INVESTIGATIONS INTO WEB SCIENCE AND THE CONCEPT OF WEB LIFE

PHILIP DAVID TETLOW

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Abstract

Our increasing ability to construct large and complex computer and information systems suggests that the classical manner in which such systems are understood and architected is inappropriate for the open and unstructured manner in which they are often used. With the appearance of mathematically complex and, more importantly, high scale, non-deterministic systems, such as the World Wide Web, there is a need to understand, construct and maintain systems in a world where their assembly and use may not be precisely predicted. In Addition, few have thus far attempted to study such Web-scale systems holistically so as to understand the implications of non-programmable characteristics, like emergence and evolution – a matter of particular relevance in the new field of Web Science. This collection of prior published works and their associated commentary hence brings together a number of themes focused on Web Science and its broader application in systems and software engineering. It primarily rests on materials presented in the book The Web's Awake, first published in April 2007.

Contents

1 Introduction

The following commentary for the qualification of Doctor of Philosophy by Prior Published Work rests primarily on the ideas and evidence presented in the book *The Web's Awake (An Introduction to Field of Web Science and Concept of Web Life*, ISBN: 0-470-13794-0) [26]. This was the sole work of the author. Four further published papers/notes are also included for consideration to help provide background and context for the book. These are listed as follows:

- Paper: SOA, Glial and the Autonomic Web Machine, http://www.alphaworks.ibm.com/g/g.nsf/img/semanticsdocs/$file/soa_semanticweb.pdf[1].
- W3C Editors' Draft: Ontology Driven Architectures and Potential Uses of the Semantic Web in Systems and Software Engineering, http://www.w3.org/2001/sw/BestPractices/SE/ODA/[2].
- W3C Note: A Semantic Web Primer for Object-Oriented Software Developers, http://www.w3.org/2001/sw/BestPractices/SE/ODSD/[3].
- The Potentials of Software Recycling using Semantic Web Technologies, 4th European Semantic Web Conference 2007, http://swese2007.fzi.de/[1].

[1] Written solely by the author.
[2] Primarily written by the author in association with other members of the W3C Semantic Web Enabled Software Engineering Taskforce (Dr J Z Pan, E Wallace, D Oberle, M Uschold, E Kendall).
[3] Co-authored with Dr H. Knublauch and reviewed by D .Oberle and E Wallace.

Central to the works submitted runs a common theme. This seeks to examine how particularly simple forms of computational pattern (both informational and functional) can aggregate with recognisably complex characteristics, especially in terms of abstract graph structure and semantic relationship; *complex*, that is, as is now explicitly understood by contemporary fields such as Complexity [5][13][14][15], Network [11] and Chaos Theory [41], and more implicitly in the broader natural sciences of Physics, Chemistry, Biology and their many derivatives.

One particular example of complex computational aggregate provides the focus of attention. This is the social machine[4] [18] commonly referred to as the World Wide Web, or “Web” for short. It is the largest human information construct in history [4] and easily provides the best example of combined social and technical capability in existence today, many studies having documented its unparalleled growth[5] thus far [110][111].

There are further good reasons to single out the Web as being different from most other man-made computer systems. As a case in point the Web is not built on deterministic principles like so many of its digitally related forebears. Rather it is discernibly irregular at just about every level. The original language at its nucleus, the hypertext mark-up language HTML, can be

[4] A popular term used to describe the amalgamation of Web technologies with the gross social capabilities of mankind.

[5] Widespread use of the Web did not really begin until around 1995 when studies accounted for around 16 million users. By 2001 this figure had grown to over 400 million and some estimates now predict that it should have topped 1 billion by 2005 and will surpass 2 billion by 2010 [3] – around a third of the world’s population by most common accounts.

thought of as a non-Euclidean[6] technology, connecting Web-resources to form a corpus of utterly unplanned global organisation [11]. In short it is complexly “messy.” [5] [7]

There is little doubt that the Web is having a profound effect on our personal and social existence [11][46]. As such it has attracted much research interest [11][16][19][26][43]. Nevertheless, few studies have chosen to look at the characteristics of the Web from the perspective of holistic complexity, structure and growth. Why is the Web evolving in the way that it is? What does the Web actually look like now and what will it look like in the future? Is “evolution” even the right word to use to describe its progression? These are all questions that have been relevant for some time, but which have appeared to be unthinkable in all but the most open-minded of circles. In truth new thinking is needed to help address such questions; thinking that combines the classical empirical strength of the natural sciences while still embracing the synthetic expression granted by the abstract worlds of contemporary computing. It is this area that provides a source for the thesis’s subject matter.

[6] That is to say, holds the potential for infinite capabilities in apparently finite contexts (this is especially relevant in terms of information content). By way of analogy, the outline of a Mandelbrot Set graphic [135] is non-Euclidean, as the formation’s fractal geometry yields more and more points when areas of apparently fixed detail are magnified.

[7] This specific reference to “messiness” can be found on page 329 for reference [5] - Waldrop, M.,M. (1992). Complexity – The Emerging Science at the Edge of Order and Chaos, Simon & Schuster, ISBN 0671872346.

2 Contribution, Significance and Originality

The label "Web Science" denotes a field focusing on the understanding and engineering of large-scale complex Information Technology systems and, in particular, variants such as the World Wide Web. Through prior published work this thesis presents for the first time an integrated set of hypotheses and supporting evidence to assist in scoping Web Science. As a further aid the concept of Web Life is also refined as a means to show comparisons between characteristics common to high scale, complex real-world systems and similar "synthetic" traits already evident on the Web. Through such means, many concepts, well proven in their native fields of complexity theory and the natural sciences, are examined for the purpose of unification with, or extension to, established principles and practices of Computer Science when applied to vast, complexly irregular systems like the Web.

The thesis is hence both broad and deep in its presentation, with a particular strength being its bringing together of tried and tested techniques and applying them to the Web as a concrete example in complex systems. It can hence be seen as providing a novel, significant and coherent contribution by:

- Providing an early and comprehensive insight into of Web Science.
- Extending initial attempts to define Web Life [148].
- Introducing concepts from Complexity Theory into modelling specifications common to Information Technology.

- Promoting the synthesis of ideas from the natural sciences with those from Computer Science, which in particular:
  - Places an emphasis on the physics of computing when considering the Web as a large scale, complex blend of the social and technical capabilities.
  - Advocates a move from Euclidean to geodesic geometries when conceptualising large scale complex IT systems. This stresses the importance of broken symmetry in systems through the explicit use of curved graph paths.
  - Proposes the relevance of the Second Law of Thermodynamics when considering the Web as a large scale open system.
  - Explores the relevance of contemporary computational paradigms such as Quantum Computing to the Web.

Through such coverage this thesis accents criteria and concepts hitherto uncommon in mainstream computing. These include emergence and evolution and a strong appreciation that many of the fundamental laws of physics carry significant weight in the context of vast "open"[8] spaces such as those found on the Web.

In doing so it takes a liberal stance by considering all computation as a matter of information dynamics; ultimately promoting Gödelization as a means to remove the distinction between informational and algorithmic perspectives, thereby providing a platform on which graph-based models can be applied

[8] Here "open" specifically refers to a definition imposed by the Second law of Thermodynamics. This states that the entropy of an isolated system which is not in equilibrium will tend to increase over time, approaching a maximum value at equilibrium.

uniformly. This is supported by a detailed examination of the nature of information which advocates new conceptualisation approaches to generalised geometries and models; approaches in which well ordered sets of data can be seen to observe curved rather than straight paths. This is a significant, compelling and novel hypothesis as it naturally leads to other fundamentals with known dependencies centred on curvature. These include concepts deeply ingrained in theoretical physics both at micro and hugely macro scales, such as “spin” and relativity in general. This thereby opens up possibilities to achieve congruity across large ranges of scale and complexity in computing by using graph-based geometry as a vehicle for unification within modelling specifications like the Object Modeling Group’s Meta Object Facility (MOF) [146] or their Ontology Definition Metamodel (ODM) [154] – for which the author was individually acknowledged as a contributor up until its sixth submission [155].

The ODM specification represents the foundation for an extremely important set of enabling capabilities for Model Driven Architecture (MDA) based software and systems engineering; namely the formal grounding for representation, management, interoperability, and application of semantics. It offers a number of benefits to potential users, including:

- Options in the level of expressivity complexity, and form available for designing and implementing conceptual models, ranging from familiar Unified Modeling Language (UML) and Entity Relationship (ER) methodologies to formal ontologies represented in description or first order logics;

- Grounding in formal logic through standards-based[9], model-theoretic semantics for the knowledge representation languages supported (such as the World Wide Web Consortium's OWL Language [30], which itself is based on first order predicate logic [168][10]), sufficient to enable reasoning engines to understand, validate and apply ontologies developed using the ODM; and
- Profiles and mappings sufficient to support not only the exchange of models developed independently in various formalisms but to enable consistency checking and validation in ways that have not been feasible to date.

The ODM is applicable to knowledge representation, conceptual modelling, formal taxonomy development and ontology[11] definition, and enables the use of a variety of enterprise models as starting points for ontology development through mappings to UML and the OMG's MOF. [153]. It has a wide remit, attempting to encompass such areas as Complete MOF (CMOF), Common Logic (CL), Computation Independent Model (CIM), Description Logics (DL), Entity-Relationship (ER), Essential MOF (EMOF), interpretation, Knowledge

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[9] The ODM includes four normative metamodels – RDF, OWL Topic Maps and Common Logic (CL). Common Logic is published by the International Standards Organisation (ISO) as "ISO/IEC 24707:2007 - Information technology — Common Logic (CL): a framework for a family of logic-based languages". The standard includes specifications for three dialects, the Common Logic Interchange Format (CLIF), the Conceptual Graph Interchange Format (CGIF), and an XML-based notation for Common Logic (XCL). The semantics of these dialects are defined by their translation to the abstract syntax and semantics of Common Logic. Many other logic-based languages could also be defined as subsets of CL by means of similar translations; among them are the RDF and OWL languages.

[10] Further to a telephone discussion with Dr Jeff Pan of Aberdeen University on Jan 27 2009. Dr Pan was the author or the OWL-DL language, a subset of the full W3C OWL specification.

[11] An ontology is a model of entity and relationship in a specific domain or universe of discourse (UoD). An ontology can vary from a taxonomy (knowledge with minimal hierarchy or a parent/child structure) to a thesaurus (words and synonyms) to a conceptual model (with more complex knowledge) to a logical theory (with very rich, complex, consistent and meaningful Knowledge). The current focus of the industry is on conceptual model and logical theory (such as OWL) [174].

Interchange Format (KIF), Platform Independent Model (PIM), Platform Specific Model (PSM), RDF Schema (RDFS), Resource Description Framework (RDF), Topic Maps (TM) and traditional first order logic in the Web Ontology Language (OWL).

The ODM does not cover specification of proof theory or inference rules, specification of translation and transformations between the notations used by heterogeneous computer systems, free logics, conditional logics, methods of providing relationships between symbols in the logical "universe" and individuals in the "real world" or issues related to computability using the knowledge representation formalisms represented in the ODM – for example, optimization, efficiency, tractability, and so on. Because of the broad range of modelling conventions covered, graphing concepts such as arc and node are not treated homogeneously across the entire specification.

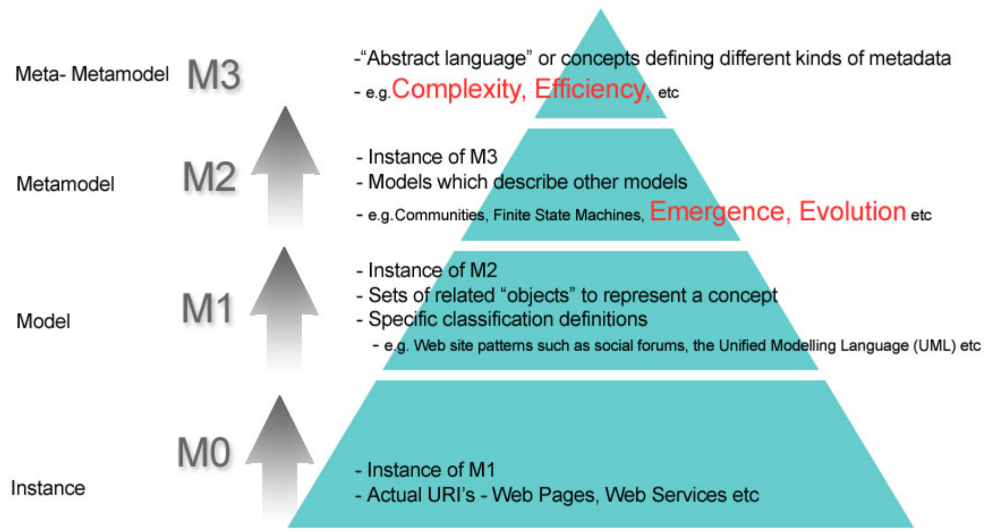


Figure 1: The MOF specification as a means to consider complexity at differing abstraction levels

This thesis represents a first and unique attempt to explicitly combine complexity schemas [5][12][13][14][15] with multi-tiered modelling specifications like those of MOF and the ODM; specifications which, until now, have been designed for much smaller and simpler application in software and systems' design.

Regardless of the grammars employed by such specifications, all are dependant on graphs, and hence geometry[12], as a primary means of communication. Therefore, introducing emergence and evolution at the M2 layer and complexity and efficiency at the M3 layer, as illustrated in Figure 1 above, are particularly novel and noteworthy for the following reasons:

- Established models for emergence and evolution are often tightly coupled with the constraints and qualities of their surrounding contexts – a condition often understood as co-evolution [5][26][158]. Emergence, for example, may be triggered by actuators outside the immediate confines of the system(s) under direct consideration. Such emergence may also produce characteristics absent from the context prior to the change taking place, hence breaking the closure [160] of

[12] It is important to note that graphs are treated as abstract structures within this context and that the term "geometry" is merely used to convey the notion of structure based on the arcs and nodes present. Geometry is traditionally considered as a means for visualising graphs and it is important to appreciate that multiple geometries can be applied to any abstract graph for this purpose. It is valuable to also note that geometry can further be used as a means of eliciting metadata from an abstract graph and that the choice of geometric framework adopted is critical in assessing the validity of both the elicitation process and the data derived from it. Chapters 3 [26, pp61-70], 4 [26, pp71 – 100] and 5 [26, pp 101-119] of the Web's Awake introduce the idea of using graph structures where the boundaries between individual elements, and hence the definition of the elements themselves, are described by means of arcs tangentially aligned to their predecessor(s) within a graph's structure. Chapter 2 [26, pp 42-43] also describes why Euclidian geometry might not be best suited for describing the Web's structure. The Potentials of Software Recycling using Semantic Web Technologies [125] further introduces the concept of using geometry to extract metadata from software, but it is not explicit in its description. Detailed information on such matters exists within IBM's Service Oriented Architecture Centre of Excellence and Legacy Transformation Practice, but almost all of this is not open to public disclosure. IBM has published some material in this area such as that at [175].

the models under construction. In traditional modelling specifications, like MOF and the ODM, such dependencies are not respected, as they deliberately separate out the concerns of resultant models from those of their associated source and target contexts [157].

This presents a significant challenge as complexity also makes it difficult to preserve boundaries between abstraction layers and may ultimately demonstrate that traditional modelling specifications are too simplistic for truly complex problem spaces. As a case in point, it remains unclear how emergence might be effectively represented from M0 through M2 in both the OMG's MOF and the ODM. This is because a precise definition of all the variables and interactions contributing must be captured at all levels. This creates significant potential for information loss when moving up the specification stack, currently making such specifications vulnerable because:

- The map of dependencies involved may be so large and complex that current tooling could not scale to meet modelling, analytical and proof requirements. This is certainly still true of popular Semantic Web inferencing tools like Protégé from Stanford University [159] – the accepted "best of breed" tool for ontology engineering[13] at the time of this submission.
- The complexity inherent in many large-scale systems stems from a variety of causes. Such systems are often designed to address problems which, by their very nature, cannot be completely defined [152]. They are hence less amenable to static modelling approaches like that advocated by MOF.

[13] No formal statistics exist to support this proposition. It is based on experience within the Semantic Web community from 2003 to present and numerous discussions with IBM specialist tools teams such as that based at IBM's Hursley Laboratories and Rational Software.

Specifications which do not employ a tiered approach to abstraction and are not prescriptive in their approach to dynamic modelling, such as RDF and to a lesser extent the more expressive OWL, are hence gaining popularity amongst systems and software engineers [123][157]. As a consequence there has been some work, such as that on RDFS with Fixed layered meta-modelling Architecture - RDFS(FA) [161], which tries to extend RDF with MOF-like stratified semantics, thereby enabling users to employ meta-classes and meta-properties in their ontologies. This has, nevertheless, proved less popular.

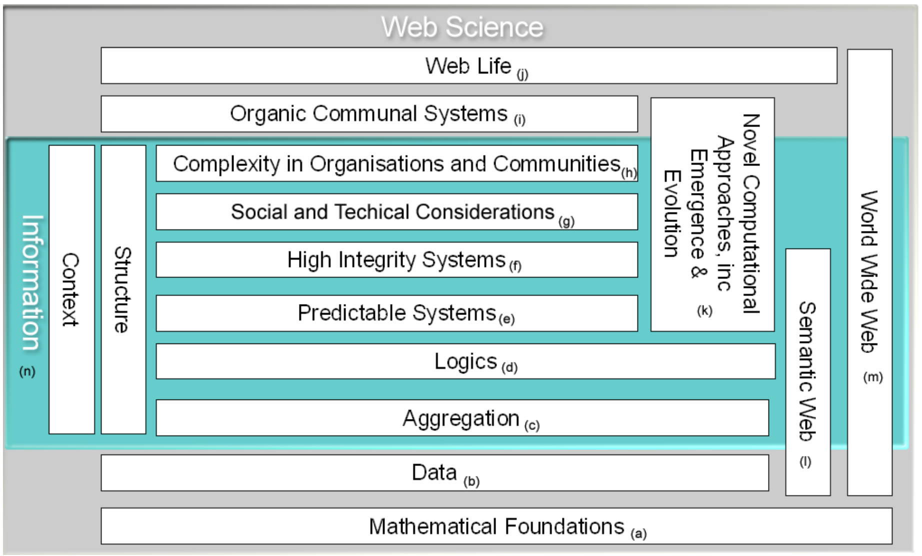
- As a general rule, the higher up the modelling stack one goes, the less information is expected to describe the models found [5][26][153]. This contradicts with accepted definitions of complexity in which associated models require large amounts of information at M2 and M3 levels [5][21].

The value that specifications like MOF and the ODM can add to Web Science should be not be underestimated, as they help to ground thinking much more rigorously than other attempts at definition thus far [4][147][150]. These emphasise less formal characteristics, like individual and social “creativity”, yet still propose that they might support engineering at large scales without further clarity. Such approaches contain the essence of what Web Science is, or should be, but are not mature enough to suggest ways in which relevant domain traits might be utilized for meaningful or measurable application.

3 Relevance, Application and Impact

Treating Web Science as an information centric problem within a hierarchical model driven [151] characterisation, like that illustrated in Figure 2, is particularly useful as it:

- Provides a means to consolidate a number of hitherto disparate areas and ideas into a generalised definition of Web Science.



Relevant References in The Web's Awake [26]

a) pp. 64,65,115,161,177
b) pp. 40,45,47,54,55,60,62, 65,70,102,103,106,107, 114
c) pp. 76, 167
d) pp. 4, 46,62,75,119, 126,137, 138,142,143,159,166, 219
e) pp. 31, 49, 51, 58, 59, 77, 93, 111, 122, 124, 134, 137, 142, 145, 167, 169
f) pp. 205-123
g) pp. 1 – 16,
h) pp. 108, 193, 200
i) pp. 153, 155, 157, 165
j) pp. 61
k) pp. 12, 17, 18, 19, 20, 24, 29, 33, 34, 35, 36, 37, 40, 42, 51, 60, 67, 68, 71, 72, 76, 85, 93, 97, 119, 120, 121, 124, 125, 134, 140, 141, 142, 146, 148, 158, 200, 201, 203, 213
l) pp. 8, 15, 136, 137, 140, 143, 161, 165, 173, 197, 205, 206, 207, 208, 209, 210, 211, 212, 215, 216, 218, 219
m) pp. 156, 202, 62, 32, 16, 207, 213, 209, 171, 167, 61, 42, 15, 7, 88, 8, 107, 12, 167, 38, 201, 5, 215, 197, 13, 31, 199, 212, 210, 106, 180, 1, 6, 7, 12, 49, 119, 145, 160, 165, 186, 206, 218
n) pp. 104

Figure 2: The Web Science Matrix[14]

[14] Based on the LCITS stack [152].

- Highlights appropriate levels of abstraction at which complexity formalisms should be considered when modelling;
- Aligns Web Science with proven tools and techniques used for engineering, hence pointing a way through to practical application; and
- Focuses attention on areas of weakness in existing approaches and specifications.

It is difficult to anticipate the impact this will have because Web Science has been announced to the World only recently. First discussions[15] were had in the spring of 2005 at the World Wide Web Consortium's plenary session in Boston U.S., and the first formal Web Science workshop took place in September of that year [149], at the same time as *The Web's Awake* was in writing. As such, this thesis is believed to be the first to provide any significant narrative in support of a conceptual structure for Web Science. It is hence refreshing to note that significant organisations such as IBM are now taking this field seriously, having formed a working group late in 2006 to investigate its relevance and commercial application.

[15] Of which the author played a significant part.

4 Relevance and Selection Criteria of Methodologies Used

The findings presented in this thesis are predominantly backed by desk-based research, personal interviews with leading industrial practitioners and recognised academics, and practical experience gained over twenty years in industry. This approach was adopted on the basis that:

- Taking an experimental approach to research would require much larger volumes of data than could be sensibly analysed by an single research project,
- Appropriate test conditions, metrics and success criteria for experimentation would be difficult to establish and validate given the immaturity of the study area [4][167].
- Prior experimental results were already available to support a number of key claims made by the research.

5 Themes of Defining Coherence

The concept of "Web Life" [47] is also extended, further to the works of Capra [148], Stock [170] et al, thereby providing a coherent theme from which more generalised discussions on Systems and Complexity Theory are built. This is because one could philosophically argue that life represents the known Universe's pinnacle example in terms of complex system. Furthermore recent breakthroughs [13][14][15][16][20] are strengthening our understanding of just how complexity contributes to the very notion of life in areas such as informational content, structures and associated developmental processes [5][12][13][14][15][48][49][51][52][53]. Today we recognize schools of thought that quite freely separate the essential characteristics of life from the physical confines of the flesh. For example Chris Langton's work on Artificial Life[16] [5][59][60][61][62], Richard Dawkins work on Memology [6][63][64][65][66] and Stuart Kauffman's work on co-evolution and emergence [12][13][14][15] stand out. And what is interesting about the conclusions of such work is that similarities are apparent in patterns found at both high and low scales and high and low abstraction points [16] on the Web [26]. Outlining such similarities, therefore, provides the core subject matter of *The Web's Awake* [26] and supplies a continuing theme running through the other publications presented.

[16] Commonly referred to as "A-Life".

6 The Impetus for the Research and the Approximate Timeline Involved

The pivotal motivation for research on the themes of Web Science and Web Life came from work as a Lead IT Architect on one of the most ambitious IT programmes Europe has ever seen. This was the Department for Work and Pensions' Benefits Processing Re-Engineering Programme (2003 – 2006), a national government initiative to update automated benefits processing capabilities in the UK. This commanded a development budget of nearly £500 million and employed over two hundred and fifty IT professionals at its height.

Not surprisingly this large undertaking presented a number of noteworthy challenges, two of which were particularly prominent:

- The need to unify the understanding of complex requirements across several independent and disparate stakeholder bodies. Technically this can be interpreted as a need for strong semantic interoperability [40] across multiple software development work streams.
- The need to design systems in a manner capable of Web-based deployment.

The first of these requirements pointed towards the use of strongly formal [27] knowledge representation [54][55][56]. This needed to reduce semantic ambiguity while still providing a framework for exacting systems and software specifications to be written, verified and applied across multiple development activities. Adding the requirement for Web-friendly technologies provided a strong incentive to explore ideas based on formal ontologies [31][57], description logics [56] and description languages such as the Resource Description Framework (RDF) [29] and the Web Ontology Language (OWL) [30]. These are central to the World Wide Web Consortium's (W3C) Semantic Web initiative [28] and hence led to the author joining the W3C's Semantic Web Best Practices and Deployment Working Group (SWBP) [57] in 2004. This was primarily to investigate how Semantic Web technologies might best be applied on the Benefits Processing Re-Engineering Programme.

6.1 The Glial Language

Ontology implementation, as advocated by the Semantic Web initiative, is founded on graph-based techniques for information representation. Through such graphs, richly overlaid networks of interconnected data can be created without the need for explicit sub-graph[17] separation relating to individual categorisations of concern or interest. This raises the question as to what effects might arise if the sub-graphs contained were allowed to interact, thereby stimulating self-actuated change in the wider ontology. This question provided the motivation to design the XML-based language "Glial" and write the first of the papers [122] included for consideration in this commentary. The eventual outcome of this work, a prototype Glial interpreter, successfully demonstrated a framework for creating dynamic HTML pages containing self-generated X-Links [32] based on a separate ontology of pre-defined search preferences.

[17] Collections of data relating to a specific area in underlying problem domains.

By the time that work on Glial neared completion it became clear that the use of XML ontologies need not be confined to rigorous Web-targeted information representation. For a number of decades formal methods have been used in domains such as systems, and more noticeably, Software Engineering. Nevertheless it is commonly accepted that they have failed to make significant impact due largely to the mathematical abstractness of the specification languages involved [33]. This, however, need not necessarily be the case with Semantic Web technologies like RDF and OWL, as the use of domain specific[18] natural language terms in such syntaxes can lead to rigorous statements[19] being captured via colloquial terminology. This aids human interpretation and, essentially, lowers the level of skill required for use. In short such technologies can make formal specification informal in the eyes of the domain-acquainted user. Furthermore, the interconnectivity afforded by graph-based ontologies allows a number of specification concepts to be freely intermixed. Hence, data, constraints, transformations and dependencies can all be combined together in one unified model – a capability hitherto uncommon in Software Engineering circles.

6.2 Semantic Web Enabled Software Engineering

The advantages highlighted above provided strong reasoning for the application of Semantic Web technologies in Software Engineering and consequently encouraged the formation of a Software Engineering Task

[18] Domain specific, refers to the use of XML namespaces.
[19] The use of XML namespacing to predicate natural language terms is intended to make them unique within a particular knowledge domain.

Force[20] (Semantic Web Enabled Software Engineering - SWESE) [126] in 2004 under the remit of the W3C's SWBP Working Group [57]. The main outputs from this activity can be seen in the two W3C notes listed for consideration in this commentary. The note on *Ontology Driven Architectures and Potential Uses of the Semantic Web in Systems and Software Engineering* was written by the author in the main, in his position as chair of the task force. The note on *A Semantic Web Primer for Object-Oriented Software Developers* was co-authored with Dr Holger Knublauch, of the University of Manchester.

Following the W3C SWSE activity, workshops on the use of Semantic Web technologies in Software Engineering have been held at three International Semantic Web conferences (2005, 2006, 2007) [34][35][58]. These have proved a resounding success, with the 2005 workshop being one of the best attended at the conference. The author helped to coordinate all three workshops.

6.3 The Web as a Platform for "Open" Systems Development

Following on from work on Glial and SWESE, it became apparent that designing systems for use in a Web context is significantly different from doing so in more conventional circumstances. Such types of system may appear overly haphazard, but they can carry an extraordinary ability; under the right set of circumstances [12][13][14] they are capable of bringing forth order out of disorder.

[20] At the request of the author, sponsored by Dr Jeff Z Pan, then of the University of Manchester.

Living things are open systems, that is they exchange matter and energy with their surroundings. For every bit of order created within them a greater amount of disorder is created in their surroundings. The process of biological growth produces a great deal of heat, for instance, which causes the surrounding air to become more disordered. Thus entropy is preserved and such processes stay within the bounds of the Second Law of Thermodynamics [37][5] providing a key example of positive feedback in our Universe [5][12][13][14][15][26].

Realizing this potential for the Web to be considered as an open system prompted the writing of *The Web's Awake* in the summer of 2005.

6.4 Software Recycling

As the W3C SWESE activity tailed off, its value started to be realized by Industry. Sun Microsystems and Adobe began to embed RDF databases into their multi-language content-management projects [38] and IBM started to use RDF and OWL for agnostic data storage in internal products used for legacy systems transformation[21].

Legacy systems transformation[22] is the automated process by which software is used to inspect other (legacy[23]) software in order to transform[24] it, through a

[21] Source IBM Watson Labs.
[22] Also referred to as "Software Recycling" in IBM.
[23] A legacy system is an existing computer system or application program which continues to be used because the user (typically an organisation) does not want to replace or redesign it. Many people use this term to refer to "antiquated" systems.

suitable Context Free Grammar (CFG) [112][113][114], for redeployment using more contemporary languages and architectures.

Software transformation has a long history dating back to the work of Darlington and Burstall on pure functional languages [128]. As such, a sequence of simple transformation steps can be applied to a program to translate it from one form into another. All approaches to transformation share the common principle that they alter the program's syntax without affecting its semantics [127].

Transformation is familiar from its use in compiler technology where, for some time, it has been used to support optimisation. Transformation can also be applied at higher levels of abstraction where the goal is to restructure the program in some way, to partially evaluate it, or to support activities typically associated with the later phases of the software development life cycle, such as maintenance and re-engineering [127].

The work on legacy systems transformation is still ongoing at IBM[25] as part the US Service Oriented Architecture Center of Excellence (SOA COE) initiative. From mid-2003 the author played an integral part in architecting the software tooling involved and was instrumental in choosing RDF as its core data storage mechanism. The summer of 2006 saw the start of a significant

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Legacy systems are considered to be potentially problematic by many software engineers for several reasons. They often run on obsolete, and usually slow, hardware. These systems are often hard to maintain, improve, and expand because there is a general lack of understanding of the system. The designers of the system may have left the organisation, leaving no one left to explain how it works.

[24] Using XSLT in the case of IBM's tools.

[25] As of July 2007.

documentation exercise to record the work undertaken by the SOA COE up to that point and the final paper for consideration through this commentary, on *The Potentials of Software Recycling using Semantic Web Technologies* [125], was a byproduct of that work.

7 Major Themes and New Contributions to the Field Introduced via the Published Works

Under the general themes of Web Science and Web Life a number of new ideas are introduced through the published works listed in this commentary. This unfortunately creates a challenge as not all could be adequately summarised in the space allowed. As a result the following sections concentrate on two further new contributions central to the concept of Web Life. These are the notions of "X" and "Y" shaped axiomatic patterns [26, p.71-78] and the concept of curvature in computation [26, pp. 90-100].

7.1 Differentiation (Through Broken Symmetry) as a Basis on Which the New Contributions are made

By adopting a bottom up perspective[26] on computing it can be shown that a surprisingly small number of axioms are needed to produce a viable framework [100][101][166]. Indeed paring back to an absolute minimum leads to reliance on a bipolar model [26, pp. 61-68,]; that is the ability to differentiate one thing from another, be that by either variation in one or more characteristic at singular point in time, or via a change in one or more characteristic over time. Such delineation produces a separation of structure into two branches or parts, generally referred to as bifurcation [5][165][26, pp. 67, 68, 72, 73, 74, 115, 119, 137]. Logic relies on such a capability to harness conditionality, for example, the binary number system holds it as fundamental to its makeup and even quantum computing carries inherent dependence through the concept of decoherence [5].

[26] This is independent of whether imperative or functional paradigms are favoured.

Through geometric expression, differentiation is often represented by two divergent arcs or arrows, giving a characteristic "V" shape (as seen on the right side of Figure 4), if observed from a point perpendicular to the splitting point and adjacent to the resultant fork. Adding one further arc as a predicate, thereby specifying that differentiation is dependent on some prior, adds a tail to the "V", extending it into a "Y" pattern and thus providing a starting point for the contribution on "X" and "Y" patterns.

Such patterns are not restricted to simplistic or even deterministic systems, be they abstract or naturally occurring. For instance they are often seen in the period doubling, quadrupling and so on that accompanies the onset of chaos [5][165]. This and other similar manifestations of differentiation patterns drive a significant theme, in The Web's Awake, on highly complex systems and the appearance of emergence [5][12][13][14][15] in such systems. Furthermore such patterns are not always directly observable and the concept of symmetry, or rather the lack of it, has been used by many branches of science and mathematics for some time [2] as an aid to identifying differentiation – a concept commonly referred to as broken symmetry[27] [26, pp. 72, 90, 91, 119, 179, 190, 191]. This thesis thereby also promotes the use of broken symmetry [2][69][70][78][138] as a method for outlining computation and information representation across a number of domains.

[27] Broken symmetry is a concept in mathematics and physics when an object breaks either rotational symmetry or translational symmetry. That is, when one can only rotate an object in certain angles or when one is able to discern if the object has been shifted sideways.

Finally this thesis outlines a significant failing of contemporary graphing techniques in Computer Science by highlighting an affinity with flat plane, or Euclidean, variants of geometry. It therefore explores the fact that Euclidean geometry is merely one tiny subset of geodesic geometry - as similarly the straight line is merely one member of an infinite group of curves - and begins to consider the potential of describing computational systems in terms of geodesic graphs or manifolds, thereby offering greater potential to model the "strange loopiness" [130][26, pp. 176], often found in high scale complex systems.

7.2 "X" and "Y" Axiomatic Patterns

When trying to make comparisons between the types of "natural" [53] computation found in the physical world and more synthetic variants such as those found on the Web, one fact must be remembered. By definition, real-world computation manifests itself through physical presence and the observable change[28] of that presence over time. Thus the blooming of a flower, the erosion of a mountain over multiple millennia and the collision of two subatomic particles all hold up as equal examples of computation in the raw.

A reductionist viewpoint on computation relies heavily on underlying mathematical formality. For such reasons the fundamental patterns on which computation itself is built are also intrinsically formal and, by implication, inherently simple. Simple that is in a mathematical sense[29].

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[28] The term "change" can also be seen as meaning "pattern".
[29] Requires a small amount of information to describe [21].

Set theory is central to ideas on systems theory[30], of which computation is a significant part. This is an important point, as all mathematics can, in the broadest sense, be viewed in terms of sets as well, a set being seen as a collection of things which can be thought of as a single object [1]. Furthermore, from a computational perspective, four main themes of categorisation overlay the basic notion of sets. These can be seen as concerning:

	Categorisation	*Properties Derived*
1	The identifiable objects[31] and concepts that any computation is interested in	• Identity • Addressability
2	The associations, constraints and/or transformations between those objects and concepts	• Association • Transformation • Connectivity
3	The methods of grouping both objects and concepts together	• Aggregation • Abstraction • Encapsulation
4	The types of the objects, concepts, associations and groups used	• Typing

Table 1: A Summary of Computational Categorisation Themes

Key to the notion of sets in computation is the property of "discreteness" across both membership and set definition. That is, unambiguous differentiation exists across all aspects, attributes and components involved in the grouping characteristics of a given system, with regard to both static spatial qualities and temporal transformations.

[30] Systems theory [88], in its broadest sense, is the interdisciplinary study of the nature of complex systems in nature, society, and science. It covers a wide range of fields, including mainstream digital computing.
[31] Here the term "object" is used in a loose sense.

Paul Benacerraf’s work in this area [67] has proved seminal, introducing the concept of mathematical structuralism in the 1960’s. In this, Benacerraf addressed the view in mathematics that treats mathematical statements at face value, so committing mathematical formulae to a realm of eternally abstract objects and concepts with no direct connection to the real world. Benacerraf further posed a dilemma, questioning how one could actually come to know such objects or concepts if no causal relation with the observer is in place. In other words how could mathematical concepts, or abstract notions of computation for that matter, be of any value if they have no direct effect in the real world? Benacerraf further questioned why multiple set theories exist that allow the reduction of elementary number theory into sets, so raising the problem of which set theory is true.

The answer to Benacerraf's concerns lead to structuralism becoming a viable philosophical school of thought within mathematics. This is through the belief that the essence of mathematical concepts or variables lies in their relationships with the wider structure of their mathematical context as a whole. This rhetoric then runs on into the area of computational theory, providing a firm basis on which to explain the same concepts in a wider “systems” context. Structures are hence exemplified in abstract systems in terms of the relations that hold true for that system.

This fits with versions of Model Theory where a key property in conveying semantics is not to provide any deep analysis of the nature of the things being described or to suggest any particular processing model, but rather to provide a technical way to determine they preserve truth through entailment.

There is a natural temptation to reach out for comfort of Finite Model Theory here because of its proven application in areas such as abstract machines and database theory. However such acceptance implies that the Web can be wholly limited and formalised at every level of abstraction and at all scales. Certainly this is true in circumstances where low scale, properly namespaced sub-graphs are in question; for example ontologies built on low orders of predicate logic at M0 and M1 levels, using Semantic Web languages like OWL. Nevertheless this assumption appears unfortunately flawed for the greater majority of Web content. This is because it may not easily lend itself to the removal of ambiguity amongst terms – typically held in natural language. And if this were possible the resulting ontologies would further demand accurate membership cardinality and the ability to effectively reason over every single element or subset contained, both of which are currently constrained by the scaling capabilities of relevant technologies such as IBM's DB2 [174] and Oracle's 11g [173] databases.

Representations of the Web at higher scales or abstractions may require heuristics and hierarchies of quantification in graph construction. For example the concept of "community" on the Web is self-reflexive and can be highly subjective in both its denotation and containment. Communities of Web designers, for instance, may be enclosed within communities of bloggers, which may be part of wider social networks and so on, all of whose boundaries may be hard to pin down for denotational and containment purposes. In theory, containment, denotation and precise assessment of cardinality are possible, but in practice the number of elements and the range of defining characteristics involved will be too large to make such assessments realistic. This points toward the application of higher-order logics (HOL) or infinitary logics[32] (of which RDF particularly has a type of HOL syntax) but the value of their application is also ultimately questionable because of their foundation on reductionist principles. Other appealing approaches are those deliberately targeted at analyzing problem spaces with vast ranges of variables and interactions and an appreciation of the uncertainty of measurement involved. In particular the framework offered by Quantum Mechanics stands out because of its ability to accommodate logical, probabilistic and vector space models via a single formulation.

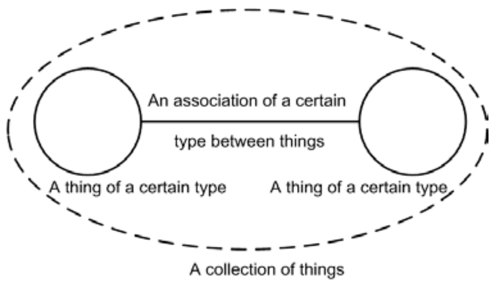


Figure 3: The basic triple model of computation[33].

At its most mathematically simple, structuralism can be seen to generate graph structures commonly referred to as “triples”, as illustrated in Figure 3. These can be considered as depicting the smallest sequence of constituents

[32] An outline of how these might be appropriate is outside the bounds of this thesis.
[33] In mathematics, a triple is an *n*-tuple with *n* being 3. A triple is a sequence of three elements. It is not a set of three elements, as the ordering of the elements matters, and an element can be present more than once in the same triple

required to form an arc within a conceptual graph - that sequence being the encapsulation of a single predicating relationship between a *subject* and *object* node.

On their own such patterns do not contain enough content to adequately address the entire range of differentiation needed across graph axioms[34]. This is because at least two arcs and two nodes are needed to demonstrate differentiation across both arc and node types and hence outline the full vocabulary of axiomatic Lagrangian[35] [129] interaction patterns possible. This is also a concept needed to form the most basic "true/false" construct of Boolean logic and the fundamental unit of distinction in the physical world – a concept often referred to as "symmetry breaking" [69][70].

Symmetry is a regularly used term, often interpreted to mean "balance" or perhaps "harmony", or sometimes even "beauty". Mathematics and Physics carry an inbuilt appreciation for the same qualities in symmetry, but also use a more stringent definition: "something has symmetry if one or more of its properties remain unchanged when some other property is changed[36] [69]." A group of ten identical objects possesses symmetry - line them up and it's impossible to know if any or all of them have switched position in the line. But if the line were composed of five objects that had one shape, followed by five

[34] Individual arcs and nodes.
[35] A Lagrangian $\mathcal{L}[\varphi_i]$ of asystem undergoing continuous change or activity is a function that summarises the dynamics of the system. It can also be considered as a description of the interaction between fundamental "elements/constituents" at a particular level of abstraction.

[36] An equally good definition also states that a symmetry is an operation that doesn't change how something behaves relative to the outside world. For example, one can rotate a ball and it does not necessarily change as it is still a sphere [2].

that had another, some of the symmetry is broken by observable variation. Swapping numbers five and six, for instance, would produce an obvious change.

To help visualize this idea, graphs similar to Feynman diagrams [7][71][73] found in quantum mechanics [2] can be used as a means of expressing the patterns involved. Such graphs are typically used to show how particular or possible aspects of a system inter-relate or change, capturing relationships or transitions between a system's individual elements or states in a graphical form. Several variations of such diagrams exist [72]. In one variant the steady state of a system can be drawn as an arc between two points or nodes, often drawn as circles if at all. Alternative representations can choose to use the reverse convention, using nodes to represent steady states or constituent parts and arcs to represent transitions or relationships between them. Arcs can thereby represent a "step" [7] in the characteristic(s) of the underlying system or problem space being studied. In their sparsest forms, like Feynman's schematics, such diagrams describe the interaction between two facets of a system as a quantified outline of their interaction.

A graph drawing should not be confused with the graph itself (the abstract, non-graphical structure). All that matters is which vertices are connected to which others by how many arcs and not the exact layout. In practice it is often difficult to decide if two drawings are isomorphic and hence represent the same graph. Depending on the problem domain some layouts may be better suited and easier to understand than others [137].

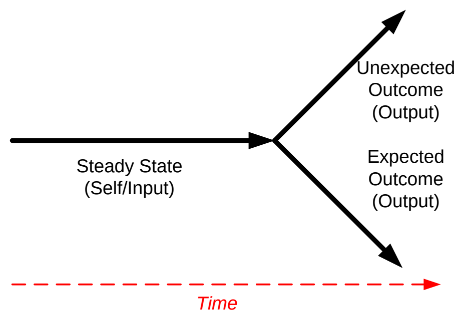


Figure 4: A state-based directed graph showing spontaneous bifurcation – An example of the “Y” shaped pattern

Graphs using lines between nodes imply that the relationships involved are commutative[37]. Graphs containing arrows instead of lines imply directionality or order. At the start of any such arrow, the point at which a system last became stable is hence represented, and at its tip is the point at which the system ultimately changes condition. Graphs can hence be seen as being generically isomorphic in their capability to describe structural and transformational characteristics of a system or problem space [76].

Systems undergoing spontaneous [2] or self-generated symmetry breaking through bifurcation[38] can therefore be described using the graph shown in Figure 4, with transformation into all possible states – often considered to be “true/false” or “expected/unexpected” outcomes, as depicted by Boolean logic [74][75] - being shown as two further outbound arrows. In such graphs the steady state duration of any arrow is of little concern.

[37] In mathematics, an operation that is independent of the order of the objects concerned.
[38] Common in chaotically emergent systems [5][13][14][15].

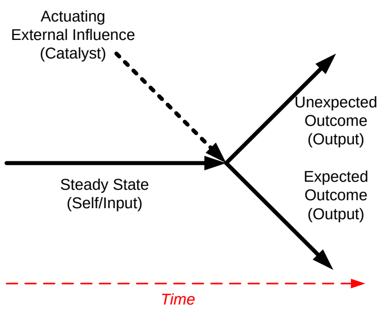
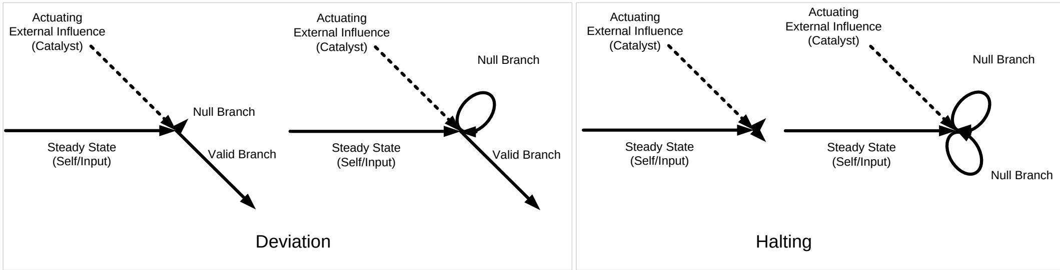


Figure 5: A state-based directed graph showing induced bifurcation - An example of the "X" shaped pattern

Induced bifurcation needs one further arc to represent the external causal source of change – as shown in Figure 5. This can be considered as an extension to the "Y" shaped pattern in Figure 4, thereby creating a more encompassing model. This is capable of describing both spontaneous and induced symmetry breaking via the inclusion of the optional actuating leg. Basic aggregation models, such as sequences, clusters, hierarchies, ontologies and so on, can hence be created by linking multiple "X" shaped patterns together.

Bifurcation [26, pp. 67, 68, 72, 73, 74, 115, 119, 137] is a term normally used to describe forking or splitting structures, but further special cases can also be considered, as in Figure 6. In particular it is acceptable for one or both of the resultant branches produced to be effectively null[39]. In such circumstances "X" shaped patterns can also be seen to cover the concept of qualitative change or deviation [77], which includes the concept of halting.

[39] A logically valid branch that will either halt without further effect or be cyclical without further effect [121].



Figures 6(a), 6(b), 6(c) and 6(d): Qualitative change in terms of bifurcation, showing nullification of outbound branches via both nonexistence and cyclic arcing[40].

7.3 Bifurcation, Switching and Non-Determinism

None of the above should surprise those familiar with basic computer architecture, as the "X" and "Y" patterns described merely present graph-based schematics for actuated switching. The important point however, is that these patterns are relevant across all systems theory at a number of levels. They might just as well have been introduced on the premise of real-world behaviours like a single species of animal splitting in two [78] or the formation of a black hole in some far off galaxy [138]. This is a blunt, yet overwhelmingly powerful observation. A relay is nothing more than a special type of switch that opens and closes under the control of another circuit. It is therefore one of the most important components in just about all systems of notable complexity.

[40] Note that in the case of cyclic arcing the arcs involved inherently contain self-symmetry and are hence "unobservable" in a computation and informational sense. This renders them null as no transformation is presented.

Regardless, there are some less than obvious observations here and these are crucial. Bifurcation is not only a defining characteristic of deterministic switching systems, but is it also a common trait amongst certain types of non-deterministic, “chaotic” [79][84][85] or complex system. Furthermore, it is closely associated with the concept of emergence [5][80][81] in such systems, a concept that underpins mainstream thinking on subjects such as evolution and ultimately the existence of life.

Emergence is often associated with self organising complex systems and can be broadly seen as a frequently significant [167] change in the presentation of a macro, or system-level, phenomenon, resulting from the cumulative effect of multiple micro-level changes within. It can hence be seen as being ostensively supervenience[41] and of downward causation [167].

Experts like Stuart Kauffman, see emergence as being classified according to two points of view; namely the epistemological and the ontological perspectives. The former says that complex systems are too complex to be explained by reductionistic practices, but that ontologically, reductionism holds. The ontological view is that new entities with their own properties and causal powers arise and are part of some fundamental framework that underpins the growth of complexity [168].

In many ways emergence can be seen as being diametrically opposed to the concept of entropy - the tendency of a system to enter a more probable state

[41] Something additional or extraneous.

of disorganisation. Indeed well understood laws of physics, such as the Second Law of Thermodynamics outline an apparent preference for systems to veer away from emergence. Nevertheless, if this law is to be believed, then there should be no order at all in the Universe. A totally disordered system, as implied by the big bang, cannot create order except randomly, and even then the tendency would be to immediately disintegrate again. Nonetheless, as far as is known, the Universe has persistent order at all scales - and possibly that order is increasing rather than decreasing, at least from our own viewpoint [2][169]. Thus examples like life itself illustrate hitherto unidentified counter laws which can patently overwhelm entropic attraction. This has led some, like Kauffman[42], to believe the laws of thermodynamics to be incomplete.

Interestingly order, and hence emergence and entropy, can be considered in terms of information content, so it is possible to classify the complexity of a system by how much information is needed to describe it [21]. If this is done, then familiar physical concepts, such as solids and gasses, can be seen as having low complexity, given that their description is a relatively simple matter. Nevertheless, to fully describe a whirlpool, for example, would need a very extensive description, forever changing with time. Local interactions of liquid molecules give a dynamic structure to the liquid which can cause the emergence of unexpected features. These features are not predicted by traditional entropy considerations, simply being too improbable.

[42] As explained during several lengthy phone calls with Stuart Kauffman between March and August 2008.

7.4 Computational Curvature

For aggregation, and hence abstraction, to take place in systems, relationships[43] need to form between the constituent parts involved. This is predicated on all elements involved in a relationship being part of a wider collection or composition [129] of at least two, not necessarily material distinct, things that differ in at least one way, be that via static characteristic or state[44]. Furthermore aggregates only come in two basic types, mathematical sets and sequences. In sets the order of constituent elements is unimportant, whilst order is paramount in sequences. Sets are therefore the most encompassing type of collection, as sequences can also be viewed as a special type of set – a “well ordered” set to be mathematically precise [8].

It is essential to connect the notion of aggregation with that of the relationships[45] between the various elements involved. This is because only through the process of aggregation can complexity be cultivated, relying primarily on the compounded effect of underpinning relationships as its feedstock.

Mathematically sequences are ordered aggregates based on a particular and continual type of progression. These progressions are often complex, and under rare, but not statistically implausible circumstances, systems incorporating such types of complexity can spontaneously form in self-

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[43] Graph arcs.
[44] i.e. at least one symmetry is broken between both nodes (elements) at either end of an arc (relationship).
[45] Interaction also being considered as a form of relationship.

organizing ways [5][13][14][15]. Thus, given the right conditions, credible macro-level processes of evolution can take hold.

Significant portions of both the natural and digital world rely heavily on the notion of sequential association. Furthermore, take a well-defined sequence of operations and the concept frequently referred to as an algorithm is formed [9].

When thinking of the syntax of any arbitrary “string” of information, convention suggests the use of a straight line directed graph, like the one below in Figure 7, for visualisation purposes. Unfortunately, however, this depiction is somewhat deceptive, as sequences need not always follow a “straight” course.

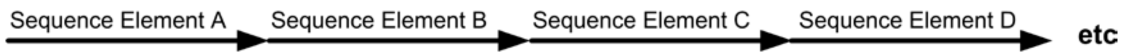


Figure 7: A “conventional” representation of a sequence using a directed graph

For a sequence to form there are principally two requirements; firstly that one or more elements must be present and, secondly, that these elements are arranged in some particular order. This may appear straightforward, but there are strong dependencies on symmetry involved. For example, symmetry breaking must be present to force noticeable boundaries within a sequence, promote discreteness and allow ordering to take place. Add the capability to switch between different ordering schemes, through the notion of bifurcation, for example, and the potential to compose extremely complex and elaborate systems of rules, processes, and information is formed.

This essential notion of inter-elemental symmetry breaking is often overlooked but it is nevertheless always present. The arrowheads in the direct graph above provide markers to indicate the points at which symmetry breaks for instance, as well as denoting directionality. Nevertheless these are merely graphical shorthand added for convenience. Such breakpoints can be represented using countless other methods and manifest themselves in the real world in innumerable ways across a myriad of observable properties. Physical shape, weight, texture, colour, electrical potential and perhaps even the divergence of the Semantic Web from the mainstream Web [26, pp., 136, 137], are all the result of aggregated patterns of symmetry breaking. Without such differentiation no evidence of progressive change would ever be apparent and two neighbouring elements in any given sequence might as well be considered as one continual same. They would simply be unobservable[46] in their own right [2]. Simple sequences therefore provide examples of a consistent rule of symmetry breaking imposed uniformly across a set of more than one element.

Returning to the axiomatic "X" and "Y" patterns characteristic of symmetry breaking. This time, to simplify representation one can remove the arrow heads and create a scenario where external influences are not needed to

[46] Observability relates to a property of the system state that can be determined by some sequence of physical operations. For example, these operations might involve submitting the system to various electromagnetic fields and eventually reading a value off some gauge. In systems governed by classical mechanics, any experimentally observable value can be shown to be given by a real-valued function on the set of all possible system states.

instigate change, i.e. the basic "Y" pattern. To further simplify the point being illustrated one can insist that all cases of change are as expected. By doing so, two of the arcs in an "X" shaped graph become redundant - namely those needed for actuation and unexpected outcomes. In this way the boundary between subsequent elements in a sequence can be shown as one arc veering away from the other along a tangential path. This produces a much less artificial model of differentiation, with the angle of the tangent between the two arcs marking change borders and hence outlining the break in symmetry present.

Using this graphing technique produces a characteristic "kink" or "bend" between neighbouring arcs, as can be seen in Figure 8. And when more arcs are added, this pattern ultimately forces the sequence's structure to twist round a curved path, as in Figures 9 and 10. Such curvature therefore makes it equally relevant to think of sequences as being curved rather than straight.

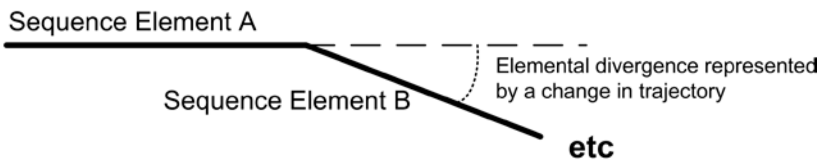


Figure 8: A conceptual graph of element-to-element change in a sequence, producing a characteristic "kink" or 'bend'

This now allows a number of similarities of form to be studied. Classical Newtonian [2][104] viewpoints on science and engineering might well favour the straight lines of Euclidean geometry, but the natural world also has inbuilt preference for the curvature inherent to more generalized views of geometry, primarily out of a need to reduce any energy coefficients involved. Galaxies spiral [87], seeds and petals mostly cluster in accordance with spiral placement patterns and the helical structures of RNA and DNA curve for similar reasons [48][49]. All are examples of rounded sequential progression based on minimal energy coefficients.

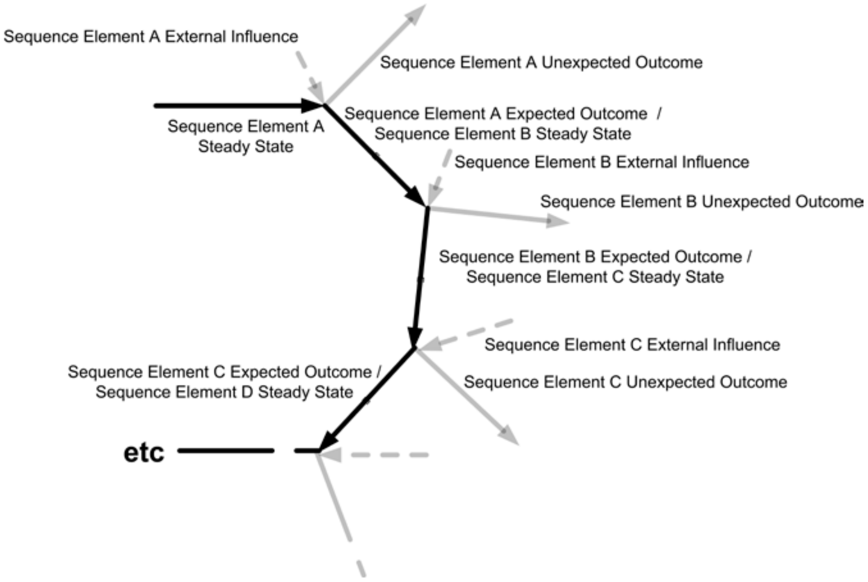
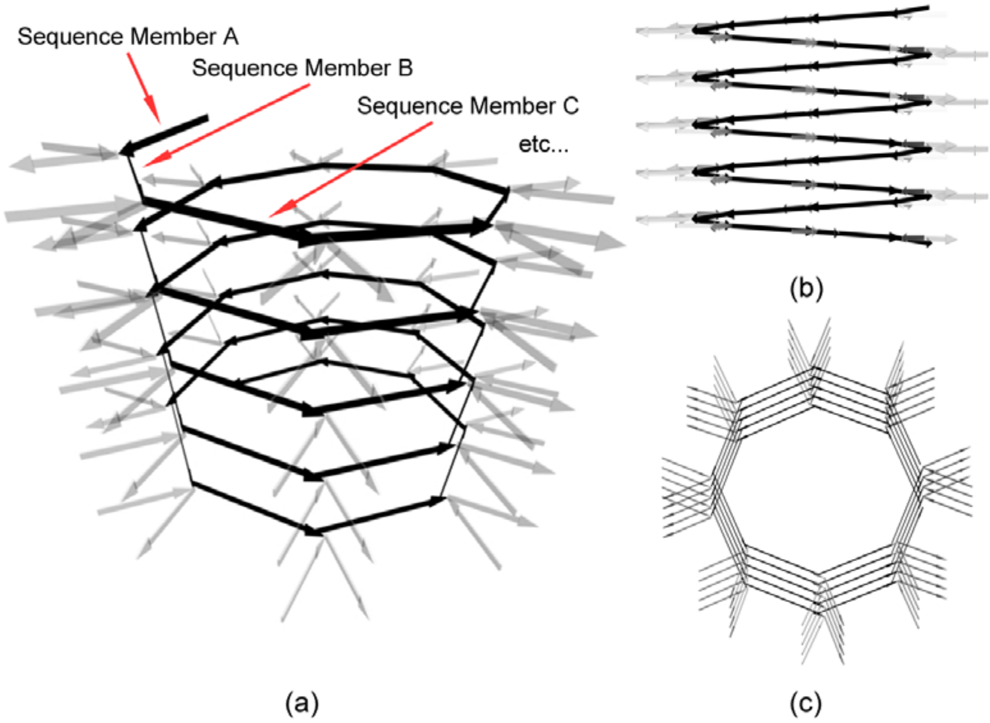


Figure 9: A two dimensional directed graph showing a sequence of equally sized elements [26]

In collections where progression not only dictates the ordering of elements within a group, but also the size of those elements, highly regular spiraling structures can be produced. Not surprisingly, because of their geometric simplicity, such schemes are popular in the natural world and, also being fractal [1][82], have a direct link with many higher orders of complex phenomena. In particular one such arrangement, known as a Fibonacci sequence [53][86], appears to play an interesting, if not crucial, part in the way that certain parts of the physical world hang together.



Figures 10(a), 10(b) and 10(c): A three dimensional graph showing a sequence of similarly diverging elements [26]

But why this emphasis on curvature in nature, and what has this got to do with the Web? The point is merely to demonstrate that sequential structures are just as prolific in natural systems as they are in those made by man, and that the notion of curved geometries derived through sequential arrangement may actually be preferential, and indeed more fundamentally encompassing, than straight line alternatives in certain contexts[47] – a concept recognized through Bernhard Riemann's work on geodesic[48] geometry in the 1850's [90][91][92], for example.

[47] Frames of reference were the underpinning environment is itself curved. Examples include space-time curvature in general relativity.

[48] In mathematics, a geodesic is a generalization of the notion of a "straight line" to "curved spaces". In presence of a metric, geodesics are defined to be (locally) the shortest path between points on the space.

It is a well known fact that the majority of the Web is constituted from long intertwined hyperlinked chains of information and process. In addition, studies have now also shown that the Web possesses a fractal structure from many different perspectives [16][93][94]. The common conceptualisation of its maelstrom of pathways, however, is one in which traditional Euclidean geometry is applied.

An alternative model is presented here, one intended to specifically cater for multi-dimensional problem/information spaces which incorporate strangely loopy[49] [2][5][13][14][26, pp. 176][130] undulating[50] manifolds similar to those found in fitness landscapes[51] and the concept of coevolution [13][117][118][119][120]. Such manifolds are also considered as being the outcome of the complex compounding of a finite vocabulary of Lagrangian [129] "X" patterns at a number of levels. These concepts provide the cornerstones on which the concept of Web Life is based and advocate a metaheuristic [128] viewpoint whereby the Web can be seen as being analogous to a bag of loosely entangled springs[52] of information and transformation - a conceptualisation not dissimilar to that favoured by scientists researching into protein folding [95][96], as in Figure 11.

[49] "Strange loop" is a term popularised by Douglas Hofstadter in his book "Gödel, Escher, Bach: An Eternal Golden Braid" [130]. A strange loop arises when, by moving up or down through a hierarchical system, one finds oneself back where one started. Strange loops may involve self-reference and paradox [130].

[50] "Undulating" is used as a loose term here to convey the concept of information spaces that are not constant across all dimensions. In such spaces the landscapes described are not flat. Instead a more preferential analogy is to call to mind the surface of the ocean, that being incredibly dynamic, with great waves and small ripples in it [2].

[51] Sometimes also referred to as "knowledge landscapes".

[52] A quantum view of such "springs" might well be seen as spinning fundamental particles.

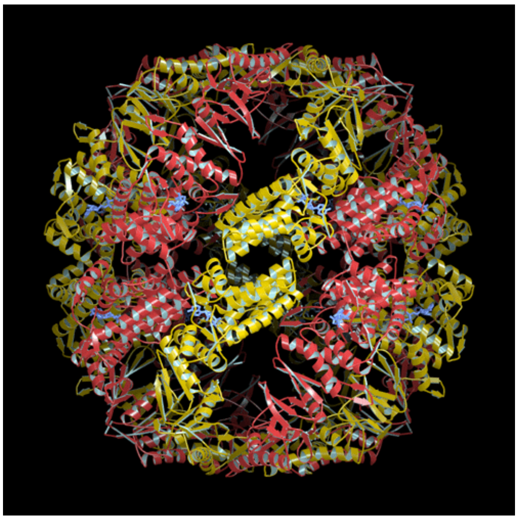


Figure 11: A conceptualization of the Web by way of a protein analogy[53]

This idea is not as radical as it might first appear. Certainly modern physiology appears to be warming to such thinking [5][20][41][49][51][52][53]. It is well understood, for example, that curves provide some of the most economic structures possible [117]. Furthermore, it has long been established that constructing such curves out of anything that has discrete value must involve broken symmetry across all the units involved [79] [139]. Therefore, given nature's propensity for economy, an in-built preference for bundled coils of information and computation should be clear. That's why most low level biological material comes curled up for example. The helix axis of DNA in vivo[54] is usually curved as a case in point. This is a necessary condition, as the stretched length of the human genome is about one meter and needs to be "packaged" in order to fit into the nucleus of a cell [106].

[53] Originally taken from http://www.biochem.mpg.de/xray/projects/hubome/thermosome.html. As of September 6, 2007 this image is no longer available at that URL.

[54] In vivo (Latin for within the living). In vivo is used to indicate the presence of a whole/living organism, in distinction to a partial or dead organism, or a computer model.

Through such elucidation a change in perspective is advocated supporting geodesic models as the norm when using geometry for considering abstract computing systems such as the Web. This is relevant across all levels of abstraction and across all axiomatic patterns, like the “ X ” and “ Y ” examples, first introduced in section 7.1. Not surprisingly this also promotes “loopy” structures as being commonplace and not just a consequence of modeling rare highly complex systems. It also implies that properties such as emergence can be considered in terms of geodesic representations, potentially opening up further lines of investigation which incorporate the contemporary study of complexity and the until now distinct study of high scale, highly connected semi-synthetic systems such as the Web.

8 Supporting Evidence

It is difficult, if not foolish, to try and to produce a condensed, coherent and flowing description of “life”, or any matter seriously associated with it. This is not, however, because contemporary thinking is unclear or lacking in its theories about “what life is”. It is simply because life is indisputably a multifaceted concept and to serve one set of characteristic above any other, solely for the purpose of brevity, would be to do an injustice. There is just too much ground to cover in such a short space. Nevertheless, what evidence exists to suggest that the ideas presented in the works submitted are relevant and/or provable, especially in relation to recognized theories from established fields of scientific endeavor?

Although mankind’s advancing understandings of life are rich and varied, a number of well proven research works on life’s mechanisms can be linked with the ideas presented in the publications summarised. It is well understood, for example, that many life processes are mathematically complex, relying heavily on complexity’s existence at the very edge of chaos for their life-giving qualities [5][82][83][84][85]. Its is also well understood that such complexity need not be isolated to one level of abstraction, with the self-reflexive loopiness of fractal geometries being a common motif across many life systems. As such, the text of *The Web’s Awake* carries many examples 26, pp. 88, 89, 90, 91, 96, 97, 98, 104, 106, 107, 112, 113, 157, 159, 171] linking well founded research with fresh ideas and observations focused on the Web as a potential candidate for life-like characteristics. These concentrate strongly on the importance of delineation patterns, as outlined in Section 7.1, and the fact that such patterns are invariantly manifest across all possible levels of abstraction. Bifurcation, switching, deviation and emergence, are thus cited as patterns of particular relevance, thereby forming a thread through the supporting evidence. This links the various steps in the thesis and suggests novel similarities between well understood real world complex phenomena and characteristics apparent in the Web.

8.1 Cell Mechanics and Canalizing Boolean Functions

In specific respect to the idea of "X" and "Y" patterns, Stuart Kauffman's work on the machinery of the cell stands out [12][13][14][15]. When investigating the mechanics of living cells Kauffman used a greatly simplified network model for a deliberate reason. With this he effectively reduced the multifaceted chemical signatures of the components involved in genomic interaction into the one-dimensional nomenclature of Boolean logic. He thereby created a study method that captured the behavioural essence of such hugely complex systems and allowed the detailed study of phenomena such as clustered behaviour and stabilisation effects.

Kauffman's approach used networks of varying size, containing n number of nodes, each with K number of inputs. For obvious reasons such models are now referred to as "nK" networks and their use proved critical to large parts of Kauffman's work. It was with such networks, for example, that he and his team discovered the relevance of setting $K = 2$[55], thereby creating patterns that were neither stable nor chaotic and appear indigenous to many life processes

[55] Note the same number of inputs as the "X" shaped pattern.

[12][13][14][15]. Such tools also highlighted the regulatory effect on coalescing systems of switching nodes based on two inputs; that is to say networks made from Boolean ‘OR and ‘AND’ gates – logical axioms Kauffman chose to call “*Canalizing Boolean Functions”* [26, pp. 128].

8.2 The Bow Tie Model of the Web

But what principles allow $K = 2$ networks to exhibit such “life-giving” order? The answer appears to be that such arrangements develop a connected mesh, or “frozen core”, of elements, fixed in either an “on” or “off’” state – a concept extremely similar to the Strongly Connected Core concept present in the Bow Tie model of the Web [16], illustrated in Figure 12.

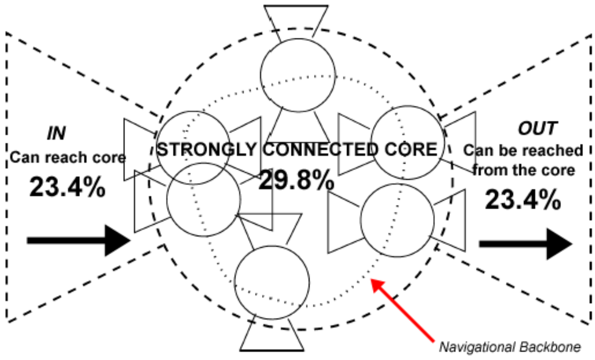


Figure 12: Similarly themed clusters of Web content connected by the navigational backbone of the
strongly connected core of the Web graph [16][19]

This model outlines a fractal model of hyperlinked connectivity on the Web and results from a study which statistically analysed tens of millions of Web sites and the hyperlinks between them [16][20]. Through this research it has been empirically shown that the Web is emerging as the outcome of a number of essentially independent and random processes that evolve at various scales. A striking consequence of this scale difference is that the structure of the Web is a pervasive and robust self-similar pattern, closely approximating to well understood mathematical phenomena such as Zipf's Power Law [16][42][43][44][50][140] – an order coincidentally known to be present in DNA oligonucleotide sequences [17] and in the dynamics of a number of online social activities such as collaborative tagging [141].

Even more compelling, these investigations point to a generic bow tie-like model of the Web that is itself self-similar. This is again not at all unlike the "X" shaped pattern concept, given that the configurations in question represent an overlay of multiple inbound and outbound linkages concentrated around a fractal hierarchy of intersection points. Such bow ties are centered about a "Strongly Connected Core" (SCC) and, as one might expect in a fractal system, when the SCC is examined in detail it recursively yields further levels of similar bow ties pertaining to finer grained clusters of coalesced Web content.

One unexpected observation from this model has shown that central regions of individual bow tie clusters are tightly connected together to form navigational backbones [26, pp. 106, 107]. These represent almost a super-structure, from which lesser used tendril routes dissipate and ultimately feedback like entry and exit routes to and from a highway. This is not dissimilar to the concept of the sugar-phosphate backbone in DNA [106].

Such models present evidence that the Web has a tendency to form information “hubs” at a number of levels. These act as concentration points for various types of information at varying levels of detail. In effect they are nodes in a fractal graph of the Web; points where symmetry breaks and the different facets of the Web meet. In such respects they quite literally represent the boundaries that produce the Web’s fractal curvature.

Studies like that which produced the bow tie model show that networked scale-free[56] systems [5][107][108][109], such as the Web, founded on recurrent “ X ” shaped patterns can not only provide all the basic parts needed for discrete, classically Turing [79], computing to take place, but are also well suited to the construction of complex schemes balanced on the edge of chaos; systems such as the evolution of life. Scientists familiar with the “messiness” of biology have known this for some time now [5], but it has only been recently that those with more abstract backgrounds like Computer Science and Physics have started waking up to the idea.

8.3 Autocatalytic Sets

Through the work of Stuart Kauffman et al [12][13][14], it has been realised that if the conditions in complex networks are right – in any given “primordial soup”, as it were – then there is no need to wait for random reactions to occur at all. The constituents or agents involved should simply gravitate to form a coherent, self-reinforcing web of reactions. Furthermore, each constituent in

[56] In scale-free networks, some nodes act as "highly connected hubs" (high degree), although most nodes are of low degree. Scale-free networks' structure and dynamics are independent of the system's size N, the number of nodes the system has. In other words, a network that is scale-free will have the same properties no matter what the number of its nodes is. Their most distinguishing characteristic is that their degree distribution follows a power law relationship

the network should catalyse the formation of other constituents in the network so that all the constituents steadily grow more and more abundant relative to constituents that are not part of the web. Taken as a whole, in short, the network should catalyse its own formation and in doing so be categorised as an autocatalytic set [5].

Such autocatalytic behaviours provide “order for free” [5][15], possessing the distinctive “messiness” of complex emergent behaviour [5]. This is natural order arising through cleaner, more “fundamental”[57], laws of the Universe, order that comes from molecular-like complexity involving high orders of interaction, manifesting itself ultimately as a system that just grows [14][15].

The mathematics underlying work on autocatalytic sets demonstrates that the number of reactions goes up faster[58] than the number of polymers - connections and types of resource in the case of the Web. So, if there is a fixed probability that a polymer will catalyze a reaction, there is also some complexity at which that reaction becomes mutually autocatalytic[59]. If any domain passes a certain threshold of complexity, then it will undergo a peculiar phase transition [13][14]. The autocatalytic set will indeed be almost inevitable [5]. And by such principles, if the conditions are right, the Web too is destined to ”live” merely as a consequence of its growing complexity.

[57] Kauffman has argued [168] that the laws of thermodynamics are incomplete and that a fourth law might exist which, under certain circumstances, can overturn the effects of the second law and resist entropy through self-organisation.
[58] In accordance with a sigmoid, or “S”-shaped function [171].
[59] It is hence similar to the genetic networks found in Chris Langton’s Artificial Life [5][83][84][85].

When the ideas behind autocatalytic sets are analyzed it becomes apparent that they have the potential to be universal across all complex systems, not just those restricted to biological classification [52][26, pp. 130, 131]. Autocatalytic sets can be viewed as webs of transformation amongst interconnected elements in precisely the same way that the economy is a web of transformations amongst goods and services [11] or the Web is a network of transformation of data and knowledge. In a very real sense the Web is an autocatalytic set.

8.4 Computational Efficiency and Quantum Computing

At the most obvious level curvature is observably apparent in many life systems as an aid for achieving efficiency [83]. The truism is that nature is attracted towards the evolution of efficient algorithms. It strives to be computationally efficient in the presentation, preservation and procreation of its information content.

From a Computer Science perspective the idea of efficient and inefficient algorithms was made mathematically precise by the field of computational complexity. What was noticed in the late 1960's and early 1970's was that it seemed as though the classically discrete Turing model [97][98][99] of computation was at least as powerful as any other model of computation, in the sense that a problem which could be solved efficiently in some model of computation could also be solved efficiently in the Turing model, by using a Turing machine to simulate the other model of computation. This observation was codified into a strengthened version of the Church-Turing thesis [100][101]:

Any algorithmic process can be simulated efficiently using a Turing machine.

The key strengthening in the strong Church-Turing thesis is again the word “efficiently”. If the strong Church-Turing thesis is correct, then it implies that no matter what type of machine one uses to perform an algorithm, that machine can be simulated efficiently using a standard Turing machine. This is an important strengthening as it implies that for the purposes of analyzing whether a given computational task can be accomplished efficiently, one may be restricted to the analysis of the Turing machine model of computation.

Despite its clear abilities, a major challenge to the strong Church-Turing thesis arose in the mid 1970’s when Robert Solovay and Volker Strassen showed that it is possible to test whether an integer is prime or composite using a randomised algorithm. That is, the Solovay-Stressen test for primality [22][23] used randomness as an essential part of the algorithm. Thus it seemed as though computers with access to a random number generator would be able to efficiently perform computational tasks with no efficient solution on a conventional deterministic Turing machine.

Randomised algorithms pose a challenge to the strong Church-Turing model of efficient computation, suggesting that there are efficiently solvable problems which, nevertheless, cannot be efficiently solved on a deterministic Turing machine [21][23][115]. This challenge appears to be easily resolved by a simple modification to the strong Church-Turing thesis:

Any algorithmic process can be simulated efficiently using a probabilistic Turing machine.

This ad hoc modification has the potential to threaten the stability of the strong Church-Turing thesis. Might it not turn out at some later date that yet another model of computation allows the efficient solution to problems that are not efficiently soluble with Turing's model of computation? Is there a way to find a single model of computation which is guaranteed to be able to efficiently simulate any other model of computation? The answer is apparently "yes" and this reintroduces the notion of axiomatics into the discussion.

Motivated by the concept of fundamentalism in computational models, in 1985 David Deutsch [24] asked whether the laws of physics could be used to derive an even stronger version of the Church-Turing thesis. Deutsch looked to fundamental physical theory to provide a foundation for the Church-Turing thesis that would be as secure as the status of that physical theory. In particular Deutsch attempted to define a computational device that would be capable of simulating any arbitrary physical system. Because the laws of physics are ultimately quantum mechanical, Deutsch was naturally led to consider computing devices based on the principles of quantum mechanics.

But what do quantum models of computation have to do with the relevance of curvature, high orders of systems' complexity and any abstract concepts relating to the notion of life or the Web? The answer appears to lie in the very notion of information itself.

What is information in the first place? To say that information differs from data is an indisputable fact. On its own data is meaningless. The number 19061966 is worthless in isolation, for instance, merely representing a sequence of digits. Add some structure in the form of a couple of hyphens or slashes and its starts to make more sense, easily being recognisable as a date of some kind. But it is only when context is set and one is informed that this is actually someone's date of birth that the true value of the information being conveyed is realised[60].

This is a theme already well established in the natural sciences. For example, work from recognized pioneers such as Christiane Nüsslein-Volhard and Eric Wieshaus[61], into the embryonic development of Drosphilia [20] has emphatically demonstrated that intracellular genetic processes provide a self-contained mechanism for making sense of the various elements needed to provide intrinsically informative systems. Descriptive and positional proteins provide the data and structural elements of the equation, while the surrounding chemical concentrations of such proteins provide the appropriate developmental context for the right cells to form in the right place at the right time. This inbuilt and interlinked process results in the system we refer to as metabolism.

[60] Hence the reason for explicit context setting using XML namespaces on the Semantic Web.
[61] Christiane Nüsslein-Volhard is a German biologist who won the Albert Lasker Award for Basic Medical Research in 1991 and the Nobel Prize in Physiology and Medicine in 1995, together with Eric Wieschaus and Edward B. Lewis, for their research on the genetic control of embryonic development.

Field	Equation					
Information Technology	*Information is a function of*	*Data*	***with***	*Structure*	***and***	***Context***
Developmental Biology		*Characterising Protein(s)*		*Positional Protein(s)*		*Presence of Specific Diffuse Protein(s) Concentration(s)*

Table 2: A comparison between the "Information Equation" in Information Technology and Ontogenetics

From a quantum mechanical perspective there is a further interesting connection. If the physical theories of quantum mechanics are indeed correct and the quantum mechanical version of the Church-Turing model is indeed valid, then the term "context" in the above equation is especially relevant. Its inclusion implies that information is a concept which can rarely be treated in absolute terms. In other words context restricts the ability to process or understand information accurately across all observable dimensions and scales. It hence makes the notion of information, and thereby all but the most localised forms of information processing, "relative".

Both Physics and Computing have embraced the notion of relativity as a general underlying theme in many of their most fundamental models, the physicists commonly referring to it as "background-independence" [2] and computer scientists favouring the term "context-free" [113]. What Albert Einstein taught the world was that at larger scales the differences between observable phenomena are not intrinsic to the phenomena but are due entirely to the necessity of describing the phenomena from the viewpoint of the observer [23].

Furthermore in the 1960's a different explanation of relativity was proposed, positing that the differences between unified phenomena were contingent, but not because of the viewpoint of a particular observer. Instead physicists made what seems to be an elementary observation: A given phenomenon can appear different because it may have a symmetry that is not respected[62] by all the features of the context(s) to which it applies – an idea that gave rise to Gauge Theory in Quantum Physics and a concept that is also completely sympathetic with broken symmetry being the driving principle behind the "X" and "Y" axiomatic patterns presented.

One could hence argue that if quantum mechanics presents a fundamental model of the Universe [2] which should in turn, one day, be unified with other fundamental models of the Universe, such as general relativity, then perhaps the most fundamental models of computation should also follow suit.

In many ways, current mainstream theories of computation are in a similar position to that of geometry in the 18th and 19th Centuries. In 1817 one of the

[62] Under normal circumstances symmetries are identified by the direct process of observation and/or measurement, but there are certain circumstances where this is not always possible, such as in quantum field theory. In such cases indirect means of discovery may used such as studying the domain in which a suspected symmetry is expected be found. Many powerful theories in physics are described by Lagrangians which are invariant under certain symmetry transformation groups. When they are invariant under a transformation identically performed at every point in the space in which the physical processes occur they are said to have "global symmetry". Lower grades of invariance are referred to as "local" or "gauge" symmetries. Studying such "spaces" can therefore yield insight into possible redundancies across all possible observables. This is equivalent to having identified localised symmetry.

most eminent mathematicians, Carl Friedrich Gauss, became convinced that the fifth of Euclid's axioms[63] was independent of the other four and not self evident, so he began to study the consequences of dropping it. However, even Gauss was too fearful of the reactions of the rest of the mathematical community to publish this result. Eight years later, János Bolyai published his independent work on the study of geometry without Euclid's fifth axiom and generated a storm of controversy which lasted many years [116].

His work was considered to be in obvious breach of the real-world geometry that the mathematics sought to model and thus an unnecessary and fanciful exercise. However, the new generalized geometry, of which Euclidean geometry is now understood to be a special case, gathered a following and led to many new ideas and results. In 1915, Einstein's General Theory of Relativity suggested that the geometry of our Universe[64] is indeed non-Euclidean and was supported by much experimental evidence. The non-Euclidean geometry of our universe must now be taken into account in both the calculations of theoretical physics and those of a taxi's global positioning system [116][143][144][145].

Those who subscribe to the quantum school of computation also freely align with the idea that the laws of quantum mechanics are responsible for the

[63] If a line segment intersects two straight lines forming two interior angles on the same side that sum to less than two right angles, then the two lines, if extended indefinitely, meet on that side on which the angles sum to less than two right angles.
[64] Considerations of the shape of the universe can be split into two parts; the local geometry relates especially to the curvature of the observable universe, while the global geometry relates especially to the topology of the universe as a whole—which may or may not be within our ability to measure [145].

emergence of detail and structure in the Universe [21]. They further openly consider the history of the Universe to be one ongoing quantum computation [21] expressed via a language which consists of the laws of physics and their chemical and biological consequences. The laws of general relativity additionally state that at higher orders of scale, complexity and connectivity the physical fabric of the Universe must be seen as curved and not straight, physical space itself being considered as simply a warped[65] field through its most fundamental definition. Indeed the geometry of space is almost the same as a gravitational field [2].

So it appears justified to compare the existence of vast, highly complex computational spaces like the Web with the grander material properties of the physical world. And if this is a legitimate proposition, it further appears common sense to think of such systems as being capable of curvature at a number of levels. In support, those at the heart of quantum computing liberally subscribe to measurements of effective complexity as relating to the amount of information required to describe a system's regularities [21] and this points to a propensity for greater levels of curvature, rather than less. This is obviously an exciting concept and one which deserves to figure highly in the emerging field of Web Science.

[65] This does not mean that there is some other fixed geometry that characterises space – that space is like a sphere or a saddle instead of a plane or straight line. The point is that the geometry can be any type of manifold (abstract mathematical space), because it constantly evolves in time.

9 Conclusions

The works submitted for consideration represent the summation of nearly two decades of research by the author. This has been motivated by real-world experiences gained while delivering some of the largest computer systems in the UK today and has resulted in an eclectic collection of publications with a noteworthy culmination in The Web's Awake. These openly and originally seek to advance contemporary thinking on a number of fronts while still being well grounded by material commercial need and academic supervision[66].

From the findings encompassed, a number of conclusions can be drawn. Certainly the contemporary view of the material world as a complex computational entity, currently in favor with physicists, appears amenable to direct comparison with the Web as seen today. Furthermore this comparison is supported by a strong prima facie case that the fundamental patterns of complexity manifest themselves ubiquitously across the Universe. Therefore a seminal question addressed by this submission explores whether such patterns can be seen to carry forward into synthetic, high scale, highly complex manmade domains like the World Wide Web.

The answer to this question appears to be a very strong "yes" - a substantial and significant conclusion of particular relevance in today's technology dependent world. Nevertheless this is constrained by a current lack of empirical evidence. This is for number of reasons. Although large quantities of

[66] Later versions of The Web's Awake were written under the direction of Prof John Tait of the University of Sunderland.

data are now available to qualify many of the Web's simpler characteristics (growth, population densities etc), few studies [162][172], have focused on understanding more complex characteristics like emergence or evolution. Such studies would need to analyse the Web at high scales and levels of abstraction, specifically looking for patterns (graphs) which are absent and of little or no relevance at the atomic level[67] or when small localised sample sets are used.

Difficulties in such studies are likely because the collection and study of suitable sample sets is a nontrivial task, needing huge volumes of data to investigate all but the most localised of Web regions. Calibrating such data sets for measurement and comparison purposes will also be difficult and this thesis does not address or present any contribution to thinking in this area. Nevertheless, localised studies have demonstrated the Web's graph to be scale-free, fractal and subject to power laws [43][44][46][131], all traits common to complexity as seen in the material world. Furthermore, the few studies that have incorporated large volumes of data have also indicated underlying pattern [16]. Through findings like this the need for a new field of study has been made clear, a field that can explore and explain the Web at higher levels of generalisation than are common at the moment. This is the new field of Web Science of which Web Life is undoubtedly a subtopic. It is therefore stimulating to note that *The Web's Awake* is the first book to be published in both areas, breaking fresh ground as it does so.

[67] Individual Web pages or Web sites, for example.

What is fascinating about complexity's place in the Web Science context is that both it and its associated traits, like efficiency, carry recognised relevance in well established models of computation. Efficiency, for example, also ranks highly on nature's list of priorities, accounting for large parts of the way the world is. In just the same way it plays an equally significant role in the formalities of Computer Science. So there appears an orderly fit between the two, suggesting that both complexity and efficiency act as meta-metamodels, as outlined in Figure 1, shared between real and synthetic variants of computation. Could it also be that generalised notions of computation fall under the hierarchical control of the ultimate unification physicists refer to as the Theory of Everything (TOE) [26]? Certainly, given that physics and computation are both concerned with the concept of transformation. Does this also mean that the idea of the Web Life is plausible to the point of absolute proof? That will undoubtedly remain a matter of debate, as serious definitions of life are inextricably tied up with philosophy, thereby making them a target for intense intellectual debate well into the future.

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10 Appendix A: The Prior Published Works