization. The self-regulating machine of cybernetics was under the guidance and control of humans and not, as presently conceived by IBM, the distributed control processes coded to interact with its digital environment in the exercise of capacities for communication, all without human intervention. Through these guidelines, opacity and obscurity become a characteristic of the vital network, where the notion of life-like
maintains the old idea that vitality and biological life do have some sort of mysterious quality that cannot be seen or explained (and I will expand on this point in Chapter Three and Six). As Chapter Six will detail, IBM exerts tremendous influence over how other researchers understand autonomous systems and adapt the principles of design into new digital systems and network control (and see Hamar and Dove 2012; Winograd 1991; Woolridge and Jennings 1995).

Computer scientists and engineers studying the Internet’s architecture, organization, and data flows consider it to be the world’s newest large-scale complex system (Meisel, Pappas and Zhang 2009, 1). Biological systems “share several fundamental properties with the Internet, such as the absence of centralized control, increasing complexity as the system grows in size, and the interaction of a large number of individual, self-governing components” and this comparison is what drives technologists to closely examine biological models of control and organization (ibid., 1). It is estimated that by 2020 there will be a trillion communicative objects with information gathering capability and connections to the Internet—coordinating such a vast web of interactions will require automated processes such as are found in biological systems and modeled in IBM’s eight principles (Wright and Steventon 2006, 2). I return to these points in detail in Chapter Six.

**Posthumanism**

Researchers in biology and the artificial sciences have often not left humanism out of their work: the notion of a human, or human-like rational actor, as a self-determining individual entity has persisted in research that draws either from the general
model of humanism to create a defined, bounded entity that then figures in theoretical
excursions, or specifically looks to the human-animal cognition function to construct a
model of autonomous system intelligence. I want to conclude this chapter by examining
how sociologists and communication scholars have come to the posthuman as a
constituent of contemporary life and respond to this construct by presenting the
nonhuman as a more robust constituent for and within a vital network.

As the preceding sections outline, researchers in the world of microbiology and
the artificial sciences categorize and designate nonhuman worlds in classically human-
centric or anthropocentric conceptualizations and terms. This vantage point, from human
down to nonhuman, is hierarchically organized around structured and programmatic
research agendas and centralized work practices, wherein “placing the human and human
vision at the centre – leads ... to anthropomorphism – seeing the world in our own image”
(Fudge 2000, 7; see also Hird 2006; 2009; Schrader 2012). Microbiologists commonly
anthropomorphize bacterial worlds to explain observed phenomena: bacteria are
constituted as cheap labour for environmental clean-up and bio-fuel production (Dwyer et
al. 2008); as “nanofactories” working to remediate industrial and human waste (Arya
2010); as having social lives and rudimentary social intelligence (Ben-Jacob 2004; West
et al. 2007a, 2007b); living in colonies with crowd control (Cho et al. 2007); and as
voters, miners, loners, cheats, and altruistic, cannibalistic, coercive and manipulative
(Bassler and Losick 2006; Crespi and Ragsdale 2000; Diggle et al. 2008). Artificial
intelligence and artificial life researchers invoke similar kinds of anthropomorphic and
gendered terms, such as ‘the thinking machine’ (cf. Turing), mother and daughter cells
and ancestors in cellular automata simulations, robots that are “fast, cheap, and out of control,” ‘seeds of code’ propagating through passive, receptive cell space (feminized), and God-like programs and codes of creation (masculinized) (Adam 1998; Brooks and Flynn 1989; Hayles 1999, 227; Helmreich 1991, 387-388; Kember 2003, 54).

Artificial science research that descends from a thoroughly human perspective of cognition and intelligence has produced popular scientific and fictional accounts for human advancement through computational enhancements and the augmentation of life through digital technologies (Herbert and Anderson 2003; Kelly 1994; Kurzweil 2005). Anthropocentric readings of artificial science breakthroughs are problematic because of claims that advanced technological systems will “enhance, augment, and advance the human into a posthuman future” based upon qualities of the human programmed into the computer artifact (Thacker 2003, 75; Kurzweil 2005; Moravec 1998, 1999; and see Hayles 1999, 2003, 2005; Wolfe 2010). This posthuman variant, which Eugene Thacker labels “extropean” to link it directly with the transhumanism of the now defunct Extropy Institute, privileges the technological as critical to human progress whereby the human is centrally located in relation to technology (2003, 74).

Transhumanism presupposes the eventual disembodiment of human life, in which consciousness is uploaded into intelligent machines rendering the human as the post- or transhuman in artificial life (Kurzweil 2005; Moravec 1988; 1999; Wolfe 2010). It assumes a universalizing AI that transcends race, gender, social, and political differences.

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8 See http://www.extropy.org/. Hans Moravec goes so far as to describe a “postbiological world, dominated by self-improving, thinking machines” (1988, 5; and see 1999), an idea Kevin Kelly runs with in his popular book Out of Control: The Rise of Neo-biological Civilization (1994) which is an excursus on the future of human society tied to AI and Artificial Life capabilities that draw on nature to enable human progression. See also http://www.kk.org/outofcontrol/ and Kelly (2010).
in a convergence of human nature with machines, though does not clarify how this
transcendence will overcome those very human, embodied prejudices (Hayles 2005,
145). Transhumanism is part of the wave of futurist proselytizing that promoted the idea
that “The central event of the 20th century is the overthrow of matter” (Dyson, Gilder and
Toffler 1996, 295), and against which new materialism and realist ontology pushes back
(and see Coole and Frost 2010; Galloway and Thacker 2007; Hird 2009). In fact, most
self-regulating technologies are far less dramatic and more subtly diffuse than
transhumanism predicts: they are targeted at monitoring the trivia of life produced
through our many digital transactions and social communicative practices enabled by
information technology (Kallinikos 2011; Lyon 1994, 2002).

Katherine Hayles, ever critical of the utopian transhumanist vision of machines
with human or human-like consciousness intended to surpass human material constraints,
suggests that such visions ignore the fundamental embodied interactions of life, in which
“the mind/body is experienced as an emergent phenomenon,” not separate, autonomous
parts that can be uploaded, downloaded and parsed in and by machines (2004, 232, 234;
see also 1999, 290). In direct response to Ray Kurzweil (2005) and Hans Moravec’s
(1988, 1999) brand of trans- or posthumanism she notes it “downplays ... differences
between biological organisms and computers and dehistoricizes what has been a very
long process” of invention and entanglement between biology, culture, and human
cognition at work for millennia (Hayles 2010, 154), alongside the confluence of life
and/as information that has blurred the boundary between biology and technology (Clark
A central thread of Hayles’ argument is that posthumanism extends rather than challenges the notion of the human as having dominion over the world through, and in the use of, technology. The human, specifically the liberal subject, remains inviolate in the posthuman, and certainly in the transhuman future, in which “boundaries of the subject continue to be clearly delineated from an objective world” in a continuing division between nature and mind (Hayles 2004, 246). This observation brings me back to one of the lingering problems for biology’s quest for a unified theory of the organism such as in autopoiesis. A strong affiliation with the bounded, integral self persists in Varela’s description of autopoiesis and autonomous biological systems (1979, 1992). The stubborn adherence to humanism suggests that the human notion of what a self is, is located far deeper than first assumed within biological systems research; it appears deep within the cellular matrix of autopoetic selves. As an example of this, Varela suggests:

autonomy [in living organisms] refers to the basic and fundamental capacity to be, to assert their existence and to bring forth a world …. Thus the autonomy of the living is understood here both in regards to its actions and to the way it shapes a world into significance … hand in hand with the design and construction of autonomous agents … from cells to societies (1992, xi).

This vision of the organism within an autonomous system leaves very little room for it to be, simply, nonhuman because it is imbued with goals, acts of creation, actions, and even hands defined as human. Such a strong sense of the organism as an autonomous being modeled on the human is difficult to dislodge from scientific and social scientific discourse and I will expand on this point in Chapter Three. In the effort to move away from this perspective, we have yet bound up our liberal human selves with technologies that extend many of our capacities through a “host of peripheral devices [that] store,
process, and re-present our meanings” (Dennett 1996, 134-135; and see for discussion Hayles 1999; Wolfe 2010). Posthumanism is precariously positioned because of its trenchant grasp on humanist values and the historical configuration of a disembodied autonomy, and in this there is nothing ‘post’ about it at all (Wolfe 2010, xv; and see Hayles 1999; Mitchell and Thurtle 2004). As Diane Currier points out: “the everyday ubiquitous and intimate connections with technologies renders any recourse to an organic, stable, self-contained, natural body in order to distinguish the Human from the nonhuman untenable” (2003: 322).

How do we undertake research without being drawn into this centuries old scaffolding of liberal humanism and of personifying nonhumans and their processes and functionality if we use them as models for autonomous systems? Donna Haraway’s emphasis, begun in The Cyborg Manifesto ([1985] 2004) and reflected more distinctly after, explicitly moves the human out of the central role relevant to posthumanism, yet over time I think her position has been forgotten in the discursive battles between social constructivists and materialists (I return to this point in Chapter Four).\(^9\) Thus, one path is to reconsider Haraway’s appeal to a world of pluralized becomings, and of “meeting with” other forms of life (2008: 17); a way of seeing through a “critical account of emergent, differentiating, self-representing, contradictory social subjectivities” to trouble the humanist master narrative and “reconstitute what counts as ‘human’” (2004: 57-58).

I interject here with the figure of the nonhuman as the constituent of the vital network to encourage a more explicit thinking that takes us toward an extensively

\(^9\) As Haraway explicitly says in When Species Meet, “I never wanted to be posthuman” (2008, 17).
oriented, more all-encompassing being-in-the-world than posthumanism's continued adherence to the human within the posthuman allows. I champion a reconfiguration in which the nonhuman, inspired by Haraway, is not what is left out of the human, but “traverses the human, that runs through the human,” re-working boundaries and the binaries of human/machine, nature/culture, and subject/object (Galloway and Thacker, 2007: 141, emphasis in original; see also Giffney and Hird, 2008: 2-6). The “comfort of the subject-object distinction” whereby “[m]achiness are clearly objects, produced by, and subject to, human will” is particularly difficult to dislodge (Hamilton 2009, 151). The posthuman, as drawn in most accounts, does not liberate us from that distinction, maintaining a human-centred and anthropomorphic worldview, which anchors us in our humanist past in the face of a technological future that ramifies control, communication, and information in autonomously enabled digital systems (and see Hayles 1999). The communication systems we encounter in the vital network and engage with on a daily basis are populated by powerful object-processes that are arguably agential, and can do things without direct human oversight. The relational milieu of vital networks such as the Internet consists of these tightly woven object-processes inspired by nonhuman life systems—more and more its operation can be characterized by non-anthropomorphic behaviour not based upon a system of cognition most individuals would recognize (I return to this point in later chapters).

I argue that turning to nonhuman self-organization modeled in microbial life points away from the human and posthuman, toward a radical model that can furnish quite different modes of communication and control than came to us through cybernetics
and the posthuman. This is not the organized matter of the organism as in autopoesis, but rather matter outside the boundary of the single organism: biological inspiration looks to the self-organization of the many, a multiple of organisms where interrelation and interconnection produce a dynamic changeability immanent in its mode of existence (see Cheah 2010, 87; cf. Deleuze and Guattari). Whereas the autopoetic organism can be said to be dialectic, always recursive, always rounding back to its own self-production, the self-organization of the nonhuman, the swarm, or the colony, as the actionable multitude, is much more productive for a decentered, anti-anthropomorphic vital network. This suggests a nonhumanism, not anti-humanism, which recognizes no centre, no privileged human agency and wherein humans are but one relation among many (and see Galloway and Thacker 2007; Thacker 2008).

Haraway’s idea of pluralized becoming, of meeting with other forms of life (2008, 17), resonates within Ansell Pearson’s suggestion of a “radical inhuman philosophy” that reveals a “plurality of beings and world” (1997, 6; and see Braidotti 2010, 210). In the context of my dissertation I concur; the posthuman is what was supposed to arrive after the human. However, the human persists, yet folded into the multiple, nonhuman constituency—an assemblage of the “life-multiplicity relation” (Thacker 2008). Biological theorizing such as in autopoesis maintains the individual, the unitary self as the basis of form, and so retains the humanist fundament from which explanations of life unfold, whereas it might prove useful for purposes here to think about sets of relations that capture processes of life as they unfold. It requires, as Thacker notes, a shift from thinking about biology (and biological inspiration) only as a “principle of life
[with] boundaries of articulation,” such as in the bounded self of autopoiesis, toward pondering the relations within life and the unfolding of “univocity-through-assemblages” in self-organization, which may help us understand networks as vital (2008, 141, 140).

**Conclusion**

The foregoing gives some sense as to the main contours in research located around control, self-organization, autonomy, and life that figure in/for vital networks. These four themes resonate in subsequent chapters. The notion that there is a governing logic emerging from the intensification of communication networks within societies has been explored by Castells (1997, 2004), Deleuze (1995) and others, but in each case these approaches do not sufficiently address how network control changes as the systems and subsystems enabling it grow more sophisticated. From my perspective, generalized theories of social organization such as the network society and the control society do not capture the increasingly dynamic array of processes assembled in contemporary networks, which reach deep into our social field by organizing most of our communication and transactions. To be able to understand how autonomous systems within and as part of networks such as the Internet work, we must also understand how the control apparatus is designed to function, and this is increasingly difficult given the push toward non-transparency and complexity within the self-organizing logic of networks.

Haraway said that information technology and biology pivot on the “translation of the world into a problem of coding” and this serves to remind me that control can be understood not only through the code or software that enables particular features and
functionality, but how we configure its logic depends on where in ‘biology’ we find inspiration (2004, 23). This is ever more the case as the artificial sciences seek to capture self-organizing models of control and simulate such ‘natural’ behaviour in computer logic echoing in Johnston’s observation that the “computational assemblage” found in “liminally lifelike” machines actualizes “new forms of computation and life” increasingly significant to contemporary systems of communication and what I call the vital network (2008, xi; emphasis added).
Chapter Three

Theory and Methodology

Introduction

In the previous chapter I surveyed theories, debates, and definitions organized around four themes: control, autonomy, self-organization, and life. Each of those themes is crucial to outlining aspects of the vital network across different disciplines and through ideas as diverse as biological self-organization and complexity, cybernetics and the artificial sciences, and posthumanism. If the last chapter traced the edge, or outline, of ideas, theories, and debates significant to the vital network, this chapter opens up the crucial elements of that space through vitalism, communication, and simulation. It furthers theoretical and epistemological manoeuvres necessary to move from object to process in this dissertation by linking the spatial dimension of assemblages to particular capacities and tendencies that structure it. The vital network is fundamentally open and dynamic, and the vitalist motif is intricately connected to the biological turn in computing, whereby more and more of the code and programming pivots on the logic of self-organization found in living systems.

In what follows, I examine the conceptual space Manuel De Landa calls the “space of possibility,” which he locates within his assemblage theory (2011, 5). De Landa argues that any assemblage is characterized by a set of emergent properties and by the structure of the possibility space that defines the assemblage’s dimensions by mapping its capacities and tendencies (ibid., 188). Determining the dimensions of a possibility space
requires the use of models and simulations that perform iterations (repetitions) of many possible outcomes (differences) using a continuously modulating set of inputs, variables, flows, and processes on the vital network. Simulations stage the encounter between emergent control processes based on mathematical models constructed from the biochemical processes of communication in microbes (in my dissertation), and the contingencies of a dynamic vital network. Chapter Five will examine how biological processes come to be modeled mathematically and coded in computational simulations. De Landa’s explication of the space of possibility (originally a mathematical concept adapted by Gilles Deleuze) is to see it as a diagram for the assemblage that can be modeled and manipulated in a simulation. The simulations can be run repeatedly disclosing the ways the assemblage may change—it enables scientists to see the objects and processes under study. As elsewhere in science, sight is privileged as the way of knowing the object: the disclosure is rendered visibly on screen as the simulation unfolds, giving scientists a line of sight into the control apparatus itself (how well the code functions) and visual cues as to its behaviour.

In the second half of this chapter I detail my three-stage research methodology, mapping the process and identifying key resources that were significant to the dissertation. I conducted research across three main areas in relation to biological inspiration: first, the areas of artificial intelligence, agent-based systems, networks, complexity, and self-organization within computer science; second, the microbiological literature addressing microbial communication (quorum sensing) and self-organization; and finally, philosophical and theoretical texts within sociology, science and technology
studies, philosophy, and communication studies. I had encountered processes of control in software in earlier professional work in information technology, but these were not biologically inspired algorithms. Earlier approaches to control followed a programming logic based in procedure, whereby error handling was programmed rigidly into the code scheme as opposed to the software responding dynamically to error conditions or changes as they emerged, which is the more common approach today. However, I understood control processes to be significantly complex, and thus one of the key questions I had at the beginning of this project was how do I, as a social scientist, make sense of the organizing logic of a vital network that self-regulates through processes of control modeled on nonhuman biochemical communication and self-organization? Early research during the literature review identified key questions and themes that raised important issues about the significance of biologically inspired control and how a biological attribute, for example ‘swarming,’ becomes a model of control for digital systems and networks and why that is significant for Internet functionality. What is the mobilization process for knowledge about biological complexity, and of self-organization in microbes, for application within the system of control necessary for our complex networks and digital systems? In relation to that question, it was important to identify how self-organization is understood within computer science, and where and how computer scientists locate knowledge about biological life and make sense of it in relation to a set of problems in computation.
Theorizing the Vital Network

Vitalism

John Johnston’s recent work details the nascent form of machinic life arising from a “new kind of liminal machine,” which mirrors the purposeful behaviour of living entities and is “increasingly directed toward its own autonomization” (2008, 1, 11). In the previous chapter, I outlined the original goal of cybernetics to build self-regulating machines, but computer science and engineering after the post-war period reached well beyond that goal toward autonomous systems with wholly emergent behaviours and capacities acting from within a “biotechnical matrix” to self-organize “following principles characteristic of living systems” (ibid., 13, 15). Johnson argues that a new machinic life is produced out of this emergent ‘soup,’ which continues to blur the distinction between life and technical objects and between the organic and inorganic (2008, 3). For some in computer science, such as artificial life researcher Christopher Langton, “to animate machines … is not to ‘bring’ life to a machine; rather it is to organize a population of machines in such a way that their interactive dynamics is ‘alive’” or capable of life-like functionality and adaptation, such that it elicits dynamic situational responses from single entities as well as in a wider electronic network (1989, 5; emphasis in original). This does not mean that networks or digital systems simply produce themselves, yet these autonomous processes, as part of a system or network, can, without direct human intervention, reroute information around broken network connections and make repairs, initiate self-diagnostic procedures, control data load balancing and download and upload speeds, and carry out analytical routines, and make
‘decisions’ (Biggins, Hiltz and Kusterbeck 2011; Dressler 2005). These capacities convey a sense of dynamism that has an ‘aliveness’ about it, and also reflects what Langton makes obvious: that it is not the singular machine, device, or process that need to be conceived as ‘alive,’ but all together, when viewed as a “population of machines” in a network, the multitude manifest a life-like quality. This sense of ‘aliveness’ or of becoming ‘life-like’ is what is taken to be vital; vitality emerges out of the interactions of many nonliving entities without central coordination. Thus for Langton, life arises out of dynamic processes and the dynamic form generated through those processes: life is a collection of processes that organize matter, and as such those processes can be simulated in an artificial environment to produce life-like behaviours (1995).

The notion of ‘vital’ has several entries in the Merriam Webster Dictionary: the definitions run from a ‘manifestation of life’ to being ‘full of life’ or having ‘characteristics of life.’ These definitions reflect a long history of vitalist thought from Aristotle to medieval theology, through Renaissance vitalism to the Enlightenment, and culminate, in many ways, in nineteenth and early twentieth century scientific debates about life (Burwick and Douglass 1992; Rousseau 1992). Vitalism complicates the open-ended and philosophically vexing question, ‘what is life’? It became an historical debate within biology and philosophy, instigated by Aristotle’s investigations into the ‘principle of life.’ Aristotle distinguished the living from the non-living by the capacity for self-maintenance invigorated by a ‘life force,’ or what he called entelechy (Rousseau

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10 Vitalism influenced nineteenth century Romantic and Gothic fiction, such as Mary (Wollstonecraft Godwin) Bysshe Shelley’s *Frankenstein* (1818), that betrayed a deep fascination with how life becomes life, and how it might be re-animated, revitalized, or regenerated.
1992; Thacker 2010a). This biological vitalism was an organized response to eighteenth century Cartesian dualism and its mechanistic descriptions of life—a response that suggested, yet could not explain, a “biotic energy” as the “source of all life’s phenomena … [a] special energy connected with the living organism” (Chiari 1992, 248). This idea of an enigmatic vital energy held an enduring fascination for many philosophers and scientists through the nineteenth century as a possible explanation for the growth and development of organisms (morphogenesis) and life’s complexity more generally. Modern biology, as a discipline and concept that arose after the Enlightenment, effectively refuted all notions of a ‘life force,’ what Henri Bergson called the *élan vital*, as the cause of life’s becoming by explaining ‘life’ through the structure and mechanisms of physics and chemistry, cell theory, and later the atomic sciences and genetic ‘codes of life’ (Rousseau 1992; Thacker 2010a; Wolsky and Wolsky 1992). I return to Bergson’s vitalism in the forthcoming chapter, and its importance to the work of Gilles Deleuze.

Yet the idea of vitality remains salient for sociology, politics, philosophy, and the artificial sciences, as Langton’s quote above makes obvious. Scott Lash views vitalism as relevant to the forces and convections of contemporary information flows, to the logic of flows, arguing that vitalism presumes some kind of self-organizing form (2005). Nikolas has taken up the theme of “circuits of vitality” to explain how elements of life such as DNA sequences, tissues, stem cells, and so on are accorded a new mobility and circulate between scientific stakeholders with diverse interests in the ‘biovalue’ of such elements (2007a; 2007b, 7). Rose argues that the politics of life itself (biopolitics) has become a vital obsession in circuits of capital, genetic codes, seed banks, and so on. In the social
sciences and humanities, vitalism has recently reappeared as part of a “new materialism,” as an ontology that emphasizes “active processes of materialization” that “affirm matter’s immanent vitality” (Coole and Frost 2010, 8). This ‘immanent vitality’ is not simply the matter of flesh and blood, of cells and genes that concern Rose, but of all sorts of matter including rocks, weather, and trash, all folded into planetary processes of life—the organic and the inorganic. The contemporary vitalism of ‘new materialism’ pivots on the becoming of life as active process. This vitalism is more a return to the view of all matter as lively, or as Jane Bennett labels it, a “vibrant matter,” which is not “raw material for the creative activity of humans or God” or a supplement to life, but an acknowledgement that there is a vitality or liveliness intrinsic to matter and materiality itself unfolding around myriad processes in the world (2010, xiii; and see Mitchell and Hansen 2010). This perspective is the impetus for re-thinking self-organization and communication as vital in my project. Digital systems and networks are not alive in a metabolic sense, like a dog or a slime mold, yet have propensities for action that unfold in response to coded processes that, as a matter of their operation, also generate further, unanticipated emergent processes of control. The processes have material outcomes for constituents, human and nonhuman, of the vital network: connecting cell phones or dropping calls, transmitting satellite images, searching data sources, downloading from the ‘Cloud,’ or streaming Netflix content. For human network clients, a vital network apparatus organizes events, opportunities, and transactions that are consequential. The logic of flows organizes the human as part of an inhuman network apparatus that governs itself—its material outcomes are the result of human-machine interactions, machine-to-machine
communication, coded processes, databases, signals, and all the digital bits and circuit boards in between.

For the vital network, the affiliation with life is rooted in, and routed through, the biological models that influence the design, coding and circuits that constitute the network. It begins with the coding decisions at the design stage of systems development, not simply after the implementation of the digital system or network, whereby metaphors are used to describe life-like functional properties. As above, the vital network includes the hardware infrastructure of networks, the processes, information, circuits, relays, switches, code and control that combine under more and more subsystems predicated on biological life and self-organization. This communicating array of heterogeneous entities and processes, which Tiziana Terranova (2004) calls the ‘hyperconnected many’ and which is for Langton (1989) a ‘population of machines,’ —[is] amalgams of organismal life and self-organization cleaved to the structural logics of the network. Lash, in his critique of information, argues that “[c]ommunication imparts to information a dynamic, a force: a source of energy” (2002, 204; emphasis added). This suggests communication is itself a vitalizing force, and as I go on to argue in this dissertation, the vital communication properties of nonhuman life underwrite the design of code and processes in new forms of control, embedding a particular control logic that is more swarm than carefully structured population, and more meshwork than network.

**Communication**

In 1990, and again in 1995, Deleuze offered tantalizing hints about the role of control in late twentieth century life. In his 1990 interview with Antonio Negri, Deleuze
refers to “control or communication societies” as those that “no longer operate by confining people but through continuous control and instant communication” dominated by cybernetic machines and computers that enable continuous monitoring (1990, 4). By 1995, Deleuze explained the control society more lucidly; control is numerical, modulating, transmutable and continuous, yet as noted in Chapter Two, this ‘postscript on societies of control’ did not bring the concept of either control or communication into dialogue with other aspects of his philosophical program in any detail. In the case of control, Deleuze understood it as code that would “mark access to information, or reject it,” but he was silent on the matter of communication itself in this context (1995, 5). At other points in his philosophy, communication is clearly important yet not clearly defined (Deleuze 1993b, 134; Deleuze and Guattari 1994, 108; and see Ansell Pearson 1999, 10). It conveys temporalization and movement; it ‘feels’ vital and lively. Communication is sometimes ‘relay’ or ‘circulation’ occurring between or among processes, events, and becomings; or a ‘resonance’ between orders, for example between a population and an individual; at other times it is an alliance, or fully a mode of communication suggestive of some form of exchange within a decentred network assemblage (Deleuze 1993a; Deleuze and Guattari 1987). Communication, as a concept, is adrift in Deleuze’s cosmology, yet entangled with processes of becoming—the processes of change, of difference, as a force or vector, that directs or shapes the becoming of the real. The more transversal the communication’s movement or relays, or the more it cuts across networks, environments, individuals, or institutions, the more acute its effects and change (I return
to Deleuze’s philosophy in detail Chapter Four to assemble the ontological foundations of my dissertation).

While Deleuze’s use of communication is never precise or definitive, it is nevertheless suggestive of flows, of circuits, and of a movement of forces that carry or convey potentials, possibilities, and creative affects. In the book *Critique of Information* (2002), Scott Lash argues for a sociology of communication that closely examines the logic of flows in critical response to the rise of ‘informationality’ over sociality, whereby communication processes now organize social relations. This does not mean that information replaces things such as the production of goods or social relations themselves; rather, information reflects the contemporary “order in which the principle of ‘society’ becomes displaced by the principle of ‘information’” (ibid., 75). Specifically, Lash understands communication as the dominant organizing feature of contemporary life for what he calls a “communications order,” which privileges information flows and networks over the social and symbolic order (ibid., xii; emphasis in original). The ‘communications order’ includes the technical processes that enable transmission of information between points or nodes on a network that consists today of many interconnecting circuits and paths, coordinating communication between and among humans, nonhumans, and machines. This technical aspect retains a foundational cybernetic logic: control is the order over a communication system that, at its simplest, is predicated on the sender encoding a message (information) and transmitting it through a channel to a receiver that decodes the message (although contemporary communication networks are multi-directional) (Banzal 2007; Walrand and Parekh 2010). In the vital
network, much as in Deleuze’s control societies and Lash’s information society, “control ‘matters’ through information—and information is never immaterial” (Galloway and Thacker 2008, 41). Yet, information and communication often become confused in this orientation: does one stand in for the other? Are they the same thing? Even Lash alternates between the ‘communications order’ and the ‘information order.’

Information is part of communication; it is the material exchanged amid processes of communication understood on the one hand as technical transmission, and on the other, as a component within heterogeneous network assemblages that are active, agential, and consequential (Boczkowski and Lievrouw 2008; and see Kittler 1999; Parikka 2010; Packer and Wiley 2012). In this dissertation, communication concerns the circuits and channels of networks, the busy meshwork of connections, processes, entities and infrastructure, whereby various types of information travel. Communication is not one, but multiple in a vital network. It is not one message sent in one direction; it is the profusion of contact, connection, signal, response, modification, routing and re-direction that happens in complex, dynamic systems. It occurs in biological organisms and digital systems. Human-constructed environments for communication within and through digital systems and networks produce a necessary condition for information flows that enable and organize human-to-machine (and machine-to-machine) contact and interaction through applications and services such as Google or wireless cellular services.

In my dissertation I signal a shift in how network capacities, applications, and services are controlled. Control over communication processes is an event outside of or beyond human-computer client applications: the matrix of control over communication,
while initially programmed by humans, increasingly takes a form that actualizes fundamental principles of biological life to be self-organizing, whereby purposeful action on the network emerges in response to all the traffic in communication (see Johnston 2008). The communication processes and information flows are always in flux, always responding to how human clients of networks use and interact with the network and control is emergent within that dynamic environment; it is directing but not directed, and it is unpredictable and full of unintended consequences (Lash 2002). For the purposes of my dissertation, the ‘communication order’ is about control, an explicitly nonhuman, distributed control that is opaque and emergent. I suggest that what Lash refers to as the ‘information order’ is aligned more with the logic of information flows: the circulation and organization of all aspects of life as information.

Communication is, of course, not only technical. Within communication studies and sociology, the notion of communication is understood across social, economic, political, and cultural formations and considered as an expressive act between individuals and communities, or between institutions and populations, in which ideas, meaning, attitude, argument, and understanding significant to human social and cultural life are conveyed (and see Peters 1999, 7-8; Lash 2002; van Loon 2008). My dissertation is not an argument for technological determinism, but rather an acknowledgement that network control processes, even when unseen or at-a-distance, are never inconsequential: they constitute a line of flight or deterritorialization of the network. Biologically inspired control within communication systems and networks has the capacity to act, but by no
means the capacity to solely determine social, political, technological, and economic life (see van Loon 2008).

For John Durham Peters (1999, 24), information is sometimes the “intellectual connective tissue” between different disciplines such as biology and computer science, and so too, I argue, it becomes the connective strand between the organism and the machine necessary to contemporary efforts to capture, contain, and code self-organizing behaviours found in biological life as simulations (see below and Chapters Five and Six). In the context of the study undertaken in this dissertation, Peters’ notion of ‘connective tissue’ is particularly helpful. Whether from Deleuze’s notion of communication as integral within processes of becoming in and for life, or Lash’s sense of energy and force within the logic of flows, communication itself is a dynamic within the vital network, and the challenge is to “diagrammatically map … the becoming-other of communication, to follow its flows and connective energies … asking how it works rather than defining what it reflects or verifies” (Genosko 2012, 16). Communication occurs across life forms from human to dog (Haraway 2008) and bacteria to squid (Bassler 2002; Margulis and Sagan 1986), and in human-constructed environments that merge human and nonhuman, machine, program, and process within a vital network and its possibility space.

**Assemblages: A Space of Possibility**

In *Philosophy and Simulation*, Manuel De Landa suggests that every aspect of life is a “space of possibility,” a space defined by the tendencies and capacities of entities, assemblages, networks, and flows, from thunderstorms to bacterial ecosystems (2011, 5-6; see also 2002). While De Landa (2002, 2006, 2011) has developed his own theory and
philosophy of assemblages and the space of possibility, his approach is in dialogue with much of Deleuze’s work. An assemblage is a concept developed by Deleuze and Felix Guattari (1987) and refers to wholes that are comprised of heterogeneous parts that arise out of processes of becoming and can include institutions, organisms, or, as in my project, the objects, processes and events that congeal in a vital network. Assemblages are characterized as having ‘relations of exteriority,’ meaning their constituent parts can and will detach from the assemblage and join with another (De Landa 2006). The network assemblage, as an example, has everything from cars, banks, and weather stations, to laptops, iPads, and cell phones connecting and disconnecting at any given moment. This mutability and movement of components maintains the heterogeneity and autonomy of the assemblage, but does not recreate the same assemblage elsewhere. There are continuous processes occurring that operate through tension: mutable forces that territorialize (stabilize) and deterritorialize (destabilize) the assemblage. While many things can alter the stability of an assemblage, control is a feature that is productive to change. In contemporary digital systems and networks control is fundamentally responsive (adaptive) to change.

The fundamental changeability of an assemblage, or its potential for change, is an important inflection point. The processes of control I discuss in my dissertation are complex and obscure by design, and fundamentally different than historic approaches to control centrally organized around a stable system such as pre-Internet networks; for the vital network the program of control within the assemblage is one of iteration (repetition) and change (difference). The control algorithms are designed to both respond to change
on the network (or in any digital system) and at the same time to expand their capacities through a self-learning routine programmed into their code base. This iterative, cyclical ‘learn’ and adapt routine produces a different outcome for the material and expressive properties of the assemblage. As network assemblages continuously vary and change, the operative capacities of control are increasingly difficult to follow. One approach is to work through the constitution of assemblages by examining them as a space of possibility; that is, a space through which to examine and diagram the possible ways the assemblage changes as the algorithms of control respond to variation in the system. In the context of my study, this approach situates the role of models and simulations within the space of possibility as useful for both biologists exploring nonhuman biochemical communication, and for computer scientists devising biologically inspired control algorithms.

In De Landa’s assemblage theory, the space of possibility encompasses the possible ways an assemblage may change in relation to its capacities and tendencies: capacities to affect are limitless, requiring only something to be affected, whereas tendencies are a particular finite set of possible states expressed when assemblages tend to act, or tend to do something (2011). Capacities make the assemblage exhibit features and behaviour that were previously hidden but become visible once affected—this is how control features in the vital network become fleetingly visible and affective. The vital network has capacities for control and self-regulation that affect communication and information flows dynamically, resulting in an exercise of control that alters the network, and it has tendencies, such as the tendency toward, or manifestation of, emergent and
unpredictable behaviour on the network, and together these shape the possibility space of the vital network. The vital network assemblage thus has an emergent property that is determined by its capacities and tendencies.

Through the concept of the space of possibilities, De Landa explores the role of computational simulation for conceptualizing emergence in assemblages in which different simulations “stage interactions between virtual entities from which properties, tendencies, and capacities actually emerge” (2011, 6). These simulations make the concept of emergence and its analysis intelligible in the study of complex, dynamic systems including weather, financial systems, bacterial populations, and digital networks, and they give analysts the ability to see the behaviour of a system. Simulations are crucial to the mobilization of knowledge about microbial communication processes using mathematical models that are implemented as computational simulations, as discussed in Chapter Five. Mathematical models of bacterial and slime mold communication processes are a diagram of the assemblage (the aggregate population of organisms) that can be manipulated computationally, and visually, in simulations to create the dimensions of the space of possibilities: that is, the ways the assemblage may change, revealing potential emergent behaviours and events that can be analyzed and taken as prototypical (see De Landa 2011, 189). The simulation as prototype is the technical means out of which to code control algorithms for the vital network, and Chapters Five and Six will detail these factors.
**Models and Simulations**

Models and simulation are intertwined with methods and approaches to sight in the sciences. The privileging of sight has dominated visual cultural history and philosophy. Plato argued that knowledge and ‘ethical universals’ must be accessible to “the mind’s eye,” Aristotle termed sight the “noblest of senses,” and René Descartes associated truth with “clear ideas and a steadfast mental gaze” (cited in Warnke 1993; see also Keller 2002). Hannah Arendt observed that “from the very outset, in formal philosophy, thinking has been thought of in terms of seeing,” until just after Henri Bergson’s decline in influence and the rise of analytical philosophy, in which language and discourse trumped sight (1978, 110; see also Levin 1993). But arguably, sight has remained crucial elsewhere and certainly in scientific disciplines. Lorraine Daston and Peter Galison (2007), in their study of objectivity and the way scientists see and perceive their research objects, propose that different epistemic virtues within particular scientific eras organized knowledge as a new way of seeing (see also Barad 2007; Keller 2002). Sight dominated scientific image making from the era of hand-rendered image atlases of the eighteenth century, to the new nineteenth and twentieth century tools required for mechanical objectivity such as photography and radiology (x-rays), and to the recent era of trained judgment, which combines complex apparatuses of sight such as electron microscopy, computerized tomography scanning (CT scans), and magnetic resonance imaging (MRI), with rigorous and repetitive training for human technicians and scientists to learn how to interpret the visual data (Daston and Galison 2007). Contemporary science maintains sight as crucial to knowing, but ways of seeing incorporate the move
from model to simulation whereby the image functions as a process through which objects are made not found; this is a constructive approach in which images are presentational and simulations are interventional—simulations permit the scientist to manipulate the model by altering the state space or properties of the space of possibility (ibid., 382-383; De Landa 2011; Friedman 2005). Scientific sight continues to use still images of objects under study—a drawing, x-ray, photograph, or digital still image—yet many of the sciences today, from biology to astronomy, incorporate computer simulation to ‘see’ their object, organism, or process interactively, whereby the objects become clickable, editable, and lively on screen (ibid., 383).

Simulations do not simply spring from the object under examination; they require a model that captures something about the object or process being examined. Models structure the space of possibilities that the simulation produces (De Landa 2011), and as will be detailed in Chapters Five and Six, simulations referenced in my project are grounded in mathematics that captures the behaviour of material processes, including the growth and form of microbes and their biochemical communication. Models can be considered idealizations that capture generalized processes, operations, action, and structure and can be put to conceptual work in science, the social sciences and communication studies to support theoretical suppositions and, in specific contexts, to conduct experimentation (and see Genosko 2012; Keller 2002).

In recent work Gary Genosko examines the role of models in and for the social sciences and communication, from cybernetics and information theory to explanatory models of communication processes for mass communication (2012). The models
relevant to my dissertation are scientific, which I detail in Chapter Five, and are not part of the specific history of communication models described by Genosko, but they are communicative, both in the sense of conveying a complex process of communication in organisms as well as in their role in mobilizing information from the domain of the biological sciences to computer science. However, what does resonate in Genosko’s analysis of models is his insistence upon a post-representational theory of communication, which turns away from categorization (classification), metaphor, analogy, and stable structuration, toward a Deleuzian emphasis on the materiality of communication as dynamic (2012, 16). For Genosko, models about communication ought to be more like they are in science: “productively configurational,” such that an understanding about the behaviour, process, object, or action can be understood through interaction with the model. In my dissertation this is how the biochemical communication circuits of microbial life function in a model that is presented in simulation; the simulation configures the many potential ways the vital network could change depending on how object-processes—coded objects and processes of control for networks—interact at the local level giving rise to global self-organizing behaviour across the network. As noted elsewhere and detailed in Chapter Five and Six, the control features of the vital network are in this way isomorphic to the organism, but never re/produce identical behaviour because the control algorithms are coded to mimic only the rules for interacting with the digital environment and information flows (rules extending from the model), and respond dynamically and uniquely to the problems within that environment.
Simulations not only invite a new way of seeing, but also open an ontological aperture into worlds of matter, objects, processes, and the nonhuman, wherein scientists make contact with their object of study and manipulate its capacities and tendencies. The profusion of contact between objects and processes of communication that produce particular consequences on the vital network requires analytical work to disclose, and simulations create visualizations of the space of possibilities for a given assemblage, and as such can help to reveal how obscure and embedded capacities for control are exercised on networks.

In recent work, Sherry Turkle argues that simulation wants to “propose itself as a proxy for the real” to generate alternate realities (2009, 80). These alternate realities, as noted above, actualize the emergence of “novel properties and capacities” arising out of a self-organizing machinic population or assemblage in the simulation creating a “space of possibilities” (De Landa 2011, 5). Yet, as Turkle emphasizes, this vision pivots on the simulation as a proxy for the organisms and/or the assemblage—it is not ‘the real’ but one possible ‘real’—the Deleuzian virtual potential actualized when the program executes coded parameters to create proximal life. Deleuze and Guattari argue that “[m]imicry is a very bad concept, since it relies on binary logic to describe phenomena of an entirely different nature” (1987, 11). In the research into control relevant to digital systems and networks under discussion here, the emphasis is not on the re-creation or

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11 The rise of simulation has fostered innovation in computer games. Ted Friedman notes, in his discussion of computer games, that simulations “communicate structures of interconnection” and are “allowing the individual not only to observe structures, but to become experientially immersed in their logic” within a simulation game (2005, under Cognitive Mapping). These simulation games include franchises such SimCity (Electronic Arts Inc.) and Sid Meier’s Civilization (Take-Two Interactive Inc.), which enable players to control and influence digital populations across technological, social, cultural, and economic aspects.
simulation of the world of digital creatures per se, in the sense of producing a synthetic
mimesis of a population of digital organisms that discloses something about biological
life in the abstract; rather, it is the rules and control features that model how such
synthetic populations interact, communicate, and self-organize (see Amos 2009).

Simulation is a way of “coding reality” such that the simulation becomes “a new
kind of power, a force that ‘produces reality; it produces domains of objects’” and
processes not otherwise seen (Loukissas 2009,169). Microbial objects and
communication processes mobilized across disciplines through simulation are productive
non-metaphorical constructs: simulations open the ontological aperture onto microbial
worlds in ways computer scientists would not otherwise see. Simulations move life to the
realm of ‘life-like,’ conveying detailed processes of vital communication that, once coded
in digital systems and network control, impart a dynamic, changeable, and self-capable
form of control and communication for engineered systems. The “slippage between
mechanism and model,” or between process and simulation, can amplify the distancing
effect of technology (Hayles 1999, 57). As the above discussion outlines, on the one hand
simulations can help analysts see how biologically inspired control is conceived by
computer scientists, and how it may function in its application in contemporary networks;
yet on the other, those same simulations operate as a prototype for the development of
control as part of the shift toward complexity whereby control processes are embedded
within the network and operate unseen.

Simulations based in biological inspiration are not simply copies or imitation for
the production of sameness or of something that is ‘just like’ nature (and see Barad
2007); rather, their very basis in organismal communication processes and self-organization produces constant difference and infinite spaces of possibility for the vital network. I cannot stress this point too strongly: simulation of biochemical communication in microbes does not recreate or replicate the organism in digital form and it does not recreate life. Simulation enables a deeper entanglement between computer science and biological life processes, but the software simulation is not actual life. The coding of communication processes and control produces capacities and tendencies in the vital network that are life-like and affective: we feel the vital network’s capacity for control when it is exercised, for example when our Internet is slow, or our password is rejected, or we successfully send a text. The concern reflected in my dissertation is over the opacity of that control, and its complexity, and the social and political implications of communication technology that organize most of life around a fundamentally different model of control (radically decentred) than has been in place over the last century (centralized).

Methodology

The idea of a line of sight into a complex digital system and network, much like the world Flynn thinks he will never see described in the opening of my dissertation, gestures toward the privileging of sight as a way to know the world. I have held a long interest in computing technology and networks—how they work, what they can do—stretching back to the early 1980s when the first desktop or personal computers (PCs) became available commercially, through more than twenty years of professional experience in the information technology sector. In this section I discuss the method I
developed and applied to see into communication and control, into the network, through an intellectually rigourous enquiry into the design and development of contemporary network processes, and in particular, how control is coded and functions when based upon specific biochemical processes of communication found in microorganisms. The combination of digital network complexity and obscurity means that as a sociologist I required a new analytical method to interrogate the material configurations of networks and communication processes that have a functionality, based in life systems, with significant implications for how other aspects of networked communication work. Adrian Mackenzie recently argued for moving the analytical “focus away from abstract understandings of code, calculation, and software to specific design processes,” mindful that “[u]ntil we can think of technical objects, machines, [and] ensembles in their own terms, then their role in constituting who or what we are remains shrouded” (Mackenzie 2009, 2; 2002, 3; cf. Feenberg 1990). I go further and argue that design inspiration is crucial to the direction and outcome of any system; where we find inspiration matters. My project intervenes in the sociology of communication and science and technology studies through a specific and detailed examination of the biochemical communication processes of microbes, tracing their form of molecular signaling through the process of model-making and simulation necessary for the design of communication processes of control intended to be distributed and self-organizing in the vital network. In this way, my project moves from microbe, to simulation, to control in order to detail the transversal becoming of matter in one domain transposed into another.
In part, my dissertation is also an evolution from work undertaken in my Master of Business Administration, in which I specialized in digital technologies broadly and software analytics specifically, or what was then known as decision support systems and now popularly as ‘big data’ analysis. These are algorithm-based analytical systems capable of autonomous decision-making in variable environments, using an artificial intelligence to sift through an enormous amount of data searching for patterns and relatedness between different types of data, including commercial, social, economic, and scientific, or any other large data set. In my Master of Legal Studies I narrowed that interest in an examination of autonomous data collection systems and the implications for individual privacy. I argued that in a society of control individuals are monitored, analyzed, sorted, and profiled by sophisticated analytics in which the database governs the constitution of the subject as a crucial instrument of control at-a-distance, whether by governments, state security agencies or corporations. In both those earlier projects, the aspects of control, complexity, non-transparency, and obscurity were crucial to maintaining overall system opacity as a feature of those systems. This dissertation looks more closely at how such features of control are conceived and designed to be self-regulating systems coordinating flows of information and communication, and do so with increasing complexity and obscurity, which amplify the distancing effect between human clients of the network and the processes of control.

The Research Process

My research method was organized around the substantives in my dissertation, which tracked three key moments that explain how biological inspiration is incorporated
into the digital domain: thinking first in terms of Deleuze’s notion of differentiation from the one to the many; secondly, from organism to simulation, through the use of models to describe microbial processes in informatic terms that can then be simulated on a computational platform; and finally, from description to control, through the progression in computing from an emphasis on structure and descriptive procedures, to processes of control. In the main, my research process followed that template to explore the ‘becoming-machinic’ of microbial life through the capture of their biochemical processes of communication and organization in informatic terms, first through mathematical biology, and then rendered as simulation on a computational platform. This trace can be simplified as a movement from microbe to simulation to control.

At the start of my research, I read two popular technical books that each addressed an aspect of my project, alongside a third academic text that helped me organize my project and identify key questions and themes. The first was Steven Johnson’s (2002) *Emergence: The Connected Lives of Ants, Brains, Cities, and Software*, which re-works the logics of cybernetics as adaptive, self-regulating feedback systems to explain everything from the self-organization of the city to ant swarms and the Internet. This book introduced me to the research on microbes and self-organization and its application in computer science. It seemed significant that nonhuman organisms so utterly different from humans provide such a radical notion of decentred control. This book raised three important questions for my project: first, what must occur to graft the biological complexity of self-organization in microbes onto the system of control necessary for our complex networks and digital systems?; second, how is self-organization understood
within computer science?; and finally, where and how do computer scientists locate knowledge about biological life and make sense of it in relation to a set of problems in computation?

The second book was Alexander Galloway and Eugene Thacker’s (2007) book *The Exploit: A Theory of Networks*. The book’s goal was to assemble a theory for a biopolitics of the network as ‘living networks,’ and a ‘becoming-swarm’ to explain network self-organization. It merged Foucauldian biopolitics with Deleuzian control in the abstract, but there was no sense both of how contemporary networks might be swarm-like or what was distinctive about the features of control that instantiated such a profoundly nonhuman mode of, and for, control. What is swarm intelligence and why does this organismal attribute become a model of control for digital systems such as networks? How does the Internet behave like a swarm? Why is that a significant formation for how the Internet functions?

The other popular text I consulted was Janine Benyus’ *Biomimicry: Innovation Inspired by Nature* (1997), which did not examine the specifics of any one program of self-organization, but looked broadly at the issue of nature as inspiration. The book details three concepts: “nature as model,” whereby forms and processes of nature can perform as models for innovation; “nature as measure,” whereby nature serves as the “ecological standard to judge the ‘rightness’ of our innovations;” and “nature as mentor,” to encourage a new appreciation of nature based in learning from it, as opposed to extracting proprietary commercial value from it (from *Biomimicry*, front matter;
emphasis in original).\textsuperscript{12} Benyus’ book was very popular, and tapped public enthusiasm for ecological and environmental knowledge through her examination of how nature has inspired human innovation, emphasizing ‘inspiration rather than imitation’—although she refers pointedly to biomimesis, which is the imitation of life. In the context of my dissertation, her book motivated me to look carefully at what terms computer scientists are using to describe technology that innovates, adapts or constructs a system or solution found in nature.

For Benyus, there is a “hard distinction” between humans and nature and her narrative of biomimesis extends human effort as exceptional—humans are unique and thus positioned to take from nature—thereby ignoring the agential doings of matter, of nature, concentrating instead on imitative design as commercial inspiration for proprietary development (Barad 2007, 368-369). Benyus’ work made the idea of nature’s capacities for problem solving accessible to the public. However, biomimicry and biomimesis are not terms that have (yet) been taken up in the scientific community. In the academic literature, one term or short phrase dominates the computer science and engineering journal articles, monographs, and conference proceedings concerned with inspiration found in nature: ‘biological inspiration’ and ‘biologically inspired’ technology.\textsuperscript{13} For this reason, I adopted the term ‘biologically inspired’ as the main

\textsuperscript{12} Biomimicry, while in part promoted as a way to appreciate nature’s ‘genius’ and, through Benyus’ Biomimicry 3.8 project and foundation, to encourage environmental awareness, preservation, and appreciation, is also directly linked to industry development and retains an element of ‘extraction’ versus simply ‘appreciation’ of nature (see http://biomimicry.net/about/our-people/founders/janine-benyus/; and see Barad 2007; Frenay 2006). Benyus and her colleagues advise companies to turn to nature for inspiration as a beneficial and sustainable corporate innovation strategy; however, this strategy seems to extend tropes of control, of harvesting nature, of mastery over nature, and to be similar to what Donna Haraway calls “salvation drama,” whereby nature will more or less save us from ourselves (2004, 243).

\textsuperscript{13} In directed searches in computer science and engineering databases ((IEEE)Xplore and ACM Digital Library),
concept for the technology explored in this dissertation. Systems that are biologically inspired are also systems constituted in the technical literature as having artificial intelligence (Brooks 1999; Bongard 2009). In the artificial sciences, there is no single definition for ‘biological inspiration,’ just as there is no single biological process, structure, pattern, or behaviour that can serve as inspiration. In the broadest sense of the term, it signals the biological turn in computing toward various systems in nature, whether human-animal neural networks, fish scales, bacterial swarms, bat ‘sonar,’ or bird flight, which can be adapted to solve a computational problem. My attention is tuned to software (computer programming or codes), not hardware, which is designed to control larger digital systems and networks, but wherein processes, properties, and attributes found in a biological organism are emulated in software. Biological inspiration serves many disciplines including computer science and software engineering, but also specializations in those broad fields such as robotics, biomechanics, materials science, and nanotechnology (Bar-Cohen 2006; Bongard 2009).

I conducted my research and document analysis in three phases after an initial literature review. Each of these phases represents intensive research and analysis that link to my substantive chapters—though I did not always complete each stage before beginning work on another—and as I developed my ideas I often had to return to each substantive subject. The first stage maps to the philosophical and theoretical texts within sociology, science and technology studies, philosophy, and communication studies that ‘biological inspiration’ returned 2164 results, whereas biomimicry returned 38 and biomimesis only 5. The term ‘biomimetics’ returned 4796 results, but biomimetics appears with the qualifier ‘biologically-inspired’ (Bar-Cohen 2006).
helped me construct the ontological aperture through which to view the object-processes of control emerging in contemporary digital systems as constitutive to the vital network. This stage enabled me to assemble the theory and philosophy in the first part of this chapter and in Chapter Four, but it also contributed to the expansion and reorganization of theoretical aspects of the theory and literature review in Chapter Two. In the second stage, which informed Chapter Five, I examined the microbiological literature addressing microbial communication and self-organization; and in the third, I studied the technical literature contending with biological inspiration, artificial intelligence, agent-based systems, networks, complexity, and self-organization within computer science and systems engineering discussed in Chapter Six.

is more detailed than Katherine Hayles’ (1999) cultural history of cybernetics and the posthuman. It introduces the notion of ‘machinic life,’ and was a key resource in shaping the conceptual boundaries of the vital network. De Landa’s philosophy and theory on the space of possibilities and assemblages was an important resource that offered a counterpoint to the idea of machinic life in which I consider the vital network as a vibrant, dynamic, and changeable whole (a space) rather than strictly as a domain of and for a novel form of life.

I examined key philosophical works by Deleuze from *Difference and Repetition* (1993) and *Bergsonism* (1990) to *A Thousand Plateaus* with Felix Guattari (1987), a challenging entry point into thinking differently about communication and information technology and a vital network. Deleuze prompted me to think about control, in particular through its conception as an emergent process within a complex and heterogeneous assemblage or network, as in-process; as dynamic, changeable, and differentiating, making control difficult to grasp as it moves away from or outside of direct human coordination. Thinking with Deleuze also brought a focus to the detail about biological communication in bacteria and slime molds that literally forced me to think differently about those life forms and to appreciate that their capacities for becoming-other, from singular organism to multicellular assemblages, present computer science with a radically different model for control, one that is outside of the rational and calculated model of control that governed communication and information technology for much of the nineteenth and twentieth centuries. Deleuze also contributed an alternate vocabulary that relies less on human social terms to describe inhuman systems, processes, and action—
things, events, organisms, processes, and humans all ‘become’ and they ‘differ’ (I discuss these aspects in later chapters). This vocabulary is important to my effort in the dissertation to explain biological inspiration and autonomous systems that exhibit altogether different capacities and tendencies than classically controlled communication systems for which humanist language worked to describe their characteristics organized around the human. Yet, there are many places in the dissertation where I use language bound to humanist terms to describe quite different, nonhuman processes. Biologists and computer scientists rely on human social terms to describe their systems, whether organismal or artificial, and whereby bacteria ‘decide’ or machines ‘think,’ and my work reflects those terms, which I most often place in quotes to distinguish their human social origins (and see Chapter Five and Six).

In the second phase of my research I followed the research trail from computer science back to biology. To a large extent the wider field of research into bacteria owes much to the ground-breaking work of Lynn Margulis, whose work I relied on to situate and explain the role of bacteria in and for life on the planet through endosymbiosis (see Chapter Five) (Margulis and Sagan 1986). The book *March of the Microbes: Sighting the Unseen* (2010), by John Ingraham, was foundational to my understanding of bacteria as a life form and, together with Margulis’ work, *showed* the bacterial multitude as it is in planetary life, whereas most journal research on bacteria is limited to reporting on laboratory findings. For the specific features of bacterial communication, the work of

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14 Margulis’ work demonstrated that bacteria are entangled in every aspect of life, organic and inorganic, and that the eukaryotic cell (a cell with a nucleus and organelles) emanated from a series of endosymbiotic mergers in which various organelles of eukaryotes evolved symbiotically with bacteria (the endosymbiont), including cellular mitochondria (the cellular energy producer) (and see Hird 2009).
Bonnie Bassler at Princeton University on bacterial quorum sensing (QS), the biochemical signaling process in bacteria detailed in Chapter Five, was a key resource and highly referenced in computer science and engineering and in microbiology. The research into bacterial communication is very active and productive, and new disclosures about bacterial signaling and QS emerge through new techniques in analysis tied to improvements in electron microscopy and chemical signal detection (Bassler 1999; Bassler and Losick 2006; Ben-Jacob and Levine 2006; Diggle et al. 2008; Williams et al. 2007). Bassler’s research into bacterial QS guided my investigation of the biochemical processes of bacterial communication. Her published work was very technical in terms of mapping the biochemical circuitry (detailed in Chapter Five), but Bassler has also worked to publicize bacterial communication through TED Talks and public venues and this made her science much more accessible for my project (2009). In this way I could move between the highly specialized microbiological publications about QS and conceptual models in Bassler’s academic research and her public work. In microbiology, some conference proceedings debut new research, but the main secondary sources were found in peer-reviewed journals such as Cell, the Journal of Bacteriology, and Proceedings of the Royal Society B: Biological Sciences.

I used a similar process to investigate slime mold self-organization and communication, as there is an effort to publicize the science around slime mold path-finding (Fricker 2010; Latty 2010; and see Chapter Five). Peer-reviewed findings are published in some of the same journals as research on bacteria, but also in Science and the Journal of Theoretical Biology, and much of the research cites the work of John T.
Bonner (1999; 2000; 2009), a pioneer in slime mold research. Research on slime molds has benefited from a well-developed interdisciplinary tradition between decades long research on slime molds, mathematical biology, and computer simulation (Adamatzky 2010; Bonner 1999; Keller 2002; Keller and Segel 1970). The contributions of the philosopher of science, Evelyn Fox Keller, whose own work detailed the importance of modeling and simulation in relation to slime mold self-organization (2002; and with Segel 1973), was a crucial source for my project. In particular, I drew on Keller’s (2002) book *Making Sense of Life: Explaining Biological Development with Models, Metaphors and Machines*. Keller’s book details the genealogy of the scientific practice of using models, metaphors, and simulations to theorize about biological life and it makes connections between cybernetics, biology, mathematics, and the informationalization of life (bioinformatics) explicit. This provided a map as to how to locate historical influences, within my dissertation, that are significant to the discourses around biology and technology that share language, concepts, and terms (and see Chapter Two). In Chapter Five I examine bacterial signaling and communication and slime mold spatial path finding and trace their significance as models for nonhuman control. I created simulations that modeled slime aggregation following the description of the rule set available in NetLogo software based in Craig Reynolds’ ‘Boids’ program (1987). These exercises and the models that were generated are detailed in Appendices I and II, and were immensely productive to grasp the simplicity in self-organization expressed in algorithmic terms.
In the third phase of my research, I limited my research to software-based systems and not robotics, as I was interested in the codes of control that are developed for software systems. I refined my research within biological inspiration through specific searches for correlated terms such as ‘control’ and ‘self-organization’ and ‘network,’ and this produced material on biologically inspired models of control for digital systems and networks. If I searched ‘self-organization’ in computer science and engineering databases, it returned results similar to the search for ‘biological inspiration.’ Computer science and engineering research relevant to my dissertation is published in peer-reviewed collection series including Lecture Notes in Computer Science (LNCS) and the IEEE Explore and ACM Digital Library academic databases, and there is a strong tradition of peer-reviewed conference proceedings and edited volumes over journal articles. One key source was Christopher Langton’s (1995) edited volume, Artificial Life: An Overview, which has a diverse collection of chapters on self-organization, emergence, and artificial intelligence, reflecting particular specialties including cellular automata, computer modeling, autonomous software agents, and learning algorithms. This volume was instrumental to my technical understanding of important foundational concepts that figure in autonomous computing systems.

As I proceeded through academic sources in the artificial sciences, a term inclusive of computer science, systems engineering, and artificial life and intelligence research, it was clear that many of the assumptions that guided mid-twentieth century cybernetics continued to govern contemporary research: researchers kept self-regulation and autonomous functionality for digital systems as a central goal for a diverse range of
technologies, from washing machines and automobiles to cellular phones and the Internet (Bucher 2012; Dove 2011; Thrun 2010; Riva et al. 2005; Winograd 1991; Wright and Steventon 2006). From the IBM guidelines (see Chapter Two) on autonomic computing to later proposals for autonomous systems that extend them (detailed in Chapter Six), the notion of a self-regulating machine, of a computational platform that could ‘think’ and calculate and ‘decide’ was persistent in the artificial science research, but with one crucial distinction or difference. Contemporary research into control had clearly moved on from the solitary, rational actor as a model of computation in cybernetic machines, and the human-animal model of cognition as inspiration, to a model inspired by nonhuman organisms, and in particular, inspiration drawn from ‘brainless’ organisms that exhibit a collective swarm intelligence, such as ants, bacteria, and slime molds (Brooks 1999; Dorigo and Stützle 2004; Froese 2007; Langton 1995; Maes 1995). Projects that maintain an interest in a machine that can mimic human thought and decision-making, such as IBM’s ‘Big Blue’ chess-playing computer(s) and ‘Watson,’ the Jeopardy television show digital ‘contestant,’ continue to pit the human against the machine in the spirit of Alan Turing’s imitation game and to make the subject-object distinction obvious—machines are objects, and humans are subjects (Hamilton 2009, 151). However, in terms of my dissertation, those systems are not foremost in my research; rather, I focused on the nonhuman, on the swarm, and on programmed control that has shifted away from the human (see Chapter Two and Chapter Six).

In the computer science research into self-organization and control, the literature was replete with references and models inspired by the swarm intelligence of ants
(Dorigo and Stützle 2004; Johnson 2002; Ramos, Fernandes and Rosa 2005), bacteria
(Amos 2009; Bassler 220; Norris et al. 2011; Peysakhov et al. 2006; Beckmann and
McKinley 2009), and slime molds (Bebber et al. 2007; Nakagaki, Yamada and Tóth
2000; Tero, Kobayashi and Nakagaki 2007). While social insects, and in particular ants,
are detailed in Jussi Parikka’s (2010) work as a provocation for thinking ‘organismically’
about media whereby social insects perform as an object-to-think-with in media design
and theory and as a form and organization for ‘insect media,’ there was no close
examination of how social insect self-organization is translated to network control or its
appropriateness beyond the swarm metaphor. In contrast, it was apparent very early in
my research that bacteria and slime mold behaviour is modeled in computer simulations
that provide a prototype for digital network design and control (and see Amos 2005;
Beekman, Sword and Simpson 2008; Ben-Jacob, Aharonov and Shapira 2004). How are
these simulations created? What was different about the biochemical processes of self-
organization in bacteria and slime molds that it produced research activity in computer
science in which the simulation generated behaviour isomorphic to the organism?

As I proceeded in my analysis, I was struck by the philosopher Isabelle Stengers’
observation that discussions about philosophy often slip into comparison, which “always
entails the risk of reducing philosophical thoughts to a matter of opinions to be compared
from an outside, apparently neutral standpoint” (2009, 28). For my effort to construct the
vital network as a space of possibility through specific forms of life that are emulated in
machinic processes, and to look to philosophy to assemble an explanation of this space,
Stengers’ concern is valid. I endeavoured to strike a balance between mobilizing
philosophy and theory to scaffold my conceptual framework, and at the same time trying
to theorize anew.

As the above discussion outlines, my documentary research extended across
several disciplines, each with their own complex theories, observations, and ideas that are
peculiar to specific domains of biology and the artificial sciences. In an effort to ensure
my own understanding and interpretation of such highly specialized knowledge, I sought
out the expertise of a scientist in microbiology, as well as systems developers in
computer science and engineering, who served as subject matter experts (see the list of
projects and labs in Appendix III). The purpose of my dissertation was not an
ethnographic study of scientists and laboratories. Therefore, my consultations with
subject matter experts was to verify that, at least in broad terms, I understood the key
aspects of the specialized communication processes and self-organization in microbial
life systems as they are documented in microbiological literature, and the use of
biologically-inspired models in computer science and systems engineering necessary to
designing and developing network control and functionality.

Although there were laboratories and research centres in both microbiology and
the artificial sciences that were not amenable to contact and discussion about my project
(and see Appendix III), I was fortunate to make contact with engineers in two
engineering projects researching autonomous systems, and a biologist researching slime
mold path finding. I spoke with engineers at Carleton University’s Technology Assisted
Friendly Environment for the Third Age (TAFETA: Smart Systems for Health) and the
University of Toronto’s Intelligent Assistive Technology and Systems Lab (IATSL). I did
not deploy a structured interview technique, given that I was not investigating their laboratory process, practice, or research agenda; rather, I used the opportunities to discuss my methodology and technical understanding. I contacted Tanya Latty, a Canadian researcher working at the University of Sydney in Australia, after hearing her interviewed in 2010 on the CBC radio program, *Quirks and Quarks*. Latty was outlining research into slime mold path finding and its capacity for ‘computing’ many possible solutions to the problem of food scarcity, location, quality, and energy expenditure (versus quality of food source) (and see Latty and Beekman 2010). The discussions I had with these subject matter experts substantiated my research direction at early points in each of the first two stages and also brought the notion of Peter Galison’s ‘trading zones,’ which I had encountered in my research, into focus (1997).

Galison proposes that interdisciplinary communication and information exchange occurs across “trading zones” between different scientific disciplines and projects. While these exchanges may not begin as explicitly collaborative exercises, they may become so, and hold a benefit for each discipline in spite of their different research agendas and culture. It was apparent in my research that biology and computer science have found a productive trading zone in spite of the fact that they are “groups with different technical traditions,” because they mingle in artificial life conferences attended by microbiologists, theoretical biologists, computer scientists, and philosophers (Galison 1997, 275; and see Langton 1995; Goujon 2006). As Norris *et al.* (2011, 212) suggests: “[i]f microbiologists and computer scientists are to interact fruitfully, microbiologists need to have an idea of some of the problems that are of interest to computer scientists whilst computer scientists
need to see solutions—perhaps to other problems—in the knowledge and intuitions of microbiologists.”

Trading zones are not only for speaking about a shared interest or topic, but are highly diverse spaces that may be negotiated by information and objects, such as mathematical models and computer simulations, that permit the sharing of highly specific forms of knowledge in one domain with another. A trading zone is demonstrated by Dr. Tanya Latty’s work with mathematicians at the University of Leipzig, an effort that began informally and has evolved into a direct collaborative research project. Latty’s research objectives are situated around her requirement for a quantitative model that can describe biochemical pathways as part of the slime mold guidance systems that have proven very difficult to isolate and understand in the physical world. The research project at the University of Leipzig is interested in using slime mold self-organization as a model for network design based in shortest path or network optimization strategies (Latty 2010; personal communication). In this instance, the groups of biologists, mathematicians, and computer scientists have a shared interest in developing mathematical models that describe microbial communication and self-organization, although their research goals are quite different; and yet, these scientists can “productively trade objects and information without having the same understanding of the exchange” across trading zones (Loukissas 2007, 168; Galison 1997, 46).

**Chapter Summary**

The chapters in this dissertation follow a progression from the literature review and theoretical framework to the detailed microanalysis of the substantive aspects of self-
organizing microbes, and then to the biologically inspired developments in technology that follow. In the first part of the dissertation, the contours of the vital network were mapped through the Introduction and the literature review in Chapter Two. In the preceding discussion I drew on key terms that are threaded throughout formative literature, theory, and debates relevant to the dissertation, but not adequately theorized in Chapter Two, including communication, vitalism, models and simulations, moving toward the space of possibility as a conceptual ground that enables a shift from epistemology to ontology taken up in the next chapter.

Chapter Four is a philosophical intermezzo: it approaches the vital network through the tensions and problems of two different and opposable frameworks, those of linguistic construction and material theories of reality. It starts from a discussion of object philosophy and the move toward a new materialism, which contributes to a shift from epistemology to ontology prevalent in recent scholarship attempting a re-engagement with the forces and effects/affects of a material world. The purpose is to examine the opportunities for an ontological approach to the vital network, devising a way to ‘see’ and understand the vital network emerging out of the growing complexity of network and systems not easily understood through linguistic construction nor only object philosophies. Object philosophical approaches that seek to explain reality in material terms are a powerful oppositional framework to linguistic construction and its claim that knowledge of the world, of reality, can only be explained through language and discourse. While I am congenial to a theory of reality constituted by relations between objects, I argue for an analytical framework that looks through an ontological aperture
into worlds through matter, through the nonhuman, and through things-in-process. This approach, I argue, is best understood through Gilles Deleuze’s theory and philosophy, wherein there are no levels of being and no special status for the human over the nonhuman, and in which the genesis of the real is immanent in the world.

Deleuze fashions his philosophical program by re-working three Bergsonian terms: difference, multiplicity, and becoming. Henri Bergson outlined his metaphysics of life in *Creative Evolution* (1922) as essentially creative, durational, and in constant flux—a wholly integrated sphere of life in a state of continuous becoming through self-regulation. For Deleuze and Bergson the notion of a multiplicity replaces the traditional philosophical notion of essences, and so is foundational to the ‘repetition of difference,’ a difference that is produced through morphogenic processes within and as part of the becoming of life. This approach enables a theoretical and philosophical approach that can conceptualize the becoming-life of microbes explored in Chapter Five and the subsequent creation of those life processes assembled as working simulations that provide inspiration to forms of control and organization in digital systems and networks.

In Chapter Five, I turn to the modes of vital communication and self-organization of bacteria and slime molds. The emphasis in this chapter is on particular aspects of microbial communication and bacterial quorum sensing and slime mold network path finding, that have so far proven to be an inspiration to computer science and engineering in the design and development of digital systems and networks. The fact that microbes have so far been incorporated into models of vital communication that can be adapted for control within digital systems makes them a fascinating object to study. Microbes have
innovative capacities for a vital communication in social bodies, which enable them to become-other: microbes go through a radical differentiation as part of their life cycle, transforming from singular organism to univocal assemblage. The assemblage has astonishing capacities for habitat formation, foraging, and other environmental adaptations. This aggregate entity is not reducible to any individual organism. The singular bacterium or amoeba cannot behave in ways the multitude does; rather, it takes on a new form with its own set of properties. The differentiation of the microbe from singular organism to the multitude proceeds through a complex biochemical communication process that effectively measures chemical gradients in its surrounding environment and passes signals to other microbes to begin a process of aggregation and self-organization of a vast assemblage of networked microbes. Understanding this process offers a line of sight into which particular self-organizing control processes become biological inspiration for the design and development of human constructed technical systems for networks.

Mathematical biology is crucial to the construction of models that quantify and informationalize the capacities and processes of cell-to-cell communication, cellular differentiation, and self-organization in microbial life, and are, in turn, rendered as computer simulations. The capture of these life processes in simulations simplifies informatic translation between biological life and the computational milieu, making it easier for computer scientists and engineers to access this mode of life and its vital communication and self-organization routines and then design coded processes for computation and digital control based in biological life. However, what results is a
radically different model of control over digital systems and networks that ‘feels’ lively and vital and is capable of self-regulation and control.

In Chapter Six, I examine current research in computing that draw on life systems, such as the microbes detailed in Chapter Five, highlighting the shift toward ‘smart’ systems and distributed control necessary for the vital network. This chapter details the movement away from the human-animal model of cognition and control of cybernetics, to the biologically inspired control of distributed and interacting agents, software, and processes. It explores the features of a vital network around the notion of control as it has changed in response to three inter-related shifts: the shift from computing power to so-called smart systems; from mechanisms and structures of control to coded processes and emulation; and from procedural logic to distributed control. Taken together, those shifts intensify efforts in computer science to design self-regulating systems, in which communication is key to the unfolding of self-organization, autonomous functionality, and distributed control across the network. Achieving these features ensures that system complexity is obscured beneath simplified surface applications effecting a gap between human network clients and the complex systems of control organizing digital communication and transactions. Control has thus expanded its reach, while at the same time ‘softened’ its routine through self-governing processes of control that coalesce within a new ‘abstract machine’ (and see Deleuze 1995; Galloway 2010; Terranova 2004). This abstract machine normalizes the rational calculus of algorithmic control, which surveys more of life’s activity, transactions, and communication so that it becomes an ordinary consequence of the vital network.
Chapter Seven revisits the questions and concerns addressed in the dissertation. It reexamines the features of communication, self-organization, autonomous functionality, and distributed control that constitute the vital. I reiterate the concern over the outcomes of autonomous control processes that amplify the distancing effect and growing gap between human clients of networks and the self-organizing features of control. Obscurity, I argue, is the goal of programmers, who want to push the boundaries of autonomous systems ever farther, but obscurity is also the goal of private corporations and governments that have a variety of motivations for keeping citizens and human clients of the network at-a-distance from the organizational features of the vital network.
Chapter Four

From a Philosophy of Objects to a Philosophy of Process

Modernity is often defined in terms of humanism, either as a way of saluting the birth of ‘man’ or as a way of announcing his death. But this habit itself is modern, because it remains asymmetrical. It overlooks the simultaneous birth of ‘nonhumanity’—things, or objects, or beasts (Latour 1993, 13).

Introduction

In the previous chapter I explored some of the key terms and concepts that were first encountered in Chapter Two as part of the literature review to establish how aspects of vitalism, communication, and simulation are implicated in the space of possibility and the vital network through Manuel De Landa’s assemblage theory. Here my aim is to establish a philosophical approach that joins with the conceptual notion of a space of possibility by exploring the move from language to object to process, providing a more nuanced understanding of how the turn to biological inspiration in the twenty-first century, accompanied by renewed interest in vitalism and biophilosophy, can explain the behaviour of, and subsequent implications for, contemporary digital networks and autonomous systems necessary to vital networks. As discussed in Chapter Two, biological inspiration is by no means new to the artificial sciences, philosophy, or theories about social and political organization. What has occurred, however, is an intensification of its application in computational systems, underwriting the expansion of software used in communication and information technology (CIT), and in many other
digital system that rely on increasingly complex computational systems to collect, transmit, process and analyze information.

For much of the twentieth century the privileging of language and discourse across the humanities and social sciences led us away from matter, a matter that was too often seen as inert, lifeless, and passive. This chapter examines recent philosophical responses to the predominance of linguistic constructivism of the last half century, in an effort to bring ‘the material’ back in and to reconsider the interconnection and inseparability of the human and nonhuman in the world. New materialist views are, as Diana Coole and Samantha Frost point out, giving us an opportunity to rethink “the whole edifice of modern ontology regarding notions of change, causality, agency, time, and space,” and to locate new “capacities for agency” that are not exclusively human:

For materiality is always something more than ‘mere’ matter: an excess, force, vitality, relationality, or difference that renders matter active, self-creative, productive, unpredictable. In sum, new materialists are rediscovering a materiality that materializes, evincing immanent modes of self-transformation that compel us to think of causation in far more complex terms (2010, 9).

Bruno Latour’s reflection, which opens this chapter, concerns the world’s nonhuman constituents, objects and things, and is a lament, in a manner of speaking, over modernity’s attempted erasure or removal of such things from having any power or agency in the world. Yet much of the contemporary world functions around a network logic that is predicated on communicating with and through things or objects, and that is in turn increasingly enabled by a self-regulating and self-organizing network. Taken philosophically, Latour’s concern is modernity's rigid separation of nature and culture, of
subjects and objects, in which the human became the central feature of social and political life and communication. His interest in materiality and an embrace of things, of a sort of ‘thing-power’ attributed to actor-network theory (ANT) (see below), has informed wide-ranging scholarship, from sociology and science and technology studies (Haraway 2004; Hird 2009; Lash 2002; Suchman, Blomberg and Trygg 2002), to philosophy (Bryant 2011; Harman 2009), communication studies (Galloway 2004; Galloway and Thacker 2007; Packer and Wiley 2012; Thacker 2010b; Wise 2012), and politics and law (Bennett 2010; Coole and Frost 2010; Hildebrandt 2011, 2013). In this chapter, I start from Latour’s things and move to Gilles Deleuze’s processes of becoming by working through the shifts necessary to navigate from a strictly analytical position, which understands reality as produced through language, to one which recognizes how “matter comes to matter” (Barad 2003, 801). This is a crucial maneuver, I argue, for understanding networks as material assemblages and the role of the nonhuman as inspiration within the development of processes of control and communication in/of the vital network.

**Thinking With Matter**

Latour’s philosophy of objects brings matter and material objects, things as actants in actor-network vocabulary, forward to a place in which the human and nonhuman figure relationally (1988; 1999; 2005). In this approach, the human and the nonhuman interact in relation, producing a distributed agency that confers no special status to any thing (object or entity) or ‘actant’ assembled in the ‘actor-network.’ Action and agency are thus not a “property of humans but of an association of actants” humming
along in dynamic relation; the more articulations or interactions between actors and actants, the more stable objects and networks become (Latour 1999, 182). In actor-networks, such occasions of interaction between actants, human or nonhuman, produce moments of stability or ordering that generate consequences that can be ‘seen’ or sensed by an observer or observational apparatus (Latour 1999; and see van Loon 2008). This observer could be a human or just as easily be a piece of software programming that records and relays the action, but it is this visibility or appearance of consequential, measurable action that signals or exposes that something is happening. The emphasis on visibility in an actor-network, in which “the reality of a thing is defined by the ways in which it is registered by other entities,” suggests that the “relational theory of actors borders on a kind of verificationism” to define the reality of an object (Harman 2009, 112).

Emphasizing visibility and presence, over absence and invisibility, makes what is present to apprehend—a thing, an object, an actant—‘counted’ or ‘accounted for’ in the network of relations of the actor-network; however, what is unseen (though not necessarily absent) remains undetected because it lacks the amplitude of many relations through which it would gain more force and more visibility (Latour 1999, 196; van Loon 2008, 142; and see Harman 2009; Star and Bowker 2006). In many ethnographic studies of science and technology actor-network theory works well to uncover the performative basis of the “ecology of practice” within the socio-technical collective (Stengers in Zournazi 2002, 262), but such an approach does not easily reveal aspects of code and software design common in contemporary digital systems and networks, in which
processes and functionality are designed to be non-transparent, to be unseen (Bucher 2012; Chun 2011). Given this limitation, while actor-network theory has much to contribute in terms of ‘seeing’ the nonhuman and constructing a reality that has an agential, material basis in which all actors and actants matter, it does not offer a strong framework for the analysis of a mode of control, or of the design for network self-regulation, that “privileges surface over source” and “hides itself at exactly the moment when it expresses itself most fully” (Galloway 2010, 292).

While these are limitations to actor-network theory in terms of my project, I want to recognize the part of Latour’s work that highlights the gap between linguistic construction and material theories of reality. Through actor-network theory and beyond, Latour poses a complex challenge to the established ways of knowing and seeing the world that rests upon philosophical and scientific notions, deeply entrenched through and beyond the Enlightenment, which Latour calls the modernist or “old settlement” (1999; 1993). For Latour, “we have never been modern” (1993): it is only that we settled on the discrete separation of nature and culture and called it modernity, thus preserving the Kantian duality of subject and object, of reason and culture, cleaved from the separate and unattainable beyond—nature. Latour’s commitment, therefore, is to unsettling modernity’s grip on reality by fashioning what he calls a new settlement to resolve “the fundamental issues of language and reality posed by modernity,” which assumed an unbridgeable fissure between nature and culture (Hekman 2010, 7).

Several scholars have worked to ‘think with matter’ and to scale the wall between discursive and material theories of reality from Karen Barad (2007) and Donna Haraway
Hekman offers a keen reflection on the limits of linguistic construction in direct response to Latour’s lament over modernity’s failings. Hekman’s own project is to describe a critical social ontology, but her argument is that linguistic construction, while important, is not enough to grasp the dynamics of a material world. She argues that new settlements are emerging from, or can be grasped within, a series of scholarly efforts in response to the epistemological “modernist predicament,” which carves out a strict division between the knowing subject and the outside world, and a linguistic constructionism that “constitutes the reality that we as humans inhabit” (Hekman 2010, 1). For Hekman, these new settlements signal a shift in emphasis away from epistemology toward ontology, bringing matter forward and addressing all at once “ontological, political, scientific, and technical issues” (ibid., 67; see also Coole and Frost 2010). The philosophical synthesis found in both Barad’s and Hekman’s work is instructive: it highlights how analysts can work to incorporate sensibilities gleaned from linguistic construction while at the same time come to ‘see’ that matter ‘matters.’

In pursuit of a similar material reality, Barad argues that “agential realism” provides an “understanding of the nature of the relationship between discursive practices and material phenomena, an accounting of ‘nonhuman’ as well as ‘human’ forms of agency” within technoscientific collectives (2003, 810; 2007). For Barad, agency emerges out of the entanglement, the interplay or “intra-action” between theory, matter, and language. Her work is an important precursor to Hekman’s intervention into the dominance of language over matter as Barad forcefully suggests, “[l]anguage has been
granted too much power. The linguistic turn, the semiotic turn, the interpretative turn, the
cultural turn: it seems that at every turn lately every “thing”—even materiality—is turned
into a matter of language” (2003, 801). Barad’s thesis proceeds from the idea of the
entanglement of “things-in-phenomena:” that objects are disclosed through intra-relating,
that is, how objects relate and the phenomena observed have something significant to
reveal about the objects themselves (2003, 815; 2007; 2010). This notion bumps up
against Latour’s object-centred universe in which, as Graham Harman notes, “Things in
themselves lack nothing” (2009, 24; and see Hird 2009, 340). For Latour, objects are
simply there, even when unseen by humans; they are concrete and “a sense of the proper
reality of objects apart from all their alliances” within actor-networks persists (Harman
2009, 24-25), such that “every actant makes a whole world for itself” (Latour cited in
Harman 2009, 25; and see Bryant 2011; Latour 1988). This is an important distinction:
for Barad, the primary ontological unit is the phenomenon, not the object itself, and
agency is produced in the intra-action within an inseparable entanglement of the observer
(or the observational system) and the object.

My differences with Hekman, Latour, and Barad are not so much an abrupt
departure away from object-centred philosophy nor their particular recuperation of
materiality, but a movement toward Deleuze’s philosophy, and the biophilosophical
approach it inspires among scholars in dialogue with his work, including Keith Ansell-
philosophy permits analysis of the processual aspect of the vital network: it opens an
ontological aperture into worlds as in-process. It enables disclosure of nonhuman worlds and networks of relation that do not privilege the human and facilitate correspondence between a Deleuzian philosophy of assemblages, that is, the linkages, connections and transitory forgings of matter, and the articulations, translation, and forces of Latourian metaphysics. Where Hekman’s emphasis lies in the latter, I emphasize the former: Deleuze’s philosophy and theory is conducive to an understanding of information technology broadly and for my examination of vital networks.

Deleuze’s philosophy, as I discuss below, offers an approach for apprehending the dynamics of shifting network connections based on demand; of objects joining or leaving the network with rapidity; and of control structures morphing in response to the network itself. A biological model of communication and self-organization for digital network control fundamentally shifts the idea of stationary, static control over stable objects toward one of dynamic self-capability and self-regulation not reliant on persistent human intervention, but rather, enabled by a vital, organically mutable code of control that emerges in response to many different system cues and an Internet of communicating processes and things.

Thinking With Bergson

There are important connections in Deleuze’s work to the philosophy of Henri Bergson, which appear most concisely in Bergsonism, but continued to shape Deleuze’s thought throughout his other work alone and with Guattari (1990; 1993a). Bergson’s philosophy was motivated, in part, by the turn to increasingly mechanistic explanations of biology and of organic life (as distinct from the inorganic), alongside the shift in
philosophy in his lifetime from matter to language. His philosophy also flowed from an understanding of the world through what he called ‘life itself’ with particular emphasis on aspects of time, difference, and change; aspects that would profoundly influence Deleuze’s philosophy of difference (Bergson 1911, 1922; Deleuze 1993a). Bergson believed that the dualisms of positivism, the “intellectual construct” of mind/body and of nature/culture, gave priority to a “mechanical reality” in which consciousness is ‘out front’ directing the show (Lehan 1992, 308, 325; Mullarkey 1999, 2000). Bergson posits the universe as an interconnected milieu in which the *élan vital*, or creative life force, gives life an internal push that joins with the material world (Bergson 192215, loc.1588, 1629; Lehan 1992, 326, 327). As outlined in the preceding chapter, in the twentieth century, biologists distanced themselves from any notion of an invisible, vital force in favour of mechanistic explanations of life, which gained an increasing power as new technologies enabled advanced molecular analysis for scientists to view the complex molecules and genetic material of life (Wolsky and Wolsky 1992). Contemporary biophilosophy rejects both mechanistic explanations and the more mercurial *élan vital*, adopting instead an approach that considers matter and material flows as in-process (I expand on this term below).

For Bergson, writing as he was in the early twentieth century, questions about the matter of life itself were paramount. His work provides a turning point for contemporary biophilosophy and for an understanding of vital communication and networks. I have

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15 The electronic version of Bergson’s *Creative Evolution* (1922) consulted for my dissertation is no longer under copyright and the citations refer to the location (loc.) in the file and not the original published book page numbers. I am using the academic citation style recommended in the Chicago Manual of Style for author-date referencing of electronic books that do not have the original hard copy book page numbers.
already detailed key aspects of vitalism in the preceding chapter and its important link with the vital network, and in this section I look specifically at how Bergson’s philosophy is important to Deleuze’s principle of becoming. One of Bergson’s contributions to philosophy lies in his claim to “mediate between idealism and realism, subjectivism and objectivism, and even between science and metaphysics” (Douglass 1992, 372); that is, between the empirical, reasoned, logical abstractions of mechanistic science that produce facts about the world and objects (and distinguish mind from universe), and on the other, a more organic, intuitive belief that the universe (nature) is inseparable from mind and we are ourselves entangled in it (Lehan 1992, 311).

_Creative Evolution_ (1922) outlined Bergson’s metaphysics of life as essentially creative, durational, and in constant flux: a wholly integrated sphere of everything living “in a state of continuous becoming and self-regulating … from bacteria to the biosphere and noosphere” (Chiari 1992, 254). For Bergson, life is a continual and non-linear state of becoming in which everything is a matter of duration. This is not time in the sense of clockwork and sequential movement; this is a temporal “virtual realm of creative processes and becomings” (Ansell Pearson 1999, 11). Duration is part of “the growth of information,” likened to deep memory about ourselves and the world through the “cultivation of a ‘sympathetic communication’ that it seeks to establish between the human and the rest of living matter” (ibid., 24). Bergson’s duration, then, is a whole feeling of living matter connected through processes of becoming real—this is the aspect of life as in-process taken up in contemporary biophilosophy’s engagement with vitality and materiality. Bergson’s vitalism was important to Deleuze’s philosophical
development in the shared notion of a life’s becoming real, of a flow and movement to
life that gives it its dynamism and changeability, yet their vitalist programs differ in an
important way. Bergson’s turned on the unseen forces of the élan vital, whereas Deleuze
writes of passive vitalism as a “disrupting and destructive range of forces” very unlike the
active vitalism of Bergson that “posits ‘life’ as a mystical and unifying principle”
(Colebrook 2010, 142).

Alongside his differences from the vitalist tradition, it is difficult to categorize
where Deleuze’s thinking on life sits within philosophy. There are complications in
attempting any correspondence between what is sometimes labeled process philosophy
and an object-centred metaphysics discussed in the preceding section, but both are
speculative philosophies. Considered speculative because of an engagement with reality
itself through the “ontological vision of an asubjective realm of becoming,” rather than
through everyday experience, speculative philosophy is a response to analytical
philosophy’s emphasis on the analysis of texts and the structure of consciousness
(Bryant, Srnicek, and Harman 2011, 4; and see Debase 2009). In process philosophy,
processes rather than objects are identified as the main feature of the real; an object is
understood by what it does and not what it is (K. Robinson 2009; Stengers 2009, 2011).
Bergson understood that an “object exists in itself” (1911, loc. 46), yet from his
perspective simply enclosing facts about objects within knowledge does not really tell us
much about the object, whereas the processes of becoming give an object, and indeed all
of life, its shape. For Bergson, the object is an entity that emerges through the unfolding
of continual processes of life and this is primary within his philosophy. In Alfred North
Whitehead’s process philosophy the same sort of plurality of processes and movements persists (“all things flow”), and the object is known as an “actual entity” given as “the final real things of which the world is made up;” it is the “plurality of actual entities” conjoined in/by relatedness that dominates over the quality of the thing itself ([1927-28] 1978, 206; emphasis added).\textsuperscript{16}

Deleuze, Bergson, and Whitehead each use the term ‘event’ within their philosophy. For Whitehead, “events are relational and interlocking ‘movements’ of activity out of which the actual makes itself” (Whitehead 1919, loc. 1929). For Deleuze and Bergson, the event is considered dynamic and intensive; events in and of life are instances such as a birth, writing, and speaking, which produce the sense of the world, and life itself is constituted by “events of difference” (Colebrook 2002, 31, 33).

The similarities and differences between Latour and Whitehead, and Latour and Deleuze, do not make either pairing a perfect understanding of process or objects. Within Whitehead’s philosophy there is talk of processes and of things, and through his “ontological principle” he posits “definite actual entities” in the world that arise in a process of becoming (Harman 2009, 101; Stengers 2009, 2011; cf. Whitehead 1919). However, as Graham Harman has noted, “[for] Bergson and Deleuze … becoming is what is primarily real, and discrete individual entities are derivative of this more primal flux or flow” (2011, 292). It is not that objects do not exist for either Deleuze or Bergson, but they are not stable fixtures set amidst a static reality. Deleuze drew on Bergson and to

\textsuperscript{16} Where Bergson had his \textit{élan vital}, Whitehead holds to God as part of his cosmology. God is an affirmation of both “creatures of creativity and the conditions of creativity” (Stengers 2011, 450; cf. Whitehead 1978). Whitehead notes in \textit{Process and Reality} that, “God is an actual entity, [as] is the most trivial puff of existence in far-off empty space” (1978, 207).
a lesser extent Whitehead, and it is to Deleuze’s philosophy that I turn to explore the possibility of a synthetic theory that peers through the ontological aperture toward the idea that reality is becoming or process as a central feature of the vital network, a vital reality populated by things, amid self-governing communication processes.

**Thinking With Deleuze**

The development of Deleuze’s biophilosophy draws on significant aspects within a wellspring of philosophy including Benedict Spinoza, Gottfried Leibniz, Immanuel Kant, David Hume, Whitehead, and Friedrich Nietzsche, among others (Deleuze 1990, 1993; and see Deleuze and Guattari 1987, 1994; Douglass 1992; Due 2007; Marks 1998). Deleuze’s philosophy is challenging to define: it is part process philosophy and part speculative realism that, as Reidar Due suggests, is a “speculative account of reality [wherein] the human being is not presented as a conscious centre of action and belief” (2007, 1). It is a metaphysics of immanence: there are no levels of being, no special status for the human over the nonhuman, and no transcendence of being by deities or thought outside the world. Rather, the genesis of the real is immanent in the world and “life itself is a process of creative power” (ibid., 7; Colebrook 2002, loc321). This genetic or creative principle accounts for reality through three re-worked Bergsonian terms: difference, multiplicity, and becoming, which pivot upon Deleuze’s notion of the virtual, the actual, and the intensive in the genesis of reality as a set of potentials (Deleuze 1990, 1993; Deleuze and Guattari 1987). The term ‘genetic’ for Deleuze, as it is used here in relation to his philosophy of difference and becoming, denotes the genesis or germinal force of creative becoming and not the contemporary science of molecular genetics.
Deleuze views difference as a primary trait of all that is (1993). The concept of difference moves across Deleuze’s philosophical program, but is featured cogently in *Difference and Repetition* (1993), in which it is really as much about the difference of repetition wherein becoming never produces exact sameness. Difference is a differentiating process and an intensive continuity that is creative and productive to new modes of being: an ontogenetic force of relations such as in/through multiplicities and assemblages (Douglass 1992, 375; Parikka 2010, xxii-xiii). Within Deleuze’s philosophy the dynamic structure he calls a ‘multiplicity,’ which comes from the mathematics of Bernhard Riemann and is interpreted by Bergson, is thus crucially important to difference. Multiplicities define or specify the structure of a space of possibility (as do capacities and tendencies) and are immanent to material processes that give form to processes such as self-organization, but not the final entity or assemblage (De Landa 2002). Multiplicities do not have a fixed identity, and they are not divisible, nor are they simply a combination of the one as the many. They are heterogeneous and require no fixed order.

Bergson ([1913] 2001) identified two types of multiplicities, durational and spatial, and Deleuze labels the former as an ‘intensive multiplicity’ and the latter an ‘extensive multiplicity’ to correspond with “the dynamic movement of temporalization and change” that is the becoming of the real (1990; K. Robinson 2009, 221; Deleuze 1993). Intensive multiplicities are virtual, continuous, indeterminate, and an expression of “pure potentiality”; whereas an extensive multiplicity is actual, spatial, territorialized, and
determinate (K. Robinson 2009, 228; and see Ansell Pearson 1999).\textsuperscript{17} The virtual is the condition for the genesis of real experience that may resolve or be actualized in a determined or local moment, process, or act: “the virtual is not realized but actualized, and the principles of actualization are not resemblance and limitation but difference and repetition” (K. Robinson 2009, 234). This means a multiplicity is not a unity; nor is it preceded by a unifying force, and it replaces the traditional philosophical notion of essences. It is composed of heterogeneous flows yet is different than each singular part or flow that constitutes it. Thus, intensive multiplicities are understood as potential expressions that are actualized through a progressive determination of relations, a pulling together, if you will, of more and more divergent strands or processes of becoming and out of which assemblages emerge. Difference itself generates this flow of potentials, which remain virtual until actualized, resulting in “the production of the actual things of the world” (Protevi 2012, 3). A multiplicity is, therefore, indeterminate, yet holds the capacity to be affected and once it has developed an actual consistency is “the most basic element of being, a something which can be affected by forces [and once] affected it is organized as a set of relations” (Due 2007, 131). This set of relations and potentials of the multiplicity is comprised of relays that congeal in a particular sort of composition central to Deleuze’s later work: the assemblage.

As I discussed in the preceding chapter, Manuel De Landa has developed an assemblage theory rooted in Deleuze’s philosophy, but has disassembled or opened up the assemblage to its constitutive parts as a space of possibility, making it a more

\textsuperscript{17} The virtual within Deleuzian philosophy should not be taken to correspond with contemporary accounts of the Internet or cyberspace as a virtual space.
practical and analytically productive theoretical framework put to work in my dissertation, whereas Deleuze’s particular use of the term for his philosophy is more abstract. Deleuze’s assemblage, a translation of the French word *agencement*, denotes a “composition of forces” that can act “to produce a specific agency” (Due 2007, 132-133). It is not a cohesive theoretical construct for Deleuze, but appears most pointedly in *A Thousand Plateaus*, where it figures as part of the expression of “dimensions of a multiplicity that necessarily changes in nature as it expands its connections” to form an assemblage (with Guattari 1987, 8). An assemblage is thus an emergent, self-organizing entity, stabilizing around an arrangement of parts that include “any number of heterogeneous elements—‘things’ or ‘parts of things’” that can act upon social, linguistic, and material flows and processes (Van Wezemael 2008, 170-171; Deleuze and Guattari 1987, 22-23). Assemblages stabilize when variable processes are fixed or territorialized, and hold a degree of internal homogeneity—though assembled from heterogeneous flows or inputs—giving the assemblage a visible boundary or edge that marks out an identifiable territory for it (De Landa 2006).

As examples, human institutions and organizations are recognizable assemblages comprised of human workers, parts, and processes from building infrastructure and material components to labour practices (De Landa 2006). Cars and washing machines are assemblages comprised of many parts, but in Deleuze’s universe not all assemblages are the same. An assemblage once formed cannot be broken into constituent parts. It is not derivative; when it disperses it does not reduce to any particular original form(s). Its
disparate parts dissolve back into the flows out of which new assemblages arise.\textsuperscript{18} A washing machine dismantled is no longer an assemblage; its disassembled parts do not individually wash clothes. Do washing machines therefore become, do they differ in the Deleuzian sense? They may well if we consider them as an assemblage that is slowly decaying with its parts rusting, and through which new assemblages form in relation to bacteria and water in the scrap heap, but commonsense suggests a far less radical end at the point of disassembly in the scrapyard. Deleuze’s philosophy is highly abstract, but its role here is to provide a conceptual framework in which continuous change and differentiation are recognized as powerful forces significant to complex, dynamic assemblages such as organisms and their circuits of communication as well as to digital networks. To that end, Deleuze’s theory and philosophy “performs its conceptual duties” in turning our attention toward the processes that assemble heterogeneous parts into wholes (De Landa 2006, 3; and see for related discussion Hacking 1999). The aforementioned examples highlight a simple explanation for what is a difficult Deleuzian construct, but the case of communication and information technology is also an assemblage.

Communication and information technology systems (and networks) are assemblages comprised of flows of the human and nonhuman, of information, of their environment, machines, wires, pixels, networks nodes, and more. For Deleuze, the assemblages that constitute networks are subject to organization in which “controls are a

\textsuperscript{18} Processes of territorialization also include social profiling as “non-spatial processes which increase the internal homogeneity of an assemblage, such as the sorting processes which exclude a certain category of people from membership in an organization,” such is the case of no-fly lists that exclude profiled individuals from boarding commercial aircraft, based on a security profile that marks them out as high risk (De Landa 2006, 13; and see Haggerty and Ericson 2000).
modification … that will continuously change from one moment to the next, or like a sieve whose mesh will transmute from point to point;” these interlaced lines and points form a highly unstable and continually changing network grid (1995, 4; emphasis in original). This modulation ensures persistent coding and decoding processes of control within and across distributed meshworks or complex, de-centred networks, which affect organization and structure across social, political, economic, and technological domains facilitating networked digital transactions of all kinds. Control, in this configuration, is a destabilizing force or “line of flight,” which disrupts and “determinatizes” the flows of the assemblage (Deleuze and Guattari 1987, 4, 9).

In the context of communication and information technology, Deleuze understands coding and decoding as a part of the numerical language of computers, but not strictly as binary code (the ones and zeros of computing code), rather, as the passwords and authentication that enable inclusion in and exclusion from networks for human and machine (1995). Communication processes destabilize spatial boundaries by operating across jurisdictions, places, and time zones, and no entity, actor, or process need be physically co-located or present to communicate. This lack of co-presence and the sheer heterogeneity of communication processes is fundamentally deterritorializing (De Landa 2006, 13; cf. Deleuze and Guattari 1987). Deterritorializing forces always disrupt the ordering of the assemblage and these forces include the continuous change within digital networks as information flows expand, network connections increase or decrease, and data pathways re-organize to accommodate network load balancing.
Networks are capable of dynamically forming entirely new assemblages by adding, dropping, or rearranging elements.

Deleuze and Guattari also draw upon the notion of the rhizome in assemblage theory, a term taken from the root structure of certain plants that grow in a profuse tangle, as a model to illustrate the branching connections of assemblages and deterritorializations (1987, 5). The rhizome is conceived in process terms as consisting of “partial processes which are not integrated within a structure,” where the relationality is always shifting and never exactly reproducible (Due 2007, 129; cf. Deleuze and Guattari 1987). For network theorists, in terms of imagining the sheer profusion of connectivity in contemporary networks, social and technological, the rhizome has become a powerful model for the “ordered set of relations in which each element relates to every other, without any hierarchical, functional or centralized order being imposed” within the network (Due 2007, 129; and see Galloway and Thacker 2007). Deleuze and Guattari’s rhizomatic ordering is thus understood as a form conveying the dynamism of contemporary distributed digital networks in which connectivity is not bound to central nodes or hubs that provide hierarchical coordination across entire networks. However, in my dissertation I do not invoke the rhizomatic model because it has been overly simplified in its extraction from Deleuze and Guattari’s complex plane of thought; it has become a convenient graphical representation of contemporary networks as a tangle of connected network nodes (1995; and see Galloway 2004; Galloway and Thacker 2007). By contrast, the vital network is not a representation of a biological system. It is isomorphic to
particular biological processes, and its behaviour emerges out of the interaction of local network nodes and processes.

Assemblage theory is strategically important to the vital network precisely because it describes entities, matter, and flows as in-process, as dynamic and changeable wholes capable of acting. Networks are an “assemblage of information nodes” (Bogard 2009, 29), and of abstract, autonomous control, which focus our attention on what things do and how they act, by identifying the “productive connection of elements” in articulation (Currier 2003, 332). It is important to note that Deleuze neither alone, nor with Guattari, engaged directly with computational machines (computers and computing) or with what Johnston (2008) calls the “computational assemblage” within communication and information technology. Nevertheless, I argue that their work provides a framework for understanding the vital network and the various autonomous and self-regulating communication processes at work there.

Ansell Pearson makes clear that for Deleuze and Guattari, machines are processes or “systems from the ‘biological’ to the ‘social’ and economic [that are] made up of machine assemblages, complex foldings, and movements of deterritorialization” (1997, 125). Extending this “machinic philosophy” to physical computing devices, given the preceding discussion, is obvious if we consider that contemporary computing devices are at the very least a machinic assemblage comprised of physical components (hardware), programmable software, information, and humans (and see Johnston 2008; Protevi 2012). From this perspective, the generative processes in vital communication and information technology are a “becoming machinic” necessary to self-regulating vital networks (see
In Deleuze and Guattari’s *A Thousand Plateaus* (1987), the abstract machine is a deterritorializing force that is neither corporeal (material) nor semiotic (141). The abstract machine is not insignificant to assemblage theory, and it figures in the analysis of the spatial and territorial arrangements of social stratification and power within an assemblage, in which the abstract machine operates as an intensive ‘deranging’ or deterritorialization process within the assemblage (as diverse as the processes of social profiling within surveillance assemblages or in institutions) (Due 2007; Haggerty and Ericson 2000).

The notion of “becoming machinic” signals a “new process of dynamic self-assembly and organization in new types of assemblages” within a “space of machinic becomings [and] an increasingly self-determined and self-generating technology” (Johnston 2008, 107-108). This new ‘space’ corresponds to Deleuze and Guattari’s “machinic phylum” constituted by transversal movement across assemblages, elements, and forms “freeing matter and tapping forces” (1987, 335). The machinic phylum is “materiality, natural or artificial, and both simultaneously; it is matter in movement, in flux, in variation, matter as a conveyor of singularities and traits of expression.” It suggests an interface between human and nonhuman, organic life and artificial life, combining aspects of both (Deleuze and Guattari 1987, 409; and see Johnston 2008, 107).

In other words, it is the register of the nonhuman constituent, of human-machine couplings, the cyborg, the intelligent software agent, and of self-regulating network control operands.
In Chapter Five, in the context of microbial communication networks, it is this “becoming machinic,” and the ‘life as information’ relation, that brings the affects, intensities, and potentials of microorganisms into the machinic phylum through bioinformatic capture: the detailing of quantifiable and measurable chemical signaling among bacteria and slime molds that model communication and self-organization applicable to complex dynamic networks.

**Univocity**

While much of Deleuze’s philosophical program is speculative in its turn away from linguistic philosophy and everyday experience, he is considered a philosopher of immanence (Due 2007; Bryant, Srnicek and Harman 2011; K. Robinson 2009). For Deleuze, the idea of an immanent being in the world, as opposed to a transcendent being, comes from Spinoza’s principle of immanence: “[to] be is … is to belong to nature” (Due 2007, 36; see Deleuze 1993, 35; Thacker 2010a, 116-119). Deleuze’s commitment to immanence underwrites much of his other philosophy with its convolutions and compositional attributes discussed above, such as multiplicities, assemblages, and even rhizomes, each with its roots in genetic thought as a “process of immanent differentiation” that produces reality (Due 2008, 39; Deleuze 1990, 1993). At each turn, the genetic or creative process Deleuze proposes evokes the principle of univocity. Univocity was taken up Scholastic debates in the late twelfth through to the fourteenth centuries over the idea of ‘life itself’ and of what ‘life’ is explored through the “relation between the life-that-forms and life-forms” (as creatures) that bring univocity into close relationship with vitality itself (Thacker 2010, 103, xi). The univocal principle posits that
being can be understood as the same for all in life—in this view even deities differ only by degree from other life in the world (considered an heretical position in the Middle Ages) (Deleuze 1993; Thacker 2008; 2010a). Univocity enters Deleuze’s philosophy through the thirteenth century philosopher Duns Scotus, and Deleuze acknowledges his attachment to the idea that “Being is univocal. There has only ever been one ontology, that of Duns Scotus, which gave being a single voice” (1993, 35). Deleuze argues that all being is univocal and therefore “[u]nivocity of being thus also signifies equality of being” (1993, 35). Univocity, as expressed by Deleuze, becomes the theoretical abstraction for what is an expression of the self-organization of life. This is important here insofar as it denotes that a whole is greater than the sum of its parts, that the drawing together of disparate entities and elements is together a unity capable of acting and being acted upon as one, understood as “univocity-through-assemblages” (Thacker 2008, 140).

‘Univocity-through-assemblage’ is the instrumental feature of emergent action which arises out of self-organized life such as with bacteria or slime molds: what the aggregate does is utterly different from the individual microorganism, and the process of aggregation, of assembling, is itself about differential relations gathered together as a wholly new mode of being and action. Microbial life is able to transform from the one to the many, and this transformation, between sameness and difference, defies categorical clarity by becoming so obviously other-than-itself in a continuous process of creation. In the next chapter I explore the particular forms of life that disclose a communicative and self-organizing capacity and are providing biological inspiration to a new generation of
computer scientists and systems engineers seeking to expand the self-regulating capacities of contemporary digital networks.

**Synthesis**

Neither Latourian metaphysics nor Deleuzian biophilosophy is an ideal approach to develop an ontology for vital networks and an understanding of vital communication. As the preceding discussion shows, we can take from Hekman’s synthesis of multiple strands of philosophy and theory, language and the material, a model for a set of creative analytical manoeuvres to disclose aspects of vital networks. If we accept Hekman’s insistence to forge ahead with Latour’s call for a ‘new settlement’ then it seems necessary to sheer off a thin piece of what object theories can tell us about connecting with nonhumans, combined with Deleuze’s program in which the material world is a continual process of becoming.

Latour and Whitehead furnish an object-centred approach that opens the door to worlds in dynamic relation (or at least we see the door), and Deleuze and Bergson remind us that contemporary systems are in-process, becoming, and ever-changing. In both cases, and even with the differences between these philosophies, each takes us beyond our anthropocentric realm of human self-consciousness and reason and into the material messiness of simply becoming. And becoming is a happening, a mangling, a materiality, a process that inhabits the mettle of networked connections, both in our human social worlds and in relation to our hyper-connected neighbours, be they animal or machine.

Harman suggests that “[f]or Latour there is no stream of ‘becoming’ compared to which momentary states are a mere abstraction: becoming is produced by actors, not
presupposed by them,” and therefore actor-networks must be viewed as a happening-in-the-now, not as precursors to what will happen in the future (2009, 144-145). I argue that Deleuze is not talking about presuppositions brought about by stationary actors/actants, but about actualization through a process of continual becoming for all things in life. A Deleuzian approach to the becoming of the real can be construed as full of potentialities: of potential paths and diagrams of possible relation. This will be particularly well illustrated in the next chapter through the capacities of slime molds to generate this sort of potential, topologically-driven future, which has been mobilized as a model for digital network design (see Adamatzky 2010; Tero et al. 2010).

**Conclusion**

De Landa (2006) views assemblage theory as having an emphasis on relations of exteriority and crucially on what is present or absent, where absence indicates the “existence of borders separating one network from another,” (56) and, I would add, the absent (or invisible) layer, interstices, or sub-level that contains the code enabling network system self-regulation. The surface arrangements of digital systems, the user interface and user applications (such as Facebook or Google) are privileged in our communication and information technology and obscure the complex computer code that enables the more sophisticated capabilities of programs themselves (such as Google’s search system). Uncovering these capabilities is critical to disclosing their autonomous functionality.

Deleuze inspires a biosophy that resists the anthropocentric lure of describing life through the lens of human attributes and social meaning, for one that
focuses on “modes of biological life that simultaneously escape being exclusively biological life” such as microbes, swarms, packs, and flocks, as a “whole bestiary that asks us to think the life-multiplicity relation” (Thacker 2008, 136; see also Bell 2007, 110; Deleuze and Guattari 1987). Deleuze’s work is often concerned to address what life itself is: what he calls biological life, or organic or nonorganic life, or sometimes simply a life. In early work he makes explicit contact with Bergson’s “creative evolution” and process-oriented philosophy (1990), and as co-author with Guattari in A Thousand Plateaus (1987), Deleuze’s own creative thought and philosophy meet biological life in a direct engagement with (and against) orthodox biology, a point I will expand on in Chapter Five. This fascination with classical biology, in particular the aspect of classification and taxonomy that is so much a part of modern biology, informs Deleuze’s work with Guattari, and I will revisit assemblage theory in relation to two distinct biological life forms, bacteria and slime molds, in the forthcoming chapter.

In this dissertation, my goal remains the explication of vital communication processes of control that are assembling a new form of network; a highly adaptable and contingent grid of connections that function without constant human intervention and that are part of the machinic phylum, not because they are a ‘monstrous coupling’ of life and machine, but rather because they are a new assemblage (and see Haraway 2004; Johnston 2008). This assemblage conjoins bacterial syntax and slime mold rational calculus to the growth and expansion of digital networks in contemporary society with its ever-expanding requirement to automate more and more of our digital transactions and communicative exchanges. It is to these microorganisms that I turn in the next chapter, as
specific examples of organismal life that provide biological inspiration to twenty-first century computing and communication technology and underwrite the shift to self-organizing and self-regulating digital systems.
Chapter Five

Vital Communication

Introduction

This chapter explores the meeting of biological life and computational simulation in the “machinic phylum,” where as noted in the preceding chapter, materiality can be “natural or artificial, and both simultaneously” in a constant movement from the one to the many, producing variation and differentiation through the interface between human and nonhuman, organic life and artificial life, and combinations of all (Deleuze and Guattari 1987, 409; and see Johnston 2008, 107). In this chapter, I examine the collective dynamics evident in bacteria and slime molds, in which “highly structured difference arise[s] from similarity” in the now classic instance of local organismal interactions furnishing emergent global organization resulting in an entirely different social body acting in unique ways (Keller 2007, 300). The complexity of the ‘part-to-whole’ transformation of bacteria and slime molds increases the dimension of their possibility spaces; the transformation from singular organism to massive, multicellular aggregate is a dynamic response to environmental cues, in which a capacity for control and self-organization is exercised producing an entirely new and differentiated whole or assemblage.

Sociomicrobiologists study sociality in microorganisms with regard to particular cooperative or antagonistic behaviours that may imply or suggest human and animal
social developmental behaviour from an evolutionary perspective (West et al. 2007; West, Griffin and Gardner 2007; Velicer and Vos 2009). In the instance of chemical signaling among bacteria and slime molds, particular organismal responses enable bacteria to act as one large socially cooperative body, in effect enacting multicellularity and conferring survival advantages afforded more complex multicellular organisms (Bassler 2002; Bonner 1999). Bernard Crespi proposes that bacterial quorum sensing is intricately tied to sociality among and between different bacteria because it coordinates complex environmental adaptations that require cooperative behaviour for habitat construction (biofilms), specialized foraging and food provision, hunting and defending, and suicide (2001; and see Kjellberg and Givskov 2007). This view also reveals the influence of human social language and terms to describe organismal behaviour, in much the same way as it is used in the artificial sciences to describe communication, self-organization, and control (and see Chapter Two and Six). The idea of nascent sociality among bacteria, particularly given their status in biology as an originary form of life, suggests that communication and communicative social processes are a central component of what is considered life (Crespi 2001; Kjellberg and Givskov 2007; West et al. 2007; West, Griffin and Gardner 2007; Velicer and Vos 2009). As the forthcoming discussion will reveal, slime molds also have cooperative, self-organizational capacities similar to those observed in bacteria (Bonner 1999).

The goal in this chapter, then, is to explain vital communication and self-organization across three biological examples: bacteria, the cellular slime mold *Dictyostelium*, and the larger *Physarum* slime mold. Each of these complex life systems
has something unique to contribute to biologically inspired digital systems and networks, and helps to uncover processes of control and organization. In the first part of the chapter, I detail bacteria networks and demonstrate their strength as a model of vital communication and control for communication and information technology. In the last section of the chapter, I point to the role of slime molds in the historical development of mathematical biology, the discipline concerned with configuring biochemical processes as quantitative mathematical equations, and its relevance to computer simulations of biological systems (Keller 2002). Mathematical biology and computer simulation are crucial to the mobilization of knowledge, from microbiology to computer science and engineering. It is the capability of simulating microbial communication and self-organization with computers that enables researchers in network science to emulate biological communication and self-organization in digital systems and networks. Offering a different model of inspiration, *Physarum* slime molds are considered by researchers as computational ‘machines’ or basic ‘organic computers,’ which can solve problems within their own matrix and environment that have application across a range of human contexts, but most significantly for network design and planning (Adamatzky 2007, 2010; Adamatzky and Akl 2012; Bonner 2000, 2009; Norris et al. 2010; Tero et al. 2010).

Bacteria and cellular slime molds have developed complex communicative and self-organizing capacities as adaptations to a range of environmental constraints and opportunities. This distributed, non-hierarchical form of control, communication and self-organization, serves as a model for the design of dynamic, self-organizing, scalable
distributed digital networks such as physical robot coordination, computer network security, network design, intelligent software agents, communication and information technology, the Internet, and network reliability and robustness (Amos 2005; Balasubramanian et al. 2008, 1673; Bongard 2009; Dressler 2005; McGibney, Botvich and Balasubramanian 2007; Peysakhov et al. 2006). The communicative processes of bacteria and slime molds do not simply inspire one or two ideas as metaphors for digital system and network design and organization; these complex life systems can also be understood as vital networks through their autonomous functionality, communication, self-organization, and distributed control. Crucially, the organisms discussed here are capable of radical transformation from single-celled entities to multicellular aggregate, and what the aggregate does is significantly different from the capabilities of the individual microorganism. Taken together, these biological capabilities give computer science a radically different system-wide model of control and communication for digital networks that organize our (human) communication and transactions in life.

**Assembling the Organism**

[N]ot only does the living thing continually pass from one milieu to another, but the milieus pass into one another, they are essentially communicating (Deleuze and Guattari 1987, 313).

I want to begin with Gille Deleuze’s heterodox image of the organism as constructed in *Difference and Repetition* (1993) and (with Felix Guattari) in *A Thousand Plateaus* (1987). As much as these two philosophers drew on science to engage ideas about being and becoming and about life, they were strongly opposed to orthodox
biology’s rigid taxonomy and classification system, which divided variations of life into distinct categories (species) hinging on the central dogma of molecular genetics and DNA. As Keith Ansell Pearson has noted, for Deleuze orthodox “[b]iological classification has always been a problem of ordering differences by establishing a continuity of living beings, a problem of genus and a problem of species” (1999, 61-62). As an example of this, microbiologists often stress a deep division between unicellular (prokaryotic) and multicellular (eukaryotic) life, and yet at the same time acknowledge that bacterial communication works between these forms, crossing this supposed divide (see Archibald 2011). This suggests that the classification of kingdoms and species organized in genetically determined relationships dismisses what Donna Haraway points to as life’s potential for ‘pluralized becomings’ between and among forms of life, making any boundary or divide between the domains of life appear porous and full of extraordinary couplings (2004, 2008).

As the opening quote suggests, what Deleuze has assembled in his philosophy is a becoming of life that turns away from rigid classification toward difference as a continual generative process that is “multiple, mobile and communicating” across a field of intensive potentials for life (Deleuze 1993, 254). Deleuze sets communication as a primary part of life, such that “modes of communication ... allow for novel becomings and transformations” as crucial aspects of becoming (Ansell Pearson 1999, 10). Deleuze is not concerned with what will be produced through this creative process, whether an individuated human subject or microorganism or a blade of grass: rather, his interest is in

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19 Eukaryotic organisms have cells with a nucleus, a membrane-bound organelle with the cell’s genetic material (DNA/RNA) (Ingraham 2010).
the morphogenetic process itself as an “act by which intensity determines differential relations to become actualized” in the entity (1993, 246). For Deleuze, any rationally organized description of life as in genetic science is mere representation, a static snapshot of life organized around serially linked mechanisms and structure. Deleuze adopts Bergson’s view that the living is not distinct from the non-living, that the organic and nonorganic together constitute life itself and there are infinite potential variations for this life that are not adequately represented in linear classification schemes (Wolsey and Wolsey 1992, 167; Deleuze 1993; Deleuze and Guattari 1987). What is distinct in Deleuze’s philosophy (and with Guattari), however, is that the life of the organism is not autopoietic; everything does not turn around the membrane-bound organism. For Deleuze becoming precedes being and he put “sense before and beyond meaning, and before and beyond the organism,” so that the question is about “what it is to live” and not simply how life is categorized and understood by enclosing the organism in a world that turns on, or is explained through, its perception (Colebrook 2010, 5).

Moving with Deleuze (and Guattari) into this realm of becoming, then, means understanding life as a continuously vital and dynamic process. What Deleuze proposes is a view that emphasizes relations of exteriority, the assembling of unstructured parts into a non-hierarchical and self-organizing whole: a “Becoming-animal, becoming-molecular, [or] becoming-inhuman” that flattens the distinctions between organic and non-organic life (Deleuze and Guattari 1987, 51; De Landa 2006, 12). This attaches to broad themes within complexity science around self-organization and emergence in any complex system, but here is directed at the constant becoming as difference, through
which “organisms display innovative capacities for self-organization and self-regulation” emerging out of variant processes within its milieu, which include metabolism, mobility, defense, environmental adaptation, and so on (Ansell Pearson 1999, 98). And I will go further in the forthcoming discussion to argue that microbes display this becoming through innovative capacities for a vital communication in social bodies that enable them to become-other, from singular organism to univocal aggregate as a multitude capable of sometimes astonishing capacities such as habitat formation, foraging, and other environmental adaptation. This aggregate entity is not reducible to any individual organism. The singular bacterium or amoeba cannot act as or behave in ways the multitude does; rather it takes on a new form with its own set of properties, as we shall see in the forthcoming discussion. The organism is thus both an assemblage in and for itself as well as a component force within larger assemblages.

**Bacteria in Life**

In 1676, the Dutch merchant and amateur microscopy enthusiast Antonie Philips van Leeuwenhoek peered through his homemade microscope at a “great company of living animalcules” in matter that he had scraped from the inside of human mouths and between teeth, and observed “with great wonder, that in the said matter there were many very little living animalcules” (1684). This great company, this “teeming world of microorganisms” were bacteria common to the human mouth and this was the first known microscopic sighting of bacteria (Losick and Bassler 2006, 237; and see Ingraham 2010, 296-297). These ‘animalcules’ increasingly became the object of study for generations of scientists, due in part to van Leeuwenhoek’s efforts.
Bacteria are enormously significant to life on earth: they are bound into a complex ecology of forms that compose the planet. There is the oft-repeated fact that humans are comprised of 10 to 100 trillion bacterial symbionts: we are literally heaving with a lively constellation of bacteria entangled with our metabolic processes, engaged in pathogenic trials of strength in and on our bodies, and meeting us in surface-to-surface encounters between skin, membranes, and the physical environment of our daily life (Ingraham 2010, 22; Margulis and Sagan 1986; and see Hird 2009). A microbiome of bacteria, viruses, fungus, and human cells in vibrant association as “mobile scaffolds for microbial ecosystems”—microbes effectively ‘rule’ us and our planet (Heim 2012; see also Bennett 2010). Or, as Lynn Margulis notes, “[f]ar from leaving microorganisms behind on an evolutionary ‘ladder,’ we are both surrounded by them and composed of them” in a symbiotic entanglement (and Sagan 1986, 28).

Research suggests bacteria are an originary form of life on earth, progenitors from which all life has evolved over 3.5 billion years, and “we are the recent intruders into their well-established and self-developed world” (Ingraham 2010, 1). Thus, bacteria are fully part of planetary life assemblages, from the deepest oceans to the outermost biosphere; they are mutually entangled with plants, animals, humans, viruses and other bacteria, waterways, soil, metals, minerals, rocks, and more. Margulis (with Sagan 1986) has shown that the eukaryotic cell itself emanated from a series of endosymbiotic mergers and various organelles of eukaryotes evolved symbiotically with bacteria (the endosymbiont), including cellular mitochondria (the cellular energy producer) (and see Hird 2009). It is generally recognized by researchers that cell to cell communication
governing the endocrine, immune, and nervous system in eukaryotes evolved through lateral or horizontal gene transfer (HGT) from bacteria, as these chemical processes rely on rapidly diffusible messenger molecules much as with quorum sensing (Iyer et al. 2004). HGT occurs outside of reproductive genetic replication and is not simply an evolutionary or prehistoric bacterial phenomenon, as the ongoing transfer of bacterial DNA between bacteria continues today (de la Cruz and Davies 2000; Dunning Hotopp et al. 2007; Zhaxybayeva and Doolittle 2011). Bacterial symbiogenesis illustrates an adaptive capacity for a multitude of communicative and symbiotic relationships within and across other life forms.

The instance of symbiosis is important to Deleuze and Guattari (1987) and they identify it as a multiplicity; a clear instance of ‘becoming’ that cuts across evolutionary lineages along transversal branching paths to bring different life forms together (and see Ansell Pearson 1999, 103). Deleuze and Guattari see symbiosis and its mixings as neither hereditary nor reproductive; rather, “each multiplicity is already composed of heterogeneous terms in symbiosis …; a multiplicity is continually transforming itself into a string of other multiplicities, according to its thresholds and doors” (Deleuze and Guattari 1987, 242, 249).

While their composition turns on ‘becoming,’ this becoming-symbiotic is a deterritorializing event brought about by “lines of flight,” considered by Deleuze and Guattari as radical ruptures of stratified or stable assemblages such as those carefully assembled boundaries and divisions within orthodox biology that classify organisms

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20 I refer here to life forms because the very idea of bacteria as separate species is highly contested (Ingraham 2010; Margulis and Sagan 1986).
through linear arrangements of hierarchical ordering (1987). Any multiplicity (as becoming) is therefore “potentially subject to mutation or transformation simply because of a change in the dimensions that deterritorialize it” (Ansell Pearson 1999, 103). For Deleuze and Guattari, life hinges on communication and transversal passings through various “thresholds and doors,” and as organisms pass from one milieu to another, so too the milieus pass one into the other (1987, 313; and see Deleuze 1993, 246). In the section that follows I explore bacterial communication linked to transformation and transversal passing from the one to the many in a distinct process of differentiation.

**Bacterial Communication and Control**

Life did not take over the globe by combat, but by networking (Margulis and Sagan 1986, 29).

Molecular biochemical communication processes are a key aspect of the bacterial lifecycle. Quorum sensing (QS) begins as a sequence of events in response to different organismal and environmental cues and ends with a particular collective action among all the bacteria: this collective action may include cooperative colonial movement and foraging enabled by their distributed communication pathways, with far-reaching effects for their environment and colonial success (Bassler 1999, 2002; Camilli and Bassler 2006; Keller and Surette 2006). QS is part of the bacterial gene regulatory apparatus and is sometimes referred to as “diffusion sensing” or “compartment sensing,” in reference to instances when the bacteria are sensing their surrounding environment as much as their population density (Williams et al. 2007, 1120).
As Figure 1 shows, at the start of the QS cycle an individual bacterium produces a signal molecule, a pheromone known as the autoinducer, which stimulates or induces its own synthesis based on the extra-cellular concentration of the molecule, such that the “increase in bacterial cell population density is concomitant with an increase in the concentration of signal molecule(s)” (Atkinson and Williams 2009, 959; Williams et al. 2007, 1119; see also Bassler 2002). During this cycle the bacterial population increases as the signal molecule synthesis increases and when the threshold is achieved, or a ‘quorum’ of signal molecules is detected by receptors in the bacteria in the colony, the bacteria “synchronize particular behaviors on a population-wide scale and thus function as multicellular organisms” (Waters and Bassler 2005, 320; and see Bassler 1999, 2002; Bassler and Losick 2006; Williams et al. 2007). If no quorum is detected, the bacteria do not collectively initiate any response and no global action is taken. Bacteria reside in this continual state of awareness by monitoring their environment via their molecular circuits in readiness for aggregation through this combination of sensing and/or signaling (Bassler 2002; Ingraham 2010).

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21 The QS molecule is considered a pheromone because it is excreted by the cell producing it and operates outside its own membrane between bacterial cells (and occasionally eukaryotic cell receptors), as opposed to a hormone that functions internally, acting within a multicellular organism and integral to its metabolism, growth, reproduction, and so on (Williams et al. 2007, 1119).
There are three archetypal QS programs relatively well understood by researchers, although bacteria can have parallel QS circuits for communication that sense signal molecules from the same bacteria, other bacteria, and other life forms including an animal or plant (Bassler and Losick 2006; Waters and Bassler 2005). I will detail the acylhomoserine lactone-dependent (AHL) autoinduction circuit because it is the most well documented and understood of all the circuits and the one referenced in computer science. In the AHL QS network circuit, an autoinducer synthesis protein acts as the signal synthase (manufactures the signal) and once AHL is produced the molecule diffuses passively out of the bacterial cell (Bassler 2002; see also Atkinson and Williams 2009; Xavier and Bassler 2005). At the stimulatory threshold, when enough of the signal molecule accumulates, it is detected by specific receptors on the surface of other bacterial cells and binds with these receptors: this molecular complex then triggers a specific population-wide gene expression such as bioluminescence, swarming, habitat formation, or defense (Bassler 2002; Williams et al. 2007). The capacity for self-awareness through the auto-induction cycle enables bacteria to continuously optimize and self-configure their organismal network while being energetically conservative. Each bacterial cell only signals or receives from its near neighbours, negating the need to expend energy across a large population. Such capacities for energy conservation and self-capability are conspicuous requirements for digital autonomous systems and networks and I will return to this point in Chapter Six (and see Table 1 in Chapter Two and Table 2 in Chapter Six see also Balasubramanian et al. 2007; IBM 2012).
The process of QS induces a state change in the organisms—it alters the possibility state for the bacterial assemblage—and, through this flurry of signal molecule exchange, including the signal release and reception, a population-wide response occurs, involving many thousands of bacteria coming together to form a coordinated, self-organizing aggregate or assemblage. The transformation from the one to the many confers an advantage for bacteria, which usually enables an adaptation to environmental conditions whether to coordinate actions for foraging or to react to a stress situation such as starvation or predation by another form of bacteria (Williams et al. 2007). For example, in the bioluminescent marine bacterium, *Vibrio fischeri*, and the squid *Euprymna scolopes*, QS controls gene expression for light production in bacteria symbiotically housed in the squid’s light organ. In this instance, QS is crucial to Vibrio ‘switching on’ its light-producing capability following the autoinduced signal cascade of QS at the threshold concentration (Miller and Bassler 2001; Waters and Bassler 2005). For both bacteria and squid this symbiotic relationship is a necessary survival strategy. The light organ in the squid aids in protection from its predators at night by countering moonlight filtering from the atmosphere above—the light organ cancels the squid’s own shadow on the seabed—and for the bacteria the squid provide necessary nutrients. *Vibrio* stands as the paradigm QS system because it thrives in laboratory cultures and it has been intensively researched for more than three decades (Nealson and Hastings 1979; Waters and Bassler 2005).^{22}

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^{22} The bioluminescence circuit is more complex than outlined here, however, and involves the squid being able to excrete excess bacteria at dawn (the squid hunts at night). This decrease the number of bacteria, reducing the bacterial quorum, and thus reducing the light level. By the end of the daylight hours, the process re-engages as the bacterial population has increased and bioluminescence is triggered once again by QS (see for further explanation and
There are two examples of bacterial self-organization leading to specialized multicellular aggregation that explicitly demonstrate processes and behaviour consonant with a vital network, and these are biofilm self-assembly and swarming. In both cases, these assemblages act within a constellation of processes that together form a vital network displaying autonomy, vital communication, self-organization, and distributed control.

**Biofilm Self-assembly**

Biofilms are “sessile consortia,” a vast population of bacteria, consisting of “surface-associated, structured and cooperative” bacteria that self-assemble a complex array of material structures that adhere to a physical substrate in an environment that can furnish nutrients (Kjellberg and Givskov 2007, 1; Wood and Bentley 2007). Bacterial congregants adhere to surfaces across a range of environments such as water, soil, human and animal bodies, and even medical devices such as dental instruments and catheters (Wood and Bentley 2007). Biofilm self-assembly requires cell-to-cell communication across its growth and maturation cycle, with myriad processes of communication occurring across a dynamic field of relations. This field of relations is bio-diverse and includes different types of bacteria cooperating in biofilm self-assembly and maintenance and requires constant and intensive inter-form communication, considered by researchers to be among the most socially complex (Kjellberg and Givskov 2007; MacEachran and O’Toole 2007; Stoodley, Costerton and Stoodley 2004). Biofilm construction proceeds through five phases. The first begins when the bacteria translocate to a surface from their discussion Miller and Bassler 2001; Bassler 1999, 2009).
water-born and free-swimming planktonic being; then an initial, and at this early stage reversible, attachment to the surface begins; in the third and fourth stages an irreversible attachment occurs, whereby the bacteria commence biofilm assembly and the formation of micro-colonies, growth, and maturation; and finally, at the fifth stage cells are dispersed (MacEachran and O’Toole 2007, 23; Stoodley, Costerton and Stoodley 2004, 97-98). In the early stage of biofilm adherence, the bacterial population is low, and research suggests that QS becomes central to the biofilm mode of life only after initial attachment. This is likely due to the low signal molecule density in the beginning of the formation (Atkinson, Cámara and Williams 2007). As bacteria attach to a surface there is, however, another signal pathway that cues the aggregating bacteria to produce adhesins (sticky protein bits), which further the likelihood of attachment. Once this attachment phase occurs, biofilm self-assembly unfolds in earnest (MacEachran and O’Toole 2007, 28).

Bacteria such as *Escherichia coli* congregating in biofilms are persistently monitoring the consortium and their environment, and ‘listening’ for other bacteria. This means bacteria are detecting and intercepting other bacterial QS signal molecules, but not necessarily responding to these signals (Atkinson and Williams 2007; Bassler and Losick 2006). Computer scientists have adopted this particular capacity for detection in the development of biologically inspired control features for multi-agent systems and networks (and see Figure 7 in Chapter Six; Balasubramanian *et al.* 2007; Dove 2011). For bacteria, detection of other bacteria while remaining silent and non-detectable (hidden) at
the same time is a significant adaptation. This capacity gives bacteria an edge in terms of their survival and competition:

“[B]acterial ‘eavesdropping’ confers on the organism the ability to intercept signals, which will provide important information about the local environment and the other species contained within. Sensing, but not synthesizing, a signal confers several advantages. For example, the organism may reduce the metabolic cost of QS signal biosynthesis and avoid conveying information about its whereabouts to other species in the immediate vicinity” (Atkinson and Williams 2009, 967).

In this event, signal monitoring (as opposed to active signaling to induce gene expression) can be a defense against, or provide resistance to, antimicrobial agents present in the bacteria’s environment generated by other bacteria, by eukaryotic cells, or by synthetic biochemical antibiotics delivered as a treatment to infected plants, animals, and humans (Kjellberg and Givskov 2007). Biofilms are contingent on this dynamic, vital communication: their chemical signal pathways are continuously active throughout the lifecycle whether in explicit QS circuits or within the substrate or matrix that functions as a physical network of cell-to-cell interconnections (Stoodley, Costerton and Stoodley 2004). The matrix is called the extracellular polymeric substance (EPS), and is comprised of polysaccharides (long chain sugars such as cellulose), extracellular DNA, mating pili (fibrous tendrils that enable DNA to be passed from one bacterial cell to another), and more (Pamp, Gjermansen and Tolker-Nielsen 2007, 38-39). As the matrix self-assembles, it diversifies its structure and network architecture, facilitating a range of communicative capacities across a heterogeneous field of relations comprised of the intercellular exchange of genetic material, cell division, metabolite circulation, and chemical signal
circuits (Stoodley, Costerton and Stoodley 2004, 96). Biofilms are assemblages in the Deleuzian sense: they are based on relations of exteriority in which diverse bacteria congregate to assemble a whole that operates as a unified entity, yet entire parts of a biofilm can detach and disperse and join with other bacteria and a substrate to form a new assemblage.

What these biofilm assemblages show us is that organismal communication has solved many of the problems of coordinating a multitude through vital communication activating very specific molecules as signals coded for these purposes of communication. In the case of bacterial networks, communication unfolds as a process with a variable capacity to monitor and interpret a broad range of signals. The cascade of events that lead to population level changes through an ‘exact’ fit of the primary signal molecule to the receptor on another bacterium—these are “high fidelity” circuits (Waters and Bassler 2005, 322). Such high fidelity circuits are able to filter the ‘noise’ of multiple signals, delineating critical molecules necessary to biofilm self-assembly from those of other bacteria that may threaten it (ibid.; Kjellberg and Givskov 2007). QS is a complex model of distributed control operating within a complex system in which coordination emerges from the local interaction of bacteria producing global self-organization and population level adaptation. Control does not emanate from a central cognition module, or respond to a ‘pacemaker’ cell or director. It arises out of the local interactions of communicating entities (and see Bassler 2002; Keller 2002).

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23 As these micro-colonies flourish they are subject to a QS-induced dispersal phase (although very little is known about this process). The dispersal of free-living cells ensures the colonization of new surfaces and such ‘seed’ populations carry advantages from the biofilm consortia including higher growth rates due to increased nutrient availability, motility improvements, and enhanced cellular adhesive capabilities (Webb 2007).
These distinctive communication processes and capacities for potential action are precisely what are simulated in digital QS algorithms for digital systems and networks (Balasubramanian et al. 2007; Peysakhov et al. 2006; and see Chapter Six). Rather than a linear program, which contains a list of potential problems that may occur and a parallel list with possible solutions as in mid-twentieth century computing, contemporary digital systems that adopt biologically inspired models do not have such preconfigured solutions to potential problems; these programs are designed to respond dynamically to problems that arise (see Keller 2007). There is no pre-articulated solution set but rather the digital system ‘decides’ on how to resolve a particular condition or situation on the network much as a biological organism would do. This complexity arising through communication is a vital network: it is self-regulating, self-aware, communicative, dynamic, self-ordering, and context aware, and more often its complexity is organized around communication pathways that are obscure and difficult to decode. Understanding the source of inspiration for contemporary network control provides a line of sight into the hidden complexity of networks.

**Myxobacteria Swarming**

Bacterial aggregation and biofilms are assemblages that arise out of a social-communicative milieu—they are multiple and one, yet connected further and beyond to still other milieus, other networks, in continuous processes of communication and differentiation: they are vital networks. The process of differentiation is what Deleuze labels becoming-other, and in the event of bacterial aggregation the many singular organisms stabilize as an assemblage that behaves as a unity of one (though it is

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multiple). This process of becoming other, of becoming multicellular via processes of communication, also explains the swarm, but with a difference. A final example of vital communication in bacteria is drawn from myxobacteria, a bacterium common to soil, tree bark, water, and animal feces (Velicer and Vos 2009). Myxobacteria undergo a process of differentiation as with other bacteria through QS and also through near-field signaling as forms of vital communication that prompt aggregation resulting in a multicellular assemblage known as a swarm (ibid.; Miller 2007).

Swarming, as outlined in Chapter Two, is a collective behaviour that occurs among a range of organisms from bacteria and slime mold to ants and bees, and is considered a classic instance of self-organization (Camazine et al. 2001, 7; see also Hölldobler and Wilson 1990; Wu et al. 2007). Myxobacteria swarms can thus be understood as both a large assemblage, a multitude acting as a ‘superorganism’ similar to the colonial movement of ants, but also as an ‘event’ arising out of self-organization (Hölldobler and Wilson 1990; Bongard 2009; Whitehead 1920, 1978). The swarm is, in the event ontology of Alfred North Whitehead, an event precisely because it is relational and extensive and an actual entity arises that is capable of acting (the swarm), but Whitehead’s event does not give us the same emphasis on communication and process as Deleuze makes (Deleuze and Guattari 1987, 313). For Deleuze, the process of aggregation and differentiation is primary, and the actualization of this becoming stabilized in the assemblage (swarm) is secondary.

Myxobacteria self-assemble into swarms consisting of thousands of cells and these densely packed aggregates are required for predation of other bacteria that they
surround and consume (Dworkin 2007; Wu et al. 2007). These swarms rapidly spread over surfaces, searching for other bacteria, and rely on cell-to-cell communication signaling as well as a physico-chemical process that enables motility based on the shape and orientation of each bacterium. Unlike other bacteria such as E. coli, myxobacteria cannot communicate over any distance (they require close, physical contact); rather, they pass signals between their very near neighbour and rely on physical cell-to-cell contact, known as contact-mediated signaling (ibid.). The significance of these two different signal circuits is that in the first instance, the A-signal circuit, a ‘decision’ is taken by the bacterium in determining its nutritional state. At the starvation point, or near starvation, the diffusible cell-to-cell A-signal is involved in the calculation made by the swarm as to whether to continue to grow and feed on declining nutrient levels until cells begin to die, or to use the remaining nutrients to power the metabolically costly synthesis of proteins necessary to begin differentiation and self-assembly (Kaiser et al. 2010, 15). The self-assembly is a conversion process of bacteria into a fruiting body, which is a cluster of cells that produce a stalk with myxospores at one end that can be dispersed into the environment. The A-signal circuit is similar to QS in other bacteria. Myxobacteria sense whether or not there are enough cells to self-assemble by detecting the concentration of the signal in the extracellular milieu (ibid.; Wu et al. 2007). The cells are already at much closer physical proximity than in other bacteria QS programs because of the swarming

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24 Myxobacteria are rod-shaped with a pilus one end (a tiny fibre-like flagella) and at the other what researchers describe as a slime secretion ‘engine’ (Wu et al. 2007; Kaiser, Robinson and Kroos 2010). The exact swarm behaviour is not well known. However, it is generally understood to be linked to social cues such as the physical interactions between the ends of the bacteria that are structurally different (slime or pilus) and switch polarity from positive to negative (ibid.). Collisions between swarm members are productive to movement because one bacterium’s pilus ‘grasps’ the hairy fibrils (fine hair-like threads) that are on the surface of other cells when they make contact, and this creates a stop and start motion, sometimes reversing, and the swarm moves (Wu et al. 2007).
behaviour, and at the crucial threshold a C-signal is released to induce conversion to fruiting bodies and sporulation (Kaiser 2004).

I draw on the myxobacteria example because their population dynamics are a crucial example of a swarm network, a vital assemblage predicated upon signal pathways that orchestrate the progression from local and intensive interaction between cells to population-wide action and differentiation. Myxobacteria display the action of a global population or swarm through collective feeding action (predation) as well as the developmental progression to form a multicellular aggregate capable of producing fruiting bodies as a successful survival strategy. Myxobacteria are a vital network, a unity of the one to the many actualized in an assemblage that is a predatory swarm, a ‘becoming-animal,’ which some researchers label as “wolf packs,” which initiate directed attacks on other bacteria by secreting digestive enzymes that destroy (lyse) the cells they then consume (Diodati et al. 2008; Jiang, Sozinova and Alber 2006; and see Deleuze and Guattari 1987).

In the section that follows, I will explore a different organism, the slime mold, and its aggregation and behaviour. The slime mold *Dictyostelium* is significant not only for its vital communication circuits and cellular differentiation, but for its place in the shift, within the sciences broadly, to understanding organisms in informational and programmatic terms and for a curious contribution to a computational model of self-organization (Keller and Segal 1973; Keller 2007).
Slime Molds

Here is an object [Dictyostelium] that traffics back and forth both between the one and the many and between sameness and difference (Keller 2007, 298).

The cellular slime mold, Dictyostelium discoideum, is a fascinating case for study: they are bacterivores (they consume bacteria) living in soil and an organism that, as Evelyn Fox Keller’s opening quote suggests, is interposed between single-celled oneness and the multiple. For most of their lifecycle these organisms exist as solitary cellular amoeba surrounding bacteria in the soil and extracting nutrients, but when the bacteria supply in an area is exhausted they begin a cycle of aggregation and differentiation (Bonner 1999; 2000; 2009). These amoebae move, quite literally, between single-celled solitude and multicellular assemblage when faced with ‘starvation’ conditions (Bonner 1999; Keller 2007). This process of aggregation from the one to the many resolves in a multicellular entity that gives rise to a ‘slug.’ The slug consists of the aggregate enclosed in a slime sheath, which migrates upward in the soil, and as it does, a process of cellular differentiation ensues creating stalk cells at one end for giving it sufficient rigour to rise up from the soil, and creating spores at the opposing end that are lifted up by the stalk to be dispersed by surface creatures such as insects (Bonner 2009, 12-13).

At the point of nutrient exhaustion or near nutrient limits, the impetus for aggregation in Dictyostelium is the emission by the amoeba cell of an attractant, a

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25 Dictyostelium is considered a eukaryote even though a single-celled organism at the start of its lifecycle because, unlike prokaryotes (bacteria), it has a cell nucleus (or sometimes many nuclei in one cell) (Bonner 2009).
chemical called cyclic adenosine monophosphate (cAMP), which is sensed by its near neighbours. Amoebae begin to turn toward the direction in which the cAMP is strongest and slowly aggregate in a multicellular mound of up to 100,000 cells. All the while each migrating cell is generating and emitting cAMP, intensifying the extracellular signal concentration (Bonner 1999, 2000, 2009). This process turns on chemotaxis: the ability of slime molds to detect chemical gradients within the extracellular environment and move either toward or away from the chemical attractant (Bonner 2009). Chemotaxis occurs as the amoebae each orient according to the strength and direction of the chemical gradient (cAMP) and elongate as they move, migrating toward the main mass and leaving behind a trail of ‘slime’ and each subsequent amoeba ‘gets in line,’ drawn toward the aggregating mass (ibid.). The amoebae then begin the process of cellular differentiation.

The transformation between sameness and difference, between the one and the many in cellular slime molds (and bacteria) defies classification by becoming so obviously other-than-itself. For these organisms, vital communication is the genesis for self-organization and differentiation, out of which emerges an assemblage, a multicellular entity, tuned to quite different modes of action than the singular organism. This is a very Deleuzian mode of life, a generative process that is “multiple, mobile and communicative,” as noted at the beginning of this chapter, and results in “novel becomings and transformations” (Deleuze 1993, 246; Ansell Pearson 1999, 10). The event of aggregation also has a distinctive resonance, as noted above, with Whitehead’s idea that any event is the “relational and interlocking ‘movements’ of activity out of which the actual makes itself” (K. Robinson 2009, 226; Whitehead 1919, loc. 1929). For
Deleuze, as for Bergson before him, the emphasis remains on becoming, and the final entity (assemblage) is derivative of this primary process (Harman 2011, 292; K. Robinson 2009). This means that processes of communication and differentiation among microbes say more about life than the assemblages they produce: the act of self-assembly trumps the final configuration or assemblage.

**Protist Programs: Simulating Self-Organization and Networks**

Dictyostelium’s contribution to the contemporary understanding of self-organization is significant not only for what it reveals about aggregation and differentiation from the one to the many, but also for what those processes reveal about the capacity of complex systems to self-organize. In 1970, Keller and Lee Segel published their mathematical model for the self-organizational capabilities of Dictyostelium. Their objective was to demonstrate that the “aggregation of a population of single-celled amoebae [slime mold] … proceeds spontaneously” and that the aggregate “emerges as the product of decentralized and local interactions among molecules secreted by individual cells,” disclosing a capacity for communication and coordination unfolding without centralized control (Keller 2007, 303; cf. Keller and Segel 1970). Keller and Segel’s findings turned on the cellular slime molds, but the implications were much wider: their research suggested that organismal aggregation does not require a founder or pacemaker cell to direct this sort of collective action in self-organizing life systems. In the years since their publication, which was initially ignored by their contemporaries, the intriguing capacities for organization in slime mold aggregation has become a canonical example of self-organization in complex systems, standing behind several important
mathematical models within complexity science (Amos 2008; Bongard 2009; Keller 2007).

In this section I address the aggregation of Dictyostelium from the perspective of pattern formation—the emergent properties of the slime mold that become evident through its self-organization into aggregate forms or fruiting bodies—and in particular, an aspect that draws much less attention than morphological becoming from singleton to multicellular being. I outline the role of mathematical biology and the use of computational and synthetic models to disclose communication networks and self-organization in biological systems—and in this Dictyostelium occupies an interesting place in the contemporary understanding of self-organization.

Mathematical biology, sometimes interchangeable with the term theoretical biology, is an interdisciplinary field that uses applied mathematical techniques to model or explain biological processes (Keller 2002). It is important to distinguish mathematical biology, discussed here, from another well known mathematical model, genetic algorithms (GAs) (Marczyk 2004). GAs are used for a range of computational techniques that require an iterative or sequential computation across successive generations (as for a hypothetical population), in which different variables can be randomly changed, added, or removed to effect potential outcomes as in the case of testing the effects of a genetic mutation on individuals or populations (biological or digital) (Marczyk 2004.; Meisel, Pappas and Zhang 2009). Their utility resides in providing researchers with a virtual computational model that is faster than the reproductive cycle of live organisms and wherein they test out the relative ‘fitness function’ of a given mutation or variable that
permits each version of the program to be quantitatively measured (Marczyk 2004; see also Keller 2002). I do not engage GAs as the model for biological inspiration of network control because they are not the primary feature of system self-regulation discussed in later sections. GAs are, however, implemented in artificial neural nets and artificial intelligence research across different branches of the artificial sciences to advance machine learning (and ‘remembering’) capabilities and Google Inc. has a significant project underway in this area (see Le et al. 2012). In contrast, mathematical biology focuses on problems of cellular and organismal development, of cellular differentiation and growth, also known as morphogenesis (Keller 2002). These molecular processes are not strictly associated with genes and heredity; rather, the models constructed in mathematical biology attend more to problems within complexity science broadly, such as spatial configuration and mobility for swarm intelligence and self-organization, as it relates to dynamic systems and biological life broadly.

In the later twentieth century, as genetic science became the dominant explanatory paradigm for life, mathematical biology’s popularity dipped, but in the last two decades it has become apparent that genes do not govern all of life and cannot sufficiently explain biological self-organization in all its complexity and difference (see Bonner 2009; Keller 2002). As Keller notes, in Making Sense of Life, concerning the question of how living entities are formed, science has responded to that question through “models, metaphors,

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26 See Google Inc. (http://research.google.com/pubs/pub38115.html) and for discussion (http://www.dailytech.com/Googles-Unsupervised-SelfLearning+Neural+Network+Searches+For+Cat+Pics/article25025.htm), and Guizzo 2011.
and machines,” giving more credence over time to mathematically derived models (2002, 3).

Mathematical biology’s relevance is due to the sophistication of computer modeling, which has made simulations and renderings of complex physico-chemical biological processes captured in mathematical equations and constructs readily available to biologists. In turn, this has certainly made biological processes more easily mobilized for computer scientists seeking biological inspiration for contemporary problems in digital system design and networking (and see for example Figure 9 below) (Amos 2008; Latty, personal communication; Keller 2002, 2007). As Richard Doyle has observed, software turns descriptions of life into actions that can be replicated in simulations in which “code, instruction, and program” materialize scientific statements about the organism and ‘plug’ the molecule directly into the computer (1997, 3, 1).

Mathematical biology has long and variegated branches and the one I follow here starts with Alan Turing (1952) and his reaction-diffusion model, proposed before there were computing devices of any sophistication, and truncates in the swarm algorithms inspired by Turing and adapted by Keller and Segel (1970), Mitch Resnick (1994), and Craig Reynolds’ (1987). Turing, as discussed elsewhere, is best known for his contribution to the history and development of modern computing and certainly as a prime instigator for the mid-century fascination with artificial intelligence and the construction of machines that can ‘think’ (and see Brooks 1999; Hamilton 2009; Hayles 1999; Johnston 2008; Keller 2002). His contribution to understanding morphogenesis is a lesser known contribution yet equally significant in terms of his model for pattern
formation in living systems and the turn toward understanding biological life in informational terms that it entails.

Turing described a pattern-making ‘machine’ comprised of an activator molecule he called a morphogen, which can activate itself (an autoinducer or autocatalyst) and diffuse out of a cell, and a receptor or inhibitor molecule that opposes or counters the activator (Bonner 2000, 128; Keller 2002, 89-95; cf. Turing 1952). This activation/inhibition (reaction) cycle was intended by Turing as an abstract model that could explain how particular patterns emerge during an organism’s development, based on a series of chemical and mechanical events and processes during cellular development (1952; Keller 2002). Turing’s model essentially describes an ‘on/off’ switch in cellular development operating around two systems, one mechanical and the other chemical, conceived as a biological ‘program’ (Bonner 2009; Keller 2002). Keller (2002; and with Segel 1970) recognized this computational linkage in her own early work on slime mold aggregation and its self-organization processes, but resisted the ‘life as information’ and ‘information as life’ equation (see also Thacker 2010b). More recently she has reconsidered slime mold aggregation as a program or set of instructions expressed in informatic terms as a powerful model to decode processes of life through computer simulations (2007).

Thus, Turing’s highly abstract model has become attractive to biologists, even when, as Keller points out, the “notion that a model which is admittedly a fiction can, despite its fictionality, nonetheless capture the features ‘of greatest importance’” and hold some resemblance to the phenomena observed (2002, 97, 98; emphasis in original).
Turing’s early contribution to biology through his reaction/diffusion equation was a turning point: while a fiction, it showed that complex differentiation resulting in particular patterns or organism organization could emerge as a feature of interacting parts without central control via a system of molecular reaction and diffusion that was not explainable through genetics alone.

**Simulations**

Keller and Segel’s original work, while not following Turing’s reaction-diffusion equation precisely, was similar in principle: it served to explain the “emergence of structure out of the dynamical interactions … among cells that were initially undifferentiated” (Keller 2002, 102; cf. Keller and Segel 1970). Their work preceded the advanced software capabilities of contemporary computing. Resnick and Reynolds both created algorithms inspired by Turing and by Keller and Segel’s models, and successfully recreated them on a computational platform through simulations of self-organizing dynamical systems.

Reynolds created the first well-known example of computerized self-organization using digital birds created in a modeling software he called Boids, which displayed flocking behaviour (1987). The pixelated ‘boids’ flock together in response to computer code that describes three specific goals for the flock: alignment, separation, and cohesion (ibid.). These simple rules set the parameters necessary for a clear pattern to emerge in the systems as the ‘boids’ interact with their nearest neighbor, initiating local to global behaviour and enabling the many to act more as one (and see Appendix I and II for an illustration). The system has no hierarchically imposed central directive or rule. It is
guided only by control features that emerge from the three simple rules programmed in as goals of the system (ibid.). Following Reynolds’ example, Resnick was more ambitious. He set out to design a software program that was more user-friendly than Reynolds’ program and it is still in use today, known as StarLogo (2004).

De Landa argues that “simulations can play as intermediaries between theory and experiment” and the “simulation must embody its simulated organisms by giving them a metabolism and situate them in a space with a certain distribution of resources” (2011, 70). To illustrate how simulation operates, Figure 2 shows a three part slime mold simulation I created in NetLogo (and detailed further in Appendix II and III). NetLogo is an open source software version of StarLogo and can, using the same principles as Boids, simulate slime aggregation by manipulating the three parameters noted above.27 Figure 3 displays three phases of cellular slime mold aggregation—the simulation carries the advantage of being able to accelerate the aggregation cycle and thus create successive life cycles of more than one population. The software is set to illustrate how these digital ‘creatures’ aggregate into clusters. Each slime releases (or ‘deposits’ in the software simulation lingo) its chemical activator (cAMP) and the slimes ‘sniff’ ahead, trying to follow the gradient of other slimes’ chemicals toward the highest concentration of cAMP (outside the laboratory slimes react to slime trails). In Figure 3, in the first image on the left, the slimes are loosely ordered ostensibly in solitary feeding mode, and as nutritional availability declines and cAMP is generated, the slimes begin their aggregation cycle as

27 NetLogo was created by Uri Wilensky and is available as an open source software package here <http://ccl.northwestern.edu/netlogo/>. It is well thought out and simple to use, providing the basic working code for researchers as well as the simulation interface and simple explanations of the basic interactions, all within the user interface layer of the application (see NetLogo).
illustrated in the second image, and finally, in the third image the slimes have aggregated into clumps or clusters in readiness to create fruiting bodies.

These simulations of self-organization stand as important inspiration to computer scientists and network systems engineers faced with increasingly complex problems of communication and control in digital systems and networks. While I have used very simple examples to illustrate what are complex life systems, these same basic principles provide a reference for how complex networks with many nodes and edges or interconnections must self-regulate the sending and receiving of large quantities of information: these are essentially self-organizing networks that use reaction/diffusion, chemotaxis, and quorum sensing models to program self-regulation and optimization into network control (I will expand on this point in detail in the forthcoming chapter) (Balasubramaniam et al. 2008). This form of biological inspiration gains purchase not simply from the traffic of ideas passing between disciplines such as biology, mathematics, and computing, but from the capture of life processes rendered in simulation in what has become a shared informational and cybernetic elocution—itself easing the transgression between biological life and the computational milieu.
As noted in Chapter Three, the emphasis on simulation risks obscuring the logic of the biological system it is meant to model—the model can become ‘the world. Sherry Turkle claims that microbiologists’ models and simulations give the “sense of dealing directly with the molecule” or cell, and the simulation “starts to take on some of the qualities of the real,” assuaging any concern they might have that their science is “cut off from nature” (2009, 65, 67). For computer scientists and engineers the hope is that biologists will adopt “engineering-style standards for how it codes and communicates information” to make even more feature-rich and detailed simulations possible (ibid., 68). This suggests there is a heightened demand for data sets containing informationalized organismal behaviour, which technologists can appropriate to solve the increasingly complex problems of digital system and network organization and control.

To return to Turkle’s point above, data sets comprising computer simulations are only one way to see a world, but are not the world. Lorraine Daston and Peter Galison
(2007) draw attention to this point at the end of their study of objectivity in science. They view contemporary scientists as part engineer and part artist, and their simulated terrain of study has become a “hybrid of simulation, mimesis and seeing” by producing and manipulating a new world on a digital platform (2007, 414). Simulations do not have fidelity to the organism itself or the processes being modeled. Rather, simulations are just real enough. Simulations are isomorphic to the organism, but the behaviours they produce are emergent and novel. The NetLogo software simulations of slime mold aggregation, detailed in Appendices I and II, are examples of various coded components such as energy resources and spatial rules entered as data, which together create a coded assemblage for slime mold self-organization in which control emerges out of the local contact between a slime mold and gives rise to collective aggregation (self-organization) and in turn produces unanticipated or emergent behaviour. Running this simulation creates a range of potentials or different possibilities that permit scientists to ‘see’ what vital communication looks like and to see self-organization and emergence as it unfolds—it maps the dimensions and structure of the space of possibilities.

Mathematical biology and its simulations also figure in the life cycle of another slime mold: Physarum polycephalum. Whereas the cellular slime mold Dictyostelium has played a crucial role in the progression of mathematical biology and computer simulation, and bacteria as a model of network control, Physarum is an example of biological inspiration only recently recognized as a potential model organism for digital network design. This organism has been the focus of intense study in the last ten years with regard to its ability to explore alternative solutions to pathfinding problems in its
search for the most efficient route to new sources of food and this has direct applicability to digital network problem-solving (see Adamatzky 2010; Latty, personal communication; Tero et al. 2010). It may be the quintessential ‘live’ organic computer.

**Physarum Machines**

In this final example of biological networking and vital communication, I will explore the slime mold *Physarum polycephalum* as a model for network design that exemplifies both the turn to a computational (and informational) approach to understanding life itself and the rather extraordinary capability these molds have for problem solving. They are often described as “distributed information processors” for their capacity to execute decisions concerning the shortest path through a maze to a food source to solve foraging problems (Dussatour et al. 2010, 1; Nakagaki, Yamada and Tóth 2000). *Physarum* has quickly become a preferred model for experiments in network design including for rail networks (Tero et al. 2010; see AAAS 2010; Keim 2010), Canadian highways (Adamatzky and Akl, forthcoming), robot control (Adamatzky 2008; Tsuda, Zauner and Gunji 2005), and solving mazes (Tero, Kobayashi and Nakagaki. 2007). 28

*Physarum* are acellular (single-celled) multi-nucleate slime molds, which range in size from microscopic to a couple of metres, and meet their nutritional requirements by surrounding food sources (mostly decaying organic matter) and extracting nutrients (Dussatour et al. 2010). They have thousands of nuclei within their protoplasmic

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28 Researchers used a *Physarum* plasmodium embedded with an electronic sensor and a wireless transmitter to control a six-legged robot and the mold directed the robot into the darkest and furthest corner of a room—a place similar to its preferred setting in its natural habitat (Tsuda, Zauner and Gunji 2005).
envelope formed when many single motile amoeboid cells swarm together and fuse into one large plasmodium. Their life cycle turns on the depletion of nutrients initiating a process of cellular differentiation that produces stalks with sporangia (spore-filled sacks) at their ends containing many spores that will be dispersed in the air (Sauer 1982). These spores release tiny amoeboids that eventually (for they move very slowly in relation to a human sense of time) aggregate to fuse into the large plasmodium (ibid.). The processes of inter-cellular communication that trigger aggregation and sporulation are not well known, but some form of chemotaxis occurs to coordinate the process (Durham and Ridgway 1976). Current research is focused on Physarum’s ability to ‘compute’ and solve particular problems presented by their environment, including discovering optimal network paths to a food source and assessing the quality of a food source at a given location (Adamatzky 2010; Dussatour et al. 2010; Nakagaki, Yamada, Tóth 2000; Tero, Kobayashi and Nakagaki. 2007; Tero et al. 2010).

Physarum discloses a remarkable propensity for network optimization and efficiency and these problem-solving and decision-making capacities have been directed at research solving particular problems for human transport networks and digital networks. Under research conditions, Physarum creates ‘veins,’ or pseudopods, out of its cellular protoplasm that pulse, or oscillate, at certain rates and stretch out to make contact with food sources placed at different locations and intervals. Figure 3 shows an image of Physarum with its protoplasmic veins stretching out from the plasmodium mass. The oscillations, or differentially timed rhythmic pulses, are linked to its movement as the
successive waves instigate motion, responding to chemical attractors present in nutrients (e.g. sugar) (Durham and Ridgway 1976).

Recent research suggests that the oscillations are implicated in *Physarum’s* information processing capacity, but the details of this are not well understood (Latty 2010, personal communication; Tsuda, Zauner and Gunji 2005). The slime mold is able to calculate the distance to the nearest and best quality food source, at times exhibiting a risk mitigation strategy in which it will move to a more environmentally risky location, for instance in a well-lit area even though it shows a preference for living in the dark, if the nutrients are of high quality (Latty 2010; Latty and Beekman 2010; and see Adamatzky 2010). It is this probing and testing of food location and quality that demonstrates a proximity graph (also known as a relative neighbourhood graph): a graphical network diagram that shows all potential paths within spatially defined areas, and then, in the case of the slime mold, the choice of the optimal or shortest path between points to nutrients (and see Figure 3 below) (Adamatzky 2010; Fricker 2010; Latty and Beekman 2010; Tero *et al.* 2010). The capacity for mapping out the optimal path to food sources is useful to the slime mold because as it stretches its protoplasmic veins out seeking nutrients, it leaves slime trails, and as they retract these slimy trails signal where the plasmodium has explored acting as a form of memory (Reid *et al.* 2012). Once it has executed this decision-making routine, the plasmodium moves its mass to the optimal nutrient source.

*Figure 3: Physarum (image copyright Guelph University).*
Figure 4 shows the results of an experiment conducted in part at Queen’s University, Canada. To illustrate *Physarum*’s spatial calculus the researchers placed nutrients at key city locations on a map of Canada and observed how the slime mold traversed this map (Adamatzky and Akl, forthcoming). Figure 5 illustrates how *Physarum* mapped out many different nutrient locations with relative efficiency. The point is not that *Physarum* necessarily does it better, but rather how it computes: it deploys a computational method that can be constructed mathematically to provide a model for the shortest path for an object, datum, or any entity traveling a network (Adamatzky 2010; Fricker 2010). This can also be thought of in terms of De Landa’s possibility space: the *Physarum* tends toward an adaptive, emergent information gathering and calculates the possible dimensions of its state space before taking a ‘decision’ to undergo the energetically costly move toward a food source or low light location. In addition to the Queen’s University project, several other experiments have been undertaken to explore *Physarum*’s network optimizations and path-making
capacities using transport networks, including for Tokyo’s rail system (Tero et al. 2010),
the British rail network (Fricker 2010), and roads on the Iberian Peninsula (Adamatzky
and Alonso-Sanz 2011).

Researchers define *Physarum* as an “autonomous distributed system” with a
natural parallel computing capacity for information processing (Tsuda, Zauner and Gunji
2005, 4). This means plasmodium can compute multiple solutions to multivariate
problems without any centralized control and execute these computations at the same
time (in slime time, not human time) (Dussatour et al. 2010). There is no ‘brain,’ no
higher cognition centre, and no time delay in decision-making that directs this processing
capacity. As with *Dictyostelium*, researchers are keen to mathematically model the
decision-making routines and information processing capacity in *Physarum* and create
computer simulations that could one day help to solve human network problems noted
above (Fricker 2010; Latty, personal communication; Adamatzky and Akl, forthcoming).
Figure 4: Physarum mapping. On the left, the image shows the slime mold growth on a clear substrate overlying a map of Canada with all its highways. The slime mold calculated network path possibilities to maximize nutrient uptake using the shortest path to each point of node on the transport network (each node was an oat flake as a nutrient source). Physarum’s decision-making did not exactly match the human engineered highway routes. (images from Adamatzky and Akl, forthcoming).

The approach to simulating Physarum’s capacities starts from Turing’s reaction/diffusion equation because the plasmodium has both a chemical and a mechanical process coordinating its life cycle and differentiation. As stated elsewhere, not a lot is so far known about the details of Physarum’s vital communication pathways; however, it appears to communicate by using its protoplasmic flow. The “oscillatory flow of protoplasma ... provides a transport mechanism for nutrition and signals” and constitutes a dynamically “reconfiguring network of tubes [that] directs the flow of protoplasma and also the overall movement and growth direction of the cell” (Tsuda, Zauner and Gunji 2005, 4; see also Tero et al. 2010). The rhythm of flows (oscillations) in the protoplasmic veins is chemically controlled by signal molecules including adenosine triphosphate (ATP), the principle molecule for energy storage in eukaryotic cells, alongside the ‘mechanical’ or physical waves of protoplasm coursing through the plasmodium's veins (Tsuda, Zauner and Gunji 2005).
While it provides a general model of distributed control and decision-making as with *Dictyostelium* and bacteria, *Physarum* has network optimization capacities with implications for human network design. Modeling its parallel information processing capacity to enable efficient network path-finding is a primary concern for researchers, and as Mark Fricker notes, “we want to measure [and] replicate the flows and the routing of slime molds, capture these [organismal] ‘rules’ in mathematical rules ... and apply them to real networks” (2010). Fricker sees a need for self-coordinating and self-regulating network optimization in environmental sensor nets, which must operate remotely in harsh conditions, such as undersea or in the arctic, and be entirely autonomous. In practice, this means that such environmental networks must be able to self-organize and determine shortest network data paths, to ‘talk’ locally to their near neighbour sensor nodes, coordinate self-repair, communicate to external networks, and retract or shut down sensors if they are damaged, and still maintain the rest of the network (Fricker 2010; Bar-Cohen 2006; Bongard 2009). Potentially, *Physarum* can provide the model for calculating network parameters and paths and this might be combined with autonomous systems comprised of quorum-sensing like algorithms to manage many of the communication processes.

Researchers are keen to talk about *Physarum* as a simple computer; indeed, it has been connected to mobile robotic assemblies as the ‘brains’ behind the legs directing the physical motion of a robot (Tsuda, Zauner and Gunji 2005; Adamatzky 2010). One can conceive of *Physarum* as a Turing machine, a special built computing device conceived to perform a very specific function within its specialized ecological niche (and see for
related discussion Adamatzky 2010). Taking this specific purpose and simulating it in another computing device is essentially the definition of a universal Turing machine—a device that can simulate a special purpose device—as perhaps a drastic deterritorialization of *Physarum* creating a wholly new machinic assemblage based in biological processes (and see De Landa 2011, 201; Johnston 2008, 70; Norris 2011).

I have argued that bacteria demonstrate forms of vital communication, networking, and distributed control that computer scientists can access through simulations of self-organization to apply to contemporary digital systems and network. The slime molds, both the cellular variant *Dictyostelium* and its larger and more distant relative *Physarum*, give computer scientists the model for assembling computational frameworks that simulate complexity, as well as an impressive organic machinery for computing complex spatial problems that can be adapted to solving human networking challenges and opportunities. For these organisms, the bacteria and the protists, their virtual becoming is actualized in a continuous *becoming-something-else* enabled through and by vital communication. They are in constant transformation through cellular differentiation from the one to the many and, in unity, are capable of acting and being acted upon as one, acquiring “univocity-through-assemblage,” a multitude enacting multicellularity (Thacker 2008, 140).

The capacity for continuous change and adaptation, for growth and renewal, cooperation and conflict, occurring within these vast nonhuman assemblages is comprised of differential forces and relations, and together constitutes a vibrant, vital network. Bacteria and protists give technologists in both computer science and systems
engineering a model and a method for self-organization, self-assembly, and non-hierarchical communication and control that effectively embeds and distributes control across the multitude without the requirement of resource intensive centralized command (see Amos 2008). These microbial vital networks have ‘high fidelity’ communication circuits (Waters and Bassler 2005), meaning a combination of molecular, chemical, and/or physical cues lead to particular action and expression, as well as being contingent on a host of other variable signals for a range of potential actions and outcomes as in the example of myxobacteria swarms and biofilm self-assembly. Taken as a model for technological self-organization, communication and control, this flexibility, the combination of managing both accuracy and uncertainty, is a kind of ‘holy grail’ or an ideal to reach for in computing: the machine “must be able to resist the disturbances that can throw it off course, either by suppressing or by adapting to them,” and the same is true of the organism (Keller 2007, 304; Steventon and Wright 2006).

**Conclusion**

Bacteria and slime molds solve their environmental and organizational problems in a variety of ways that require biochemical communication and control. As computer scientists look to them for biological inspiration, these organisms are not only an example of distributed control and communication that can be simulated computationally, but also show how nonhuman social behaviour and organizational and communicative capacities are drawn into the human-technical milieu when models become simulations of life. John Johnston argues that this flow is part of the becoming-machinic of life, a new ‘machinic life’ (2008, ix). Machinic life entrenches the understanding of life as informational and as
nothing more than a series of computational abstractions rendered as simulations to understand the potentials for this machinic life. I argue that becoming-machinic is not reproducing life; rather it is producing vital qualities taken as life-like behaviour.

Manuel DeLanda (2011, 6) claims the recurring turn to computational simulation in contemporary human life is necessary because it stages interaction between the capacities and tendencies of emergent properties, but the question remains, then, as to what is emerging? In the next chapter I explore how computer science takes the problem-solving techniques of nonhuman life and turns them toward the design for self-capable networks and digital systems that can adapt to more and more of contemporary life organized around complex communication and information technology. The vital network emerging from this effort arguably presents both challenges and opportunities for human society and “leaves open the question of exactly what new kinds of assemblages human beings will enter into and become part of” (Johnston 2008, 22).
Chapter Six

Vital Networks

Introduction

In the preceding chapters, I traced the main features of scholarship, theory, and philosophy relevant to the constitution of a vital network and its autonomous functionality, processes of communication, self-organization, and distributed control. I also outlined the shift from the “logic of structures to a logic of flows,” which gives primacy to information, communication, and networks (Lash 2002, 208; Castells 1996, 1997, 1998). This emphasis on flows of information has re-focused the sociology of communication, where, as noted in Chapter Two, “communication and perhaps no longer the ‘social act’ [has] become the contemporary unit of analysis” (Lash 2002, 206, emphasis in original). I responded to this focus on communication in Chapter Five, in my close examination of the processes of communication and self-organization among bacteria and slime molds, which provide biological inspiration for digital systems and network design and development. These vital communication processes are inextricably linked to the role of mathematical biology and the informationalization of microbial life necessary for computer simulations of biochemical communication circuits.

In this chapter, I continue to focus on communication, turning to explicit examples of biological inspiration in digital system and network design. Throughout this chapter the themes of life, autonomy, self-organization, and control resonate as the discussion turns to specific aspects of vital networks taking shape as one space of
possibility within which a new, nonhuman form of control is unfolding. I argue here that the nonhuman organizational logic designed into our contemporary digital systems is distancing us from the more complex aspects of networks. This distancing effect is an intentional outcome of biologically-inspired design initiatives driving the development of autonomously-enabled, self-regulating digital systems and networks, the material consequences of which are more difficult to locate and understand as the gains in complexity and its control processes become more obscure.

**Assembling the Vital Network**

**The Internet: Communication and Control**

In the six decades since the Macy Conferences and the era of first-wave cybernetics, control has been conceived on the one hand within the human-animal cognition model and its capacity for autonomic function, and on the other as a source of inspiration for a quite different idea of self-regulation drawing on John von Neumann’s cellular automata theory. In many respects the former model served to govern the paradigm of control for the development of networks prior to the 1980s and for the early Internet, whereas the latter has given rise to recent efforts to locate control within complex digital systems and newer networks, robotics, and computer agent systems (explored further on), based on a simple set of rules that describe the system and its interacting parts and out of which control emerges.

The Internet of today emerged out of the military-industrial complex of the 1950s. Early networks were in place to enable communication and control for military systems
enabling specific hierarchical communications between physical structures, from troop centres to missile silos, but were highly centralized and vulnerable to disruption (Galloway 2004; Walrand and Parekh 2010). If one central hub went down, all communications on the grid would be cut off. These fixed networks were based on wire line telephone networks, which set the connection for information to flow along an established circuit, carrying voice or data, from point A to point B (Walrand and Parekh 2010). In the 1960s, a newer and more flexible communication technology was developed that could operate reliably even when parts of the network might be under attack. This model, known as packet-switching, broke down communication into smaller pieces or packets that each carried source and destination information, meaning it could be routed and re-routed in transit along a network and reassembled at the destination (ibid.; and see Galloway 2004). Packets can be switched from router to router, or point to point, to circumvent network disruptions. Packet switching made rigid, centralized networks more efficient, but the growth of networks worldwide in the last forty years has meant that to fully take advantage of the flexibility in packet switching, the network infrastructure and method of control has had to change.

**Changing the Grid: Three Network Models**

There are three main forms of digital networks, as illustrated in Figure 5 below, and each of these network organizations can be part of other networks, such as the Internet, in which connectivity is enabled by the rules and protocols that govern data transmission discussed below. The centralized network relies on a central point of control in which nodes, or points along the network, radiate out from the centre, and all
communication must pass through the centre en route to all other points. The decentralized network has a more flexible structure, in which nodes and sub-nodes can communicate without relying on a central hub, as illustrated in the middle of Figure 5 (Galloway 2004; Walrand and Parekh 2010). Finally, a distributed network, seen on the right of Figure 5, has no defined or fixed central structure and exhibits a flexibility that enables communication across the network dynamically (Walrand and Parekh 2010; and see Baran 1964; Power 1990).

Figure 5: Network diagrams (open source image).

The contemporary Internet is predominantly, though not exclusively, distributed (and see for an illustration in Figure 6 below and above on right in Figure 5), but it continues to connect to older centripetal networks in which much of the control logic is located in a central hub and communications are coordinated from within, and pass through, the hub (Galloway 2004; Power 1990; Walrand and Parekh 2010). The Internet is a meshwork of systems that must work cooperatively to coordinate the flows on the network itself as well as the multitude of networks and subnets that cross it and interconnect with it. This means a large network such as the Internet is an assemblage of
hardware and software, visible or not, with surface arrangements (software) that connect human clients to information on a network. Much more constitutes the Internet that is not seen or ‘felt’ by human clients. It is organized through/by code and protocol, or rules, that serve as detailed instructions operating between different computers and servers to facilitate reliable data communications (Galloway 2004). Thus, in addition to human clients connecting their digital devices to the network, the Internet is also full of machine-to-machine communication operating autonomously.

The design of the Internet is formally expressed in engineering specifications that denote seven layers as part of the Open Systems Interconnection (OSI) Reference Model, but more commonly a simplified four layer model consisting of the application layer, the transport layer, the Internet layer, and a link layer suffice to convey its structure (Walrand and Parekh 2010, 20-21; Cisco Systems 2012). Each of these layers requires hardware such as servers, routers, and physical ‘pipeline,’ including optical fibre and copper twisted pair wires, alongside available wireless spectrum, to function and route data. The layers contain a set of protocols or rules that provide ‘handshakes’ between different parts of the information routing infrastructure to ensure data transmissions are moving smoothly, securely, and error free (Cisco.com 2012; Walrand and Parekh 2010). The application layer is crucial to human clients; this is the layer we interact with when we engage with software applications and content such as Google. All our click-throughs, media streams, and transactions pass through the application layer and technically a layer

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29 The OSI model consists of seven layers (providing more detail including the physical carriage layer): application, presentation, session, transport, network, data, and physical (Walrand and Parekh 2010. Cisco Systems Inc. is the leading vendor for network hardware and software for Internet data flows such as data routers and has published a widely referenced set of technical specifications and explanations of Internet-working (see Cisco.com 2012).
of content as well. The connections between points on the network, between computers and digital communication devices we use in our daily lives, are served by the transport layer ensuring our communications make it across the network (Walrand and Parekh 2010, 87-88).

Figure 6 is a graphic rendering of the interconnections along routing paths (network lines) in one section of the Internet: it is a snapshot in time illustrating the billions of connections on global networks. The Internet layer facilitates the routing or movement of packet-switched data between network points, and the link layer connecting to this layer furnishes raw protocols that enable connectivity to hardware such as other computers and servers. For the most part, protocols are algorithms staged as a cascade of control processes instructing Internet traffic where to go, when to stop and go, and how to go—they have not historically ‘read’ the data to discern its meaning, although as discussion below reveals, this is changing (Walrand and Parekh 2010; and see Galloway 2004).

Data moves on the Internet and other networks at quite high bit rates, and issues such as coordinating how much data flows and on which ‘pipeline’ and the overall carriage capacity are determined by sophisticated algorithms (Walrand and Parekh 2010; and see Galloway 2004).30 This form of control over information on the network, on the Internet, is far more advanced than the one-to-one direct communication set out initially in computer communication and control in the era of cybernetics (see Wiener 1950;

30 Speed on the Internet is described as n mega- or gigabits per second, where a megabit = 1 million bits per second (mbps) and a gigabit = 1 billion bits per second (gbps) (Cisco.com; Walrand and Parekh 2010). This indicates just how capable the algorithmic code and protocols executing on the Internet are to parse/read transmission data at this rate.
Johnston 2008). Today, algorithms have decision-making capabilities and detect transmission errors and auto-repair, optimize network traffic, balance data flows, and so on. In practice, this often makes connectivity between our cell phones and transmission centres feel seamless as we move around a city; yet, our cell signal may at any time be re-routed to balance the data load on a given network.

Figure 6: Network Routing Paths. A graphical rendering of routing paths (network links and connections) for one part of the Internet (open source image).

Google Search and Apple’s ‘Siri’ software are good examples of how algorithms operate on a network such as the Internet to help us sort through the vast amounts of information circulating in the information flows. There are approximately 45 billion indexed web pages and 634 million websites on the Internet as of February 2013. 1.2
trillion searches were conducted through Google Search in 2012. It is impossible for an individual to search information of that size. Google’s search function, on any subject and for all kinds of content, is an application that enables humans to navigate the billions of pages, nodes, links, objects, and texts on networks. From the moment we type in a search query and click the search button on Google, search results appear almost instantaneously in an ordered fashion. How does Google’s search capacity actually work? We might, as human users and designers of technical objects, systems, and liminal machines, write the original code and software to enable functionality, establish a base set of instructions or goals for a system, type in a message and hit send, or input a search query, but the control over, and subsequent decision-making within the network spaces and systems with which we interact, as with Google, are beyond our direct control.

Apple Inc. has released an iPhone application known as a Speech Interpretation and Recognition Interface called ‘Siri.’ This is a voice-activated “intelligent personal assistant” that human clients speak with and pose all sorts of questions to, from driving directions to weather updates, and Siri will respond in a human voice with an answer. Siri’s marketing hype tells us, “Your wish is its command,” but in practice, Siri is simply a voice-activated search engine (Apple Inc. 2012). What enables Siri to return the most likely answer to our questions?

Google and Siri essentially work in the same manner: the software is an autonomous or self-capable system that operates by matching our natural language query to the range of possible answers stored in the repository of information on the Internet. In

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31 The number of indexed pages is estimated by looking at the big three search company statistics: Google, Yahoo!, and Bing. See http://www.worldwidewebsize.com/ and http://royal.pingdom.com/2013/01/16/internet-2012-in-numbers/
the Google example, the search engine technology uses algorithms that have been
developed to enable self-learning and therefore self-improving search functions—the
more Google is used, the more powerful and accurate its determinations become (Brin
and Page 1998; Menczer and Belew 1998; Shkapenyuk and Suel 2002). Google deploys a
proprietary algorithm called PageRank, which “deploys an automated and predetermined
selection mechanism to establish relevancy” between the search term and search results,
and measures the citation value of web pages based on hyperlinks, or links to other pages
from within a page, to further refine the results (Bucher 2012, 1167; Brin and Page 1998).
Siri and Google are each encoded (programmed) to do something in a particular way (a
goal), and search information to find and return the most likely answer (a result) (Grosan,
Abraham and Chis 2006; Maes 1995; Timmer 2009).

The substantial difference between Siri and Google is in the usability function:
Siri has been personified to interact with us by imitating a human-like intelligence, and
although Google offers similar applications on the Android phone operating system such
as ‘Robin,’ none are as slick as Siri. Using algorithms, the Siri system stores and sorts our
questions in an additive routine to increase the knowledge database through a learning
algorithm that enables it to be what its developers refer to as ‘smarter’ and more accurate
the next time (and see Apple 2012; Gruber 2011).\(^\text{32}\) Much as with Google, our individual
questions, and Siri’s responses, contribute to the system’s steadily increasing collective
knowledge drawn from all its users. Siri has a predictive function comprised of

\(^{32}\) As blog author and software developer John Gruber has noted, “Siri is indicative of an AI-focused ambition that
Apple hasn’t shown since before Steve Jobs returned to the company. Prior to Siri, iOS [Apple’s mobile operating
system] struck me as being designed to make it easy for us to do things. Siri is designed *to do things for us*” (2011;
emphasis added).
algorithms that constantly analyze questions and responses, to be able to predict the most likely answer to common questions. In other words, as with Google, Siri also utilizes algorithms to predict what its users are most likely to be looking for in terms of an answer and constantly improves itself in the process (Gruber 2011).

The complex algorithmic control and functionality behind Google and Siri are self-regulating systems capable of executing a set of computational functions without direct human intervention (Bucher 2012). There is human-to-computer interaction through the user interface, but the underlying coded processes that execute the search routines and analytics necessary to return search results are not accessible to human clients of either program. In both examples, as detailed in Chapter Two, these applications can be considered complex digital systems—systems founded in the history of biologically-inspired development in computer science from computers that ‘think like humans’ to software agents that ‘crawl’ the web like spiders (and see Adam 1998; Bongard 2009; Brooks 1999; Hamilton 2009; Hayles 1999; Kember 2003; Maes 1995). In the examples of Google search and Siri, each uses sophisticated programming to improve the quality and relevancy of information for the user, yet this ‘smartness,’ or complexity of the programming, resides below the interface, in that place we never ‘see’ as clients of the system (Bucher 2012).
Biologically-inspired Control

In this section, I outline biologically-inspired technology that enables contemporary digital systems and networks to be self-regulating. Before turning to a detailed explanation of digital quorum sensing, I touch on the general approach in engineering and computer science to biologically-inspired technology. Nonhuman organismal models are a radical departure from how digital networks have functioned in the past as centralized, hierarchically controlled assemblages comprised of nodes and edges, points and lines, that organize flows of information around a defined centre (Balasubramanian et al. 2007; Galloway 2004; Galloway and Thacker 2007). For the most part, when we think about communication technology, we think about human-centred machines, by which I mean computers and communication systems predicated on hierarchical control governed by a human logic and enabling human engagement, interaction, and intervention. This has been the logic guiding the development of machines, from computers to networks, until very recently. Current research into control is unfolding around a radically distributed field of interacting points and nodes, and communicative objects and processes, that are continually shifting their organization to accommodate a dynamic system and network structure.

Simulation is key to reproducing autonomous biological self-organization in a digital system, but computer scientists also require clear, detailed technical requirements that establish the operational parameters for a biologically inspired digital system and network control (Dove 2011; Hamer and Dove 2012; Hordijk 2005). These detailed requirements, alongside simulations, enable computer scientists to write the code to
develop the biologically-inspired digital system. There are six criteria, listed in Table 2 that a biological system must meet to qualify as inspiration for the design of autonomous, self-organizing processes as for networks (Dove 2011). These criteria are denoted by the acronym SAREPH: A biological system must be self-organizing (S); employ adaptive tactics (A); demonstrate reactive resilience (R); have a self-evolving strategy (E); be proactive (innovative) (P); and demonstrate harmonious operation (H) (Hamer and Dove 2012, 1-2; cf. Dove 2011). These characteristics manifest what engineers call self-x or self-capable properties aligned closely with IBM’s eight properties for autonomous systems (see Table 1 in Chapter Two), wherein any process or action can occur independently within the computer system or network as it interacts with its environment (physical or virtual) and its local or near neighbours on the network (see Brooks 1999; IBM 2012; Woolridge and Jennings 1995). Table 2 outlines the SAREPH attributes with the bacterial QS processes that respond to these attributes and the network processes that are designed to meet the requirements using biological inspiration (Balasubramanian et al. 2007; Bassler 2002; Hamar and Dove 2012; Peysakhov et al. 2006; Williams et al. 2007). I highlight QS as the model here because it features in ongoing research into distributed network control models as I will discuss below (and see Balasubramanian et al. 2007; Herkersdorf and Rosentiel 2005; McGibney, Botvich and Balasubramaniam 2007; Peysakhov et al. 2006; Vogt, Aycock and Jacobson. 2007).

The level of detail in Table 2 is necessary—it emphasizes how closely computer scientists follow the biological pattern or model to assemble the coded control processes necessary to create complex biologically inspired system. To reiterate IBM’s definition
for autonomous systems, it is a “systemic view of computing modeled after a self-regulating biological system” (2012). Table 2 is the expression of complex behaviour written in plain language, from which computer scientists and engineers will draft high-level system requirements and then proceed to adapt biological simulations by creating algorithms that emulate the biological process of communication and control (Amos 2009; Gorodetskii 2010).

Table 2: SAREPH Attributes: The SAREPH attributes of bacterial communication through QS (adapted from Hamar and Dove 2012, 1-3; see also Balasubramanian et al. 2007; Bassler 2002; IBM 2012; Peysakhov et al. 2006; Williams et al. 2007).

<table>
<thead>
<tr>
<th>SAREPH attributes</th>
<th>Bacterial QS process</th>
<th>Coded network process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-organizing</td>
<td>Quorum is sensed, collective action occurs</td>
<td>Network must sense the number of network nodes; require ( N ) inputs for decision-making action</td>
</tr>
<tr>
<td>Adaptive tactics</td>
<td>Ability to adapt to changing environment; communicate inter- and intra-bacteria; respond to threats and opportunities</td>
<td>Local network nodes must respond to changing network conditions such as damage, attack, new additions, and/or deletions of points and data</td>
</tr>
<tr>
<td>Reactive resilience</td>
<td>Bacteria have more than one QS circuit and can manipulate signal strength (concentration); may have circuit backups</td>
<td>Digital networks require redundancy; network must be self aware; detect failures, initiate recovery processes, re-directions, locate spare capacity, and so on</td>
</tr>
<tr>
<td>Evolving strategy</td>
<td>Selective for bacteria producing signals; bacteria population will select for mutations that inscribe a stronger signal</td>
<td>Networks require self-learning algorithms to increase its knowledge base for action</td>
</tr>
<tr>
<td>Proactive innovation</td>
<td>Bacteria can wait for quorum, proceed then cancel quorum; based on signal reception and environmental cues</td>
<td>Self-capable networks must be able to change a process or action dynamically based on changes to the network and its environment (starting and stopping processes)</td>
</tr>
<tr>
<td>SAREPH attributes</td>
<td>Bacterial QS process</td>
<td>Coded network process</td>
</tr>
<tr>
<td>-------------------</td>
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</tr>
<tr>
<td>Harmonious operation</td>
<td>This is the capacity of bacteria to cooperate such as in biofilms and swarms</td>
<td>Networks must be able to cooperatively pick up heavy data loads and re-route or ‘wake-up’ nodes or processes that enable this type of action</td>
</tr>
</tbody>
</table>

**Quorum Sensing and Network Control**

Quorum sensing has emerged as a model for computer scientists designing different types of networks in which individual units must operate as a “symmetric, cooperative and self-organising” global entity (Sacks *et al.* 2003, 1; Peysakhov *et al.* 2006). Table 2 reflects the minimal requirements for a QS-inspired model of network control, and it provides guidance as to what is required to meet the demands of diverse, heterogeneous networks. The network processes in the right column of Table 2 are all features and capabilities that must be painstakingly programmed by humans, but once such a system is launched, human programmers and operators will only interface with high level controls as there are thousands of nodes or points on a given network that will run the QS software and initiate the digital QS circuitry as/when required (see for related Arabshahi *et al.* 2004; Balasubramanian *et al.* 2007; Beckmann and McKinley 2009).

In the information technology domain, designing and applying network control is known as policy management. This simply means that the processes of control necessary for the network to function autonomously are programmed in rule-sets or protocols expressed as algorithms that form part of a policy, or description, for how to handle network data flows (Balasubramanian *et al.* 2007). The algorithms constructed from vital
communication systems are considered “survivability-related routing algorithms” by technologists because they demonstrate adaptation to changing conditions across a network (Balasubramaniam et al. 2008, 1666; McGibney, Botvich and Balasubramaniam 2007; Peysakhov et al. 2006). As with any algorithm, it is, at its simplest, a form of computation in which a number of inputs can be analyzed to produce an output. There may be one clearly defined, step-by-step calculation executed sequentially or, as is often the case, such calculations can occur in parallel with many operating at the same time as a cascade of events and decisions (Gurevich 2011). In something as complex as a biologically-inspired digital system, the algorithms consist of code blocks connecting to other algorithms and network processes. As an example of a network algorithm, the code snippet in Figure 8 is a very small fraction of what would be required across an entire autonomously-enabled network deploying a QS program.

The algorithm in Figure 7 is an example of a QS policy for network services written as a computer algorithm. Initially, this code runs in simulation mode on a computer, furnishing the researchers with opportunities to manipulate different variables that affect the network, including the size of the network or how many nodes or communicating objects are interconnected, how much data traffic flows on the network, what type of data is carried on the network, and how the network adapts to dynamic change (Balasubramanian et al. 2007, Hamar and Dove 2012). The simulation permits the computer programmers and engineers to ‘see’ what digital QS control looks like and to see the processes of communication and self-organization unfold within a space of possible outcomes. De Landa (2011) notes that simulations of complex, dynamic systems
generate emergent behaviours or unanticipated outcomes, and while these cannot be predicted, simulation allows the programmers and engineers to see examples of this network behaviour and design their system to respond dynamically to the emergence of unanticipated behaviour.

Figure 7: Quorum Sensing Algorithm: a sample algorithm as part of a QS-inspired policy management approach for a digital network. This example describes how the algorithm will handle a link (or node) failure (Balasubramanian et al. 2007, 1673).

1 if link failure detected on node m
2 m sends request for spare capacity $Q_s$ to its neighbouring nodes $j \in N_m$
3 Nodes $j$ receiving $Q_s$ reply with their spare capacity, $C_{s,j}$
4 $m$ sets total spare capacity $C^T_s = \sum_{j=1}^{N_m} C_{s,j}$
5 if $C^T_s - TH_D < S_{M,FL}$
6 $m$ sends request for additional capacity $Q_a$ to $j \in N_m$
7 $j$ receiving $Q_a$ responds with
8 \[ C_{a,j} = \begin{cases} T_{D,j} - TH_D & \text{if } T_{D,j} - TH_D > 0 \\ 0 & \text{if } T_{D,j} - TH_D \leq 0 \end{cases} \]
9 where $T_{D,j}$ is the total size of data flows currently routed via $j$
10 Set total additional multimedia capacity $C^T_{a,M} = \sum_{j=1}^{N_m} C_{a,M,j}$
11 Re-route data flows with total size not exceeding $TH_D$ and multimedia flows with total size not exceeding $C^T_s + C^T_{a,M} - TH_D$ via nodes $j \in N_m$, whilst ensuring that the total size of flows routed via node $j$ does not exceed $C_{s,j} + C_{a,M,j}$
12 else
13 Re-route multimedia flows with a total size not exceeding $C^T_s - TH_D$. Drop remaining multimedia flows. Use remaining capacity to re-route data flows and drop and remaining data flows.
14 for re-routing after failure
15 $m$ selects $\hat{G}_{a,d,i \rightarrow j}$ to re-route flow via node $j \in N_m$
The ‘multimedia routing algorithm’ example in Figure 7 is coded to handle failure detection, which is a required feature of both the SAREPH and IBM frameworks. It does this autonomously without a human operator monitoring the network node (link) problem. In Figure 7, the code snippet describes how different conditions are to be managed: node \( m \) sends a request to its near neighbours (nodes closest to it), calculates spare bandwidth capacity from those near neighbours, then calculates the total spare capacity, and finally re-routes data flows away from the failed node to those nodes that can accommodate it (Balasubramanian et al. 2007). Calculating spare capacity on nearby nodes is its version of sensing a quorum; in this case the threshold concentration is network capacity (how many network nodes are nearby) and not a signal molecule as it would be for a bacterium.

Balasubramanian’s example is interesting because in this simulation the algorithm is checking for spare capacity so that it can treat multimedia data preferentially as it is more valuable to Internet service providers (ISPs) and media content companies (they charge customers higher data rates for media content) (2007). The algorithm will direct nodes to calculate and ‘set total additional multimedia capacity’ and re-route media data away from the failed node to active nodes (see Figure 7). The goal is to keep the media data flowing because the ISPs set higher fees for customers accessing this content, so the algorithm is coded to drop voice and other data that does not provide the same revenue to the ISP. At some pre-set data capacity, the network will resume transmitting other data flows. When data is re-routed, the failed network node or point will self-repair (in an ideal scenario) and signal its local neighbours when it is ready to receive data. This
‘multimedia routing algorithm’ as proposed by Balasubramanian et al. would operate undetected on a network; each node or point on the network would run an instance of this code, alongside other algorithms, as part of its data routing control processes.

The strength of this example is that it demonstrates how hierarchy and preference can be designed into the behaviour of the network by distributing QS decision-making capacity across the nodes of the network. The algorithm is but one control process, yet its decision-making capacity includes functionality not only to redirect data flows away from problem nodes, but to differentiate the streams of data and selectively process one form over another (media over voice) (Balasubramanian et al. 2007). This is an important implication to highlight. Biologically-inspired control algorithms are designed to be submerged beneath the application and content layers and to operate autonomously without direct human intervention. These algorithms are nontransparent and obscure, and their distributed mode of control means that at each instance of the QS algorithm, it may execute its decision-making routine quite differently (ibid.; see for related Chun 2011).

The control apparatus of the Internet was originally conceived to be neutral to the content of the information carried (Galloway 2004; 2010). However, as algorithms become more sophisticated they blur this line between the straightforward mechanical routing or carriage of information regardless of content. Thus, ‘smart’ algorithmic processes are coded to be able to interact with the existing transmission protocols for networks while at the same time exercising a decision-making routine linked to the form of content of the communication and available ‘pipeline’ capacity or bandwidth. Clearly the QS algorithm can include an exception to handle a hierarchy of data expressed as
preferences between multimedia, other non-media data, and voice data. While there are practical business reasons for these distinctions noted above, it does suggest, contra Alexander Galloway (2004), that the historic neutrality or indifference of the control code to content on the Internet can be compromised at a deep level. At present there are concerns over expansive Internet-based surveillance and control and net neutrality, and as control algorithms become more sophisticated their non-transparency on the network increases (Bucher 2012; Galloway 2010). This algorithmic control may well operate alongside deep packet inspection (DPI) currently deployed to read the form of packets being transmitted. DPI permits an inspection of data that is sent between personal computers and network servers and is neither detected nor blocked by privacy enhancing technology. It has important commercial uses in providing detailed data and transmission quality for ISPs, but can be redeployed by data mining companies to detect and analyze personal communications that can then be used to tailor advertising to Internet clients (Bendrath 2009).³³

In the case of the example above, each node would only be communicating with its nearest neighbor, much as in the case of bacterial QS, and the organization of the whole network is based on local communication that resolves in network-wide action. If a node or several nodes fail, the network automatically instigates repairs after the failure detection, but only through the actions of locally communicating nodes, that is, to the nodes nearest the failure point (Hamar and Dover 2012; Meisel, Pappas and Zhang 2009;³³

³³ The National Security Agency (NSA) in the United States is thought to be using DPI as part of its expansive network surveillance program recently revealed by former NSA contractor Edward Snowden (Gallagher 2013; Yost and Apuzzo 2013).
The detection of a failure by other nodes local to the point of failure triggers re-routing, and the network will reorganize, based only on local node communications, and dynamically reroute data flows to other parts of the network. This is a crucial self-capability that occurs without human-computer intervention and an instance of self-organization within a complex digital system organized to communicate and respond dynamically, what emerges is a reconfigured, autonomous network.

**Digital Autonomy**

It is easy to think of our digital network(s) as only the Internet, that seemingly vast network of networks most of us take for granted every day when we connect to a network or what we conceive of as *the* network. In practice, we connect to many networks: wireless or wireline, broadcast media, global positioning systems in our cars and our smart phones, transportation and traffic-ways, and we also tap into the electrical grid or network that brings power to our homes. All these instances are networks, and most can interconnect and share data—that is communicate—across what we understand as *the Internet*. Each of these networks circulates information, electricity, signals, and media that interconnect across multiple networks, expanding both our conception of what communication and information technology is and of what digital networks are and can be. These networks are extensive and relational; they require autonomous controls to deal with the growth in demand, bandwidth and flow capacity (how much of a unit of data, signal, or power is carried over the network) that comes from a steadily increasing amount of information gathered from more and more of daily life processes and
transactions and carried over networks (Meisel, Pappas and Zhang 2009; Terranova 2004; van der Berg 2010; Walrand and Parekh 2010).

There are 25,000 autonomous processes running on the Internet—these do not include the autonomous processes running on our wireless and wire-line communication devices, wireless cell phone services and networks, radio frequency networks, private networks, transportation logistics networks, satellite communications, environmental and geographic sensor networks, and others (Meisel, Pappas and Zhang 2009; Steventon and Wright 2006; Riva et al. 2005; van der Berg 2010). Autonomous processes on the Internet are known as autonomous systems (AS) but are actually discrete processes that control data flows, govern which lines or links between network points will carry data based on bandwidth capacity, time of use, type of data, and so on (van de Berg 2010). More and more these processes are inseparable from, and join with, the sorts of intelligent agents (algorithms) programmed to travel the network making sense of information flows.

As the complex of systems for network control expands, there are networks within networks, and processes within processes, that are continuously extending in scope, reach, capacity, interconnection, and heterogeneity, and the control requirements far exceed the human-computer interaction model. The sheer plurality of networks, applications, structure, mobility, and information flows indicates how expansive and

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34 This may not appear a very large number of AS processes considering how vast the Internet is in terms of sheer connections and communicating objects; however, these AS processes were developed by a small engineering group (mainly the Internet Engineering Task Force or IETF) dominated by American interests (and to a lesser extent engineers from Northern European countries). The IETF also works closely with the government and private sector to maintain standards that are supportable across the widest range of systems and can interface with security and privacy protocols (IETF.org).
diverse our CITs have become, and why robust nonhuman control models are more and more the design for autonomous networks.

Self-organizing Multi-agent Systems

The plurality and size of the Internet demand that many aspects of communication must function automatically in response to various communication processes of all kinds: from informatic transactions such as online product searches and purchases by human users, to millions of tweets and Facebook posts, and overall communication is a meshwork of humans and nonhumans all sending and receiving information over the Internet. Sorting out this communicative assemblage is not easy. A small start-up company in the United States recently noticed that 80% of its advertisement clicks on Facebook were not coming from human visitors interacting with their ad, but were being clicked by ‘bots,’ otherwise known as software agents (Brodie 2012). The ad clicks seemed ‘real enough’ early on, but there was little conversion to actual sales, leading the company to deduce that automated software agents were interacting with their site. After some investigation, this company could not resolve the issue or identify where the bots originated, illustrating just how hard it is to know who or what is making contact over a large network running any number of autonomous processes. Once software agents are programmed they are left to run autonomously and in the context of the web are notoriously difficult to trace, yet can produce unanticipated material consequences such as in this example (Vender 2011).

Complex digital systems known as agent systems, as in the Google Search and Siri examples and again in the above example, follow a biologically-inspired model of
distributed, autonomous control. Pattie Maes defines a software agent, or bot, as a programmed artificial intelligence system that fulfills a “set of goals in a complex, dynamic environment” including search and decision-making processes online, in which software agents sift through enormous data stores such as web pages or respond to interactive online queries (1995, 136; and see Johnston 2008, 353; Menzer and Bewel 1998). There are bots that operate as web crawlers or spiders, programmed to catalogue pages and content on the Internet, such as are deployed by search engines including Google, Bing, and DuckDuckGo. There are shopping bots, data mining bots, predictive bots, and malevolent bots that are assembled into botnets and remotely take over computer and network services in directed denial of service attacks, spamming actions, and spreading malware (computer viruses) (Serenko, Bontis and Detlor 2007; Walrand and Parekh 2010; and see Symantec.com 2012).

Software agents are a fascinating example of an autonomous system considered a model of distributed artificial intelligence: they are self-organizing and communicative (Maes 1995; Brooks 1999; Johnston 2008; Kasinger and Bauer 2005). Agent-based systems are biologically-inspired following social insect and microbial behaviours. This suggests that the original assumption of cybernetics persists; that “some aspect of a living organism’s behaviour can be accounted for [and] modeled by a machine,” although the source of biological inspiration in these instances is a particular nonhuman intelligence not considered in that earlier effort (Johnston 2008, 31). Software agents are designated as intelligent agents, designed to both observe and effect the execution of a set of goals for a system or network, as is demonstrated in the QS algorithm example above (Maes
1995; see also Balasubramanian et al. 2007). Whereas classical procedural programming is coded to follow a set of rules to solve a problem in a particular way by acting on a specific description of the problem, agent-based systems are goal-oriented and the agent system identifies the problem and ‘decides’ how to best solve it (Argawal and Harrod 2006).

Multi-agent systems are often embedded as sub-processes and subsystems usually within a large complex system and do things for and with other machinic processes (and often indirectly for humans) within these systems (Maes 1995). It is hard to overstate the challenge in controlling large networks and digital systems; they consist of millions of entities each with diverse communication requirements, an information load, security protocols, and subunits, and more and more these entities must run autonomously with only limited awareness of the wider network (Gorodetskii 2010). In this they are not so different from the bacteria swarms and biofilms, capable of communication and coordination from the one to the many. Multi-agent systems are well situated to take on the multi-process demands of contemporary networks, and their fundamental objective is directed at goal-oriented processes that will enable complete autonomy over system decisions, network connections, and self-regulation (Serenko and Detlor 2004).

Throughout the 1990s multi-agent systems, including embodied physical robot agents and software agents, were the object of considerable research, and this generated some key system guidelines that are biologically-inspired. The four key properties of multi-agent systems consist of (Huebscher and McCann 2008, 5; emphasis added; cf. Woolridge and Jennings 1995):
Autonomy: *Agents operate without the direct intervention of humans or others,* and have some kind of control over their [own] actions and internal state. 
Social Ability: *Agents interact* with other agents (and possibly humans) via some kind of agent-communication language.
Reactivity: *Agents perceive* their environment, and *respond* in a timely fashion to changes that occur in it.
Proactiveness: *Agents do not simply act in response to their environment, they are able to exhibit goal-directed behaviour by taking the initiative.*

There is a theme surfacing here: autonomous agents are programmed with system goals that bear the hallmarks of biological systems, and in particular, of nonhuman biological modes of vital communication and of control. These system goals clearly reflect the standards established by IBM’s autonomic computing research and the guidelines for self-organizing digital systems represented in the SAREPH framework (see Goredetskii 2010; IBM 2012; Huebscher and McCann 2008). It is important to stress that the model of operation, interaction, perception, and agent initiative in Woolridge and Jennings’ (1995) goals is not based on the human-animal model of cognition outlined in Chapter Two: rather, its inspiration is drawn from biological processes discussed, in Chapter Five, that are inherently distributed and autonomous (and see also Amos 2009; Brooks 1999; Johnston 2008). Yet, the description of the system relies heavily on humanist language such as ‘autonomous agents’ and human social terms that are pulled into service to describe a system that is radically nonhuman. This tension in using human-friendly and familiar language to describe distributed, self-regulating machines maintains the humanist fundament locating even radical difference in the safe and well-understood boundaries of human social behaviour and action. Even as new forms of decentred control continue to be developed, computer scientists and those of us analyzing
these systems struggle to describe them from within a new vocabulary. The whole notion of intelligibility, as for intelligent systems or swarm intelligence, is bound to humanism’s insistence on an ‘intellective agent’ (or the autonomous human agent) and cognition and intellection are understood as a human capacity (Barad 2007, 379). However, in biologically-inspired swarm systems, multi-agent systems, and vital networks with the decentred and nonhierarchical form of control those systems manifest, there is no human styled ‘knowing’ that governs the system—intelligibility is a feature of the system that emerges as part of its becoming-swarm or becoming different.

*From the Bottom Up*

Rodney Brooks (Professor of Robotics, emeritus) and his colleagues at the Massachusetts Institute of Technology (MIT) made a software breakthrough with the control system for physically mobile robots, demonstrating that simple units can generate emergent properties from local interactivity (1999). The emphasis is on four key aspects: intelligence, emergence, situatedness, and embodiment, expressed in what Brooks calls “subsumption architecture”; a from-the-bottom-up self-organization that informs the basic parameters of behaviour-based robots (1999, 4; and see also Johnston 2008, 346). This is not so different from the local to global communication circuits, differentiation, and self-organization occurring in bacteria, cellular slime molds, and *Physarum* discussed earlier.

Brooks’ model for robot intelligence was influenced by Marvin Minsky (1988), who had proposed that simple, interacting agents could more accurately produce a kind of intelligence from the bottom-up rather than in response to a single higher-order cognitive
module, and it follows the logical model pioneered by William Grey Walter in the 1950s and discussed in Chapter Two (see also Woolridge and Jennings 1995). Brooks’ model is significant because it demonstrates that many cooperative, individually programmed behavioral modules permit more complex behaviours to emerge as the physical robots encounter each other and their environment (1999, 112)—an example of autonomously-enabled system design generating self-organization and emergence in an artificial intelligence. As a model of interaction it has underwritten research into biologically-inspired software in which many software agents must interact in a complex virtual environment in response to ever-changing system inputs as discussed above (see Abelson and Forbes 2000; Bongard 2009; Maes 1995). The QS algorithm is an example of this kind of autonomy: there would be many thousands of these QS-enabled agents across a network monitoring data capacity and network performance. Each instance of this algorithm is able to act autonomously. Its local interaction and communication with its near neighbours on the network can produce a global change of state for the network if it detects a node failure (Balasubramanian et al. 2007).

Brooks’ (1999) artificial intelligence program for robotic behaviour bypasses the notion of a separate artificial cognition module, or a higher reasoning centre common to classical human-animal inspired AI, discussed in Chapter Two, for a non-hierarchical formula that includes only the perception and action subsystems outlined in Woolridge and Jennings’ multi-agent model. This is a behaviour-based model for autonomous mobile robot, which gives rise to intelligent behaviour as the robot interacts with its environment (Brooks 1999, x-xi). It represents a significant shift from rule-based
cognition toward “embodied, concrete and experiential” models of the kind observed in social insects and microbes (ibid.; see also Turkle 1991, 225; Quick, Nehaniv and Roberts 1999). In addition to Brooks’ research, researchers have embedded an electronic sensor and a wireless transmitter in a *Physarum* plasmodium to control a six-legged robot (Tsuda, Zauner and Gunji 2005). The *Physarum* directed the robot into the darkest and furthest corner of a room—a place similar to its preferred setting in its outdoor habitat. This is a significant achievement, which suggests that *Physarum* path-finding can merge its ‘natural’ behaviours within the embedded circuitry of a digital network, whether for software or hardware agents, perhaps eroding the last distinctions between the natural and the artificial (and see Keller 2005, 2007).

Multi-agent software systems are fundamentally a nonhuman model of control and behaviour designed to interact locally with other agents and with their environment and to ‘learn’ from these interactions and adapt dynamically (Brooks 1999; Maes 1995; Johnston 2008). In applied settings, agent-based systems are a critical component of complex autonomous systems that will increasingly be considered as (and part of) pervasive systems in context-aware locales in which humans are not necessarily conscious of interacting with them (Weiser [1991] 1999). These scenarios are part of the vision for pervasive computing that embeds sensor-intensive computational platforms within a built environment, such as automated home controls, aircraft flight controls, autonomous transportation networks and vehicles, and residential and commercial security systems (Steventon and Wright 2006; RAE 2009; Riva 2005). Many of the software requirements for autonomous capability have been met, but the ongoing
challenge is the integration across a diverse range of interconnecting entities and processes these applications demand. There are some multi-agent systems successfully implemented in assistive technologies, including in-home monitoring of the elderly intended to permit people to live at home as they age, balancing digital system autonomy and intrusive monitoring with the human desire for personal privacy and autonomy (Boger, personal communication; and see Wang, Boger and Taati 2012; Townsend, Knoefel and Goubran. 2011). An overview of this type of system is detailed in Appendix IV.

**Obscuring Control**

Biological inspiration has driven the ascendancy of the software agent and reconfigured artificial intelligence: intelligence in software agents is no longer occurring in a head governing a ‘thinking machine.’ It has been re-conceived following a model of nonhuman collective intelligence that arises from local interactions with its virtual (as in cyber-) or physical environment and encounters with entities, processes, and data. It is more like the multi-tendril *Physarum*, able to compute distance and optimal paths, gather information, remember where it has been, and decide a course of action from any number of (future) potentials. What is being reached for in computer science and engineering are autonomous systems with a model of control that is vital or life-like with communication processes occurring within a complex digital system or network as it *interacts* with its

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35 Carleton University is home to the engineering research initiative into an autonomous physiological monitoring project (and other health care monitoring) called the Technology Assisted Friendly Environment for the Third Age (TAFETA: Smart Systems for Health), and the University of Toronto has a research project called the Intelligent Assistive Technology and Systems Lab (IATSL). These projects are actively building autonomous systems for health care applications. See Appendix IV for a brief review.
environment including other subnets, processes, and entities (Wright and Steventon 2006). This is control by distributed process, specifically communication processes, across a field of inter-connected digital agents. Biologically inspired control simulates the vital communication of nonhuman organisms, of bacteria swarms and slime mold aggregation, in which control is never the same, and always differentiating and productive in response to system and network cues. As Deleuze reminds us, control is ceaseless, continual, unbounded, and modulating according to the heterogeneous exigencies of networks (and see Negri 1990; Deleuze 1995).

Control in artificial complex systems is intended to be autonomous and self-regulating to enhance the human client experience on networks and ensure seamless integration between heterogeneous machines and networks. This objective ensures contemporary digital systems and networks achieve the goal of ‘hidden complexity’ by submerging the complex machine code of control deep in the system to minimize human contact with it (Huebscher and McCann 2008; IBM 2012; Woolridge and Jennings 1995). From IBM’s framework for autonomous systems outlined in Chapter Two, to the SAREPH model discussed above, each flows from Woolridge and Jennings’ (1995) original proposal for multi-agent systems in which autonomy and obscurity are programmed together so that software agents and system control processes function “without the direct intervention of humans or others, and have some kind of control over their [own] actions and internal state” (Huebscher and McCann 2008, 5). What emerges is a vital network with capacities and tendencies that are not simply mimicking the biological organism, but by simulating its behaviour a wholly new assemblage emerges.
with features of control and self-organization that are isomorphic to the organism, such as signaling near network nodes or ‘neighbours,’ counting or calculating network nodes or hops, altering network behaviour based on the active nodes or members of the network, or ‘listening’ or monitoring for external network security risks.

**Vital Networks**

**Control Shift**

There are three movements that have occurred in the decades stretching on from the heyday of mid-twentieth century cybernetics and that are significant to the biological turn in computation. The first is the shift from hardware to software, away from an earlier emphasis on mechanical calculation and power computing, with its focus on big storage, processing power and memory, to ‘smart’ systems wherein software programming maximizes functionality on microchips (Steventon and Wright 2006; Riva *et al.* 2005). From the multi-room computing devices of the 1940s to the 1960s to the size twelve shoe-sized cell phone of the 1980s, computing platforms have been shrinking and all the while software has increased in sophistication and flexibility as evidenced in the preceding discussion.

This leads to the second shift, which is an outcome of the first: as hardware importance diminished, the focus shifted from mechanical components, such as physical switches and transistors necessary to run power-intensive machines, to software processes that emulate hardware, eliminating the requirement for multiple processing boards and physical devices (Campbell-Kelly and Aspray 1996; Steventon and Wright
The final aspect is the movement in software programming from procedure (description) to processes of control (Turkle 1991, 237; see also Adam 1998; Keller 2002). This is notable in the example of the QS algorithm, or any algorithm, in which the coding does not set out a logical procedure to describe the computing problem and the rules (procedure) to solve it, but rather the algorithmic processes of control detect and identify a problem and respond dynamically to ‘decide’ how to solve the problem (Argawal and Harrod 2006). There is still programming here, but beyond a minimal rule-set running in each instance of the algorithm, part of the problem-solving routine is intended to interact with the environment and exchange information with near neighbours on the network, communicating locally, node to node, to exercise control. Control is thus produced from inducing the network to self-assemble into new arrangements and configurations while adapting to changing information flows. This move from description to control is critical to the aspect of obscurity on the vital network: there is no description of the problem coded into the control system to describe possible problem scenarios—the control algorithms respond dynamically to act.

Control also features in contemporary computing because as the hardware has become smaller and ‘lighter,’ for smaller and smaller devices, software programming is dedicated to managing fewer hardware resources and instead directed at extending system functionality and communication. This builds an added complexity to CITs, first by creating seamless human client experiences through interactive and feature-rich applications across a range of devices, networks, and media, and second by enabling the code of more complex technical communication processes to become submerged beneath
the user interface. Software is an encapsulated micro-network busy communicating with itself from the user interface where it receives input to its object libraries, which contain the code for the software’s functionality and then connecting to other external networks and processes (Galloway 2010; and see Chun 2011). These libraries of code remain hidden to the human user in much the same way as in Google Search, or with the code and control of the network such as the Internet. Obscurity is the watchword of control for vital networks.

The Diagram of Control

Control within the vital network is communicative and it is negotiable. However, unlike older forms of hierarchical control in cybernetic machines in which humans established, and could intervene in, parameters to guide system behaviour, the ‘who’ is negotiating control has become the ‘what’ is ‘negotiating:’ control algorithms negotiate connectivity, transmission, and the network path. This is a fundamental shift from older, centralized, descriptive code. Control does not reside on a designated server with one data centre; it is distributed across the network as a modulating force emergent within the transactions and communication processes of a heterogeneous assemblage. Control processes monitor information flows, detect network capacity, and ‘negotiate’ transmission routes based on the quorum of communicating object-processes. It is, as Deleuze and Guattari describe it, an abstract machine that does not have “invariable or obligatory rules, but optional rules that ceaselessly vary with the variation itself” (1987, 100). A new machinic program produced through the actions and doings of the network is an “abstract machine of soft control—a diagram of power that takes as its operational
field the productive capacities of the hyperconnected many” (Terranova 2004, 100). This is the distributed network, “characterized by equity between nodes, bidirectional links, a high degree of redundancy, and a general lack of internal hierarchy” (Galloway 2010, 288). Control has expanded its reach while at the same time ‘softened’ its routine through self-governing processes of control that congeal as this new abstract machine.

The abstract machine targets assemblages comprised of machines, networks, institutions, information, and individuals. For Deleuze (and with Guattari) the abstract machine both “defines and dissolves the assemblage” producing “continuums of intensity” (1987, 142). These continuums are for Deleuze and Guattari the “diagram of the abstract machines ... in play in each case, either as potentialities or as effective emergences ... outlining the program of the assemblages that distribute everything and bring a circulation of movement with alternatives, jumps, and mutations” (ibid., 146-147). The QS algorithm acts within the abstract machine through “ceaseless differentiation, dissociation, and division,” much as it occurs in bacterial QS when bacteria aggregate, taking “any number of forms and directions” in its becoming-other enactment of multicellularity (Johnston 2008, 120). In the digital network, a QS algorithm deterritorializes; it draws the assemblage (the network) along a vector, creating a new arrangement of forces. This new arrangement solidifies into a temporary arrangement until the next modulation or adjustment by the algorithms of control gives it a tweak in a new direction.

The forces and potentials of the vital network assemblage produce new spaces of possibility that emerge from the deterritorializing effect of nonhuman distributed control.
This, it seems to me, is well beyond what Deleuze conceived in his reflection on “societies of control” (1995). In that work Deleuze did what many social analysts do: he thought about the surface arrangements of contemporary software applications and the direct forms of control human clients encounter through processes such as account logins and password access to protected content, networks, and systems. For Deleuze, writing in 1995, the emphasis in control societies remained on the access/no access control binary, the password-enabled, cybernetic logic defining who or what is in or out, there or not there, seen or not seen on the network’s surface (the application and content layer of the Internet).

From Deleuze’s perspective, control operates on the boundary between the human and machine (or network). I would agree, but go even further to suggest it is also operational at a deeper level that is, as I discuss above, more obscure and nontransparent. This “boundary disturbance” between human and machine is part of the blurring between biological life and machinic life consonant with cybernetics’ original goal to create self-regulating machines in the image of human-animal cognition and control following the ‘life as information’ and ‘information as life’ equation (Johnston 2008, 106; see Haraway 2004; Keller 2007; Thacker 2010b). The complication is in the new model of nonhuman organismal control, which is increasingly the foundation for a decentered and self-regulating control. Autonomous control processes do things; they can act, they induce state changes in systems, and intervene in informational flows and other network processes. They evince “agential intra-actions,” as Karen Barad claims, and “specific
causal material enactments that may or may not involve ‘humans’” and so it is that machinic processes that exercise control within networks can be agential (2003, 817).

The radical re-ordering of communication and networks through algorithmic control works uninterrupted and unseen within the network, and introduces a new class of problems affecting accountability, responsibility, liability, network neutrality, surveillance, and more. Control operating through software agents and/as autonomous processes modeled after self-regulating biological life systems is decidedly nonhuman; these systems are not mimicking the human, not enacting human-like decision-making, yet have material consequences for humans. This algorithmic control is integral to “sorting, classification and ranking of the social field,” whether through marketing segmentation based on collected personal data or lawful wireless monitoring conducted by a security establishment (Bucher 2012, 1166; see Lyon 1994, 2002). It instantiates “algorithmic normativity,” normalizing the rational calculus of analytical machines that survey more of life’s activity, transactions, and communication, so that it becomes an ordinary consequence or feature of network life (Rouvroy 2011, 221), a commonplace machinic sense-making that humans accept as part of their experience on the network. As these processes gain in complexity and obscurity, individual and collective surveillance expands, resulting in greatly diminished personal privacy, autonomy, choice, personal information security, and more.

As I have explored elsewhere (2008), there are already self-regulating (autonomously enabled) data collection processes that capture and analyze personal information from every aspect of our lives as we make contact with networks through
various daily transactions and communication across different devices, software and networks. Every one of these points of contact and activity subjects us, not just the information about us, to algorithmic control and analysis. The recent revelation of the expansive network surveillance program in the United States and beyond conducted by the National Security Agency (NSA) illustrates this clearly: the NSA is using sophisticated software and hardware to capture metadata collected when individuals place a wire line or wireless phone call, use email, or access the Internet for anything from social media applications to search requests to checking the weather (Gallagher 2013). The NSA’s network analysis algorithms search for and mark out evidence of relatedness between individuals (or organizations) on the network (ibid.). Specifically, the NSA uses “3-hop analysis,” which starts with one individual of interest and examines all the telephone calls placed (wire line or wireless), and at the second stage (or hop) looks at every call to that person, and at the third hop, logs the call activity of all those connections, continuously searching for relatedness within that network (Yost and Apuzzo 2013). This form of surveillance is combined with what DPI reveals about Internet use and contacts. All of this is done in software through sophisticated and powerful algorithms that are designed to search for patterns, similarities, and identity details, and assemble a topological diagram of connectedness and relevance across the assemblage.

**Vitalities against Totalities**

New control models, those of the self-organizing, communicative biological organism, are a very different paradigm of control, which shifts how networks are and
will be organized. One could think of Deleuze’s society of control morphing into what I call the autonomic society. Whereas the control society contends with fast, powerful computer processors and passwords, an autonomic society might contend with increasing complexity and an assemblage of selves, human and nonhuman, through smart, self-capable computing systems. Thus, where the control or network society contemplates the recurrent and endless modulation of codes allowing or denying access to information and virtual or cyberspaces, an autonomic society might attend to networks of relation and a multiplicity of beings across a panoply of autonomous systems by introducing “univocity-through assemblages” (Deleuze 1995, 180; see also Thacker 2008, 140).

The logic of an autonomic society, therefore, could extend Deleuze's “apparatuses of open and continuous control” through the enabling of autonomous control in which “no one controls networks, but networks are controlled” through a distributed agency as an effect of distributed control (Galloway and Thacker 2007, 77, 39; emphasis added). Agential forces are immanent in the vital network—continuously at work in the code and control of networks. Nonhuman control enables digital systems and networks to act autonomously, to do things following coded processes that are capable of emergent behaviour with unanticipated consequences. It is, as Wendy Chun observes, a fundamentally ambiguous programming: “our computers execute in unforeseen ways, [and] the future opens to the unexpected” (2011, 9).

Paradoxically, while the algorithmic control processes organize our communicative lives, monitor us, ‘learn’ about us, identify and locate us, we remain fundamentally ignorant of their capacities, tendencies, and power. Capacities make
assemblages (as wholes) exhibit aspects of their identity that were previously hidden (De Landa 2011), for instance, when control algorithms respond to changing network conditions and act autonomously to alter the information flows. Human clients on the network cannot see the submerged, agential, autonomous capacity for control, but we feel its effect. Our Internet is slow, our email is bounced back to us, our cell phone connects automatically, or our car ‘knows’ where it is before we do. We are organized by the logic of those devices and processes, coordinating, in turn, our human actions and choices. Our dependence on technical networks and devices for critical social, political, economic, and technological transactions is re-organizing around a profoundly nonhuman model that pivots on organismal vital communication. A vital communication is designed from organismal molecular diffusion, ant foraging and bacterial swarming, and plasmodium path finding. These tendencies and capacities depart radically from centralized control and forms of machine intelligence and decision-making that followed a human-animal logic.

When I began this research thinking of nonhuman life forms serving as biological inspiration to the development of autonomous systems, I anticipated finding a more rigorous and solidifying organizational capacity that could produce a new social form I called the autonomic society. Any rigidified social form requires “relations between parts and wholes [in a] seamless totality” possessed of an “inextricable unity in which there is a strict reciprocal determination between parts” (De Landa 2006, 9). In principle, this formalism depends on what De Landa calls “relations of interiority,” much as with the “inward domain of consciousness” said to reside within the human, and this would put
the autonomic society well within humanism’s bounded, autonomous self, which serves as the centre for all communicative action and sociality (2006, 10; and see Mill 1993). Thus any notion of a new social organization that extends Castells’ network society, or Deleuze’s control society, means adopting a position that network control logic is static, predictable, and productive to a particular stable social formation pivoting around the human. As I explored microbial life, it was clear that as a model of vital communication and self-organization, the autonomic society fell short. The nonhuman, taken as a model of and for connectivity, relation, and communication, confers relations of exteriority as the primary organizing logic within the network—a reaching out and beyond to enable collective action arising from a new emergent form. In relation to microbial life, this self-organization turns on a fundamentally communicative process enabling a continuous becoming-other from unicellular to multicellular entity, creating a wholly different composite (De Landa 2006, 10). This is a crucial aspect within the concept of a ‘whole’ as an assemblage contingent upon variable processes and potentials that can change at any moment: a fluid and diffuse mode of life that turns on difference, multiplicity, and becoming (Deleuze 1990, 1993; De Landa 2006). It is a network of relations, but rather than the sorts of enrollment of actors and actants and connections that Bruno Latour’s actor-networks are meant to detail and expose, the vital network hides the one, exposes the many, and gives the network as an assemblage an entirely new set of material capacities and tendencies. The complex processes of communication and control over digital systems and networks, the instances of algorithmic control, sink deeper into the
matrix of hardware and software, setting human network clients and our simple user interfaces at a distance from the growing complexity of action within the network.

Rather than producing a unified, totalizing model of human society, such as the ‘network society’ or ‘societies of control’ or the ‘autonomic society,’ biologically inspired nonhuman control and communication produces a vital network that is a dynamic, ceaselessly churning Deleuzian difference engine. This is the network without affect: there is no feeling in our network, only a feeling for our life-like network and our human sense of networked being.

**Conclusion**

The vital network is a radical shift in the conception of network. Whereas centralized and even decentralized network configurations have a stable orientation well understood by humans, that is, networks as structures with points and lines linked together set out in a predetermined arrangement, the vital network is dynamic and distributed, following biological forms, vital communication processes, and self-organization. The resulting meshwork is an ever-changing hyper-connected swarm, a process and event-driven topology of connections oriented to dynamically occurring self-organization that does not easily translate to the human-computer organizational model. Microbial intelligence required for a vital network is a distributed intelligence; it is a fundamentally external process, a passing between population members as part of a becoming-other that produces collective differentiation and emergent action. Humans, arguably, also engage in extensive relations every day as we connect with networks online and offline, with other people, and with institutions, but our connections privilege
our possessive internal processes of thought, and our interior, private affective world over nonhuman intellection and world.

Discourses within the social sciences and science and technology studies have looked for a new constituent for worlds organized by communication technology; a constituent that captures the intensity of our networked lives. For some this new constituent is the posthuman (Hayles 1999; Johnston 2008; Lash 2002; van Loon 2008; Wolfe 2010). However, as I discussed in Chapter Two, posthumanism is bound up in cybernetic human-animal models of self-regulation, and thus, I argue, not the figure of and for twenty-first century programming. There is no ‘post,’ no after-human, no transhuman, and no anti-human within the vital network. There is a breach between the research agendas of those who would program computers to ‘think like humans’ and those who want a control model that does not ‘think’ but interacts—a biologically inspired approach based in nonhuman self-organization. It is no longer about Turing’s ‘thinking machine’; it is the ‘thinking machine’ taken over by an organismal, nonhuman process of intellection. Thus, this is the moment of and for the nonhuman, which brings forward an organizational logic that is diffuse and self-regulating, emerging dynamically along communication circuits that manifest tendencies for emergence and exercising capacities for control that are immanent within the vital network assemblage. We humans are folded into these circuits and pathways and are as much a part of the vital network as the microbes that inspire its organization.
Chapter Seven

Conclusion: ‘Postscripting’ the Postscript

When Gilles Deleuze contributed his short views on the ‘societies of control’ in the 1990s, the second one was called “Postscript on the Societies of Control” (1995). As I’ve detailed elsewhere, it was an all too brief reflection on what was coming as technologies of communication and control overwhelmed the disciplinary society; there were, Deleuze said, “new forces knocking on the door” (1995, 4). Deleuze presciently gestured toward the general problem of expansive, continuous, digital control, and clearly understood that the “computer that tracks each person’s position” signaled a new form of control (and power), which could only be understood through the “study of the mechanisms of control, grasped at their inception” (7). My dissertation can be thought of as a postscript to Deleuze’s ‘Postscript’; it responds to Deleuze’s call for the further study of control, but through an inception point that begins long before the coding, in the processes whereby organisms become-other. Control has moved on from brute mechanics and hardware, to software processes imbued with a nonhuman intellection that calculates and differentiates along the network. Control is obscure and continuous; its routine is to have no routine. There is no monolithic control; there are only distributed controls tuned to the information flows to respond continuously because there is always something to be affected on the network.

In this dissertation, my purpose was to locate and interrogate the role of nonhuman biological inspiration as a crucial feature within a development program for
the design of digital control systems that rely on self-regulation and autonomous communication processes intentionally constructed to be non-transparent—to be unseen. My dissertation examines nonhuman models of control as a response to this requirement considered through three vital objects: microbe, simulation, and control, each understood in process terms that disclose what these things do and how they act. It is appropriate to the concerns of this dissertation to think of these as object-processes occurring within three moments or transverse becomings: first, in terms of Deleuze’s notion of differentiation from the one to the many; secondly, from organism to simulation through the use of models to describe microbial processes in informatic terms; and finally, from description to control, through the progression in computing from an emphasis on structure and descriptive procedures to processes of control.

Throughout my dissertation, I have shown that networks, whether digital or microbial, are amorphous, expansive, and changing all the time—change is what keeps a network active, relative, and ‘lively.’ In the case of the Internet, these changes occur in part through the sheer force of accretion. Millions of pages are added every year and networks collect, carry, and circulate information from every conceivable aspect of global life, whether human social communication such as on Facebook or the machine-to-machine communication of botnets. Many more pages are added to the internet every year than are permanently archived and/or then deleted (van der Berg 2010). In view of the magnitude of network processes, data, and connections, the Internet has become a radically configured meshwork, or swarm-works, comprised of many self-assembling,
communicative object-processes requiring an emergent form of control and communication that is dynamic and adaptive.

The Internet is often framed as an organized assemblage that most human clients perceive as a stable entity with clear boundaries and material qualities that give it a spatially distinct ‘feel’ when we connect to it, whether from our cell phone, through a Google search, or from our cars and global positioning applications that locate and guide us. Yet, the Internet’s boundaries and parameters are highly contingent and changeable and full of material and expressive forces that act on processes, objects, and human clients. These features are in part what constitute a vital network, but they manifest because of particular coded processes of control, as detailed in Chapter Six, that are capable of autonomous action. The vital network expresses control when it ‘decides,’ organizes, communicates, filters, and alters information flows from an inhuman, machinic logic, a logic that has incorporated the world-making powers of organic life, yet is not alive. While some argue that digital systems programmed to be self-regulating are an exceptional form of artificial life (Langton 1995) or machinic life (Johnston 2008), I argue that the capacities for self-regulation and control on the vital network, and the tendency toward emergent behaviour, do not slide from the technological realm into that of life itself. A vital network is not a simplified metaphor to describe the Internet as an ‘information superhighway,’ or about creating an assemblage that mimics a few interesting features of microbial life. The becoming-vital of this human-constructed, inorganic sphere of communication consists of a multiplicity of flows that merge and dissipate, that fuse and then separate, affected by control processes acting on the
assemblage as forces of deterritorialization. Together, this is what makes the Internet ‘feel’ vital.

This mode of control serves a ‘logic of flows,’ an informational circuitry, privileging communication among and between a multitude of entities, human and not (Lash 2002). This is the network conceived as an “informational milieu [and] as a dynamic topological formation characterized by a tendency toward divergence and differentiation” (Terranova 2004, 42). The tendency toward divergence manifests the capacity for control and is crucial to the space of possibility that enumerates the many ways an assemblage (network) may change (and see Chapter Three). In the vital network, emergence is a stable property explained by the structure of the possibility space and the variance in its capacities and tendencies—this means the network will always demonstrate the property of emergence, but it will differentiate based on how the capacity of control is exercised. As information moves on the network, the capacity for control moves with/in it. Control is opaque, but affective; it operates as a progressive line of flight propagating new connections, changing direction, modifying the network topology, so long as it has something to affect. These processes of control are nontransparent yet re/active, ‘decisive,’ and self-capable; each instance of control occurs as communication takes place. *The code gets things done.*

The evolution of control over machines is tightly linked to the history and development of computing and of the challenge to produce a formative intelligence in machines that would be ‘life-like.’ Discussions of life often place self-organization and autonomy together as qualities that are essential to life itself. These qualities or aspects of
what life is informed cybernetics-era interest in self-regulating machines that could produce human-animal cognition and function ‘like’ a natural system, that is, to be self-organizing and autonomous. Cybernetic machines demonstrated that aspects of a life system could be emulated through computation and/or as information—meaning aspects of self-organization seen in nature could be reduced to a series of mathematical and computational problems readily solved by the calculative logic of machines.

At the end of Chapter Two, I touched on the figure of the posthuman in relation to technology. Katherine Hayles has noted that posthumanism “is not abandoning the autonomous liberal subject but is expanding its prerogatives into the realm of the posthuman” (1999, 287). In this manner, posthumanism holds to the ideals of liberal humanism that turn on, and require, a contained self: a self as a bounded entity around which other processes, actions, and practices revolve. In the vital network, this centrality cannot be sustained. The human is but one more entity in the ‘informational milieu’ of the network assemblage. I argue that it is time for thinking with and through the nonhuman as a transversal becoming—an object-process that operates as a relational vector to enfold the human within the vital network as part of its meshwork.

Thinking back to Chapter Three, if we reimagine the assemblage as being structured by particular capacities, such as the capacity for control, and tendencies, such as the tendency for self-organization, which together create the conditions for emergent behaviour, the material properties of the system including its control features can at least be glimpsed. This is the role simulations serve in the design of contemporary control algorithms designed to *do* and to *act* within a complex system such as the vital network.
Simulations created from models of biochemical communication processes in microorganisms have a two-fold purpose: they furnish computer scientists with a platform through which to examine and manipulate how a complex system may behave, and a procedure to program the prototype for control algorithms that are isomorphic to the organism’s behaviour. For network analysis from within a sociology of communication, simulations can expose the space of possibility as a diagram or topology that shows where to look for control operands and processes, what to look for, as well as how to look.

Deleuze stressed that control is continuous, complicated further, I have argued here, by its increasingly complex coding, configuration, and obscurity. While humans program the source code (the basic functionality of a program), when that code follows a nonhuman logic model programmed to be autonomous and self-regulating, it is always already changing once it is compiled in an executable form and installed within a digital system and network. As Wendy Hui Kyong Chun observes, “we cannot know software” and all the conditions and possibilities it enables (2011, 54); however, when considered as an assemblage that varies through forces of deterritorialization which cut across the territory of the assemblage, while we may not know the conditions of each system in absolute terms, we can study its possible states.

It has been argued that autonomous digital systems and networks, as with any complex self-organizing system, will require a technical strategy to manage emergent behaviour arising out of the many interacting digital entities, agents, and processes of control (Müller-Schloer and Sick 2006; Igel and Sendhoff 2008). This concern has long
been represented as a possibility: before digital systems were a standard part of communication and information technology, Alan Turing noted that “[m]achines take me by surprise with great frequency” and produce consequences that programmers do not expect (1950, 450-451, 459). Turing was certain that self-capable programs were inevitable, as long as programmers continued to pursue a “thinking machine” and human-centred machine learning incorporating an artificial intelligence predicated on the human-animal cognition model. While there have been and are digital systems programmed to think like humans, my dissertation has shown that nonhuman organismal communication and swarm intellection is the form and function of control for new complex networks. This gestures toward a twofold concern: that complexity is both obscuring and error prone, and making software more powerful also increases the risk of material consequences that are difficult to ‘see’ and predict. It seems to me that together these concerns further complicate the distancing effect of complex and obscure control for digital systems and networks. The future will require control systems to watch over the control systems.

My philosophical and theoretical explorations in Chapter Four traced the movement from construction to assembly, and from object to process, turning to Deleuze’s philosophy for a conceptual framework through which to understand the vital network. I began that chapter with Bruno Latour’s invocation to consider “‘nonhumanity’—things, or objects, or beasts” that slipped out of view as humanism

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36. Turing makes this statement to counter Ada Lovelace’s assertion, in the years in which she worked with Charles Babbage on the Analytical Engine (an early calculating machine design), that machines would not be prone to error (Turing 1950, 450).
gained force within modernity’s precocious grasp of mind over nature (1993, 13). From Latour’s call to ‘see’ the nonhuman, to Susan Hekman’s (2010) carefully constructed proposal for how to progress from linguistic construction to a materially significant realist ontology, the matter of life and its vital, agential capacities regains a certain presence through Hekman’s synthesis between the semiotic and the material. In the context of vital networks, the return to matter is an important repositioning of the human as but one relation among many and an acknowledgement of matter’s forces and effects which are agential and consequential.

From that foundation, thinking of the vital network as in-process, as active, and as following a nonhuman vital communication pattern means that the arrangements and location of control no longer turn around the human. Rather, these processes unfold as part of, and in combination with, the material apparatus of the network. In the case of digital networks, if the network is considered only from the vantage point of the human, its organization turns on human and computer interaction, which privileges the most obvious software and services humans interact with along the surface of the internet. This means that the human-computer interface appears most significant or crucial over the processes of control that operate within sub-layers that human clients of networks rarely encounter. By contrast, thinking from the nonhuman opens the line of sight into the network’s decentred, dynamic changeability occurring through ceaseless variation and differentiation. This differentiation continuously alters the network assemblage, but this difference targets the multitude, the many-as-one rather than a single human client, machine, or process on the network. Thus, while there can be direct contact between
surface systems, such as between the human and computer facilitated by and through applications and content, and between network logins and system access, and between security apparatuses of surveillance that monitor information flows and human network clients, at the level of data transmission, control continues to collectivize, aggregate, and differentiate communication.

That objective, of aggregation and differentiation (of assemblage-thinking) shapes how we can think of control in its relation to microbial processes of communication. As I detailed in Chapter Five, the ‘part-to-whole’ transformation of bacteria and slime molds increases the dimension of their possibility space; the transformation from singular organism to massive, multicellular aggregate is a dynamic response to environmental cues in which a capacity for control and self-organization is exercised producing an entirely new and differentiated whole or assemblage. Biologically inspired control code simulates the vital communication of nonhuman organisms, of bacteria swarms and slime mold aggregation, in which control is never the same, and always differentiating, and always productive in response to system and network cues.

The network assemblage based in the vital communication of microbes and the local-to-global processes of self-organization are not direct, solitary causal forces that necessarily create a dramatic or forceful reorganization of the network, but part of an apparatus of control expressed more subtly, which compels the becoming-organic of the many into a wholly differentiated assemblage. For vital networks, this life-like dynamism does not turn on one single communicative transaction, but on the millions of transactions occurring in a continuous flow. These transactions produce a differentiated
communicative milieu as an assemblage that is ever-changing, not because some ‘one’ or some thing ‘decides’ it will be different, but because the flows of information, of communication, produce changes in the network as an emergent feature of the many-as-one univocal force producing communicative transactions resulting in consequential actions. Scientists may have cracked the communication code for swarm intelligence and behaviour, but how do we control a process that is fundamentally repetitive (iterative) yet never the same? The response in the artificial sciences is to innovate radical forms of control inspired by nonhuman life forms; then program control deeper and deeper into the matrices of the network; and finally, attempt to control the control in what is a fundamentally dynamic assemblage—the vital network or swarm—through arcane network policy management, Internet protocols, proprietary access, intellectual property, and legislation.

Having sight into complex technology, seeing into the ‘black box,’ is crucial in terms of the social and political implications of transparency and information flows because if we neither see nor understand control within the vital network, it complicates any effort to maintain transparency about what constitutes our networks and what the content of information flows do in life. Our contemporary communication systems collect a vast amount of personal and proprietary information, through our own self-surveillance, by disclosing personal details through online services, searches, and most digitally enabled transactions. Such collection points stream data of all kinds into the global information flows. Transparency in this context refers to the ability for human network clients, as citizen-consumers, to understand what happens to their personal information,
whether it is collected by government agencies or private corporations such as Facebook and Google. Data collection, through our own actions or the actions of institutions and organizations, is, even when a simple administrative function, a form of surveillance (see Lyon 2002). In relation to the preceding discussion, transparency of data systems on the vital network means that such systems ought to be simple and comprehensible (Koops 2013). As my dissertation has shown, it is clear that control processes are increasingly at odds with the notion of transparency: new self-regulating control operands are both highly complex and opaque, decreasing operational transparency and increasing the distancing effect of communication systems that are a key aspect of contemporary life.

Given that so much of contemporary life is structured by communication technology, at widely varying scales, from our global financial markets to our personal information sharing on Facebook, what is required is an ethics of control to imagine how much and how deep the ‘rabbit hole’ should go when considering the form of control and organization appropriate to our shared, technically enabled, sphere of communication. This is an ethics that is thought in “terms of what matters and what is excluded from mattering” (Barad 2007, 394; and see Anderson and Anderson 2007), in terms of deciding how much ‘control over control’ we ought to have in society, and about how to contend with an ‘order of communication’ that is more and more inhuman and radical, requiring less engagement with human network clients and interveners, and ramifying “forms of ceaseless control in open sites” (Deleuze 1990, 4; and see Frohman 2007).

In Chapter Six, I noted that the Internet was first conceived as non-hierarchical, neutral, and open, yet new models of control when coupled to a design goal in
contemporary digital systems based in keeping system complexity at a distance from human system clients, means complexity leverages an artificial simplicity of use over a plethora of control processes that are powerful not only for coordinating communication, but for privileging certain forms of data and communication. This complexity can play out in any number of ways: it opens a new avenue for social profiling and the further segmentation of data flows of people, things, and information, and it creates formidable layers of control that reside beneath the content and application layers of the internet. These aspects surely expand surveillance, which may lead to the explicit targeting of individuals and groups, as in the example of NSA surveillance discussed in the preceding chapter, and maintain the privilege of sight exercised through panopticism (see Foucault [1975] 1995; Lyon 1994, 2002).

However, the same technologies that produce expansive surveillance within the vital network as an assemblage also enable some of its most engaging characteristics. Algorithms of control and dynamic self-organization enable our networked participatory culture and interactivity on the Internet and across our communication systems, enhancing mobility, connectivity, and reliability. Social media, online banking, travel bookings, and streaming media would not function without them. Multi-agent software systems make Google search perform as it does, park our cars, improve automotive safety, enhance flight controls, and coordinate logistical systems for shipping companies. ‘Smart’ algorithms sift through ‘big data’ repositories, making sense of everything from weather patterns and climate change to influenza trends and traffic patterns. In each of these instances we can locate problems, risks, anxieties, and ethical concerns that can be
interrogated, but so too we can appreciate the opportunities and examine the affordances that come with communication technologies.

In future research I will examine the obscurity of control processes expressed in algorithms through a particular object: Google Inc.’s ‘autocomplete algorithm’ within the context of the Google ‘multiverse’ as a vital network. Google claims to produce ‘algorithmic objectivity’ and neutrality ensuring accurate predictions within the results of personal search conducted through their search engine. Google’s assurances about the reliability of their search results reveal a tension between the algorithmic culture taking hold at this contemporary moment in our communication and information technology, and the ‘epistemic trust’ developed in the system in Google’s tenure as the leading search company (and see Hildebrandt 2013). Google clients (users) trust Google to ‘know’ almost everything, and, taken another way, Google’s ‘knowing’ is constructing and defining realities. In the context of what we know about the vital network, there are ethical concerns about how information is controlled, filtered, censored, and about what is unseen, or not visible, in the processes of control at work in the Google search engine. While some of these issues have been explored by others (Bucher 2012; Frohman 2007; Nissenbaum and Introna 2000), I will reconsider Google’s algorithmic control as a vital technology that is adapting, changing, deterritorializing, and organizing itself and information flows and data captures even as it interacts with human clients and other machines.

37 Google’s public explanation of the autocomplete algorithm feature can be seen here: https://support.google.com/websearch/answer/106230?hl=en
The analysis in my dissertation exposed a widening gap between our experience as human clients of the network and the codes of control that direct and govern our communications. There has always been a gap between what the non-technical layperson knows about an advanced technology and the complex apparatus within the ‘black box,’ and a relief people feel that it ‘just works’ without needing to know how. For most of us, this defines our relationship to our laptops and cell phones—we do not know how they work, but we are very pleased that they do. In the case of vital networks as a domain of communication, we can appreciate their liveliness, temporality, and convenience. However, the distancing effect, the gap between us as clients of a system and the features of control that organize it, has been amplified by the intensification of processes of control that remain muted and obscure, while at the same time resilient and continuous. The distancing effect pushes the human user away from the subterranean complexity of communication and control at the same time as a “deepened intimacy, a more intricate mesh” between humans and technology becomes more durable at the point of human-computer interaction (Latour 1999, 196). This is a result of the distribution of control within the subnets and sub-layers of the Internet: it suggests an exclusionary domain of control exercised through layers, levels, and classes of access and visibility whereby individuals make conscious contact with this structure only fleetingly at the surface of the Internet, as part of the multitude, the swarm, through applications that provide an interface for social communication and transactional services. We can never be certain of the network’s efficacy, its actual power, its tendencies and capacities, but rather than a neutral infrastructure that merely coordinates and transmits communication, my study
suggests that control is ‘decisive’ and agential from the surface of the net all the way down to the ‘pipework.’
Bibliography


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Appendix I

NetLogo Interface

NetLogo software program interface. This screen capture shows the user interface for setting up a simulation as well as an image of the progression to aggregation of a slime mold population as it was running. The parameters I have coded reflect the three key parameters necessary for digital self-organization and emergence: alignment, separation, and cohesion. In the case of this slime mold simulation, the cohesion aspect is linked to the pheromone or chemical trail left in the slime trail and the cAMP diffusion in the extracellular milieu. You can see this aspect in the code on the following page.
NetLogo Code for Slime Mold Aggregation Simulation

The base code for this simulation was originally written by Uri Wilensky (1997) as open source code, and while I have tweaked it for my simulation, attribution to Wilensky is given at the end of this code sequence with gratitude to his generosity to legions of researchers who benefit from his original effort. In NetLogo, the ‘turtles’ are the digital entities that swarm around on the screen (just as Craig Reynolds called his artificial creatures, ‘boids’).

I have highlighted in boldface the aspects of the pheromone/chemical diffusion to highlight the particular relevance to simulating slime aggregation as discussed in Chapter Five (with regard to chemical concentration and thresholds, local interactions, and so on).

patches-own [chemical]

to setup
  clear-all
crt population
  [ set color red
    set size 2 ;; easier to see
    setxy random-xcor random-ycor ]
  ask patches [ set chemical 0 ]
  reset-ticks
end
to go
  ask turtles
  [ if chemical > sniff-threshold ;; ignore pheromone unless there’s enough here
    rt random-float wiggle-angle - random-float wiggle-angle + wiggle-bias
    fd 1
    set chemical chemical + 2 ] ;; drop chemical onto patch
  diffuse chemical 1 ;; diffuse chemical to neighboring patches
  ask patches
    [ set chemical chemical * 0.9 ;; evaporate chemical
      set pcolor scale-color green chemical 0.1 3 ] ;; update display of chemical concentration
tick
end
to turn-toward-chemical ;; turtle procedure
  ;; examine the patch ahead of you and two nearby patches;
  ;; turn in the direction of greatest chemical
  let ahead [chemical] of patch-ahead 1
  let myright [chemical] of patch-right-and-ahead sniff-angle 1
  let myleft [chemical] of patch-left-and-ahead sniff-angle 1
  ifelse (myright >= ahead) and (myright >= myleft)
    [ rt sniff-angle ]
  [ if myleft >= ahead
    [ lt sniff-angle ] ]
  ;; default: don’t turn
end

; Copyright 1997 Uri Wilensky
Appendix II

‘Boids’ Simulation

These screen captures show a basic flocking simulation derived from Craig Reynolds’ Boids program. The program runs as an animation once coded and these images show the progression to aggregation (flocking) of ‘boids’ in flight. The parameters are coded to reflect the three key parameters in digital self-organization and emergence: alignment, separation, and cohesion (created in open source program NetLogo).

1. First phase of boids flocking randomly
2. Second phase of boids responding to local contact with other boids
3. Third phase of boids forming flocks
## Microbiological Laboratory Contact List

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Response</th>
<th>Notes</th>
</tr>
</thead>
</table>
| Dr. Bonnie Bassler  
The Bassler Lab  
Princeton University  
Bacterial quorum sensing  
(Contacted by email in early 2009 and again in mid-2010)  | • Response  
No interest  | Dr. Bassler graciously replied to me in 2009, but she was not interested in my project. She would not give permission for any of her graduate students to speak with me either. I did try contacting one of her graduate students directly (prior to Dr. Bassler’s response to me), but did not receive a reply. I did request a site visit to see her lab in 2010-2011, but the lab was not accepting any visitors. |
| Dr. Michael G. Surette  
McMaster University  
Bacterial cell-to-cell signaling and flora-pathogen analysis in health and disease.  
(Contacted by email while he was still at the University of Calgary in early 2009)  | No response  | Also emailed graduate students in his original lab at the University of Calgary, but received no reply. |
| Dr. Tanya Latty  
Postdoc researcher  
Behaviour and Genetics of Social Insects Lab  
University of Sydney  
Sydney, NSW  
Conducting research in communications and self-organization in social insects and slime molds.  
(Contacted by phone and email in 2010)  | Response  
Agreed to discuss slime mold communication and self-organization;  
Dr. Latty and I agreed to be in touch after I graduate to explore our shared interest in slime molds.  | Dr. Latty was extremely generous in two conversations we had. Although she works with social insects, she is also conducting research into ‘social’ slimes such as Physarum. She works directly with mathematicians at other institutions (see below in technology table) as they work to develop models and simulations of slime mold signaling and computation. Very helpful in verifying my understanding of slime mold self-organization. |
<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Response</th>
<th>Notes</th>
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<tbody>
<tr>
<td>Dr. Bernard Crespi</td>
<td>No response</td>
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<tr>
<td>Behavioural Ecology Research Group</td>
<td></td>
<td></td>
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<tr>
<td>Simon Fraser University</td>
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<tr>
<td>Burnaby, BC, Canada</td>
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<tr>
<td>Research in social evolution across all levels in the hierarchy of life,</td>
<td></td>
<td></td>
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<tr>
<td>from genes, to cells, to organisms, to social systems, and to the brain.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Contacted by phone and email in 2010)</td>
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**Technology Research Projects on Autonomous Computing (or related)**

<table>
<thead>
<tr>
<th>Research Project</th>
<th>Response</th>
<th>Notes</th>
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<tbody>
<tr>
<td>Dr. Daphne Townsend</td>
<td>✓ Response Agreed to</td>
<td>Met with PhD student Daphne Townsend on at least three occasions to discuss autonomous systems programming and architecture. She was</td>
</tr>
<tr>
<td>TAFETA: Smart Systems for Health Project</td>
<td>discuss autonomous</td>
<td>very helpful to my understanding of how algorithms are designed and coded to function as a layer of decision-making within the autonomous</td>
</tr>
<tr>
<td>Carleton University</td>
<td>systems</td>
<td>system. I saw their lab prototype and system implementation running in the lab. These systems are not designed around an explicit human user</td>
</tr>
<tr>
<td>Ottawa (now working in the private sector)</td>
<td></td>
<td>interface. Dr. Townsend was also very interested in issues of human privacy and personal autonomy in the context of how context-aware</td>
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<tr>
<td></td>
<td></td>
<td>systems monitor individuals, collecting and analyzing sensitive and confidential health information.</td>
</tr>
<tr>
<td>Research into context-aware algorithms for autonomous computing systems. Research focused on autonomous monitoring and analysis of sleep apnea.</td>
<td></td>
<td></td>
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<tr>
<td>(Contacted by phone and email in 2010 and 2011).</td>
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<td></td>
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<tr>
<td>Research Project</td>
<td>Response</td>
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<tr>
<td>Dr. Lorenzo Imbesi, Carleton University School of Industrial Design, Ottawa, Canada</td>
<td>✓ Response Contact developed into my two year industrial design graduate project participation; This was a good opportunity to reciprocate the support I received from the engineering faculty (see above).</td>
<td>Dr. Imbesi invited me to participate in graduate student final design project reviews and it thus became a very productive encounter relevant to the application of autonomously enabled systems designed for in-home monitoring (human-user focused technology design). Students were designing embedded intelligent systems for assisted living in the home.</td>
</tr>
<tr>
<td>MDes graduate program project review: Embedded Home Health Systems design project review; as part of their interdisciplinary design project</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jennifer Boger, MA-Sc (Eng), PEng, Intelligent Assistive Technology and Systems Lab (IATSL), Department of Occupational Science and Occupational Therapy and the Toronto Rehabilitation Institute, University of Toronto</td>
<td>✓ Response Agreed to discuss autonomous systems</td>
<td>Jennifer Boger is a biomedical systems engineer working on autonomous systems that operate as embedded (pervasive) monitoring solutions in the health care context. On two visits, after signing a non-disclosure agreement, I was shown the lab system, fall detection prototype, and the code base for the autonomous system. She and her lab colleagues outlined how their autonomous system works and the architecture and coding of the subsystems (although I do not have permission to disclose details about how their system functions). At this time the lab is designing a fall detection system to monitor the elderly. Individuals monitored by their systems cannot intervene on the system other than 'pulling the plug.'</td>
</tr>
<tr>
<td>(Contacted by phone and email in 2011)</td>
<td></td>
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<tr>
<td>Research Project</td>
<td>Response</td>
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<tr>
<td>Wendy Powley, MSc, Project Manager &amp; Research Associate Database Systems Lab (under the direction of Dr. Pat Martin) Adjunct Lecturer School of Computing, Queen's University, Kingston Lab research focus is autonomic computing which involves developing systems that are self-managing, self-configuring, self-optimizing and self-healing. (Contacted by phone and email and in person between 2008 and late 2009).</td>
<td>✓ Response No interest.</td>
<td>This group was not amenable to pursuing any contact in spite of the exact fit between the Lab's research area and my project, and the fact that we are part of the same institution. I attempted on several occasions to establish contact including attending department presentations and special lectures, all to no avail. This research group was a stark reminder of some of the lingering divisions between the ‘two cultures’ (CP Snow) and were very dismissive of any effort in the social sciences to engage with emerging computing research.</td>
</tr>
<tr>
<td>Prof. Dr. Martin Middendorf University of Leipzig Faculty of Mathematics and Computer Science Department of Computer Science Leipzig, Germany Parallel Computing and Complex Systems Group Research in ‘nature-inspired’ computing systems, autonomous computing, swarm intelligence, and self-organization. (Contacted by email and phone between 2009 and 2011).</td>
<td>No response</td>
<td>In spite of having no direct contact with this group, their research site has been immensely useful. I was directed here by Dr. Latty who is working with this group. This research group is directly involved with the research of Dr. Latty and her colleagues. In Leipzig, Dr. Middendorf and his graduate students are developing the mathematical models (algorithms) and simulations using the slime mold research from Dr. Latty’s lab at the University of Sydney. Even with Dr. Latty’s assistance, no one returned my queries.</td>
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Appendix IV

Autonomous Systems in Action

While there are many planned initiatives for utilizing autonomous systems and multi-agent systems in the future (see RAE 2009), there are pervasive systems deploying multi-agent controls that are well along in terms of research and in application. Two excellent examples in the health care field are both at Canadian universities: Carleton University’s Technology Assisted Friendly Environment for the Third Age (TAFETA: Smart Systems for Health) and the University of Toronto’s Intelligent Assistive Technology and Systems Lab (IATSL).

The TAFETA project utilizes a pressure-sensitive mat that records client health data such as blood pressure and heart rate (specifically monitoring for blocked airways caused by sleep apnea in this case) and transmits that data to a monitoring station that can undertake decisions such as calling for an attendant. It is part of a broad set of monitoring technologies for inclusion in homes and thus far is focused on specific physiological monitoring applications in the elderly.

The University of Toronto IATSL project focuses on helping seniors ‘age-in-place’ (that is, in their homes) by deploying embedded, autonomous and passive physiological monitoring technology. The U of T project monitors habitual routines and behavioural performances reflecting individual choices and responses within the home and will recommend action through verbal cues. Another project monitors an elderly
occupant’s movements using a fall detection system that will call emergency services if there is no response from the individual.

Both the Carleton University and University of Toronto approaches integrate sensors and cameras to monitor behaviour and provide a sentient space which monitors (senses) individual activities, location, choices, and so on to provide in-home monitoring. The ‘smartness’ in/of these systems lies in their autonomous capabilities; the self-capable communication routines that can collect, respond, enact, send, and receive data in communication with external venues such as health services, security service centres, or personal monitoring systems, and more (see TAFETA.ca; IATSL.org). Clearly these systems present critical challenges in terms of balancing privacy and individual autonomy under such intensive scrutiny by autonomous digital systems. The subject matter experts I met with were very sensitive to the need to balance privacy with the goals of an autonomously-enabled in-home monitoring system, however, the application of multi-agent systems within health care surveillance systems remains an ethical challenge as well as a technical one (Townsend, personal communication; Boger, personal communication; and see Townsend, Knoefel and Goubran 2011; Wang, Boger and Taati. 2012).

The TAFETA and IATSL projects are by no means unified systems and for this reason they are particularly good examples of the strengths (and also the challenge) of multi-agent systems to be reactive, adaptive, and context aware. These systems are comprised of different software and hardware components requiring specific communication protocols and algorithms to handle the wide variance in data inputs, from
digital cameras and microphones, to pressure sensitive mats and sensors oriented in the physical environment of the home, and these system must interconnect and share data within the local network and beyond (Rahimi, Chan and Goubran 2011; Townsend, personal communication). Neither the TAFETA nor IATSL projects designed and built the actual hardware used in their system; the project’s resources were directed at programming the goals of the system and the characteristics of the multi-agent system that enables its autonomous functionality using commercially available hardware (Boger, personal communication). By virtue of even the simplest monitoring routines, for example a pressure sensitive mat measuring blood pressure in the TAFETA project, to interactive agent systems in the IATSL initiative, these automated tasks signify the turn in engineering toward autonomous controls. Each system is essentially a dynamic network relying on data collection and system input, information circulation, algorithmic control, and network communications, and in each project these goals are programmed into the system.