Chapter 5
A Framework for the Local Information Dynamics of Distributed Computation in Complex Systems

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5.1 Introduction

The nature of distributed computation has long been a topic of interest in complex systems science, physics, artificial life and bioinformatics. In particular, emergent complex behavior has often been described from the perspective of computation within the system (Mitchell 1998b,a) and has been postulated to be associated with the capability to support universal computation (Langton 1990; Wolfram 1984c; Casti 1991).

In all of these relevant fields, distributed computation is generally discussed in terms of "memory", "communication", and "processing". Memory refers to the storage of information by some variable to be used in the future of its time-series process. It has been investigated in coordinated motion in modular robots (Prokopenko et al. 2006), in the dynamics of inter-event distribution times (Goh and Barabási 2008), and in synchronization between coupled systems (Morgado et al. 2007). Communication refers to the transfer of information between one variable's time-series process and another; it has been shown to be of relevance in neuroscience (Wibral et al. 2011; Lindner et al. 2011; Marinazzo et al. 2012) and in other biological systems (e.g. dipole-dipole interaction in microtubules (Brown and Tuszynski 1999), and in signal transduction by calcium ions (Pahle et al. 2008)), social animals (e.g. schooling behavior in fish (Couzin et al. 2006)), agent-based systems (e.g. the

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influence of agents over their environments (Klyubin et al. 2005), and in inducing emergent neural structure (Lungarella and Sporns 2006)). Processing refers to the combination of stored and/or transmitted information into a new form; it has been discussed in particular for biological neural networks and models thereof (Kinouchi and Copelli 2006; Atick 1992; Sánchez-Montañés and Corbacho 2002; Yamada and Aihara 1994) (where it has been suggested as a potential biological driver), and also regarding collision-based computing (e.g. (Jakubowski et al. 1997; Adamatzky 2002), and including soliton dynamics and collisions (Edmundson and Enns 1993)).

Significantly, these terms correspond to the component operations of Turing universal computation: **information storage**, **information transfer** (or transmission) and **information modification**. Yet despite the obvious importance of these **information dynamics**, until recently there was no framework for either quantifying them individually or understanding how they interact to give rise to distributed computation.

Here, we review the first complete framework (Lizier et al. 2007, 2008b, 2012c, 2010, 2012b; Lizier and Prokopenko 2010; Lizier 2013) which quantifies each of these information dynamics or component operations of computation within a system, and describes how they inter-relate to produce distributed computation. We refer to the *dynamics* of information for two key reasons here. First, this approach describes the composition of information in the *dynamic state update* for the time-series process of each variable within the system, in terms of how information is stored, transferred and modified. This perspective of state updates brings an important connection between information theory and dynamical systems. Second, the approach focuses on the *dynamics* of these operations on information on a *local scale* in space and time within the system. This focus on the local scale is an important one. Several authors have suggested that a complex system is better characterized by studies of its local dynamics than by averaged or overall measures (Shalizi et al. 2006; Hanson and Crutchfield 1992), and indeed here we believe that quantifying and understanding distributed computation will necessitate studying the information dynamics and their interplay on a local scale in space and time. Additionally, we suggest that the quantification of the individual information dynamics of computation provides three *axes of complexity* within which to investigate and classify complex systems, allowing deeper insights into the variety of computation taking place in different systems.

An important focus for discussions on the nature of distributed computation have been cellular automata (CAs) as model systems offering a range of dynamical behavior, including supporting complex computations and the ability to model complex systems in nature (Mitchell 1998b). We review the application of this framework to CAs here because there is very clear *qualitative* observation of emergent structures representing information storage, transfer and modification therein (Langton 1990; Mitchell 1998b). CAs are a critical proving ground for any theory on the nature of distributed computation: significantly, Von Neumann was known to be a strong believer that "a general theory of computation in 'complex networks of automata' such as cellular automata would be essential both for understanding complex systems in nature and for designing artificial complex systems" (Mitchell (1998b) describing Von Neumann (1966)).