

Contents

1	Introduction	1
1.1	Hypothesis and Objectives	3
1.2	Approach	3
1.3	Contributions of this Thesis	5
1.4	Structure of the Thesis	7
	References	8
2	Computation in Complex Systems.	13
2.1	Complex Systems	14
2.1.1	Order, Disorder and Phase Transitions.	15
2.1.2	Self-Organisation	16
2.1.3	Motivation for Studying Complex Systems	17
2.2	Information theory.	18
2.2.1	Information-Theoretic Measures	18
2.2.2	Localising Information-Theoretical Measures	22
2.2.3	Information-Theoretic Measures of Continuous Variables.	24
2.2.4	Reasons for Application to Complex Systems.	25
2.3	Cellular Automata	29
2.3.1	Functionality of Cellular Automata	29
2.3.2	Complex Behaviour in Cellular Automata	30
2.3.3	Computation in Cellular Automata	32
2.3.4	Examples of Distributed Computation in CAs	35
2.3.5	Filtering Structure in Cellular Automata	37
2.4	The Dynamics of Networks	38
2.4.1	Random Boolean Networks as a Model of Dynamic Network Behavior.	40
2.5	Guided Self-Organisation	42
2.6	Opportunity to Quantify the Information Dynamics of Distributed Computation.	45
	References	46

3	Information Storage	53
3.1	Excess Entropy as Total Information Storage	54
3.1.1	Single-Agent and Collective Excess Entropy	54
3.1.2	Local Excess Entropy	56
3.2	Active Information Storage as Storage in Use	57
3.2.1	Local Active Information Storage	58
3.2.2	Active Information Storage and Entropy Rate	59
3.3	Local Information Storage in Cellular Automata	61
3.3.1	Appropriate History Lengths	62
3.3.2	Periodic Blinker and Domain Processes as Dominant Storage	63
3.3.3	Negative Informative Storage as Misinformation at Particles	68
3.3.4	Particles Create New Information Storage	69
3.3.5	Structured Information Storage in Domain of Rule 18	70
3.3.6	Misinformation and New Storage Creation by Domain Walls	70
3.3.7	Local Temporal Entropy Rate Highlights Moving Particles	72
3.3.8	Absence of Coherent Information Storage Structure	72
3.4	Summary	75
	References	76
4	Information Transfer	79
4.1	Transfer Entropy as Predictive Information Transfer	81
4.1.1	Transfer Entropy	81
4.1.2	Local Transfer Entropy	84
4.1.3	Apparent, Conditional and Complete Transfer Entropy	85
4.1.4	Total Information Composition and Collective Information Transfer	89
4.2	Local Information Transfer in Cellular Automata	93
4.2.1	Inadequate Measures for Information Transfer	93
4.2.2	Particles as Dominant, Coherent Information Transfer Structures	95
4.2.3	Ambient Transfer in Backgrounds Domains	96
4.2.4	Apparent and Complete Transfer Entropy are Complementary	98
4.3	Information Flow as Causal Effect	101
4.3.1	Information Flow	101
4.3.2	Local Information Flow	104
4.4	Local Causal Information Flow in Cellular Automata	104
4.4.1	Information Transfer, Causal Flow and Emergent Structures	106

4.4.2	Information Transfer to be Measured from Causal Sources Only	107
4.4.3	Complete Transfer Entropy as an Inferrer for Information Flow	108
4.5	Summary	110
	References	112
5	Information Modification	117
5.1	Separable Information as a Detector for Non-Trivial Information Modification	118
5.2	Local Information Modification in Cellular Automata	122
5.2.1	Hard Particle Collisions as Dominant Modification Events	123
5.2.2	Soft Collisions Between Gliders and the Domain	125
5.2.3	Storage Modifications in Non-Periodic Domains	125
5.2.4	Proliferation of Information Modification in Chaotic Dynamics	126
5.2.5	Modification Only Understood in Context of Past History	126
5.3	Irreversibly Destroyed Information	127
5.3.1	Measuring Information Destruction in Distributed Computation	128
5.3.2	Irreversible Information Destruction in Cellular Automata	132
5.4	Summary	137
	References	138
6	Information Dynamics in Networks and Phase Transitions	141
6.1	Phase Transitions in Random Boolean Networks	143
6.1.1	Experimental Details	143
6.1.2	Results and Discussion	145
6.2	Cascading Failures in Power Grids	149
6.2.1	Cascading Failures Model	150
6.2.2	Measuring Information Dynamics in Cascading Failures	151
6.2.3	Results and Discussion	152
6.3	Summary	156
	References	158
7	Coherent Information Structure in Complex Computation	163
7.1	Introduction	163
7.2	Local Information Dynamics State-Space	166
7.3	Measuring Coherent Information Structure in the State-Space	169

7.3.1	Coherent Information Structure Measurements in CAs	170
7.3.2	Coherent Information Structure Measurements in RBNs	171
7.4	Summary	173
	References	174
8	Information Transfer in Biological and Bio-Inspired Systems	177
8.1	Heart and Breath Rate Interaction in Sleep Apnea	178
8.2	Establishing Directed Interregional Cortical Information Structure	179
8.2.1	Introduction	180
8.2.2	Interregional Information Structure Analysis Technique	182
8.2.3	Application to fMRI Experimental Data	187
8.2.4	Conclusion	191
8.3	Evolution of Coherent Information Transfer Structure	191
8.3.1	Evolving the Snakebot for Maximum Information Transfer	193
8.3.2	Results and Discussion	195
8.3.3	Conclusion	198
8.4	Summary	199
	References	200
9	Conclusion	203
9.1	Summary of Main Contributions	203
9.1.1	Framework for the Information Dynamics of Distributed Computation	203
9.1.2	Measuring Information Storage	204
9.1.3	Measuring Information Transfer	204
9.1.4	Measuring Information Modification	205
9.1.5	Quantitative Understanding of Information Dynamics in CAs	205
9.1.6	Measuring Computational Properties in Phase Transitions in Networks	206
9.1.7	Methodology for Studying Coherent Information Structure	206
9.1.8	Demonstrated Application Areas for Information Dynamics	207
9.2	Directions for Future Work	207
	References	210

Appendix A: Consideration of Alternative Method of Localisation . . .	213
Appendix B: Entropy Rate Convergence and Divergent Excess Entropy	217
Appendix C: Relation of Transfer Entropy to Massey's Directed Information.	219
Appendix D: Back-Door Adjustment	221
Appendix E: Complete Transfer Entropy for Causal Structure Inference	223
Appendix F: Information Destruction Only Measured in Open Computational Systems	225
Appendix G: Circumstantial Evidence of Maximum Coherence in Complex Computation	227
Author Biography	231
Index	233



<http://www.springer.com/978-3-642-32951-7>

The Local Information Dynamics of Distributed
Computation in Complex Systems

Lizier, J.T.

2013, XXIV, 236 p., Hardcover

ISBN: 978-3-642-32951-7