Quantifying Information Modification in Cellular Automata using Pointwise Partial Information Decomposition

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Abstract

Pointwise partial information decomposition provides a means to quantify information modification in discrete systems exhibiting intrinsic distributed computation. In his seminal "Computation at the Edge of Chaos", Chris Langton investigated how intrinsic computation emerges in cellular automata which support the three primitive functions of computation—information storage, transfer, and modification. Despite the appealing description, Langton gave no precise information-theoretic definition of the three primitive functions. In the decades since, information storage and transfer have been defined; however, a satisfactory definition of information modification has proven to be more elusive. This paper uses the recently introduced pointwise partial information decomposition to provide a quantitative measure of information modification. Moreover, this approach provides a hierarchy of different types of modifications, which each combine or synthesis different combinations of stored or transferred information. This ability to identify different types of information modification events in both space and time is exemplified with an application to cellular automata.

Background

Understanding how distributed systems perform intrinsic computation is a central interest in the fields of artificial life, complex systems, and neuroscience. This information processing is often parsed into three fundamental components: information storage, transfer, and modification. Cellular automata, simple discrete dynamical systems from which coherent structures known as particles emerge, have long been the choice model for exhibiting distributed computation. The typical conjecture is that stationary particles store information, moving particles transfer information, and colliding particles modify information (Langton, 1990). Recently, there has been an effort to formally quantify the three component operations using information-theoretic definitions. In previous work on *information dynamics*, Lizier et al. (2008, 2012) demonstrated how information storage and transfer can be defined in terms of pointwise information measures. Crucially, this pointwise perspective enables these measures to pinpoint where and when information is being stored and transferred within the distributed system. However, this perspective has not yet delivered a satisfactory measure of information modification (Lizier et al., 2013). Here we show how pointwise partial information decomposition (Finn and Lizier, 2018) can be used to provide a quantification of information modification which is compatible with information dynamics. We demonstrate this with an application to cellular automata.

Overview

Information modification is interpreted to mean interactions between stored and transferred information which results in a change in this information. Using this interpretation, Lizier et al. (2013) proposed how to use the *partial information decomposition* (Williams and Beer, 2010) to quantify information modification. Based upon three axioms, the partial information decomposition divides the information provided a set of sources about a target into the following atoms of partial information: the information provided uniquely by each source, the information provided redundantly by two or more sources, the information provided synergistically by two or more sources, and various combinations of these three types. Lizier et al. (2013) suggested that the *non-modified information* in the target is any information that is identifiable in any of the sources individually; in terms of the partial information decomposition, this corresponds to the partial information atoms associated with individual sources. Conversely, the *modified information* is any information which is not identifiable in any of the sources individually, but is identifiable in the sources jointly; in terms of the partial information decomposition, this corresponds to all partial information atoms not accounted for previously.

Nevertheless, Lizier et al. (2013) noted two issues with their proposal. Firstly, in order to actually evaluate the partial information atoms one must define a measure of redundant information which satisfies the aforementioned axioms. There is, however, an ongoing debate as to the properties this measure of redundancy should fulfil. Many of the proposed measures can only provide a decomposition in the case of two sources. This is not sufficient for a measure of information modification since more than two information sources may be utilised in intrinsic computation. Secondly, the partial information decomposition does not provide pointwise measures of unique, redundant, and synergistic information making it incompatible with the information dynamics approach.

Results

Recently, we took the axiomatic approach of Williams and Beer (2010) and applied it on a pointwise scale to provide measures of pointwise unique, redundant, and synergistic information (Finn and Lizier, 2018). Crucially, this *pointwise partial information decomposition* works for an arbitrary number of source variables and hence overcomes both of the aforementioned issues. We demonstrate how the pointwise measures of synergistic information can be used to pinpoint where and when information modification is occurring a distributed system. Moreover, since the decomposition works for an arbitrary number of information sources, it can identify a hierarchy of different orders of information modification—the higher the order, the more information sources involved in the processing. When applied to elementary cellular automata, we get the following results: the non-modified, order one information, which is simply translated from the past or a neighbouring cell, dominates in the background domains; the modified, order two information, which involves a non-trivial synthesis of information from two sources, dominates where gliders interact with domains; finally, the modified, order three information, which combines information from all three sources, is particularly prevalent in glider collisions. We observe that Class I and II cellular automata tend to be devoid of information modification events, while Class III cellular automata are dominated by information modification events. As exemplified in Fig. 1, Class IV cellular automata feature a balance of modified and non-modified information, enabling the system to store, transfer, and modify information at different locations in space and time.

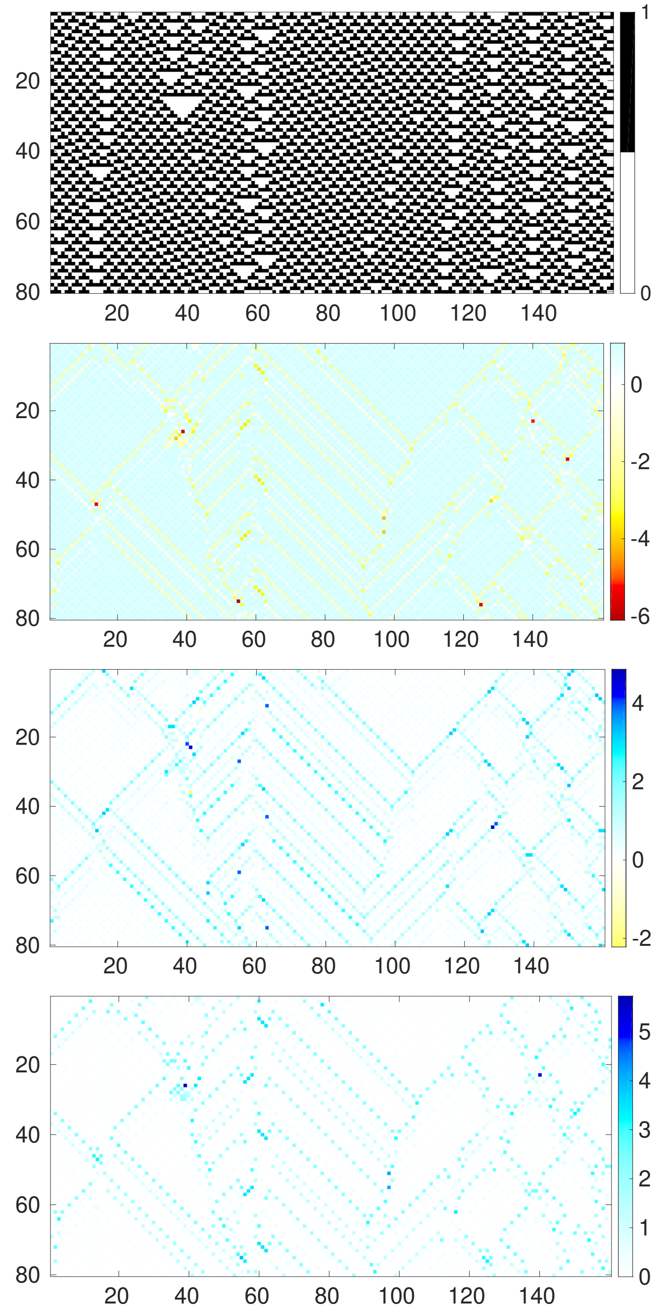

Figure 1: Class IV cellular automata feature a balance modified and non-modified information, enabling information storage, transfer, and modification to coexist at different locations in distributed computation. *Top*: elementary cellular automaton rule 54 initiated with random initial conditions. *Middle top*: the non-modified, order one information dominates in the background domains. *Middle bottom*: the modified, order two information is predominant where gliders interact with domains. *Bottom*: the modified, order three information modification is especially relevant in glider collisions.

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