OPAALS PROJECT

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WP12: Socio-Economic Models for Digital Ecosystems

D12.1 – Foundations of the Theory of Associative Autopoietic Digital Ecosystems: Part 2

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The deliverable provides the next iteration of the theoretical framework for autopoietic, associative digital ecosystems, by offering an array of theoretical and empirical discussions of core concepts as emerging from the field of complex adaptive systems.

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Dependences:

Achievements*	In the reporting period we examined a number of theories that have been highlighted during the Y2 review, such as Complex Adaptive Systems theory, social autopoiesis (Luhmann), CAS and economics, CAS and Digital Ecosystems theory. We were able to discuss in the same chapter evolutionary economics, Rosen's theory of Relational Biology, Economics of Complexity, and development economics, making a critical comparison with Digital Ecosystems in theory and in practice. Finally, we propose a new concept in distributed computing, which can be regarded as the merging of Cloud Computing with Digital Ecosystems: Community Cloud Computing. Although we believe that the above themes are in line with the integration requirements and expectations for the project, they still do not show sufficient integration. This is not surprising since this is the second in the series of three deliverables. However, we feel that we have brought together the main dimensions of an emergent Digital Ecosystems theory.
Work Packages	*What exactly were the contributions to other WP and what effect they have had on the work in these other WPs (max 2 pages)* This deliverable has been finished after the end of the reporting period, so it is too early to tell what effect it will have on other deliverables. *What exactly are the future contributions to other work packages (max 2 pages)* We expect this deliverable to have three main impacts: on D12.10, which is the third in the series; on WP11 in the conceptualisation and operationalisation of Digital Ecosystems theory in different contexts, mainly through the elaboration of theories of democracy and epistemology; and on the final synthesis of the architecture with the community of the OKS.
Partners	All
Domains	Social Science (to a strong degree), Computer Science (to a strong degree), Natural Science (to a lesser degree)
Targets	Domain researchers, scientific communities, public administrations.
Publications*	*Where the reported work was published (max 1 page)* Chapter 4 will appear as: Dini, P and Rivera-León, L (2009). "A Study List for Sounding the Epistemological Foundations of the Knowledge Economy in Support of the Practical Introduction of Digital Ecosystems in Argentina", EULAKS Latin American and European Perspectives on the Social Science-Policy Nexus in the Knowledge Society Conference, Vienna, 8-9 June 2009. Chapter 5 has been submitted to: Briscoe, G and Marinos, A (2009). "Digital Ecosystems in the Clouds: Towards Community Cloud Computing", IEEE DEST 2009, 3rd International Conference on Digital Ecosystems and Technologies, Istanbul, 1-3 June 2009. http://arxiv.org/abs/0903.0694.

	The appendix will appear as: Schreckling, D and Dini, P (2009). "Distributed Online Evolution: An Algebraic Problem?", IEEE CEC 2009, 10th Congress on Evolutionary Computation, Trondheim, Norway, 18-21 May 2009.
PhD Students*	Mehita Iqani (Chapter 1), Gerard Briscoe (Chapters 2 and 5), Alexandros Marinos (Chapter 5)
Outstanding features*	*Specify the outstanding features of the work being done (incremental change in the state of art, improving significantly the state of art, or going beyond) and if anyone outside the OPAALS Consortium has taken notice of this work* An innovative synthesis of theoretical and empirical insights in order to build a coherent, and multidisciplinary theoretical framework for digital ecosystems. We think this report represents an incremental improvement in the state of the art towards an integrated theory of digital ecosystems.
Disciplinary domains of authors*	**Social Science**: Francesco Botto (CN), Jayanta Chatterjee (IITK), Mehita Iqani (LSE), Lorena Rivera-León, Debashis Pattanaik (IITK) **Computer Science**: Gerard Briscoe (LSE), Alexandros Marinos (Surrey), **Interdisciplinary Natural, Computer, Social Science**: Paolo Dini (LSE)

The information marked with an asterisk (*) is provided in order to address Recommendation n. 4 from the Year 2 review report

Executive Summary

The deliverable consists of five chapters (apart from introductory and concluding comments) as well as an appendix. The first chapter addresses complex adaptive systems theory and digital ecosystems. Chapter 2 offers an abstract conceptualisation of DEs from a computer science perspective. Chapter 3 explores autopoiesis from a social science perspective, in the context of agricultural digital knowledge ecosystems in India. Chapter 4 presents a theoretical discussion of the interfaces between complexity science, economics and biology, and juxtaposes this with a practical enquiry into the nature of digital ecosystems and their potential relevance to the municipality of Morón, Argentina. Chapter 5 proposes a new concept in distributed computing from merging Cloud Computing with DEs. Together, these various theoretical and empirical discussions provide a context-setting overview of the central areas of conceptual concern which can frame DE research, and set the stage for a more synthetic elaboration thereof in D12.10.

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0. PREFACE

0.1 Overview of deliverable

This deliverable represents the second iteration of collaborative, multidisciplinary efforts by the OPAALS consortium towards defining and describing a theoretical framework for autopoietic, associative digital ecosystems. The authors have taken heed of the recommendations made in the Year 2 review, and this deliverable is structured around responding directly to two central requests made in the Y2 review report (see p.4). These were to:

- Engage with and address systems theory, specifically the body of thought comprising **complex adaptive systems**, as a starting point for the conceptual framework,
- Examine existing **case studies** as a source of empirical data from which theoretical principles can be identified and defined.

Chapter 1 addresses the first request, offering a discussion of the significance of complex adaptive systems (CAS) to the theorisation of digital ecosystems. This will not entail a detailed summary of the strengths and weakness of CAS, which is a large, dynamic, complex and growing body of theory. Instead, it will show how the concepts central to CAS are a fundamentally helpful starting point for describing digital ecosystems, and their operations and aims, on a theoretical level. The chapter will also address the relationship of OPAALS's three central social science research coordinates to complexity and systems theory. Far from being a reiteration of statements already made about the social science agenda of the project in other documentation, this section aims to extend the discussion in order to make clear the ways in which CAS theory ties in to the objectives of the project. The chapter concludes with a bottom up view of digital ecosystems in terms of some empirical observations from the field, and a discussion of the real-world operations of DEs in local infrastructures.

Chapter 2 considers an abstract conceptualisation of Digital Ecosystems, including the different classes of Digital Ecosystems, through Complex Adaptive Systems modelling. We provide a conceptual framework for the cross pollination of ideas, concepts and understanding between different classes of ecosystems, based on some of the simpler, but universally applicable, principles of Complex Adaptive Systems. Therefore, this chapter provides the starting point of a framework to assist the cross-disciplinary collaboration of research into Digital Ecosystems, including Digital Business Ecosystems and Digital Knowledge Ecosystems.

Chapters 3, 4 and 5 address the second request. Each selects and discusses an individual item from the research areas and directions that are present within the project. Three "case studies" (where "case study" refers to research method as much as to the object of research) are therefore offered, the first in chapter 3, the second in chapter 4 and the third in chapter 5.

Chapter 3 explores DEAL as a case study and extends the sociological systems theory viewpoint that emerges therefrom, showing how a theoretical framework centred on Luhmann's view on autopoietic social systems can emerge from empirical evidence.

Chapter 4 as a point of collaboration with the EULAKS[1] project presents a similar discussion from the point of view of complexity science, economics, and biology, and juxtaposes the theoretical discussion with some practical considerations for the adoption of the DE approach in the Argentinian context.

In Chapter 5 we consider Digital Ecosystems in the context of Cloud Computing. Cloud Computing has raised concerns of privacy, efficiency at the expense of resilience, and environmental sustainability, resulting from dependence on Cloud vendors such as Google, Amazon, and Microsoft.

[1] EULAKS: Connecting Socio-Economic Research on the Dynamics of the Knowledge Society in the European Union and Latin American and Caribbean Countries (www.eulaks.org).

Community Cloud Computing provides a socio-technical conceptualisation for sustainable distributed computing by making use of the principles of Digital Ecosystems to provide a paradigm for Clouds in the community. The Community Cloud offers an alternative architecture for the use cases of Cloud Computing, by utilising the spare resources of networked personal computers to provide the facilities of data centres, such that the community provides the computing power for the Cloud platform they wish to use.

The entire deliverable is therefore structured around a juxtaposition of theoretical frameworks with practical outlooks and actions. While Chapter 1 explores the compatibility of CAS and DEs through meta-theoretical ideas, Chapter 2 offers a theoretical discussion of digital ecosystems in abstract terms. Chapter 3 begins with a detailed theoretical exploration of the concept of autopoiesis, then applies this to the specificities of agricultural ecosystems in practice. Chapter 4 too begins with theoretical considerations, but when turning to a discussion of the application and localisation of the DE approach, switches to a focussed, practical, and regionally contextualised approach. Chapter 5 rearticulates the theories of complex adaptive DEs in an applied discussion of the latest innovations in the web, and how these can be used to influence the evolution of DEs.

The deliverable concludes with a discussion of how we believe that the OPAALS consortium – and by extension all digital ecosystems – can work productively with the broad array of theoretical traditions, including CAS, already present within the consortium and shaping our work and thinking. The conclusion discusses the links between the three case studies, and the various theories introduced in the paper. It does not attempt to offer a conclusive, synthesised and final “theoretical framework for digital ecosystems” but maps out key steps towards working productively with the existing diversity of theoretical views, so as to construct a theoretical edifice that can be applied to Digital Ecosystems research. The conclusion points towards the development of a detailed theoretical framework, operationalised as a *theoretical toolkit for digital ecosystems*, in Deliverable 12.10 (the final of the trilogy).

1. A STARTING POINT: COMPLEX ADAPTIVE SYSTEMS AND DIGITAL ECOSYSTEMS FROM A SOCIAL SCIENCE VIEWPOINT

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1.1 Systems and agents theory, integrative approaches and DEs

Digital ecosystems as complex adaptive systems

Complex adaptive systems are, quite simply, as the name suggests systems that are "*complex* and constantly *adapt* to their environment" (Yang, 2008: viii – emphasis added). This self-evident acknowledgement leads quickly into more complicated territory: this complexity means, "they cannot be fully understood by isolating their components or applying simple cause and effect reasoning" (ibid.). Nevertheless, it is clear that two central terms require a more detailed exploration in order to get to the nub of the body of theory: complexity and adaptivity.

The first key concept, "complexity" is a theoretical term that has been borrowed from natural science by social science with fruitful and — perhaps predictably — *complex* effects. Complexity can be understood as a state of disorderliness, unpredictability, chaos, ambivalence or confusion; in which outcomes cannot be predicted and clear and eliminating distinctions are impossible to draw. Theories of complexity originated in natural sciences as tools for understanding non-linear dynamics, that is "disorder – or apparent disorder – in nature, including turbulence in fluids, the erratic flows of epidemics, the arrhythmic writhing of a heart in the moments before death" (Bryant, 2007: 131). This shift from a Newtonian to non-linear[2] scientific paradigm has in turn influenced social philosophy (Fuchs, 2003: 387). Non-linear theories, as well aiming to explicitly recognise and map observed disorder, also aimed to calculate and/or reveal the patterns and structures underlying that "chaos" so as to better be able to harness and predict it (Bryant, 2007: 133). And in the social sciences, certain elements of this tradition have been appropriated and adapted as a framework in order to understand the complexities of the social world. As Dini and Berdou (2004: 25) point out in a DBE deliverable, it is crucial to bear in mind that because complexity theory is still an emergent field, caution should be exercised in any kind of sweeping statements about its applicability to all of social science[3]. Other scholars agree with this, noting, for example, that "complexity research stands only at the threshold of acceptance in the social sciences" and that it "does not offer a well-articulated body of theory, but rather a number of more-or-less related phenomena: dissipative structures; catastrophe; chaos; self-organized criticality; and self-organization" (Campbell-Hunt, 2007: 796). The conceptual plurality that underlies complexity in social theory "is mirrored and amplified in their appropriation within social sciences" (Dini and Berdou, 2004: 25). Luhmann, for example, "is particularly concerned with the *reduction* of complexity" (Bruun, 2007: 107 – emphasis added) in his theories of the autopoietic operations of social systems, while Bjerg radically reinterprets complexity in postmodern terms as an inevitable confusion of the hitherto (modernist) theoretically pivotal differentiation between system and environment (Bjerg 2006: 66n). But let us sum up complexity, as far as is possible in a field in which definitions are evolving and contested, as an inability to predict the outcomes of the activity and evolution of a system.

The second concept central to the CAS viewpoint is adaptivity, which can be understood as necessarily recursive processes of change in structure, necessary for a system's "persistence or continuity" (Buckley 1998: 85). These processes occur at "widely varying rates and degrees as a function of the internal and external social and non-social environment" (Buckley, 1998: 87). In other words, an adaptive system consists of a number of components that undergo constant modification, individually as well as in interaction with their environment (Heylighen, 2003). Heylighen (2003) outlines the following characteristics of adaptivity: *adaptation as fit*, that is, the ability of a system to maintain itself or grow within the constraints of its environment, or to achieve a "fit" between therewith: *adaptation as regulation or control*, that is, the ability of a system to produce a variety of

[2] See Chapter 4 for more on this characterisation of scientific paradigms
[3] Chapter 3 of this reference provides an excellent summary of the various ways in which complexity has been taken up in various disciplines within social science, and can be considered a preface to the current deliverable. It is available at this link.

actions in order to respond to or counteract possible perturbations, which in turn requires a negotiation between the reaching of static equilibrium and the turbulence of chaos (a state described as the 'edge of chaos' by Langton and Kauffman); and *adaptation as variation and selection*, that is, an ability to transform so as to respond to, and survive within, new situations created by environmental change. Taken together, these three broad characteristics of adaptivity show the intricate relation between a system and its environment, and the centrality of the ability to change.

Recognising the complexity and adaptivity of CAS theory itself, Wallis (2008) has noted that there are many concise yet different definitions/descriptions of CAS to be found in the literature. And across these definitions there is both conceptual overlap and inherent contradiction. In order to seek the 'core' of the theory, Wallis employed a content and narrative analysis, separately, of writings by CAS authors. He identified 26 core concepts in this body of work, which occurred across all separate authors' definitions:

> *Act in rules/context of other agents and environment*, *Adaptive*, *Agent*, *Agents are semi-autonomous*, Agents evolve, Boundary testing, **Co-evolutionary,** *Decision-making*, ***Emergence/surprise happens*****,** Evaluate effectiveness of decisions/results, *Evolves toward fitness*, Far from equilibrium/edge of chaos, ***Goal seeking*****,** *Identity*, **Interrelated/interacting,** Irreversible, *Iterative process*, Levels, **Non-linear/unpredictable,** ***Many agents*****,** *Morality*, Permeable boundaries, ***Self-organizing*****,** **Simple rules,** Self-defining, Time (Wallis, 2008: 5 – *alphabetical order and italics added)*.

Wallis argues that depending on citation and popularity, different combinations of these concepts seem to form shifting definitions of CAS. This makes sense, as in the study of complex and constantly adapting systems, theory itself would need to adapt to the unique complexities and challenges of discrete systems. But, as indicated by those concepts highlighted in bold, which are most cited by CAS scholars, there does appear a pattern in which core concepts seem to self-arrange[4]. Wallis argues that they form the core of CAS theory, with the other concepts incorporable as appropriate considering the specificities of the system under analysis. It is helpful to map these core concepts against existing and ongoing work done in the OPAALS project, in order to illustrate the appropriateness of defining a digital ecosystem as a complex adaptive system. Those concepts considered core to a CAS definition of OPAALS are highlighted in italics above – this is not to suggest that the other concepts are in no way applicable, but simply that those noted are most appropriate in the context of the current discussion.

Let us start with the recurring notion of the *agent*. There is no doubt that OPAALS is a system made up of a vast number of agents: in the form of research institutions and individual researchers. In this sense then, its agents are multiple and semi-autonomous, working independently on elements of research tasks, yet collaborating on a higher level, and being interdependent at all levels of research and exchange yet responsible for the individual outputs that are aggregated into larger research findings. Through the many flows of collaborative work, all agents in the OPAALS project must act within commonly agreed-upon rules, which constitute the environment within which agents act. An understanding of the centrality of the agent to the system is recognised by the various reflexive community-building and exchange tasks – such as annual summer schools, workshops or conferences and researcher exchange visits. The CAS agent-concepts also link in with decision-making – which in OPAALS is a democratic and transparent process in which all agents are able to participate.

The concept of *emergence/surprise* is central to any research effort: outcomes cannot be determined or defined before the processes of research and analysis are over. In social systems defined by their shared research interests and outcomes, surprise and emergence can therefore be especially apt theoretical concepts. On a grander scale, digital ecosystems could conceivably be developed, applied

[4] Eve Mitleton-Kelly (2003) proposes a similar set of ten principles that define complex evolving systems: self-organisation, emergence, connectivity, interdependence, feedback, far from equilibrium, space of possibilities, co-evolution, historicity and time, path-dependence.

and utilised by a variety of communities of interest in a number of surprising ways that might not be envisaged by current researchers. Two specific areas of research within the OPAALS project, however, also have an implicit commitment to surprise and emergence. The first is the focus on governance, which seeks to articulate an innovative governance framework for digital ecosystems, and initiated this with the outlining of a theoretical taxonomy in Deliverable 12.2. The second is the focus on (natural) language and metaphor in Work Package 6, and the ways in which a new vocabulary for digital ecosystems is being forged through the reflexive research efforts of the consortium. The commitment to observing and theorising the emerging language of digital ecosystems is defined by the ideas of surprise and emergence. Emergence and surprise can also be linked with any inter-disciplinary research, where the multiple disciplinary perspectives engaged towards solving complex research problems are likely to lead to new and surprising findings and perspectives.

Next, the concepts of *evolving toward fitness* and *goal seeking* are again central to the definition of the work of OPAALS in establishing a technological and theoretical infrastructure for the emergence of sustainable digital ecosystems. The focus of Work Package 5, in integrating the digital ecosystem infrastructure, can be understood as entirely devoted towards the idea of a DE evolving towards fitness and independence. And the focus of Work package 11, in aiming to bridge DE research with regional development and innovation in the knowledge economy, is another clear and committed iteration of the concept of goal orientation – as well as to that of *morality*, where the motivation to contribute to positive and sustainable socio-economic development is central to the original inspirations of DE research. In terms of *morality*, links can also be made with the centrality of agents' (semi-) autonomy and ways in which agents act within the context of other agents. The idea of *identity* is also central to the definition of OPAALS as a CAS. This is taken up as a specific community enlarging opportunity, through the communication and dissemination activities of Work Package 9.

In terms of the concept of *iterative process*, which can be related to *non-linearity and unpredictability*, there is a clear commitment within OPAALS for recursive and reflexive research, which aims to constantly reiterate theories, methodologies and findings so as to best suit the changing research landscape (interactions between agents within the system) and the demands of the research environment (influences from outside the system). Non-linearity is a core principle, central to the development of distributed information technology systems in Work Package 4, as well as distributed governance and communication systems. The Open Knowledge Space, addressed in tasks T10.8 and T10.5, aims to exist as an iterative communications and collaborations space where knowledge can be created, shared and disseminated in a non-linear and iterative fashion.

And finally, the concept of *self-organization* is central to the conceptualisation and research activities of digital ecosystems in general and OPAALS in specific. Automata theory and autopoiesis are central to the research activities of Work Package 1, where biological and mathematical modelling of cell metabolism aims to provide models for software development. Work Package 2 and 3 look at self-organising software and autopoietic P2P networks, respectively, and aim to advance and extend existing understandings of self-organisation in software design and run-time environments – and to become a central infrastructure that defines digital ecosystems.

This discussion has shown that there is a clear connection between core CAS concepts and the structures and functioning that characterise the aims and processes of Digital Ecosystems such as OPAALS. We acknowledge and agree that digital ecosystems must be understood as complex socio-technical systems that operate within (and therefore must constantly adapt to) complex social, political, cultural and theoretical environments. The request to address CAS as a starting point for the theoretical framework of digital ecosystems is perfectly acceptable and fits within the existing viewpoints of many of the social researchers participating in the work of the project. In this way it is clear to see that describing a digital ecosystem as complex and adaptive is an indispensable starting point for any theoretical framework. The implications of this are that, as Buckley notes, the CAS is "open to energy or information and negentropic" as well as being "open 'internally' as well as externally such that the interchanges among their components may result in significant changes in the nature of the components themselves, with important consequences for the system as a whole"

(Buckley, 1998: 79). This can be interpreted as the revolutionary aspect of adaptivity: its recognised potential to create systemic change both on internal and external levels. This can also be understood as tension, which is "ever present in one form or another" (Buckley, 1998: 84). This tension should be seen as valuable and dynamic, a positive rather than negative force, which defines and shapes a CAS, allowing it to evolve and transform.

1.1.1 Addressing the theoretical dependence between agency and structure in CAS

One of the core debates that has characterised the interdisciplinary research and dialogue within the OPAALS consortium since its inception is the relationship between agency and structure. It has been argued that Luhmannian social systems theory ignores the important role of agency in the organisation and development of digital ecosystems, and that an "associative" viewpoint is necessary in order to complement and complete the "autopoietic" viewpoint. Due to its roots in natural science, CAS has been applied to the computer modelling of non-human social systems, such as bees, ants and wasps, which are considered by some (e.g., Camazine et al, 2003) prototypical complex adaptive systems. This indicates that a different focus is necessary for the analysis and understanding of *human* social systems (Mitleton-Kelly, 2003), which highlights another area of concern for social scientists concerned primarily with human action and experience. SME owners/managers/employees and academic researchers (two of the types of agents who are active in the OPAALS digital ecosystem) are fundamentally human actors, and the CAS in which they participate in turn needs to be theorised from both an agent and a structural perspective. It is clear that despite the great value provided by understanding CAS from a structural perspective, and naming the various processes and concepts that provide that structure, it is also necessary to understand CAS from an agent perspective. These concerns are adequately dealt with by CAS, which makes it clear that an integrated structure and agency approach is fundamental. After all, any complex system is only a system due to the agents who participate in creating and living within that system. What is crucial, however, is to define that agency in *human* terms.

In terms of defining adaptivity in the context of social relations, anthropologist Jules Henry (quoted in Buckley, 1998: 87) explains that

> because (man's) mechanisms for determining interpersonal relations lack specificity, he must attempt to maximise social adaptation through constant conscious and unconscious revision and experimentation, searching constantly for social structures, patterns of inter-personal relations, that will be more adaptive, as he feels them.

The quality of being able to adapt to complex changes in the environment, stated in these terms is revealed as an innately human quality. Adaptivity is rooted in human agency and not in the structures that result from the organisation of groups of human beings; the adaptivity of a human social system is therefore rooted in the make-up of the communities of individuals who form the social and technical organisations that can be described as CAS. In Buckley's (1998: 92) words, "the sociocultural system 'structure' is only a relative stability of underlying, ongoing microprocesses". Processes can be defined as the dynamic actions and interactions of the components of an ongoing system in which varying degrees of structuring arise, persist, dissolve or change" (Buckley 1998, 93). Processes are "linked by different communication nets to form varying types of interaction matrices that may be characterised by 'competition,' 'cooperation,' 'conflict' and the like" (Buckley, 19998: 99). This argument suggests that structures are formed by the processes of interaction between agents and that, moreover, structures are merely theoretical constructs whose reference is the "patterned relations among role-playing actors" (1998: 93). Furthermore, it has been suggested that "agents interacting over time leads to self-organisation" (McDaniel et al. (2003 quoted in Wallis, 2008: 12). Structure, understood in this way to be emergent from agent interaction, is therefore dependent on agency. But in turn, agency is dependent on structure. The "collective psychosocial bondings among individuals" (Buckley, 1998: 7) also in turn form the reality for those individuals, shaping and constraining their lived experiences and activities.

The view of structure and agency as intimately linked and co-constitutive has been addressed in a wide variety of sociological writing, most influentially perhaps, by Anthony Giddens's theory of structuration, which argues that

> agents and structures are not two independently given sets of phenomena, a dualism, but represent a duality … the structural properties of social systems are both an outcome of the practices they recursively organise. Structure is not external to individuals: as memory traces, and as instantiated in social practices, it is in a certain sense more 'internal' than exterior to their activities (Giddens, 1984: 25).

We can see that there is a synergy between Giddens' descriptions of the relationship between agency and structure, and the language of CAS. This in turn illustrates that despite disciplinary differences, it is possible for theorists to arrive at similar conclusion via different routes. In the context of CAS and digital ecosystems, the important points to raise are: firstly, it is important to remember that the agents in question are human agents, and secondly that they both constitute and are shaped by the structures that emerge as a result of their (complex and adapting) interactions. It is crucial to emphasize "the human being is not swept along as a neutral and indifferent unit by the operation of the system. As an organism capable of self-interaction he forges his actions out of a process of definition involving *choice, appraisal,* and *decision*" (Blumer quoted in Buckley, 1998: 96). As Fuchs summarises:

> The human being is a social, self-conscious, creative, reflective, cultural, symbols- and language-using, active, natural, labouring, producing, objective, corporeal, living, real, sensuous, anticipating, visionary, imaginative, designing, cooperative, wishful, hopeful being that makes its own history and can strive towards freedom and autonomy. By practical social interactions in groups, new qualities and structures emerge that cannot be reduced to the individual level. This is a process of bottom-up emergence that is called agency. (Fuchs, 2003: 397)

How these agents relate with one another is therefore a crucial factor in determining the effectiveness of the structures that will result. It is exactly this question that Axelrod and Cohen address in *Harnessing Complexity* (1999). Their starting point is the acknowledgement that "agents are not all the same" but that instead, "variety is a central requirement for adaptation" (Axelrod and Cohen, 1999: 32). These differences, summarised as variation, can be manifested in geographical, linguistic or even conceptual terms. In order for diverse agents to successfully harness the complexity of their socio-technical system, they need to interact, which in turn is defined by the presence of proximity, which determines how agents come to be likely to interact and is not necessarily tied to physical space, and activation, which determines the sequencing of activity (Axelrod and Cohen, 1999: 68). Wallis (2008: 12) argues that Axelrod and Cohen's model of agents' interactions is essentially an "evolutionary process that might be seen as being based on the agents' fit with the environment".

It is clear then, that both the concepts of structure and agency are central to CAS, which makes it an especially useful body of theory to work with in defining digital ecosystems. The next section briefly dips into the same body of theory in order to address what is meant by "associative" in the project title that results in the acronym OPAALS, and which we believe is also central to theorising digital ecosystems.

1.1.2 What is an "associative" system?

The original OPAALS project proposal (Dini, 2004) discusses the term "associative" as follows:

> …the core philosophical problem at the core of a theory of self-organising digital ecosystems… is how associations and interactions between individual agents or actors can give rise to a supra-individual or systemic behaviour, and how global and associative behaviour can in turn influence and constrain – or enable – individual behaviour (p. 27).

It is quite clear that these statements resonate directly with the discussion of agents and structure from a CAS perspective. The idea of associativity is connected with that of adaptivity and complexity, in terms of a shared vocabulary and theoretical paradigm, but it implies something more, too. Digital ecosystems can be cast in Axelrod's (1984: 30) terms as "non-zero-sum settings". This means that they take into account that effectiveness "depends not only upon the characteristics of a particular strategy, but also upon the nature of the other strategies with which it must interact" as well as being able to "take into account the history of the interaction as it has developed thus far" (ibid.). A "non-zero-sum setting" is one in which participating agents do *not* believe that if one party wins, the other loses, and vice versa, but rather that it is possible to collaborate and cooperate in such a way as to create benefit for all parties, even if that benefit is not exactly symmetrical. The term "associative" was selected as an appropriate element of the OPAALS project title due to its clear resonance with the concept of cooperation and reflexive human agency. If an autopoietic system is one that recursively self-organises through the complex, adaptive interactions of groups of agents, an associative system can be defined as one with those processes as well as, crucially, a high degree of *cooperation* between agents in the project of reaching those goals and *reflexivity* about the processes and attempts at reaching them.

Axelrod explains that cooperation "can get started by even a small cluster of individuals who are prepared to reciprocate…, even in a world where no one else will cooperate". He argues that the two key requisites for cooperation to thrive are that it be based on reciprocity, and that "the shadow of the future is important enough to make this reciprocity stable" (Axelrod, 1984: 173). Furthermore, with reference to computer tournaments, the property of "niceness" consistently distinguished high from low scoring rules (Axelrod, 1984: 33). Defined in the tournament context as "not defecting", niceness can be reinterpreted in the context of complex adaptive systems as a sense of good citizenship or collaboration, simply an interest in, and willingness to, cooperate and associate, to come together to work together towards a common goal, with the understanding that the results of the cooperative interactions will be a social system that may eventually self-organise through those interactions. Although Axelrod argues that the following things are not necessary for successful cooperation: rationality (knowing why and how), explicit verbal commitment (deeds speak for them), trust and altruism (Axelrod, 1984: 173-4), he does not say that the existence of these qualities among cooperating agents will hinder the process. An associative system is one that chooses (through its agents' agency) to explicitly include such qualities in its forms of cooperation.

1.2 OPAALS's social science research coordinates and CAS

This sub-section will revisit the three social science research coordinates (RC) in the light of the key concepts from CAS discussed. The various elements of complexity and adaptivity that have been discussed converge into three core research questions (RQ) related to digital ecosystems from the social science perspective. These can be arranged and discussed under the three research coordinates, which should by now be familiar to the OPAALS vocabulary.

Research Coordinate	*Research Question*
Language	How can human agents use language in order to socially construct a digital ecosystem that can evolve to a point of self-organisation?
Governance	What kind of power-sharing arrangements can best facilitate the establishment of democratic, transparent and sustainable digital ecosystems?
Socio-Economics	What characteristics should a digital ecosystem have in order to support and catalyze socio-economic development within a knowledge economy?

Let us briefly explore each of these research coordinate concepts in relation to the research questions, within the context of the broad body of theory of complex adaptive systems.

1.2.1 Language

Language hinges on the idea of agency. Agents without language can neither interact nor communicate, language without agents is abstract and null. Cooper (2006: 65) argues that language not only acts as a system for representing the world and communicating those representations, but that it also has constitutive power, working to shape and define agency and identity: "We do not speak language; it is rather that language speaks us". And beyond constructing individuals language can also be argued to construct scientific knowledge (Leydesdorff, 2007: 379)[5]. Knowing, as we do, that words and meaning are not fixed and static (Cooper, 2006: 68), it is important to understand that language continually reproduces itself. In this sense, Cooper links it to "Luhmann's interpretation of autopoiesis as life" (Cooper, 2006: 66). Language can thus be seen to be at once linked to structure and agency; it is larger than the individual agent. But, as even Luhmann concedes, understanding lies beyond language:

> Communication happens only if somebody understands it at least approximately or perhaps even misunderstands it; in any case, somebody must understand enough so that communication can continue. Language use alone cannot assure this possibility. It lies beyond the mere use of language. Somebody must be there who can be reached and who is capable of hearing or reading (Luhmann 2006, 48).

Furthermore, language can be conceptualised as "an evolutionary tool" (Leydesdorff, 2007: 384). In this sense we can conceptualise an operationalisation of language so as to "to externalize observations as statements and thus to specify expectations". The interplay between statement, information, symbolisation and expectation is a complex web of meaning that must constantly adapt to the unique interaction patterns of human agents. Language can itself be understood in terms of the vocabulary of complex adaptive systems. The question, then, of how human agents can use language to construct a digital ecosystem that will self-evolve is of central relevance, from both a natural and formal language perspective. The formal language selected to model digital ecosystems is software, the natural language is our reflexive research discourse about our efforts. There have been many such efforts to use computer science to model systems with natural (self-organising) abilities. In this respect, Helmreich sounds a note of caution

> When cultural and natural systems are collapsed into a common language of adaptation and evolution, and when they are modeled using identical methods of computer simulation, we must be careful not to lose sight of the social histories and processes that get washed under in these practices and technologies of representation. (Helmreich, 1999: 261)

In other words, he argues that the social, cultural and "natural" complexities of human language should not be subsumed by the language of computer simulation. And it is exactly the recognition of this danger that has led OPAALS to emphasise research that addressed the language of digital ecosystems from a linguistic and metaphorological perspective (see D6.3). In this sense, language must be understood not only as a bottom-up, social-constructivist process observed reflexively by the linguistic experts in the OPAALS community, but also as an associative tool with which OPAALS can create "common language and conceptual categories, define group boundaries and criteria for inclusion and exclusion, distribute power and status, develop norms for intimacy and friendship, define and allocate rewards and punishments, and explain the unexplainable" (Dooley 1997: 86).

1.2.2 Governance

In terms of governance, OPAALS seeks to establish and understand transparent, democratic and sustainable power-sharing arrangements that can mirror and support the distributed P2P architecture developed by the computer science experts in the consortium. As we have seen in the discussion about the relationship between agents and structure, it is interactions between agents that form structure. One

[5] See also the discussion of "discourse" in Chapter 3 of this document.

element of this kind of structure-forming practice can be understood as a form of governance development. Dooley (1997: 93) argues that any organisation seeking to utilise the principles of CAS should include (among others not relevant to include here) the following aspects:

- Power and function must be distributive,
- Governance must be distributive,
- It must be malleable but durable, and
- It must embrace diversity and change.

In other words, CAS can support and inform the ways in which principles are put into practice in the day-to-day operations of an organisation, as well in terms of a broader philosophical commitment, for example, the CAS emphasis on distribution of power, function and governance implies that the decision-making capabilities of a digital ecosystem should not rest in one agent or institution. Malleability and durability can be understood to relate to how agents are able to "learn, and choose how to modify their activity to better fulfil their potentials within social parameters and processes of governance which maintain social order" (Cole, 2003: 327). This kind of social feedback mechanism is therefore a central issue within DE governance research. CAS theory already provides some broad principles related to how governance should be arranged in a digital ecosystem; OPAALS is applying and action-researching these principles in order to provide empirical evidence for best practice. Fundamentally, this is a question of democratic process (not in terms of national politics but in terms of DE 'citizenship' and participation). Furthermore, the governance structures of digital ecosystems need to be able to "evolve to reflect the growing complexity of people's deepening interdependence" (Cole 2003: 334).

1.2.3 Socio-economics

It is well known that the OPAALS project aims to establish digital ecosystems that will benefit SMEs operating within regions. It is the increasing complexity of global society itself, and the persistence of multifaceted inequities in socio-economic development patterns in different regions of Europe and the world, that provokes the need for new socio-technical solutions to contribute to the broad-scale advances in the quality of life and business. New thinking in development theory has used complexity theory in order to make convincing arguments against linear, phase-based conceptualizations of socio-economic progress (see Rihani and Geyer, 2001: 244). Development conceptualized within the complexity framework sees it "as an uncertain, open-ended and long-term process driven by a large number of local interactions that generate self-organized stable patterns capable of adaptation" (Rihani, 2002: 134). Digital ecosystems aim to provide an infrastructure for the kinds of local interactions that can generate such patters of adaptation and progress.

It is important to understand 'progress' from both a structural and agent perspective. From a structural perspective, progress could mean that the system operates efficiently and is able to repair and sustain itself. And from an agent perspective, "'progress' implies fulfilling human potentials, the realization of which improves people' s lives" (Cole, 2004: 327). Socio-economic development strategies are therefore "intended to change modes of social interaction, so as to facilitate progress and the fulfillment of individuals' evolving potentials" (ibid.). Digital ecosystems therefore aim to contribute to the sustainable establishment of mechanisms through which SMEs and their members are able to actualize their business potential, in turn feeding into personal and social improvement. Furthermore, it is also imperative (as will be explored in greater depth in the next sub-section) that we understand small and medium enterprises as "small-scale, independent entities existing *in relationship to and dependent on other entities* in the socio-economic sphere or business ecosystem (including other small enterprises)" (Fuller & Moran, 2001: 50, emphasis added). In other words, they are part of local infrastructures and need to be understood in relative terms. The following subsection takes up the issues already discussed from a high level view, in terms of CAS theory and the vocabulary to describe digital ecosystems, and takes instead a worm's eye view of digital ecosystems – from the perspective of the existing complexities of the local infrastructures that host them.

1.3 DEs as part of local infrastructures

1.3.1 The socio-technical perspective in innovation introduction

Digital Ecosystems could be understood as a broadband-based innovation grounded at the local regional level and enriched with more global relationships. In this section we will temporarily lose the systemic and CAS framework in favour of the socio-technical perspective. This perspective will be introduced as a useful theoretical tool to highlight the core issues involved in innovation introduction as suggested in Deliverable D7.1 (Botto and Passani, 2007).

The socio-technical perspective suggests considering the co-creation practices of technology and society[6]. It departs from the more systemic approaches for organizational change – *Action Research* (Reason and Bradbury, 2006) – and technology development – *Participatory Design* (Ehn, 1988) – to the various theories that emerged from the paradigmatic change of the 1980s and 1990s in fields collectively referred to as *Science and Technology Studies (STS)*. We will address the latter, and simply highlight the former two paradigms as action methodologies that could be applied for the sustainable growth of a DE.

Historically there are two main directions in STS: *social relativism* and *constructionism* or radical relativism. The first is based on the Social Construction of Technology Model (SCOT – Bijker and Pinch, 1987) and studies the construction of technology through the analysis of the innovation trajectories that emerge from the negotiation of the relevant social groups, with different interests and power. The second is mainly linked to Actor-Network theory (ANT – Law and Hassard, 1999) and represents a significant challenge inside the field of social research since it is a hybrid theory-method that tries to develop a "non Cartesian topology"[7] and accepts non-human elements as agents[8].

1.3.2 Socio-technical infrastructures: DEs are more than services

The specific theory that we are adopting from the socio-technical perspective considers infrastructures as relational and ecological artefacts. We will name it Socio-Technical Infrastructure theory (STI) to avoid the confusion with the commonsense understanding of infrastructures. In fact, technologies when understood as STIs are highly ecological and relational since they emerge, in practice, in connection with human activities and material structures (Star and Ruhleder, 1996).

Susan Leigh Star and colleagues describe STIs as transparent and complex sets that are usually taken for granted. They suggest approaching STIs with an ethnographic perspective by using the following strategies: 1) identify the different narratives used to describe them; 2) resurface the invisible by working backstage; and 3) emphasise the paradoxes. To define a STI the correct question is "how", not "what", in order to underline their relational nature and study specific issues starting from some core STIs characteristics[9] (Star and Griesemer, 1989; Star and Ruhleder, 1996; Star, 1999, 2002).

The C.I.S.G. framework has been developed in Deliverable D7.1 as a tool to define and study broadband-based innovations (like DEs and Community Networks) as STIs even before empirical analysis. There are four main dimensions – communities, infrastructures, services and governances[10] – that are rarely fully considered when reflecting on innovation. The definition of every dimension should be relational, that is, related to the other dimensions in an ecological and sustainability-driven way. In the case of DEs the most relevant element that is commonly taken for granted is the networked

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[6] "*Shaping Technology/Building Society"* (Bijker and Law, 1992).

[7] From the post-structural philosophy: when things move, they change their nature. Every action is a "translation" both in the topologic and linguistic acception, and "to translate is to betray" (Callon, 1986)

[8] In social sciences the "actor" is typically only human, then institutions could be considered as macro-actor, but machines are not considered as agencies (Latour, 1992).

[9] The following dimensions are suggested by Star (1999) and Star and Ruhleder (1996): embeddedness, transparency, reach or scope, learned as part of membership, links with conventions of practice, embodiment of standards, built on an installed base, become visible upon breakdown, fixed in modular increments.

[10] The plural form has been chosen in order to suggest an assumption of multiplicity of governance frameworks and the study of what such multiplicity implies.

infrastructures (the "I"), but broadband connectivity is not ensured in many areas where the DE model could be applied to sustain regional development.

1.3.3 Grounding DEs: the Influencers' complex innovation strategy

The "influencers" or "local decision makers" perspective is very instructive. Previous DBE research taught us that influencers should be involved in order to ensure resources to a DE regional implementation (Dory, 2007). Therefore "infrastructures" are considered as resources and the DE remains a researchers' concern, wherein experimentation is welcome and required. From an ecological point of view, when the regional catalyst opens a negotiation with the influencers, the DE becomes something different, no longer a floating research problem, but fundamentally connected with local infrastructures and activities.

If we leave for a moment the idea that we – the researchers – are the epicentre of any DE-related practice, we should follow and observe what a DE-idea becomes when it impacts regional politics, infrastructures, habits, etcetera. If there is any chance to produce a working regional system, the DE becomes one of many elements contributing to regional innovation strategy. This will give the DE a real chance of sustainability (or not), and depends on many factors. These are exactly what we should follow and facilitate once we understand that most of social life happens outside of laboratories and research centers.

What are the interests involved by a DE idea at the local level? Is the DE becoming a tool to reach other objectives? What are we going to create when we think about developing a DE? In one question: "how does a DE happen?" or "what happens when the DE idea impacts the real world?". Following the socio-technical perspective we will approach these kinds of questions in the forthcoming Deliverable D12.8, relating the Trentino Region activities.

1.3.4 Will we re-enter complex adaptive systems theory?

This kind of reasoning is well established within socio-technical theories. Both Actor-Network Theory and STI theory study "hybrids". Hybrids are things that continuously become different by interpretation and adoption. The concept of "translation" identifies the evolution of things when related to different persons, contexts, activities and machines (Callon, 1986).

Our proposal is to start studying DEs as hybrids, or living entities that become something different and for this reason survive and evolve. This perspective is in many ways compatible with the ideas of complexity and adaptivity, which are central to CAS. Nevertheless, if we study a DE as a STI in the magma of the many infrastructures and regional strategies, we are considering a rich exchange between a system and its environment or, better, between many systems interrelated in a context.

1.4 Conclusion

This chapter has framed a description of digital ecosystems within the key concepts made available by the CAS body of theory. It must be noted that the term "complex adaptive systems" is itself contested. Mitleton-Kelly (2003) for example argues that any focus on human social systems should rather be termed "complex evolving systems" theory so as to avoid a mechanical suggestion about agents being automaton- or insect-like in their conceptualisation. And Doak & Karadimitrou (2007: 217) propose evolving the concept of CAS into that of "adaptive non-linear networks", where

> Insights from actor network theory can be conjoined with notions of complexity and chaos to build an understanding of the ways in which actors actively seek to shape these structures and systems, whilst at the same time being recursively shaped by them in their strategies and actions (Doak & Karadimitrou 2007: 209).

This deliverable does not have the scope to address these nuanced versions of CAS theories in depth, but it suffices to take notice of the fact that the body of theory itself adapts to changing concepts and contexts. Furthermore, as has been emphasised several times in this chapter, complex

evolving/adaptive systems involve, on a fundamental level, human agents. In this sense, Nowotny, echoing Doak & Karadimitrou, argues that they "are not to be left to science alone, since they are entangled with the complexity of social systems. … Scientific novelty needs to be read and understood in a societally meaningful way, if it is to be appropriated" (Nowotny, 2005: 28). In other words, a sociological perspective informed by CAS is an imperative element to any theory of digital ecosystems. The concepts of agency, structure, self-organization and associativity emerge as important concepts that will be explored in this deliverable from a variety of empirical and theoretical perspectives.

The next chapter applies the CAS discourse to software infrastructure, and in particular to software ecosystems. As in the other topics of this report, the presentation of abstract concepts and frameworks if followed in Chapter 5 with an applied case study of how the DE vision is being realised.

2. Complex Adaptive Ecosystems

Chapter Author: Gerard Briscoe (LSE)

In the creation of Software Ecosystems we considered aspects of Biological Ecosystems, including Agent-Based Modelling (Green et al., 2006) and Complex Adaptive Systems (CAS) (Levin, 1998), and then constructed their counterparts in Software Ecosystems. After this, we considered the possibility of a Generic Ecosystem definition, because we used a direct unidirectional flow of information and models from Biological Ecosystems to Software Ecosystems as shown in Figure 2.1. Without the Generic Ecosystem concept some of the counterparts of Biological Ecosystems that we constructed in Software Ecosystems appeared to be compromised, when they were actually the realisation of generic abstract concepts. Most notably the network structure, which is energy-centric in Biological Ecosystems (Begon et al., 1996), while information-centric in Software Ecosystems, as shown in Figure 2.2. So, there is potential to create a Generic Ecosystem definition, using a suitable modelling technique such as CAS (Waldrop, 1992), which would abstractly define the key properties of an ecosystem, and would theoretically be applicable to any domain where the modelling technique has been applied.

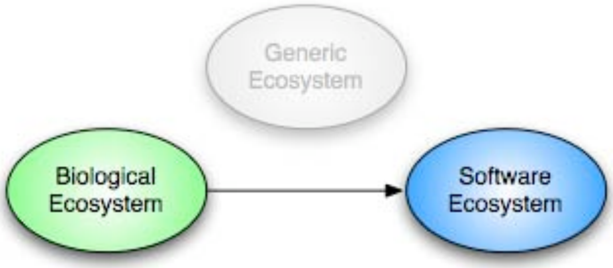

Figure 2.1: Creation of Software Ecosystems: In the creation of Software Ecosystems we considered aspects of Biological Ecosystems, using a direct unidirectional flow of Information and models from Biological Ecosystems to Software Ecosystems. including Agent-Based Modelling (Green et al., 2006) and Complex Adaptive Systems (CAS) (Levin, 1998), and then constructed their counterparts in Software Ecosystems.

Conceptualising ecosystems has been an inherent part of this work, which presents us with an opportunity to formalise our current and future efforts to improve the cross-disciplinary knowledge transfer required. There is therefore potential to create a definition of a Generic Ecosystem based in CAS, making use of Agent-Based Modelling (ABM) of Multi-Agent System (MAS), which will define the key properties of an ecosystem, in any domain, in an abstract applicable form. Therefore, the Generic Ecosystem definition would provide a framework for the application of ideas, concepts, and models from one class of ecosystem to another, including Digital Ecosystems, Knowledge Ecosystems and Economic Ecosystems.

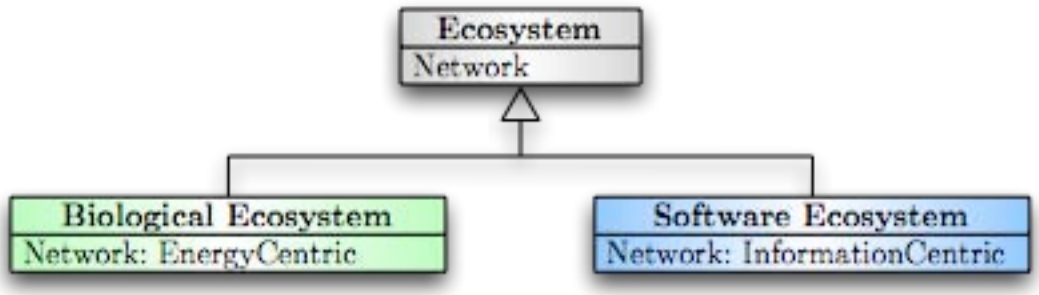

Figure 2.2: Hypothetical Abstract Ecosystem Definition: If there were an abstract ecosystem class in the Unified Modelling Language, then the Software Ecosystem and Biological Ecosystem classes would both inherit from the abstract ecosystem class, but implement its attributes differently. So, we argued that the apparent compromises in mimicking Biological Ecosystems were actually features unique to Software Ecosystems.

5.1 Biological Ecosystem

In order to create a Generic Ecosystem we will consider Biological Ecosystems in terms of the key properties, behaviours and structures that create an ecosystem. In D1.1(Dini et al., 2008) and D1.2 (Munro et al., 2008) these properties, behaviours and structures were considered extensively, and so here we will summarise the main findings.

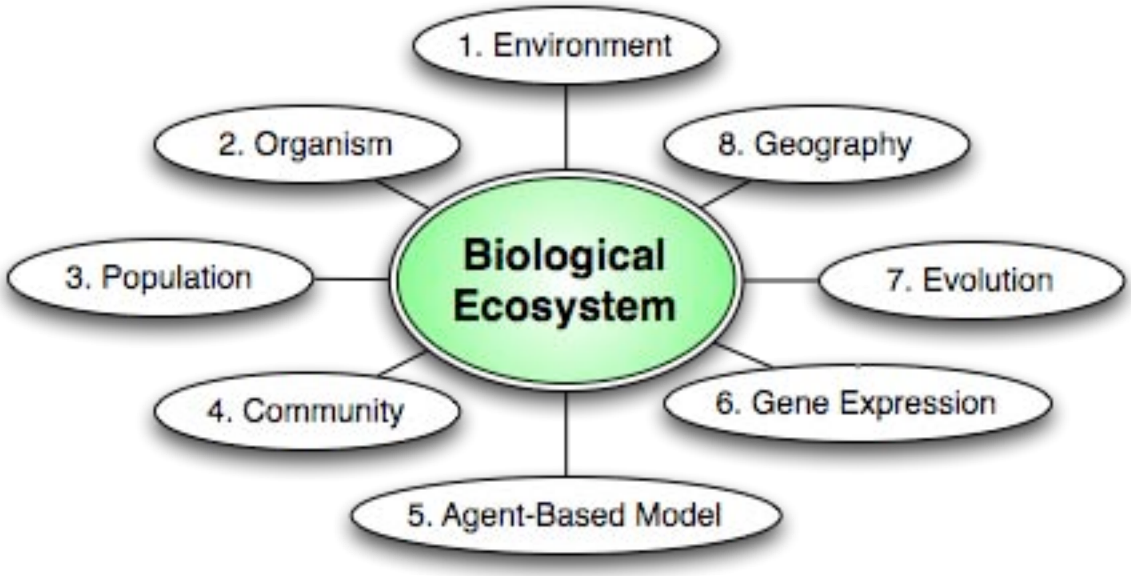

Figure 2.3: Biological Ecosystem: The key properties, behaviours and structures of a Biological Ecosystem, based on our understanding from D1.1 (Dini et al., 2008) and D1.2 (Munro et al., 2008). The aim here is provide a framework for understanding Biological Ecosystems with the aim of creating a Generic Ecosystem definition. This mind-map can easily be extended if we find new understanding that is relevant.

Ecosystems are often described as CAS, because like them, they are systems made from diverse, locally interacting components that are subject to selection. Other CAS include brains, individuals, economies, and the biosphere. All are characterised by hierarchical organisation, continual adaptation and novelty, and non-equilibrium dynamics. These properties lead to behaviour that is non-linear, historically contingent, subject to thresholds, and contains multiple basins of attraction (Levin, 1998). The features of these systems, especially non-linearity and non-equilibrium dynamics, offer both advantages and hazards for adaptive problem-solving. The major hazard is that the dynamics of CAS are intrinsically hard to predict because of the non-linear emergent self-organisation (Levin, 1999). The occurrence of multiple basins of attraction in CASs suggests that even a system that functions well for a long period may suddenly at some point transition to a less desirable state (Folke et al., 2004). Non-linear behaviour provides the opportunity for scalable organisation and the evolution of complex hierarchical solutions, while rapid state transitions potentially allow the system to adapt to sudden environmental changes with minimal loss of functionality (Levin, 1998).

In creating Software Ecosystems, the digital counterpart of Biological Ecosystems, we naturally asked their likeness to the Biological Ecosystems from which they came. Further to this, we could consider the applicability of other aspects of ecosystems theory in understanding and analysing the dynamics of Digital Ecosystems. For example, energy pyramids[11] of Biological Ecosystems, what is their equivalent in Digital Ecosystems? Given that Digital Ecosystems are information-centric, whereas Biological Ecosystems are energy-centric (Begon et al., 1996), they would undoubtedly be information pyramids, but further definition would naturally require more research.

[11] Energy pyramids show the dissipation of energy at trophic levels, positions that organisms occupy in a food chain, e.g. producers or consumers (Odum, 1968).

The aim here is provide a framework for understanding Biological Ecosystems with the aim of creating a Generic Ecosystem definition. The mind-map in Figure 2.3 is fundamental for absorbing knowledge of Biological Ecosystems. Most importantly, it can easily be extended if we find new understanding that is relevant.

2.2 Generic Ecosystem

ABM can be employed for Biological Ecosystems, leading us to define a Generic Ecosystem as a CAS, consisting of agents in place of organisms, a network in place of the geography, etc. Naturally, Biological Ecosystems will be the main source of information for the framework, allowing us to make use of various understanding in Biological Ecosystems understood from, for example, the ABM of Biological Ecosystems (Green et al., 2006). It will therefore provide a framework for the application of ideas, concepts of models from one form one class of ecosystem to another, which will be fundamental when combining different classes of ecosystems to create and define Digital Ecosystems. The evolution, change over time, is biological (Darwinian) (Darwin, 1859), and not the more general mathematical interpretation, as we are defining a Generic Ecosystem and not a generic system. Furthermore, any instantiation of the Generic Ecosystem within a specific domain, such as software systems, will create a class of that type of system with ecological properties. While some properties, behaviours, and structures will transition easily between domains, as counterparts already exist or can be easily constructed (e.g. evolution in software ecosystems), others will prove more challenging (autopoiesis).

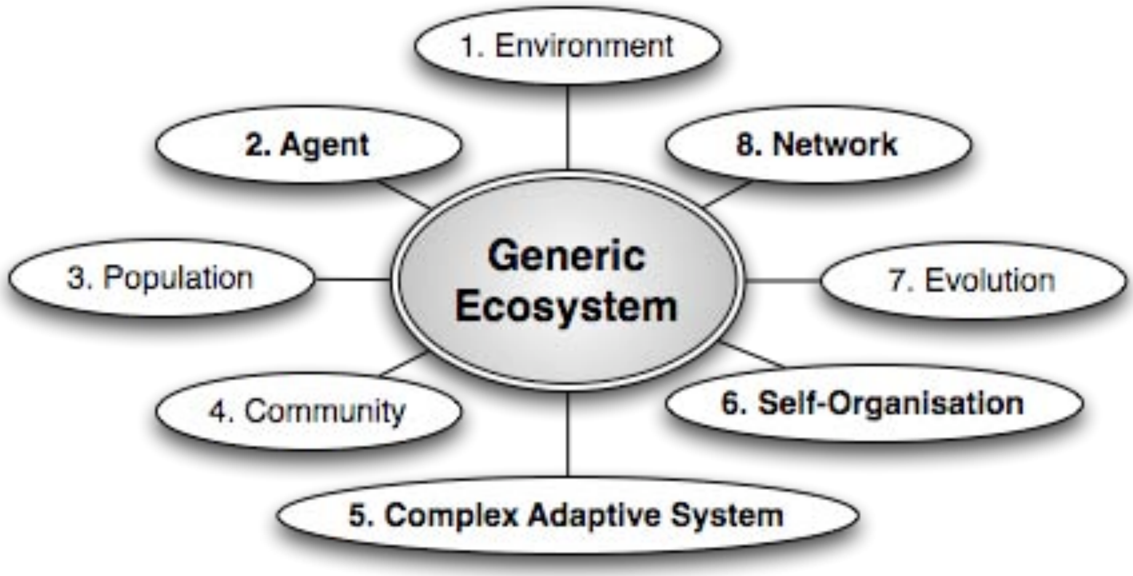

Figure 2.4: Generic Ecosystem: The key properties, behaviours and structures of a Generic Ecosystem, based on our understanding from Biological Ecosystems. The items in bold are the ones that have changed to more generic concepts from Figure 2.3.

Assuming the motivation for engineering an applied ecosystem is the development of scalable, adaptive solutions to complex dynamic problems, certain generalisations can be made from Biological Ecosystems. Sustained diversity (Folke et al., 2004), is a key requirement for dynamic adaptation. In any applied ecosystems, diversity must be balanced against adaptive efficiency because maintaining large numbers of poorly-adapted solutions is costly. The exact form of this trade-off will be guided by the specific requirements of the system in question. Stability (Levin, 1998), is likewise, a trade-off: we want the system to respond to environmental change with rapid adaptation, but not to be so responsive that mass extinctions deplete diversity or sudden state changes prevent control. This is an example of the kind of cross-ecosystem knowledge transfer we hope to facilitate.

A design pattern is a general reusable solution to a commonly occurring problem in software design (Gamma et al., 1995). It is not a finished design that can be transformed directly into code, but a

description or template for how to solve a problem that can be used in many different situations (Gamma et al., 1995). For example, object-oriented design patterns typically show relationships and interactions between classes or objects, without specifying the final application classes or objects that are involved (Gamma et al., 1995). Biological Design Patterns(BDPs) would extend this concept to catalogue common interactions between biological structures using a pattern-oriented modelling approach (Grimm et al., 2005), which when applied would endow systems with the desirable properties of biological systems, such as self-organisation, self-management, scalability and sustainability.

5.3 Software Ecosystem

The agents of the Software Ecosystem are functionally analogous to the organisms of Biological Ecosystems, including the behaviour of migration and the ability to be evolved (Begon et al., 1996), and will be achieved through using a hybrid mixture of different technologies. The ability to migrate is provided by using the paradigm of agent mobility from mobile agent systems (Pham and Karmouch, 1998), with the habitats of the Software Ecosystem provided by the facilities of agent stations from mobile agent systems (McCabe and Clark, 1994), i.e. a distributed network of locations to migrate to and from. So, the Software Ecosystem can be seen as MAS (Dini et al., 2008).

Figure 2.5: Software Ecosystem: The key properties, behaviours and structures of a Software Ecosystem, based on our understanding of a Generic Ecosystem. The items in bold are the ones that have changed to more domain specific concepts from Figure 2.4.

Evolution has been clearly identified as the source of many diverse and creative solutions to problems in nature (Darwin, 1859, Futuyma, 1998). To evolve high-level software components in Digital Ecosystems, we propose taking advantage of the native method of software advancement, human developers, and the use of evolutionary computing (Eiben and Smith, 2003) for combinatorial optimisation (Papadimitriou and Steiglitz, 1998) of the available software services. This involves treating developer-produced software services as the functional building blocks, as the base unit in a genetic-algorithms-based process. Such an approach would require a modular reusable paradigm to software development, such as Service-Oriented Architectures (Newcomer and Lomow, 2005).

The history of computer science and software engineering over the past fifty years can be characterised not only by an increasing level of abstraction in programming languages, but also by an increasing fragmentation of computational units. Whereas this fragmentation began at the level of code logic (functional sub-units, then classes, etc), with the advent of network computing, GRID, and web applications, also run-time environments have become increasingly distributed. As the size of web applications increases along with their distribution, the relative import of each participating CPU

becomes ever smaller. Our ability to theorise about these creations of software engineering, which are driven by powerful social processes in addition to relying on mathematical theorems and logic, struggles to keep up with the vastness and complexity of such web computing scenarios, with their ultimate significance in terms of fundamental computer science concepts, and with their future potential possibilities. However, this ever-greater fragmentation requires ever-greater interoperability, which is inherently an addition to functional units. Alternatively, we can build functional units with an inherent interaction dependency, which would apply at all levels of fragmentation, but this will require an alternative model of computing, Interaction Computing (Dini et al., 2008).

2.4 Economic Ecosystem

The concept of a business ecosystem (Moore, 1996) is well-defined and is focused on the micro-economic view of business networks, whereas the Economic Ecosystem has a macro-economic perspective. This should also not be confused with ecological economics, which is a transdisciplinary field that aims to address the interdependence of human economies and natural ecosystems (Costanza, 1997).

While Evolutionary theory is well understood by some economists (Nelson and Winter, 1982), ecosystems theory is not. While we could use our efforts with Software Ecosystems as a case study, following the same process to create Economic Ecosystems, we could instead make use of the Generic Ecosystem definition. There is also extensive work on the ABM of economic systems (Tesfatsion, 2002), which we can take advantage of in defining a CAS/MAS-based definition for an Economic Ecosystem.

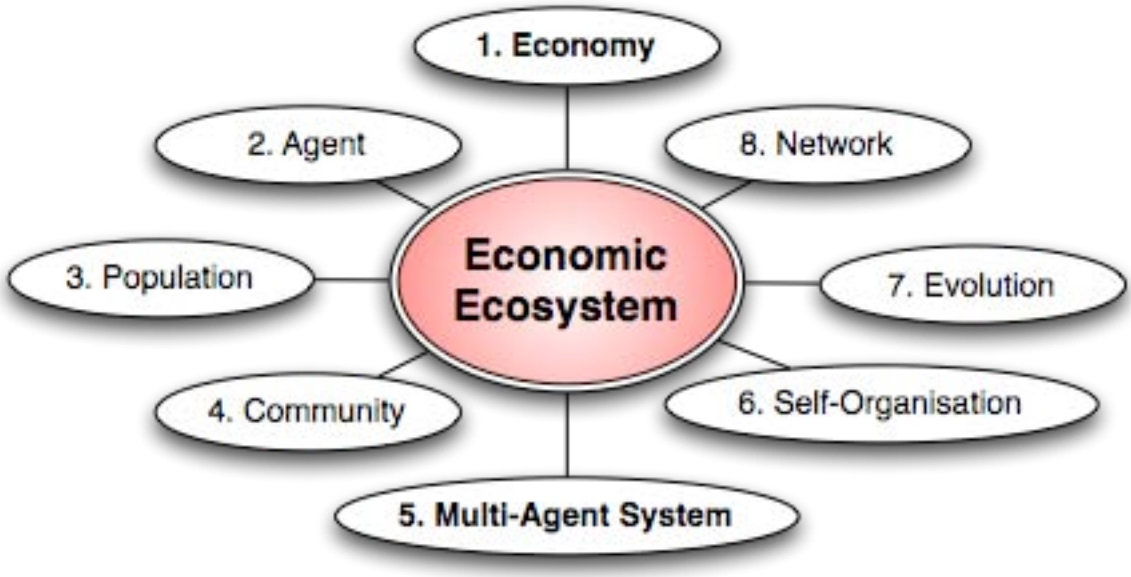

Figure 2.6: Economic Ecosystem: The key properties, behaviours and structures of a Language Ecosystem, based on our understanding of a Generic Ecosystem. The items in bold are the ones that have changed to more domain specific concepts from Figure 2.4.

An agent is a position in the Economic Ecosystem, which is subject to evolutionary change. While a person undoubtedly occupies the position, they are not in this context subject to evolutionary change, which is why they are not directly the agent. So, a community is an organisation of the Economic Ecosystem, which is supported by the observation (Mitleton-Kelly 2003, 31) that when firms and institutions cease to function like a community they break down. Therefore, each agent is a participant which both influences and is influenced by the environment (economy) of the Economic Ecosystem, which is made up of all the businesses, consumers, and suppliers, as well as the economic and legal institutions (Mitleton-Kelly 2003, 30).

2.5 Social Ecosystem

According to social ecosystem theory, populations adapt to their environment in order to survive, since it is in the environment where they find the sustenance resources needed for survival, but human populations are the only ones to adapt to their environment through culture (Diez Nicolas, 1995). Culture may therefore be considered, therefore, as an instrumental response on the part of human populations in order to achieve a better adaptation to their environment (Hawley, 1986, Diez Nicolas, 1983). Different forms of social organisation constitute instrumental responses (cultural responses) to the problem of adaptation faced by any population that must survive with the resources which it finds in its environment, and that ideational and value systems are part, as elements of the non-material culture, of the so-called social organisation. In this context an agent is a human, so their social system can be represented by a MAS.

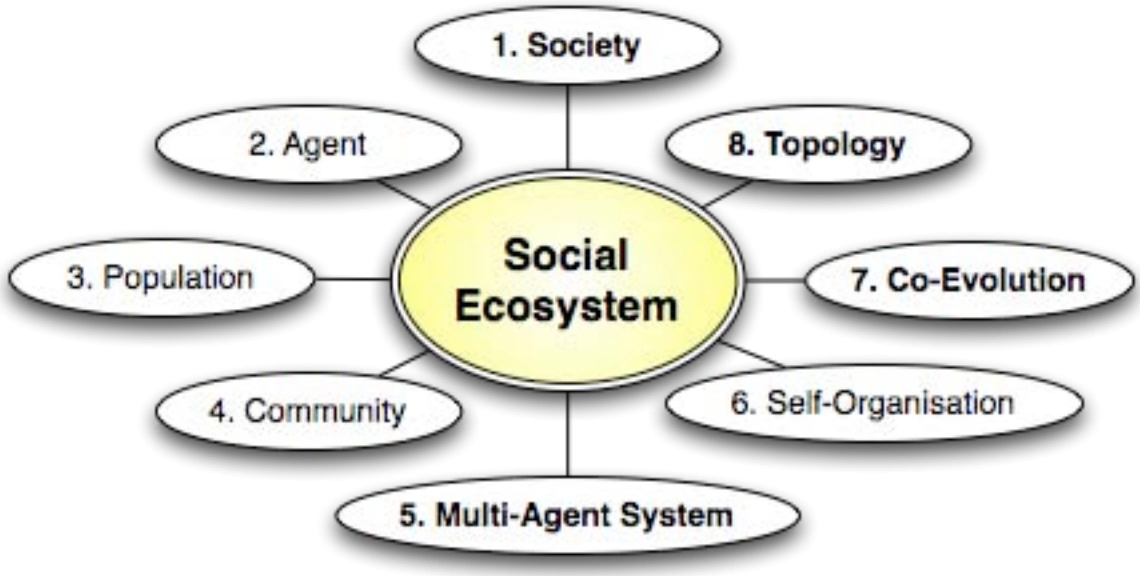

Figure 2.7: Social Ecosystem: The key properties, behaviours and structures of a Language Ecosystem, based on our understanding of a Generic Ecosystem. The items in bold are the ones that have changed to more domain specific concepts from Figure 2.4.

In defining a social ecosystem, the key differentiating point from a social system, is the interdependence among the entities within it (Mitleton-Kelly, 2003), through the phenomenon of co-evolution, which cannot happen in isolation, but must happen within the ecosystem (Mitleton-Kelly, 2003). In a Biological Ecosystems, co-evolution is the evolutionary change of a biological object triggered by the change of a related organism (Lawrence, 2005). Evolution in response to abiotic factors, such as climate change, is not co-evolution (since climate is not alive and does not undergo biological evolution). Each party in a co-evolutionary relationship exerts selective pressures on the other, thereby affecting each others' evolution. Evolution in a one-on-one interaction, such as that between predator and prey, host-symbiont or host-parasitic pair, is co-evolution, but many cases are less clear-cut: a species may evolve in response to a number of other species, each of which is also evolving in response to a set of species. This situation has been referred to as diffuse co-evolution (Thompson, 1994), and for many organisms the biotic (living) environment is the most prominent selective pressure resulting in evolutionary change. So, the majority of the co-evolution in Social Ecosystems is diffuse.

2.6 Language Ecosystem

Again, while evolutionary theory is well understood within linguistics (Croft, 2000), ecosystems theory is not (Mufwene, 2001). So, using our efforts as a case study, we could follow the same process to create Language Ecosystems, or we could now also use the Generic Ecosystem definition. In this

context an agent represents a (linguistic construct), so using an abstract definition of agent for our purposes, with a language dialects represented as a MAS.

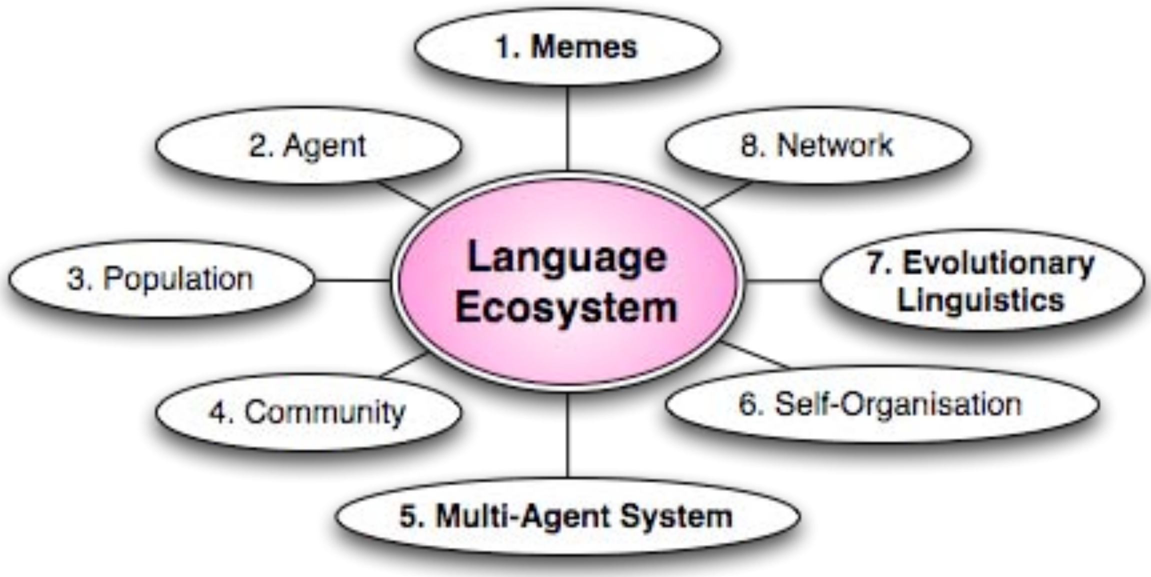

Figure 2.8: Language Ecosystem: The key properties, behaviours and structures of a Language Ecosystem, based on our understanding of a Generic Ecosystem. The items in bold are the ones that have changed to more domain specific concepts from Figure 2.4.

There are many separate efforts within linguistics using evolution to model language change (Christiansen and Kirby, 2003), but there is no unifying framework, which has resulted from different linguists independently adopting elements of evolutionary theory (Christiansen and Kirby, 2003). So, we could provide a wide-ranging and encompassing definition of Language Ecosystems, which would unify the many disparate efforts in linguistics aimed at understanding language evolution.

Evolution of an entity (linguistic construct) is dependent upon its environment, and for the evolution of language it is the cognitive environment (Hurford et al., 1998), which implicitly supports the concept of language evolution through co-evolution (Lawrence, 2005). One way to consider the cognitive environment is as a collection of memes. A meme, as defined within memetic theory, comprises a unit of cultural information, the building block of cultural evolution or diffusion that propagates from one mind to another analogously to the way in which a gene propagates from one organism to another as a unit of genetic information and of biological evolution (Dawkins, 2006). Multiple memes may propagate as co-operative groups called memeplexes. So with memes, some ideas will propagate less successfully and become extinct, while others will survive, spread, and, for better or for worse, mutate (Dawkins, 2006). Meme theorists contend that memes evolve by natural selection similarly to Darwinian biological evolution through the processes of variation, mutation, competition, and inheritance influencing an organism's reproductive success. The change of an entity relative to its environment, and vice versa, is known as co-evolution (Lawrence, 2005). Therefore, if one accepts that the cognitive landscape (environment) can be represented with memetic theory and that the evolution of memes occurs, then it makes a very strong case for the evolution of language which must co-evolve with the memes.

2.7 Knowledge Ecosystem

An extension of knowledge management ideas, a Knowledge Ecosystem fosters the dynamic evolution of knowledge interactions between entities. This bottom-up approach seeks to provide a more resilient approach (March, 1999). For example, while the lack of open access to published material is acceptable within a knowledge system, it would not be feasible within a Knowledge Ecosystem. However, this is not to say that the two could not coexist, they could similar to the way in which the publishing of Springer and the IEEE coexists with Arxiv.org.

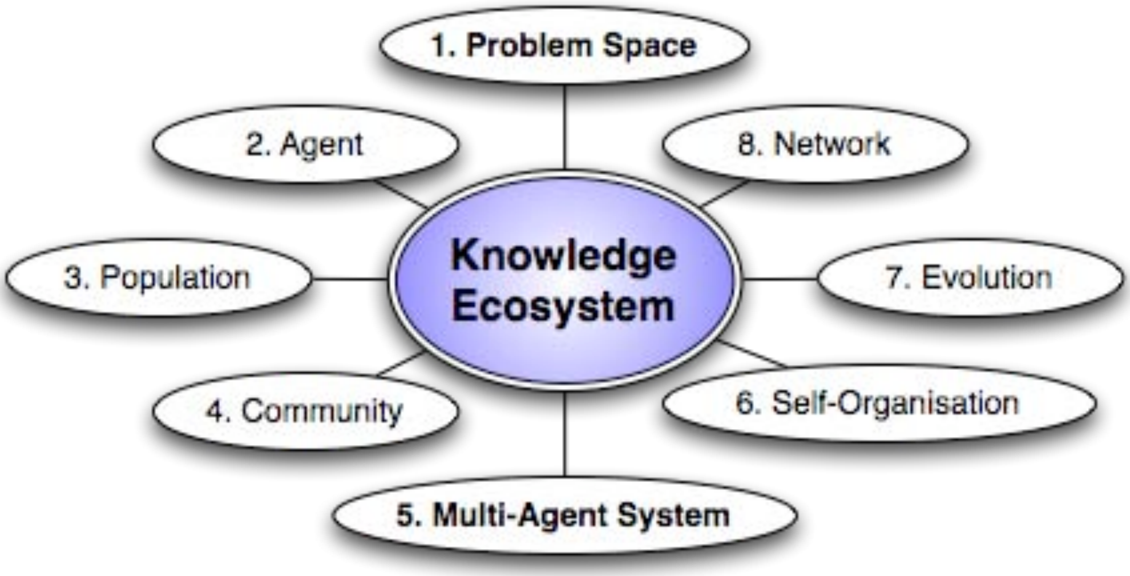

Figure 2.9: Knowledge Ecosystem: The key properties, behaviours and structures of a Knowledge Ecosystem, based on our understanding of a Generic Ecosystem. The items in bold are the ones that have changed to more domain specific concepts from Figure 2.4.

Within certain contexts (e.g., turbulent environments), top-down knowledge management is viewed as indeterminate; hence the intention of creating a Knowledge Ecosystem to improve decision-making and innovation through improved evolutionary networks of collaboration.

In contrast to directive management efforts that attempt either to manage or direct outcomes, Knowledge Ecosystems espouse that knowledge strategies should focus more on enabling self-organisation in response to changing environments (Clippinger, 1999). The suitability between knowledge and problems confronted defines the degree of fitness of the units of knowledge (memes). So, the agent in this context is a meme (Dawkins, 2006).

2.8 Digital Ecosystem

We can now define a Digital Ecosystem as the combination of software and social systems with ecosystems; therefore, any distributed adaptive open socio-technical system, with properties of self-organisation, scalability and sustainability, inspired by natural ecosystems. While the previous use of the term in industry was narrowly focused on individual businesses or sectors (Denning and Metcalfe, 1997, BBC News, 2009, Fiorina, 2000, Ximbiotix, 2005, Bennett, 2006) there is a growing acceptance of the term as defined above, most notably by the World Economic Forum (World Economic Forum). When we deal with specific examples of Digital Ecosystems, we will see how the Knowledge Ecosystem and Economic Ecosystem become significant.

As Figure 2.10 shows, with this conceptual framework the majority of information flow for defining a Generic Ecosystem comes, unsurprisingly, from Biological Ecosystems. This is partly because the use of biological concepts within other domains can be superficial, such as the use of the co-evolution concept in Social Ecosystems (Mitleton-Kelly, 2003). However, it also allows for the transfer of realised abstract concepts, through the Generic Ecosystem, from one class of ecosystem to another.

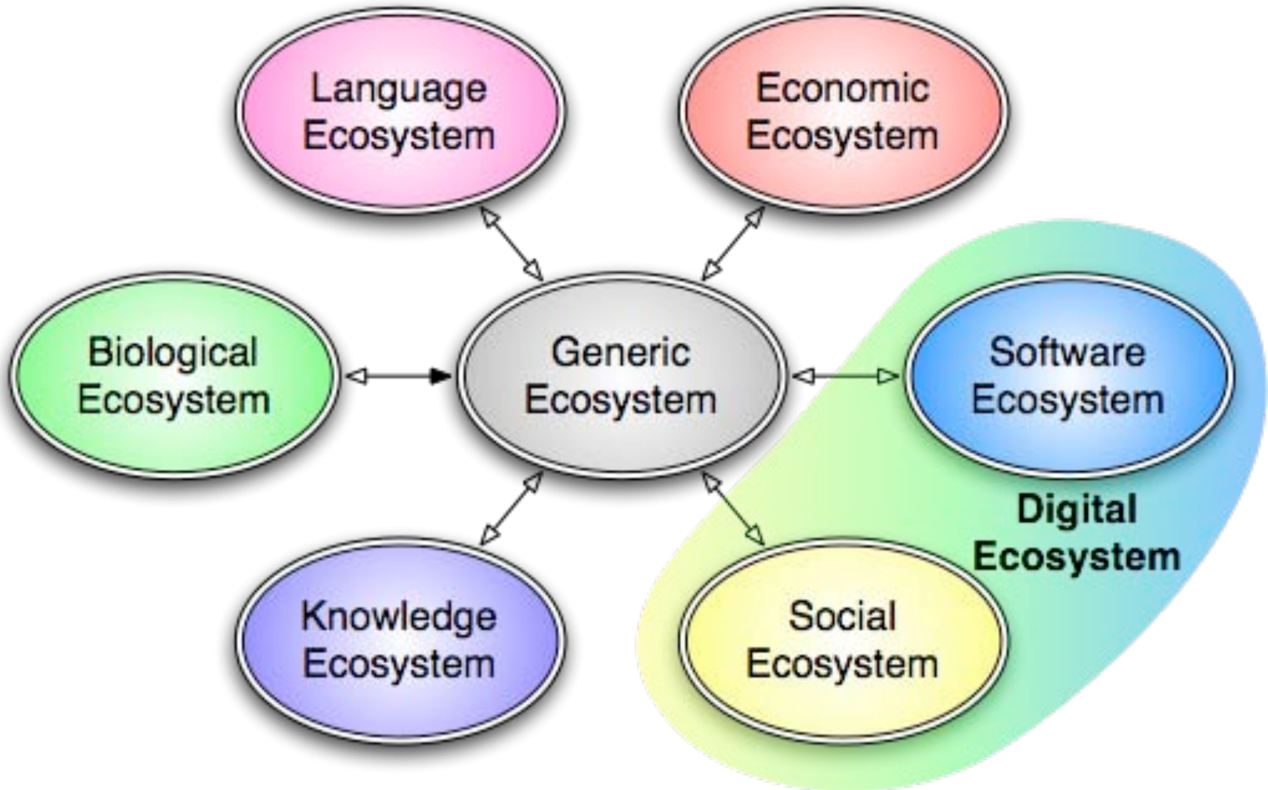

Figure 2.10: Digital Ecosystem: A combination of software and social systems with ecosystems; therefore, any distributed adaptive open socio-technical system, with properties of self-organisation, scalability and sustainability, inspired by natural ecosystems. The arrows represent information flow between conceptual models of understanding, with the majority of information flow coming from Biological Ecosystems.

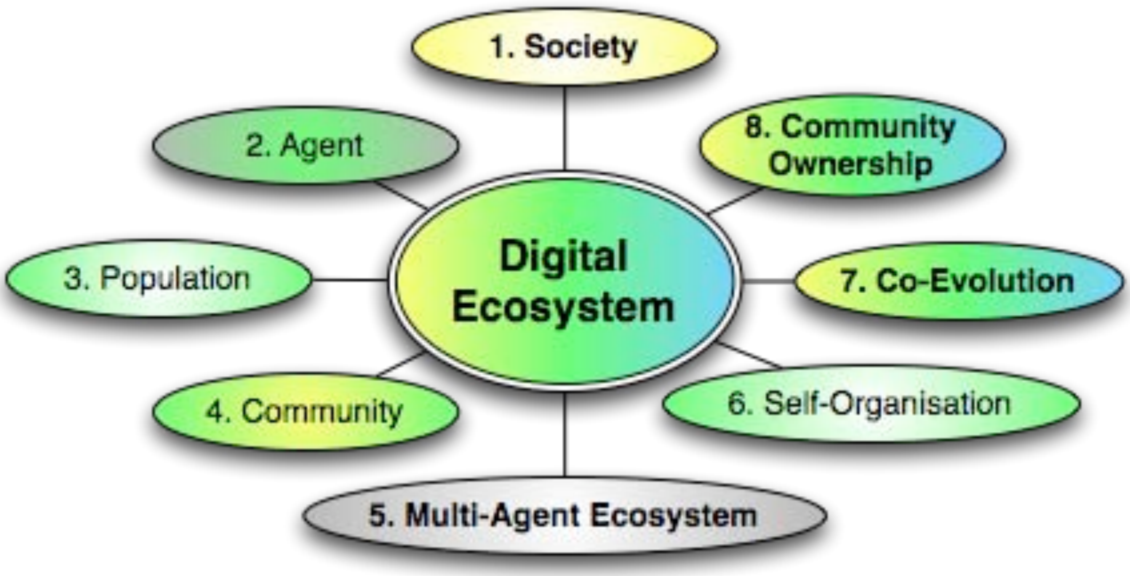

Figure 2.11: Digital Ecosystem: The key properties, behaviours and structures of a Digital Ecosystem, based on combining concepts from Social Ecosystems, Software Ecosystems, and Biological Ecosystems through our understanding of a Generic Ecosystem. The items in bold are the ones that have changed to more domain specific concepts from Figure 2.4.

2.8.1 Digital Business Ecosystem

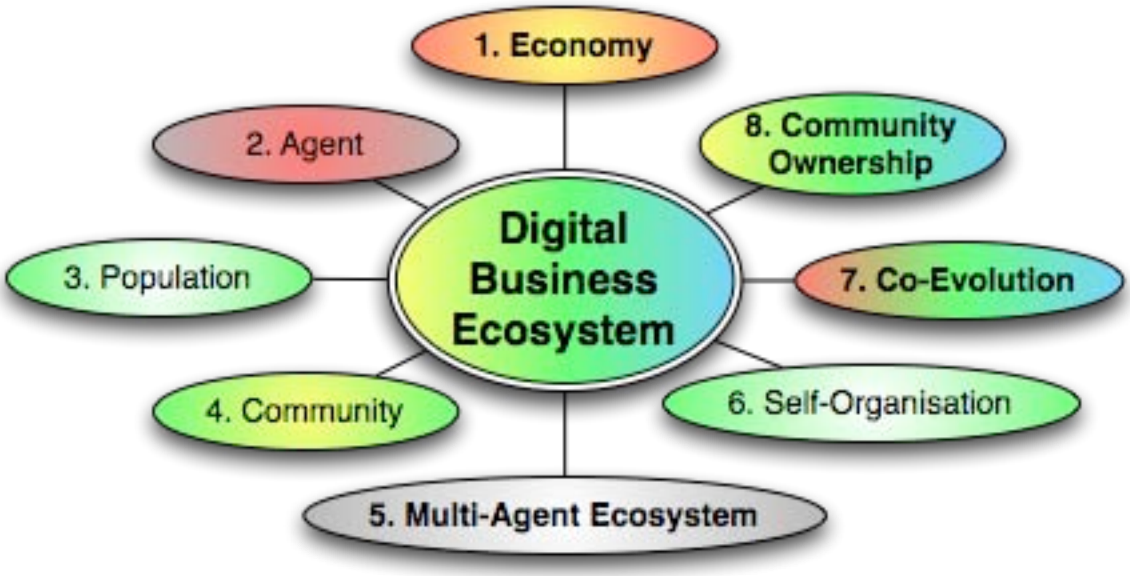

Figure 2.12: Digital Business Ecosystem: The key properties, behaviours and structures of a Digital Business Ecosystem, based on combining concepts from Social Ecosystems, Software Ecosystems, Economic Ecosystems and Biological Ecosystems through our understanding of a Generic Ecosystem. The items in bold are the ones that have changed to more domain specific concepts from Figure 2.4, with the colours indicating the class of ecosystems from which the concepts originate.

We can now define a Digital Business Ecosystem (DBE) similarly to a DE, as a combination of software, social, and economic systems with ecosystems; therefore, any distributed adaptive open socio-technical system for business, with properties of self-organisation, scalability and sustainability, inspired by natural ecosystems.

The environment in a DBE is the economy, with the actors (roles) of the system considered as agents. A population is a group of agents subject to evolutionary change, which in this case is co-evolutionary (Mitleton-Kelly, 2003) within their respective communities. Community ownership of the technical infrastructure is required, which will have self- organising properties from Biological Ecosystems. As we have considered the actors of the system as agents, we can use ABM to consider the DBE as a MAS.

2.8.2 Digital Knowledge Ecosystem

We can now define a Digital Knowledge Ecosystem as a combination of software, social, and knowledge systems with ecosystems; therefore, any distributed adaptive open socio-technical system for knowledge sharing and management, with properties of self-organisation, scalability and sustainability, inspired by natural ecosystems.

The environment in a DKE is society, with the actors (people) of the system considered as agents. A population is a group of agents subject to evolutionary change, which in this case is co-evolutionary within their respective communities. Community ownership of the technical infrastructure is required, which will have self-organising properties. As we have considered the actors of the system as agents, we can use ABM to consider the DKE as a MAS.

Figure 2.13: Digital Knowledge Ecosystem: The key properties, behaviours and structures of a Digital Knowledge Ecosystem, based on combining concepts from Social Ecosystems, Software Ecosystems, Knowledge Ecosystems and Biological Ecosystems through our understanding of a Generic Ecosystem. The items in bold are the ones that have changed to more domain specific concepts from Figure 2.4, with the colours indicating the class of ecosystems from which the concepts originate.

The Digital Ecosystem for Agriculture & Rural Livelihood (DEAL), which is discussed in depth in the following chapter, is also a Digital Knowledge Ecosystem (DKE), where the knowledge sharing and management is for the benefit of rural agriculture. The scope of society in the DEAL DKE is the parts of rural India involved with agriculture (most of it), given there plans for national deployment. An agent is an individual in one of participating organisations, e.g. farms, universities, rural government, and so a population is a group of agents subject to an evolutionary change. The co-evolution in this instance is the change in agent behaviour caused by other agents. They are still in the process of adopting a suitable distributed technical infrastructure for the required community ownership of the technical infrastructure.

Our Open Knowledge Spaces (OKSs) are also sophisticated Digital Knowledge Ecosystems. However, there are other simpler examples that can be considered. For example, Wikipedia and Arxiv.org could be considered Digital Knowledge Ecosystems, because they have many of the necessary properties, except for a distributed technical infrastructure, which could be addressed by the conceptual architecture presented in the next chapter.

2.9 Conclusions

We have provided a conceptual framework for the cross-pollination of ideas, concepts and understanding between different classes of ecosystems, based on the simple, but universally applicable, principles of Complex Adaptive Systems. We have used Agent-Based Modelling to interpret the different classes of ecosystems as Multi-Agent System. Furthermore, we have used this approach to robustly define Digital Ecosystems, and different classes of Digital Ecosystems as Complex Adaptive EcoSystem. Therefore, it provides the starting point of a framework to assist the cross-disciplinary collaboration of research into Digital Ecosystems.

The next chapter addresses digital knowledge ecosystems from the perspective of socio-technical systems, and the impact of theories of autopoiesis thereon, through a detailed assessment of the DEAL case study in India.

3. Reflections on a Digital Ecosystem Approach to Agriculture Extension Service in India and Social Network Analysis for Impact Evaluation

Chapter Authors: Jayanta Chatterjee[12], and Debashis Pattanaik[13]

3.1 Introduction

Indian agriculture engages about six hundred million people across the vast expanse of the sub continent. It is a large socio-technical system that has earlier shown remarkable adaptive capabilities over five decades. This complex adaptive system however has lately started to languish and need infusion and diffusion of knowledge driven innovation across the entire value chain – from seed farms to post harvest practices. This study focuses on the Indian Agricultural Extension Services (IAES)[14] as a knowledge- network (KN) and the impact of infusion of Digital Information and Communication Technologies (ICT) on that complex socio-technical system to enable the next stage of adaptive innovation. In that process we explore how such complex activities need to be self-organizing and self-catalyzing (Fukuyama 1999) and how digital technology deployment projects need to distinguish between organizing explicit knowledge from Agricultural experts and researchers (*Gyan Dhara*)[15] as knowledge repositories and acquiring emergent field knowledge from farmers traders and other practitioners (*Gana Gyan*)[16] through participative and nurturing circularity of communication (Luhmann 1992).

3.2 Background of the Knowledge Innovation Initiatives in Indian Agriculture

Status of Indian Agriculture

Indian agriculture is today at a cross-road: after forty years of 'Industrial agriculture' relying on 'high input technologies', i.e. heavy usage of chemical fertilizers and pesticides with copious use of mechanized irrigation enhanced production initially, but created many new problems in the long run. Today, at the threshold of the 13th 5 Year plan - Indian agricultural growth rate often lapses to about 2% against a minimal target of 4% required to maintain national food security. Under the WTO[17] regime, India started dismantling restrictions on agricultural imports and exports: nearly 3000 items have been deregulated since 2001. But as a result Indian agriculture today faces dual challenge a) from ill effects of previous planning and b) today's globalization pressures on farmers and traders (Chatterjee and Pattanaik, 2008b). Declining yield, restricted availability of farm credit, increasing variety of pests and diseases on one hand, and cheaper subsidized imports from developed countries, on the other hand, call for innovative approaches to make Indian agriculture competitive and remunerative for nearly 600 Million people who depend on it. In this scenario, knowledge creation and sharing, together with new technologies, can play a big role. Innovation in Indian Agriculture at every stage of the value chain, from seed to food processing, is a national priority. India needs to innovate and develop its own version of post-industrial agriculture. Borrowed science will often not work anymore. Associative Open Innovation is needed at grass-root level (Chatterjee and Pattanaik, 2008b).

India's first green revolution was a spectacular success. Volume of production went up by orders of magnitude for most crops particularly for basic food grains like wheat, rice and pulses through higher acreage under cultivation and vast areas were brought under pump irrigation. New seed varieties like dwarf wheat and dwarf rice were successfully introduced which significantly enhanced yield per hectare. Yield also improved due to wide spread usage of chemical pesticides and fertilizer. India became an exporter of many agricultural produce and the national buffer stock for basic grains ensured India's food security. Forty years later the situation has changed. The mismatch between supply and demand has again started widening. The increasing standards of living in India's bustling cities, higher

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[14] IAES – Indian Agricultural Extension Services
[15] Gyan Dhara – Expert knowledge
[16] Gana Gyan – Folk knowledge
[17] WTO – World Trade Organization

demand of food grains at home and around the world cannot be adequately served by declining agricultural productivity at India's countryside. This has initiated a complex downward spiral. More and more land is needed for industrial expansion. Water resources are constrained. And to complicate the situation- over tillage, over irrigation and excessive or wrong usage of chemicals, fertilizers and many other adverse effects of earlier technological approaches have severely impaired India's productivity across the most fertile and irrigated states (Chatterjee et al., 2008). For example in the case of Rice, while India's average production per hectare is 2.4 to 2.8 Tonnes per hectare, China produces 6 Tonnes per hectare (Business Standard, 11th April 2008).

To meet the growing need of food grains for a rapidly growing nation, India's policy makers have realized that new strategies are needed to enhance the agricultural growth rate to at least four percent from the current level of 1.8 to 2 percent. This level is essential to sustain a double digit growth rate for the GDP[18] while retaining inflation at a manageable level (Chengappa and Vinayak, 2007). Key components of this new strategy will be knowledge driven agriculture and innovation for livelihood development across six hundred thousand villages of India. The goal of knowledge driven agriculture will be: (a) to increase production while reducing waste and cost (b) which will enhance agricultural profitability (c) and that will make Indian agriculture globally competitive. This strategy also needs new programmes to reduce rural poverty, inequality and new initiatives to protect the environment by reversing the degradation of natural resources (like land and water) and adoption of practices that reduce green house gas emissions from the farm and forestry sectors. New programmes are needed towards innovating new forms of rural enterprises that will effectively manage the shift of labour forces, stem the migration to urban slums and will broaden the base of economic growth potential of rural citizens (Chatterjee et al., 2008).

Economic Challenges	**Knowledge Based Solutions**
India commands just 4 percent of the global fresh water resources, but supports 16 percent of world population.	Creating irrigation potential, repairing system deficiencies and inefficient on-farm water management. Adapting cropping patterns according to water availability.
Adverse effects of draught on production of crops.	Reducing the utilization gap, ground water extraction, watershed development, rainwater harvesting
Over-dependence on rain fall and monsoon. More than 60 percent of the cultivated area is rain dependent. The country's rainfall is not evenly distributed, but in total, it is adequate to meet the water requirement.	Increasing irrigation efficiency from the present level of 35-40 percent, completion of ongoing irrigation projects. River grid development will help rationalize the availability of water.
Over-exploitation of water, especially for growing rice and sugar, has seen water tables recede.	National Rainfield Authority to help conserve Water.

Table 3.1: Economic Challenges and Knowledge Based Solutions

This knowledge driven approach to Indian agricultural reform and rural livelihood generation has been well analyzed in many Planning documents. Indian Vision 2020 states that 'the pace of India's future progress will depend to a large extent on its ability to make available the latest and most useful knowledge to vast section of the population' (Planningcomission.nic.in, Last accessed: 02 May 2008).

To make good decisions, both extension workers and farmers need information from different sources and often need help to integrate the information. Due to its sole dependency on knowledge and information mainly from State Agricultural Universities (SAU)[19] and to some extent from Indian Council for Agricultural Research (ICAR)[20] institutes, the present extension largely provides information only on technologies generated by these research stations. However the current

[18] GDP – Gross Domestic Product
[19] SAU – State Agricultural University
[20] ICAR – Indian Council for Agricultural Research, it is the apex body to plan, monitor and implement various agricultural activities in India

agricultural scenario demand an increasing role of international knowledge sources as well as better visibility of local solutions developed by innovative farmers. Thus the extension needs to expand its role from technology transfer to include roles such as (self catalyzed) problem solving, education, and human development (Van Beek, 1997). The first step in this direction requires identification of the different elements in the Agricultural Knowledge and Information System and redesigning this system in a way that information flow among these elements are improved (Hall et al., 2002). It was felt that 'by infusing knowledge connectivity to human agencies' critical success conditions can be created to energize a resurgent rural economic infrastructure (Garai and Shadrach, 2006).

Technological Challenges	**Knowledge Based Solutions**
No new technological breakthrough in terms of high-yielding varieties for food grain crops.	Some promising candidates for pulse and rice should be pushed through rapidly. Accelerated dissemination
Soil fatigue due to over-exploitation of nutrients and organic matter in intensive cropping areas.	Crop rotation and replenishment of micronutrients to help restore fertility. Location specific formulation
Nutrient imbalance due to use of improper combination of fertilizers.	Optimal use of fertilizers with the right NPK mix, without overdose of nitrogenous nutrient. Use of remote sensing and satellite imaging
Non-availability of quality seeds resulting in low seed replacement rates.	Development of market and infrastructure for making seeds available to farmers through non-traditional channels
Inadequate or poor harvest management infrastructure at the farm level.	Making institutional credit available to farmers so they can make use of improved technology. Develop new post-harvest technology innovation at grass root level

Table 3.2: Technology and Knowledge Based Solutions

3.2.1 ICT as Driver of Agricultural Extension Services

The concept of Information and Communication Technology (ICT)[21] for rural development has always attracted media and corporate attention and therefore many multilaterally funded projects on this theme have been initiated over the last ten years across many developing countries. Most of these projects focused on establishing info-kiosks in villages and grappled with the initial problems of connectivity, power and other infrastructural issues. Some of them were oriented towards electronically delivered Government to Citizen (G2C)[22] services; some were focused on trade, some on a range of consumer oriented services. Our initial study across North Indian locations during 2002-2004 of many such projects led us to believe that to ignite the agricultural and rural livelihood innovation process with knowledge flow, these rural ICT kiosks not only needed network connectivity and electrical power but also the power of appropriate content and applications.

Our research hypothesis was that the process of creating a self propagating content/knowledge network and self managed knowledge repository can be enhanced by efficient networking of many conversations to build digital communities. This can then create a digital ecosystem and a dynamic grass root innovation system sustained by many feedback loops (Chatterjee et al., 2008).

Rapid growth of ICT and importance of knowledge as a basic power to deal with global competitiveness have revolutionized all organizational learning systems. Cultivating electronically facilitated knowledge and skill revolution is a highly potent strategy to achieve the goals of productive, profitable, stable and competitive agriculture (Chatterjee, Sarkar and Prabhakar, 2008). But the large scales efforts to develop ICT infrastructure through projects like National eGovernance

[21] ICT – Information and Communication Technology
[22] G2C – Government to Citizen

Plan of India (NeGP)[23] need to complement by creation of digital content for agricultural innovation. The importance of digital content in agriculture domain is clearly reflected in the Indian national planning policy framework. One of the major objectives of the proposed plan is to build capacity of the extension education professionals through increased use of ICT based knowledge modules in virtual learning environment. Keeping the structural constraint in mind the policy frame work argues for wider user base, increasing applications and greater dependency on ICT in agriculture (11th Plan Policy, Government of India) to accelerate dissemination of problem solving knowledge across a vast country like India.

The Digital Ecosystem for Agriculture and Rural Livelihood (DEAL)[24] perspective starts from the assumption that ICTs can play an important role in catalyzing development. In this statement we immediately recognize different possibilities of interpretation. If we focus on the technological aspects, we might expect efficiency improvements in those processes that can most easily be automated, such as information storage and retrieval or any of the other processes that support the business and economic life of the users of DEAL. Development in this case tends to be interpreted in terms of quantifiable economic measures. If, on the other hand, we focus on the communication processes enabled by the technology, we are led to inquire into the nature of the link between the social processes supported by ICTs and the different kind of possible economic interactions and exchanges. These two perspectives reflect a dichotomy at the heart of research on ICTs that has been highlighted by Winograd and Flores (1987) and that corresponds to the main epistemological viewpoints adopted in the OPAALS[25]/DEAL project (Rivera-León and Dini, 2008).

The development of a manageable path through the dichotomies depends on better understanding and deployment of processes that maintain a self catalyzed, self propelled dynamics between ‘knowledge stock’ (like electronic repositories) and ‘knowledge flow’ (like knowledge generating social networks). Theoretical understanding of autopoiesis in socio-technical system can help in building that process and deployment.

3.3 Autopoiesis in Socio-technical Systems

In order to understand the difficulties of applying autopoietic theory to social systems, it is useful to briefly revisit the history of the theory. Humberto Maturana and Francisco Varela originally proposed Autopoietic Theory, with the purpose of redressing what seemed to be ‘a fundamental imbalance in the understanding of the living organization’ (Varela, 1981: 36). Their concern was not the explanation of social system or organizations, but rather what it is to be a living being.

Varela (1996) suggests that the first seeds of autopoietic theory were sown in a paper by Maturana (1970) where the connection was made between the circular nature of neural processes and the notion that the organism is also a circular process of metabolic changes. In 1972, Maturana and Varela published a monograph entitled *De Maquinas y Seres Vivos: Una teoria de la organization biologica*. (*Of Machines and Human Beings: A Theory of Biological Organisation*). The English text rendered in 1980 was entitled *Autopoiesis and Cognition: The Realization of the Living*.

Central to the theory were the notions of self production and autonomy. These ideas were not new and had long been discussed in different forms by many philosophers and scientists. Varela (1996) comments on the influence of a number of researchers during the formulation of the theory, however it is unclear to what extent the ideas of social philosophy influenced its development.

Zeleny (1980) cites four authors who developed ideas of self producing social systems; Giovanni Battista Vico (Bergin and Fisch 1970), Bronislow Trentowski (1843, in his work *Cybernetyka*), Carl Menger, (1883) and Friedrich von Hayek (1975). In all cases, these theorists suggested that the social system exhibited behaviour which was self derived and wholly the result of human production. Such a

[23] NeGP – National eGovernance Plan of India, 2006
[24] DEAL – Digital Ecosystem for Agriculture and Rural Livelihood
[25] OPAALS – Open Philosophies for Associative Autopoietic Digital Ecosystem

position carries with it the implication that social systems are entities, acting with a degree of autonomy from the component organism (whether they be humans, ants or cells) that create them. In other words, social systems have a life of their own. The position of living social system was, however, only implied in the works of the above authors, and not necessarily a statement how things actually are. As already stated, autopoietic theory was originally developed as an explanation of what it is to be a 'living being'. Maturana and Varela's proposition was that 'living beings are characterized in that literally, they are continually self-producing' (Maturana and Varela, 1992: 43).

Thus the second key point of the definition is that of self production. Self production, in the context of autopoietic theory, has a very specific meaning. It refers to systems where the components of the system participate in the processes of production that produce those same components that themselves constitute the system (Varela, 1981; Maturana, 1981). Therefore autopoietic systems have a circular organization where the outputs of the system are its own inputs (Mingers, 1995).

This framework provides valuable theoretical support to the development of Digital Ecosystem for Knowledge (DEK)[26] that dynamically enhances 'self production' balances 'knowledge stocks' and 'knowledge flows'.

Historically the application of autopoiesis to living systems of different levels of complexity, from cells through to whole organisms, has not presented any great ontological problems. Taking the theory a step further to the explanation of human social systems, however, presents several difficulties in terms of ontology and accurate identification of concepts, operations and processes. To complicate matters further, Maturana (1981) suggest that a distinction can be made between autopoietic systems and living systems. He maintains that 'the notion of autopoiesis fully characterizes living systems as autonomous entities in physical space' (Maturana, 1981).

Furthermore, 'we have chosen to identify living systems with only autopoietic systems in the physical space because this is the space in which we exist' (Maturana, 1981). These quotes raise the first distinction that must be made with regard to the application of autopoietic systems to the social sphere; all living systems can be described as autopoietic, however not only autopoietic systems can be described as living. This distinction arises because of Maturana's referral to physical space.

Living systems, for Maturana can only exist in physical space or be constituted of components that are defined as physical. Autopoietic systems exist in the space of their components, which can vary infinitely so long as their properties allow the constitution of the system in the space that they define (Maturana 1981). Therefore whether a social system is believed to exist in physical space or not, determines whether it can be conceived of as a living system or not (according to Maturana). The important implication which arises from these observations is that, regardless of whether a social system is perceived to be living or not, it is possible for them to satisfy the criteria of autopoietic systems and to be understood in terms of the processes described by autopoietic theory.

A digital ecosystem for knowledge like DEAL exists in physical space as a network of village knowledge centers, agricultural service centers and other entities as shown in Figure 3.1.

By accepting the possibility that autopoietic theory can be usefully applied to social-technical systems, the non-physical space in terms of member individuals, their conversations, hopes, aspirations, problems, concepts, ideas, feelings and emotions also become equally important. In the next section we present a review of the theoretical debate with regard to this issue.

[26] DEK – Digital Ecosystem for Knowledge

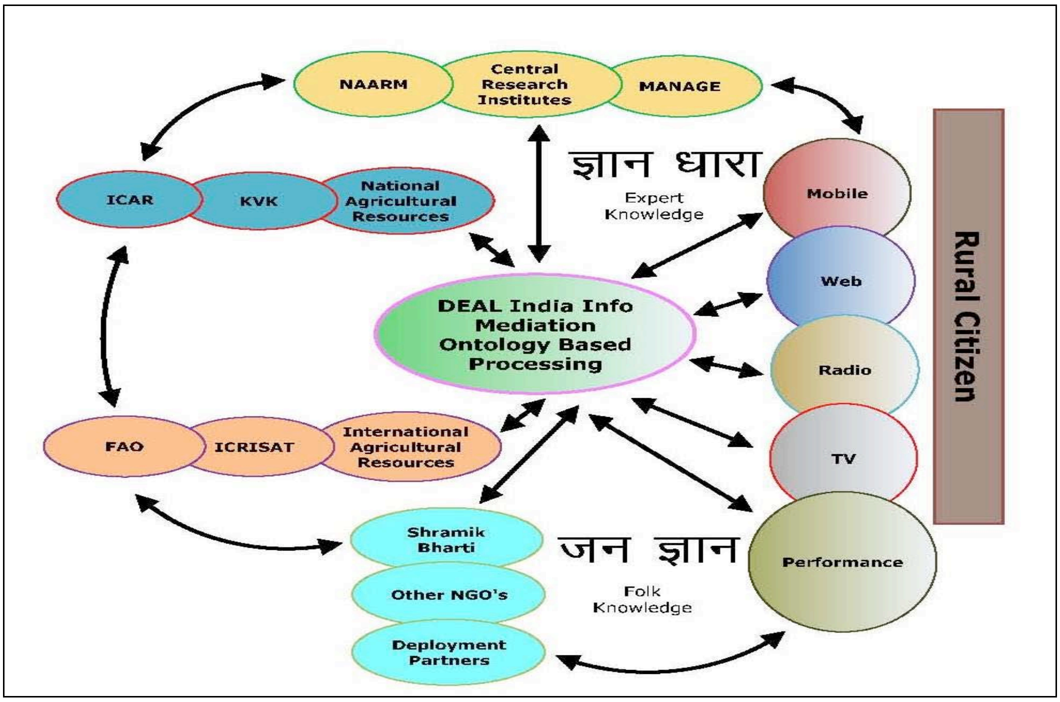

Figure 3.1: Architecture of DEAL Knowledge Network

3.3.1 Theoretical Debate

There has been considerable debate regarding the application of autopoietic theory to social systems. It should be noted at this point that the debate has not necessarily centered on the theory's application to organizations, which would constitute an example of a social system, but more commonly to the notion of society. The main proponents for the theory's application to social systems are Niklas Luhmann, who discusses the notion of autopoietic systems in a number of fields including the law, politics and the arts, as well as social systems; Gareth Morgan who takes an overtly metaphoric stance on the subject; and Milan Zeleny, who has worked with several people in the development of his ideas, including Kevin Hufford. Other theorists have also made attempts to apply autopoiesis in the social context.

There are three main perspectives or streams of debate regarding the topic: the sociological perspective of Luhmann, what may be termed the scientistic perspective of Zeleny and Hufford, and the metaphoric perspective of Morgan (1997). It is suggested here that none of these perspectives, by themselves, presents a theoretically tenable or practically workable solution to the problem of applying autopoietic theory in social or more specifically organizational contexts.

Before discussing these three perspectives in detail it is worthwhile noting the work of Beer (1981), Hejl (1984) and von Krogh and Roos (1995). These authors have each made contributions that are tangentially relevant to DEAL.

Beer's Viable Systems Methodology represents an attempt within systems theory to apply biological theories to organizations. Although this work carries some similarities to autopoietic theory, it is based on different premises and aimed at explaining different phenomena. The early work of German sociologist Peter Hejl explicitly draws upon autopoietic theory in its constitution which extends, albeit to a lesser extent, to his more recent articles (Hejl, 1993; Hejl et al., 1997). The work of von Krogh and Roos is an attempt to apply autopoietic ideas to knowledge and knowledge management in organizations. Much of their work focuses on the effect of languaging, drawing upon Maturana and Varela's epistemological position to develop a number of propositions regarding organizational knowledge. The work of Von Krogh and Roos did provide some important insights into the knowledge seeking behaviour of KVK scientists evolved by the DEAL project.

3.3.2 The Sociological Perspective

The next perspective or approach to be discussed is that of Niklas Luhmann. Luhmann's voluminous work spreads across several disciplines including politics, law, religion and the arts. We will be focusing on his application of autopoietic concepts to social systems and derive our learnings for knowledge innovation network.

Luhmann does not claim that social systems are living systems. In fact he is quite explicit that they are not. He works from the premise that if `we abstract from life and define autopoiesis as a general form of system building using self-referential closure, we would have to admit that there are non-living autopoietic systems, different modes of autopoietic reproduction and that there are general principles of autopoietic organization that materialize as life, but also in other modes of circularity and self-reproduction' (Luhmann, 1990). This concept of non-living autopoietic system can resolve some of the epistemology vs. application architecture problems.

This position is not inconsistent with the work of Maturana and Varela. However, there are two key points of separation. The first is that Luhmann refers to three different types of autopoietic systems: living systems, psychic systems and social systems. For Luhmann each of these types of system can be represented autopoietically. Maturana and Varela are not so generous in their interpretation of the concepts. The second key point of separation is in the mode of production that Luhmann promotes: 'social systems use communication as their particular mode of autopoietic reproduction' (Luhmann, 1990). The DEAL project and the impact studies discussed in the subsequent sections to a large extent validate Luhmann's second point.

Luhmann is quite specific about the meaning he gives to communication(s). He posits that these exist as a unity constituted by three elements: information, utterance and understanding (Luhmann, 1995a). These elements cannot exist independently of the system as they are co-created within the process of communication (Luhmann, 1990).

The important aspect of Luhmann's theory is that the communications to which he refers are of a different level to those which we would normally perceive in conversation. Communication is at a different level from people, thoughts and actions (Mingers, 1995), as for Luhmann (human) consciousness forms the environment of the social system. As such, people perturb the social system; however, as elements of the environment, they do not contribute to the system's operations (Luhmann, 1995b).

As such Luhmann has thus conceived of autopoietic social systems as systems in non-physical space defined by non-physical components. Elements occupying physical space, such as people, constitute the environment of the system. This is necessary because it allows sociological theory to switch from the concept of action as the basis for the production, to communication. 'With the concept of action external references can hardly be avoided. An action requires since it must be attributed, reference to socially constituted complexes: a subject, an individual, for all practical purposes even a living body, that is, a place in space' (Luhmann, 1992). This distinction between system and environment is very important in terms of understanding Luhmann's theory as 'the system would never be able to build its own complexity and its own knowledge if it repeatedly mistook itself for its environment' (Luhmann, 1995b).

A significant aspect of Luhmann's conceptualization of social systems, and within that organizations, is the notion of expectation and its relationship to the way in which the system is structured and decisions form. For Luhmann 'the structures of social systems consist in expectations ... they are structures of expectation, and ... there are no other structural possibilities for social systems, because social systems temporalize their elements as action-events' (Luhmann, 1995a). As such, self-referential social systems structure themselves through expectations of actions.

A problem with Luhmann's work in the context of Digital Ecosystems (DE)[27] relates to certain assumptions regarding the boundary of the system. Luhmann suggests that the autopoietic system of communications exists as a unity, or in other words without humans as a part of the system. Although theoretically possible, and satisfactory in terms of the three components of communication acting as a system, such a premise has little explanatory value in terms of socio-technical innovation or change management in general.

3.3.3 The Scientistic Perspective

The second approach or perspective on social autopoiesis may be termed the Scientistic approach. It is within this perspective that most debate has taken place and into which the arguments of Maturana and Varela are most closely aligned.

Maturana and Varela have distanced themselves from the application of autopoiesis in the social context. They do not even agree on an appropriate direction to address the problem. Maturana (1980, 1988) argues that social systems are the medium in which living systems recurrently interact and realize their structural coupling. Varela (1979, 1981) suggests that autopoietic notions of production are not appropriate for all systems and therefore the development of a similar concept of organizational closure is a preferred direction. Both argue that autopoiesis cannot be applied directly to social systems.

Their fundamental concern with regard to social autopoiesis is that autopoiesis, in its original conception, requires that the components of the system, through their operations, further produce the components which constitute the system. When the system under study exists in the physical space of its components, such a pursuit is not so problematic. However, social systems would appear to be non-physical in nature and yet be composed of physical components, i.e. people. This of course assumes that people, unlike Luhmann's position, produce social systems.

Varela et al. (1974) proposed six criteria that could be used in determining whether a system is autopoietic in its organization. Zeleny and Hufford (1992a) used the six criteria in order to explore the social unit of a family as an example of social autopoiesis. They also explored these criteria through examining a cellular system and a chemical system. Their approach was to discuss each of the key points, as described above, illustrating how the unity of a family satisfied the criteria. The other contributors to the debate found several limitations with their arguments. The main limitation was their failure to clearly define the elements of the system, i.e. the boundary and the components.

Mingers (1992) also pointed out several weaknesses with Zeleny and Hufford's argument. The first of these related to the lack of definition, given to important terms such as family and 'spontaneous social order'. Mingers criticized the use of the six criteria as a methodological tool for the debate, suggesting that the debate has moved on, and both Maturana and Varela have made other clearer statements with regard to social autopoiesis (e.g., Maturana, 1988; Varela, 1981). Another element of Zeleny and Hufford's (1992a) paper that drew criticism from all the other contributors was their suggestion that not only are social systems autopoietic but also that all autopoietic systems are social systems.

Zeleny and Hufford's (1992b) response to these criticisms was interesting as the arguments they put forward related mostly to what they saw as a limited view or set of assumptions regarding the domains of operation and what constituted the boundary of the system. The examples they gave of this limited perspective were the objections to their mixing of operational domains: 'We cannot commit ourselves to one 'domain' or to one component space; that type of science, a science restricted to a single domain of inquiry, has already passed. (Zeleny and Hufford, 1992b: 241). In essence, Zeleny and Hufford put forward a call for a wider interpretation of the theory, suggesting that Maturana and Varela have only brought the theory so far and, as such, it is time for a reinterpretation.

[27] DE – Digital Ecosystem

3.3.4 The Metaphoric Perspective
Gareth Morgan's metaphoric use of autopoietic theory represents a third approach that can be identified. It is the simplest and least problematic of the three perspectives. Morgan (1997) acknowledges the reservations Maturana and Varela have regarding social autopoiesis, preferring to extrapolate three 'intriguing implications' which he suggests are useful in developing an understanding of organization.

The first of these relates to the organization's organizationally closed relationship with its environment, the second to the maintenance of identity and the third to explanations of evolution, change and development which should, Morgan argues, encompass the organization's recurrent relationship with the environment (Morgan, 1997). The autopoietic metaphor, for Morgan, is one among many different metaphors that can be applied to the problems associated with managing organizations. Morgan goes on to extend the use of autopoiesis into the notion of patterns between the organization and the environment, including the work of Kauffman (1993) and Gleick (1987).

The criticisms leveled at this approach to the use of autopoiesis in social systems are not so much related to Morgan's work as to the notion of metaphor itself. Mingers, commenting on Morgan's work, states that 'in overall terms, using autopoiesis metaphorically is reasonably unproblematic one does not have to agonize over the deep ontological problems. Equally, however, the results are merely metaphoric and have no greater claim on our attention' (Mingers, 1995: 151-152). Varela (1981) has a similar view. Interestingly, Luhmann also makes a statement, in the context of applying 'a systems' theory from one discipline into another area of knowledge. 'One has to refrain from transferring purely metaphorically or by analogy the knowledge of one discipline onto other areas of reality (Luhmann, 1995b).

Here it is important to examine what is meant by the notion of metaphor. As already noted, Maturana and Varela's original conceptualization of the theory was an attempt for a literal representation of what it is to be a living being literally exist. However, the distinction between whether a particular interpretation of a subject is a literal interpretation or a metaphoric one is very 'grey'. To use Maturana and Varela's terms this distinction exists in the eye of the observer.

It is difficult to assess the metaphoric nature of the comments above. Are the authors referring to a metaphoric representation of a literal subject, or are they referring to a metaphoric interpretation of a theory? This distinction is important because to argue the useful/lessness of the autopoietic description as a literal way of being creates problems of system reification. A system, is only a way of looking at a set of relationships, it is not a literal representation of the way things are (Checkland, 1988).

To view the system other than as a way of seeing things is to misconstrue the notion of a system, autopoietic or otherwise. The difficulties involved with a metaphoric interpretation of the theory can only relate to the rigor, or lack there of, in the methodological approach of the researcher attempting to test the theory in practice. Therefore to suggest that because Morgan's use of autopoietic systems is merely metaphoric it should have no greater claim on our attention (Mingers, 1995) is over-dismissive. The relative value of an approach to the application of the theory could only be measured against the individual's reason for applying the theory in the first place, and none of the people who critique the metaphoric use of autopoiesis make their position clear in this regard.

<u>3.4 Towards an Autopoietic Perspective on Agricultural Ecosystems</u>

Thus far there are two conclusions that may be drawn from the material reviewed and may contribute to a new 'frame' for the application of autopoietic theory in organizational contexts: (a) Social systems in themselves are not automatically autopoietic. (b) Processes of social interaction can be usefully seen to involve and be constituted by many of the processes described within autopoietic theory. Accepting these two observations, it is possible to propose a new frame for the way in which this issue may be discussed.

Epistemology: The epistemological perspective adopted here could best be described as pragmatic constructivism, which can be regarded as consistent with the notion of 'objectivity-in-parentheses'. For the purposes of this discussion, the validity of truth claims resides with the 'observer' and cannot be known with any greater objectivity than that. From this perspective there is an independent reality that exists beyond the structure-bound cognitions of observers. This reality is described through metaphors that may or may not resemble the 'independent reality'.

The reason for the inclusion of an independent reality is as follows: If one is to observe organizational phenomena as if they are constituted through the processes described in autopoietic theory, it is much easier to assume that there is 'something' to which people can structurally couple, an environment which perturbs structure-determined changes of state in the people being described. Without this conceptualization, the metaphor becomes solipsistic in the extreme.

The question therefore, of whether organizations are autopoietic or not, is really the wrong question. A more appropriate question would be: what can be learnt by viewing organizations through the perspective developed in autopoietic theory? The narrative from this point may accordingly be viewed as consistent with the first of the three metaphoric approaches described by Tsoukas (1993). He has suggested that there are three ways in which metaphors and analogies have been used in organizational theory: (a) metaphors as ways of thinking; (b) metaphors as dispensable literary devices; and (c) metaphors as potential ideological distortions.

The first of these perspectives, and the one which is closest to the way in which metaphor will be used here, is based mostly upon the work of Morgan (1997) and his various collaborations (Burrell and Morgan, 1979; Morgan and Smircich, 1980). Within this perspective, the validity of using metaphors as the basis for knowledge stems from the assumption that 'metaphors are subjective images of a particular domain and they are based on certain paradigmatic assumptions which are in themselves metaphor dependent' (Tsoukas, 1993: 325).

Ontology-Knowledge Networks*:* In the approach to DEAL project the Indian Agri Organizations will be viewed as systems and therefore will be subject to the assumption that by studying the organization as a whole it is possible to observe phenomena not seen in the parts (Bateson, 1980). Having said this, to attempt the development of an autopoietic perspective on organization from an extreme holistic position would be to misinterpret autopoiesis in its original form.

The problem is that by applying autopoiesis to the social context the attempt is being made to describe the relationship between two distinct logical levels: that of the individual scientist or farmer and that of the entire DEAL network as an organization. Organizations, it will be argued, may be viewed as elements in a non-physical environment that emerges through the functioning of internal correlations in the mental models and systems of people. In order to make sense of this relationship it is necessary to take an extra step back from viewing the organization as a separate entity, to viewing the combination of organization and individual as composing a single system. If one were to approach this problem from a reductionist perspective, the individual farmer, scientist or trader would become the unit of study.

A holistic approach would be equally limiting, as the focus for study would be the emergent properties arising from the multitude of relationships that may be distinguished. The process, by which these properties emerged, however, would remain mysterious. Within the systems literature, the process by which emergent properties emerge is not really dealt with, it is just assumed that they do (Hejl et al., 1997). In this discussion neither the emergent properties nor the components of the system are the focus; rather, the process through which these two notions influence the state of each other.

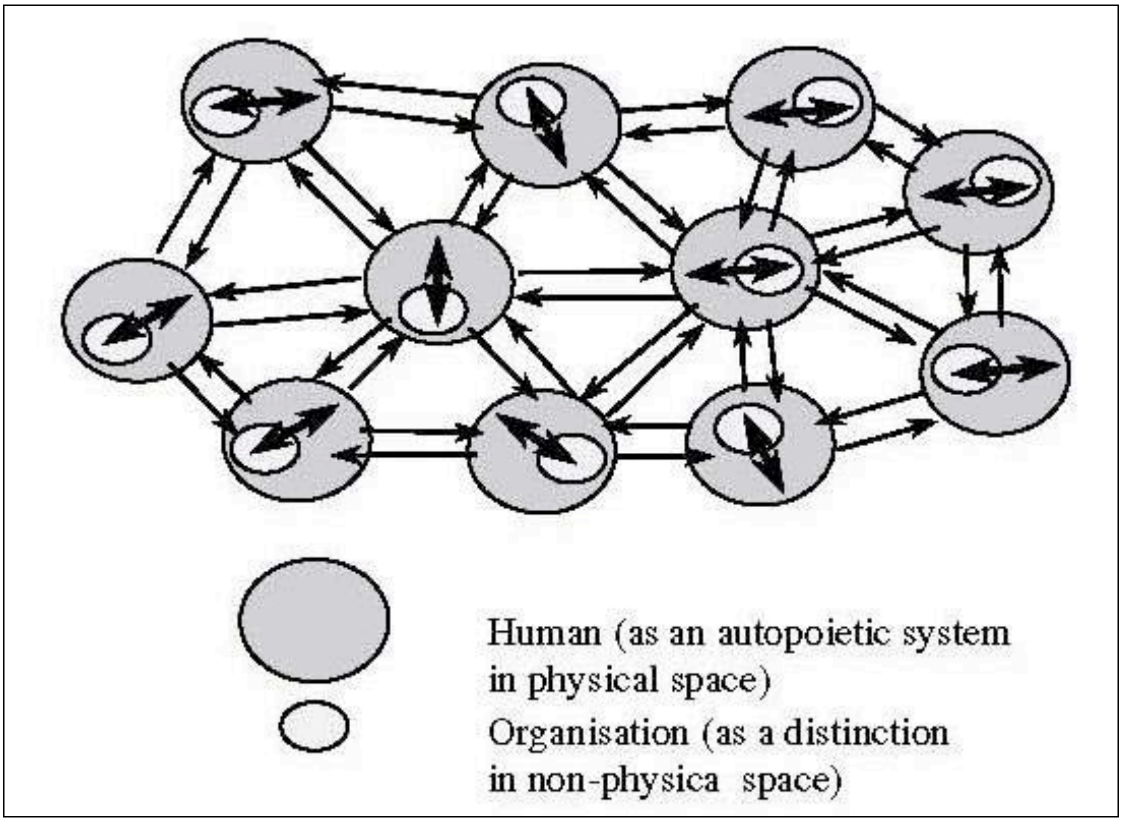

Figure 3.2: Embodied Conceptualization of the Non Physical Space, Source: Robert Kay (2001)

The organization, as Maturana observes, represents the environment or medium in which humans realize their autopoiesis. As such, it represents a source of perturbation that may trigger structure-determined changes to the individual. At the same time, individuals, through their interactions with others, produce sets of recurrent interlocking behaviours, which over time may become distinguished by observers as an organization. Therefore there are literally multitudes of distinctions that may be considered in research of this kind. The observation of interactions is possible while ever the observer is able to distinguish one entity/unity (individual or organization) from another entity/unity (individual or organization). In a DEK all these different interactions need to be sustained.

In Figure 3.2, the organization is not an entity external to the individual; it becomes an embodied aspect of the individual's world-view, both influencing and being influenced by the continuous functioning of internal correlations within the individual's nervous system. If this particular conceptualization is accepted, then there are a number of other questions that may be explored. For example, if the organization is viewed as a medium in which autopoietic systems realize their autopoiesis, how can the social system be internal to the individual? The initial confusion that arises from this question can be overcome through a more clearly defined notion of world-view.

From an autopoietic perspective, an individual's world-view is relative to the observer. The observer could be the individual themselves or an outside observer watching the individual. What the observer sees is the behaviour of the individual. An individual's world-view is therefore just as much a function of the observer as it is a function of the individual's nervous system (Kay, 2002). Consequently, it is important to separate the behaviours of the individuals, from the descriptions of those behaviours. As already stated, the organization is a description or, in Maturana and Varela's language, a distinction that allows the individual to distinguish a particular set of recurrent interlocking behaviours from all the other behaviours that they may observe. The behaviours take place in the physical space, the description in the non-physical. As such the behaviours, as they occur in the physical space, could reasonably be described as a medium for the realization of autopoiesis, while the organization remains non-physical and specific to the internal correlations of the individual's nervous system. The distinction that must be made between the different spaces in which behaviours and descriptions take

place and the mode by which they are produced must remain consistent if the 'frame', as it is developing above, is to have validity.

Earlier researchers (Ashby, 1964; Prigogine, 1984; Maturana and Varela, 1980; Capra, 1997) had pointed out three types of characteristics of self-organizing socio-technical systems, first that of 'requisite variety' – on which depends creativity, evolution and development in a system. The second common characteristics of models of self organization is that they all deal with open system operating far from equilibrium and thirdly earlier research postulated that self-organizing systems had intense non linear feedback loops. The question of whether human social systems can self organize, self propagate, evolve, that is can be organized as a 'living system' has been attractive to many researchers. Many of them have looked at the question metaphorically but some have specifically addressed the issue of an autopoietic human social system (Fleischaker, 1992; Mingers, 1995). The problem here is that the autopoiesis has been defined originally for systems in physical space and for computer simulations in mathematical spaces. Because of the inner world of concepts, ideas and symbols that arises within human thought, consciousness and language, human social systems exist not only in the physical domain but also in a symbolic social domain (Capra, 1997).

3.4.1 Autopoiesis in Social system and its Applicability to a Digital Ecosystem

According to Luhmann communication is the most fundamental social category. According to Luhmann the term social fundamentally implies a system of communications. Social actions presuppose communications in the sense that they rely on the expectation of recognition, understanding, and acceptance by others. Thus for Luhmann a social action is inevitably a communication. Above all communication includes understanding of another party and so goes beyond the individual action to form the link necessary for social operations. Only when a communication generates some meaning it leads to a further communication. Luhmann's conception of 'communication' has a specific sense. According to him Communication has a different level in relation to people, their thoughts and actions. He characterizes communication as an 'event' consisting of three indissoluble elements: information, utterance and understanding—which enable further communicative operations to occur (Luhmann, 1995a). Each of these elements is a selection from a range of possibilities. It is the operation of the autopoietic system that defines and makes the selections. In general, information is what the message is about—it's propositional content; utterance is the form in which it is produced together with the intentions of its sender; and understanding is the meaning that it generates (which can include misunderstanding). All three elements are generated or coproduced together as a unity, and this event allows the possibility of further communications. It is important to stress that all three aspects are distinctions made by the communicative system—the system determines what, for it, is information; how it may be embodied; and how it may be interpreted. This is the closure of social systems.

Of the three, understanding has a vital role. Understanding draws the distinction between information and utterance (Luhmann, 1982) and recognizes that they are selections in different dimensions. It is the understanding that ultimately determines the nature of the communication. Only when a further communication is generated (or perhaps not generated) 'in reply' does the nature of the initial communication become established. The utterance is the 'why now', the 'how' and the 'who' of the communication and so is inevitably 'auto-referential'. It is this distinction between information and utterance, which allows for a degree of arbitrariness between the two, and making further autopoietic production possible. This provides a model of the dynamism of communication both at the level of the individual interaction and moving up to the level of the social system.

There is a fundamental relationship between communications to meaning (Luhmann, 1985). Production of communication is precisely a set of selections from the multiple possibilities—distinguishing what is by what it is not. It is these related events and possibilities that constitute the system of meaning. Meaning is the openness of all possibilities: all the distinctions and relations that could be generated provide an ongoing communication is occurring. Autopoietic communication can thus be seen as 'meaning-processing' to convert the open field of meaning into the particular information/utterances, which thereby constitute a society (Luhman, 1989). The inherent uncertainty

this closed system is stabilized through the generation of shared expectations that in turn constrain or limit future interactions. Much of the processing of information into meaning is actually done sub-consciously by the body and the cognition through the selection from a range of choices. Often it involves a process of negotiation or Interchange to negate the surface meaning. If comprehensibility is a problem, it may reflect a lack of adequate structural coupling (Maturana, 1978) between speaker and receiver. This level brings in the complex of other meanings, beliefs, and implications that are associated with the primary meaning. Thus the closure of the network results in a shared system of beliefs, values and possibly praxis which is continually sustained by ongoing conversation. The digital ecosystem as a socio-digital system can exist only when communication creates more communication through the dialectic interaction between the possibilities created in the inquiring minds of the actors with their actions in the same temporal frame (Chatterjee et al., 2008).

Often Luhmann has been criticized for removing agents from his theoretical frame work. In the following section we shall try to fill the gap by incorporating some conceptual insights from social capital literature.

3.5 Social Capital and Knowledge Net

ICT mediated development projects, largely depends on ‘social contexts of design, implementation and use’ (Synder and Rosenbaum, 1999). The ‘contextually dependent nature of ICT’s suggests that similar ICT’s can have different outcomes in different situations’ (Kling et al., 1994). Thus, the ‘social context’ is the fundamental premise in understanding the relationships between people, ICT and digital information, and the setting in which these relationships evolve. A person’s role and normatively expected behavior cannot be understood in isolation, but only in terms of his relation to wider community. It is this societal sanction that induces trust- members transacting with a particular individual, will process information about his role/normatively expected behaviour with reference to the social network he is part of and then decide to trust. Thus, as Portes (1998), observes, for individuals ‘whereas economic capital is in bank accounts and human capital is inside their heads, social capital inheres in the structure of their relationships’. The importance of social capital is enhanced when knowledge sharing needs to be accelerated in a distributed innovation network like the DEAL. Social capital, manifest in social networks, can make transactions that can not happen in a free make possible, by lowering the transaction costs – costs of information collection, monitoring, negotiating and enforcing. The key role of information communication technology in a developmental socio-technical system thus becomes that of nurturing and enhancing social capital.

An ICT intervention provides the community both wider and richer access to information. Computer and information technologies can help greater infusion of information into social networks that can cause innovational change happen. The use of information communication technologies can shape the social structure through discursive loops it constructs by organizing actors in the network into action communities. The internal propensity of this community can be influenced to continually organize and reorganize itself through an autopoietic mode of discursive formation while maintaining its boundary. The process of such internal dynamics, organization and reorganization needs to be motivated by the social capital that it generates through trust based relationships. Social capital here needs to strengthen reputation mechanisms that encourage cooperation and norms that guide behaviour through reciprocity.

Bonding or strong ties networks consisting of closely knit set of connections rely on social capital based on long standing person to person familiarity and knowledge of each others’ reputation. Bonding networks however have lesser propensity for innovation or creative destructions inspired by information flow when it comes from outside. On the other hand, bridging social capital, exemplified by Silicon Valley, based on fast dissemination of reputation and transitivity of trust can benefit well from ICT based knowledge infusion (Cohen and Fields, 2000).

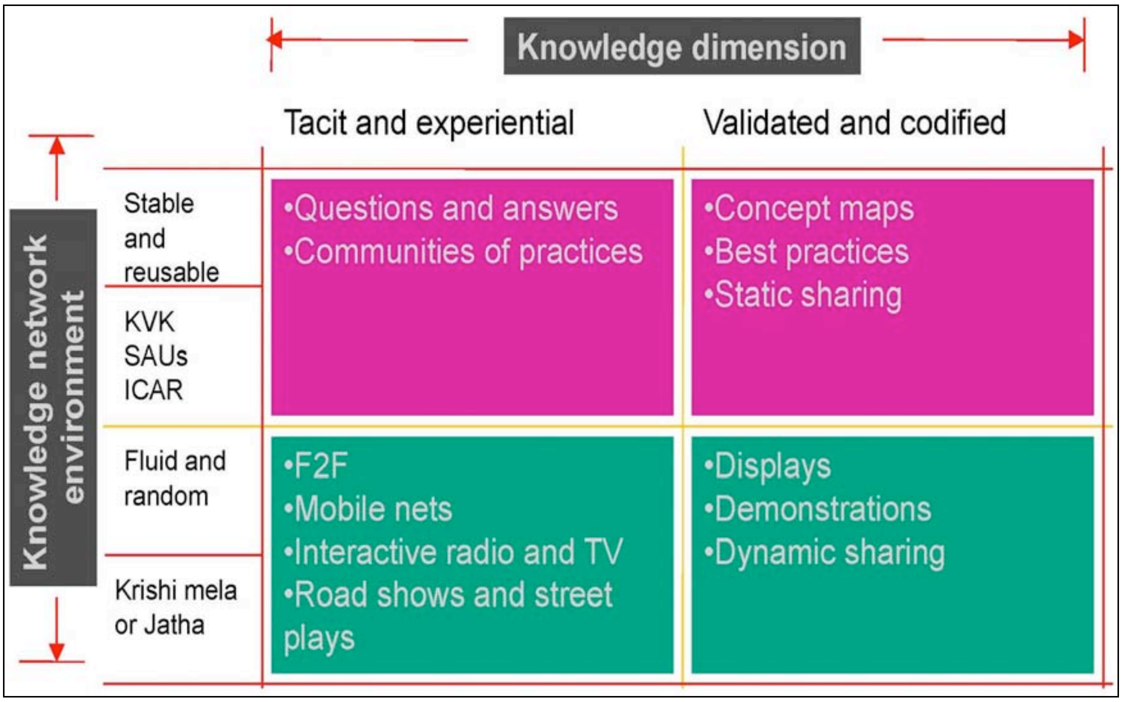

Figure 3.3: Knowledge Network and Knowledge Dimension

The DEAL project showed that ICT introduction into bonding social capital structure (of existing agricultural extension system like the KVKs) challenges the homogeneity of *Gesellschaft* (Tonnies 1957). The role of ICT, in this type of knowledge network that is dominated by 'tacit and experiential' aspects, can only be of facilitator and thread bearer and that too in the relative stable environment of the Krishi Vigyan Kendras (KVK)[28]/SAU/ICAR structure (Figure 3.3). But on the other hand when knowledge structure is fluid or random then face to face (F2F), mobile nets, interactive radio and TVs programmes are more successful modes for generating social capital in generating trust based relation building conversations through mutual respect and appreciation.

Key aspects of the 'diffusion of innovation' processes through their interplays are thus the 'dialectic interaction' among the 'innovation itself', the 'social system' in which the innovation is introduced and the 'communication channels' through which the social system 'members' learn about the innovation and the 'timing' of the processes. The communication can be better maintained through circularity, organization and reproduction by generating a social process that builds bridging social capital. Bridging social capital encourages knowledge flows within the traditional developmental organizations and also allows bridging links with external nodes and networks. Thus there is a need for interoperability of the information through its digitization created in various forms by various actors in the network, as agriculture is a complex system. Interoperability provides potential for automation and systemic self-management. Thus the goal framework in the DEAL project focused on semantic interoperability of contents produced by various entities. The goal was to facilitate context sensitive query processing over heterogeneous information sources. The agenda was to build an action oriented social network where interaction (e.g. that between KVK scientists and farmers) creates new social capital.

3.6 Agents and Networks

3.6.1 Agents and Networks - Pre Conditions

The flow of information among actors depends on their structural positions, network relations, and roles within the given social structure. In a most general way the relation between agricultural experts within the same KVK, or between a farmer and his respective KVK while portray strong tie relations,

[28] KVK – Krishi Vigyan Kendra (Farm Science Centre), is the delivery points for agricultural extension services

the relation between a KVKs and a local Non Governmental Organization (NGO)[29] may be of weak ties. Primarily KVKs are innovative science-based institutions which provide vocational training to in-service extension personnel, farmers, farmwomen and rural youths. It also conducts on farm trials for technology refinement and frontline demonstration to promptly demonstrate the latest agricultural technology to the farmers as well as the extension workers. The KVKs follow the principle of learning through practice (Khan 2002). They undertake various types of extension activities such as; farmers meetings, Kisan Melas, mass media programmes and 'Gosthi's to promote new technology and innovative practice among farmers and other practitioners (Ray, 1991). In an ideal situation there are six Subject Matter Specialists (SMS) in a KVK followed by a supporting staff of four to five members. However in reality it varies widely. Below (Figure 3.4) is an organizational structure of an NGO Managed KVK of Uttar Pradesh. The discussed KVK is officially headed by a Chairman. However in practice activities at the KVK is carried out by the Programme Coordinator of the KVK. Beside there are another five subject matter specialist with different areas of expertise in the said KVK.

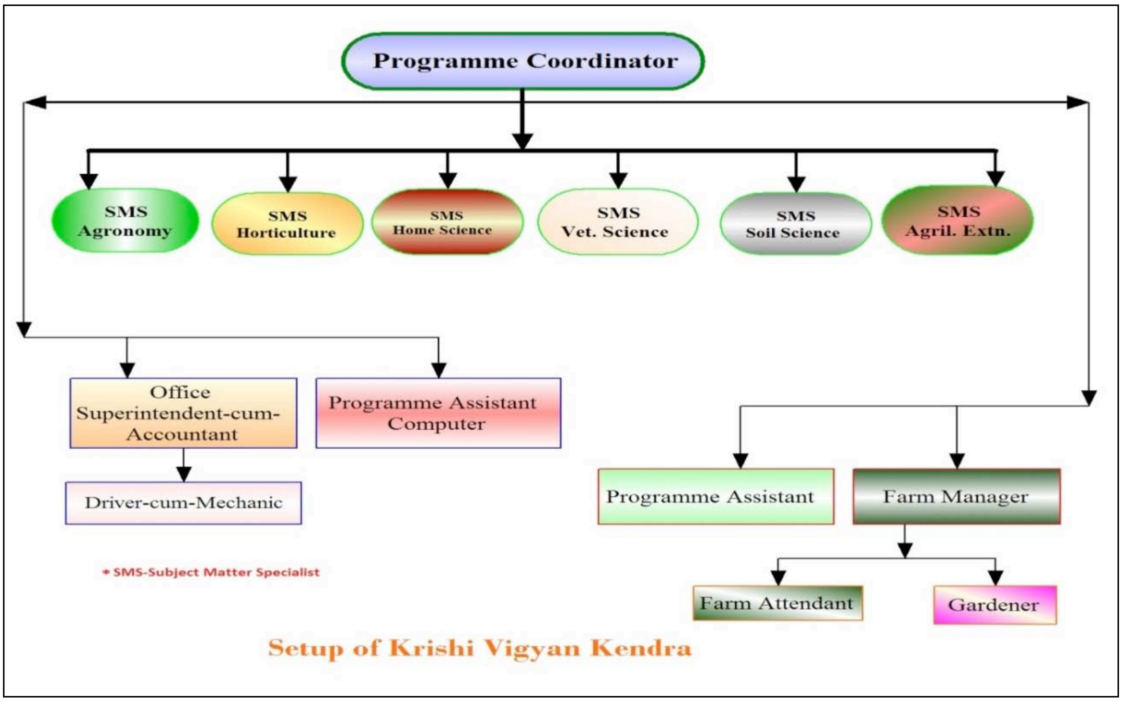

Figure 3.4: Organizational Diagram of a KVK of Uttar Pradesh

The functions and activities of a KVK by practice are managed in a hierarchical order. Each subject matter specialist is responsible to promote extension activities in her/his domain. On an average a KVK conducts 120 to130 need- based training programs on-campus and off-campus in a year for farmers, farmwomen & rural youth (KVK Report Dhaura, 2006).

The KVKs are expected to work with close coordination with the state agriculture, horticulture, animal husbandry, NGOs and other agencies working in agriculture. They are expected to maintain proper linkage with the district administration and local institutions engaged in the transfer of technology as well as the input supply system. Success of extension depends on the amount and degree of functional/effective linkages that a KVK carries in its structurally determined position. However in reality many of the linkages remain dysfunctional due to gap in communication channels among different agents. In this context the DEAL project aims to fill the gaps in the communication channels configuring many conversation loops through social networks mediated by a DE architecture.

[29] NGO – Non Governmental Organization

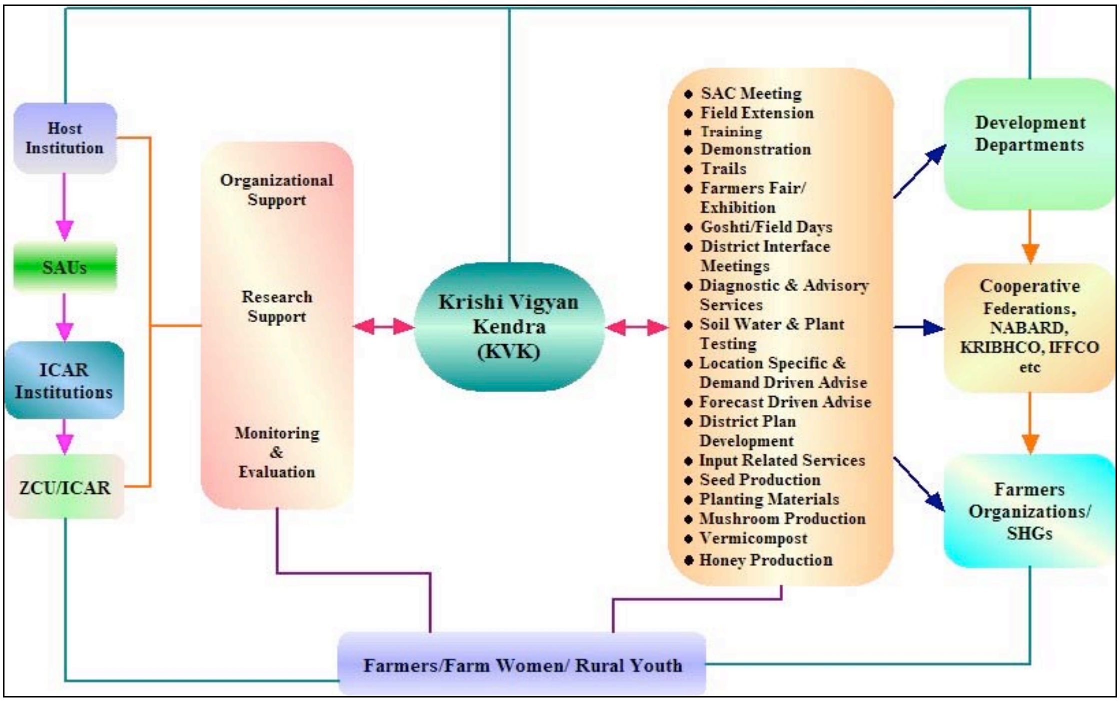

Figure 3.5: Structural Position of KVK in Extension System
(Figures 3.4 and 3.5 are developed by Dr. Vinod Kumar of OPAALS Project)

3.6.2 Agents and Vertical Networks – Pre DEAL Scenario

The positions of actors in the network are based on their role. The network shows the information flows within and across communities. Here, the community is understood in terms of the village unit. Within community linkages are those between actors in the same village – for e.g. between the farmer of a village and the respective KVK, while across links includes links between actors from different villages like the link between farmers of different villages. By the strata of operations classification, information flows between members of the same functional role also qualify– Indian Institute of Technology Kanpur (IITK)[30] is a member of the educational institutions group, KVKs are part of the villages' level functionaries, and the Zonal Coordination Unit (ZCU)[31]/ICAR are all implantation and monitoring agencies. The network diagram (Figure 3.6) shows different sources of agricultural information and the interrelations, both formal and informal, between them. Formal links are characteristic of the reporting relationship between actors – for instance, in the case of a KVK and the ZCU, and informal links are characteristic of the social relations between actors – like relations between farmers of adjoining villages (Rajagopalan and Sarkar, 2008).

In a network the reporting relationship between members consists of different layers – administrative, academic and functional. It is found that while there are well established and clearly defined relationships between members from the different layers, there are very few formal ties between the members of the same layer. For example, the relationship between the ZCU and a KVK, or between a KVK and farmer close and well directed, but there exist no direct links between the four KVKs. Communication is routed through the ZCU, and is conducted face to face at periodic zonal meetings (Rajagopalan and Sarkar 2008).

[30] IITK – Indian Institute of Technology Kanpur, is a higher institution for technical education in India and also the designer of DEAL project

[31] ZCU – Zonal Coordination Unit, is the regional unit of ICAR

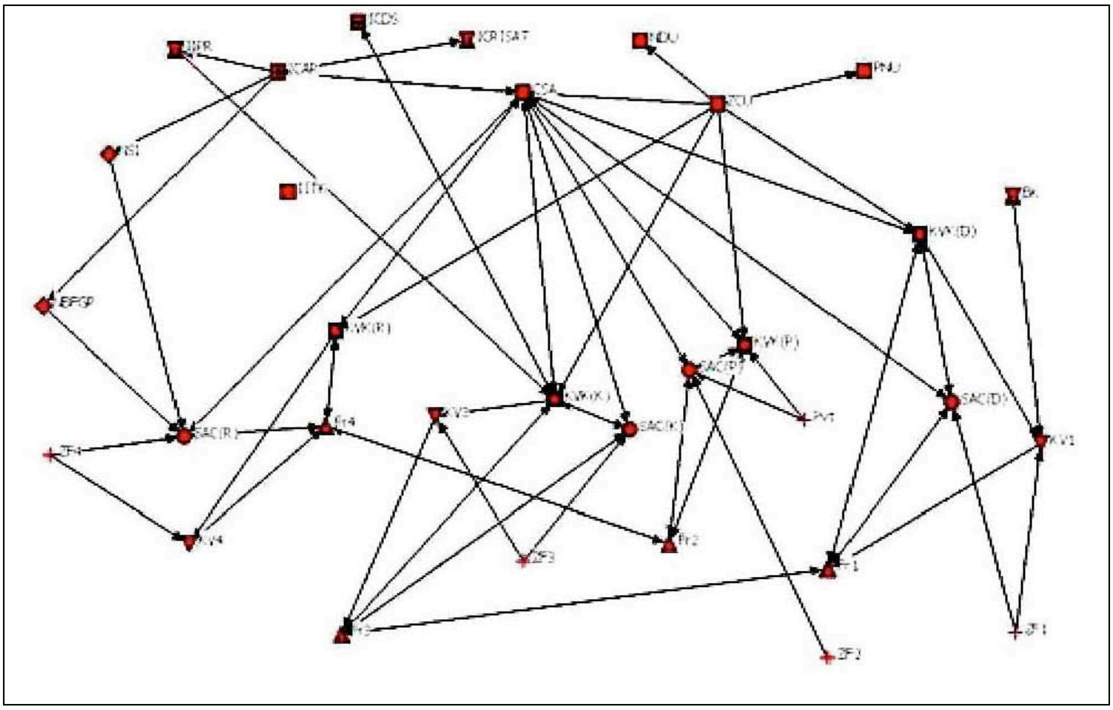

Figure 3.6: Network Ties before DEAL

In the pre-DEAL scenario, except for the informal links between farmers of neighboring villages, the other links represented in the network are structurally determined. There are very few reciprocal ties between members of the same layer – for instance, the links between Pant Nagar University (PNU)[32] and Indian Institute of Pulses Research (IIPR)[33] are both indirect and non-reciprocal (Rajagopalan and Sarkar 2008).

3.6.3 Agents and Vertical Networks – Post DEAL Scenario

Figure 3.7 represents the ties after implementation of the DEAL project. IITK (through the DEAL project) is the new actor introduced into the existing network. Its integration into the network is represented by the arrows between it and other nodes, signifying an increase in information flows. The dotted lines represent ties that have been formed due to content co-creation and sharing by partners that were facilitated by IITK through DEAL, while the solid lines represent the preexisting network ties. By implication, ties formed through DEAL are mostly weak links. These are voluntary clusters of members who are from different groups. Groups in the network can be understood at two levels – one, at the geographic level, which consists of members of different types (farmer, KVK and research institute) at a specific location, and the other is related to functional relationships. These could include academic ties, administrative reporting relationships (financial flows) or operational ties, for example, between KVKs. Linking together all the actors in dynamic relationships helps retain both strong and weak ties.

The total number of ties increased from 77 to 183, and no old ties were displaced. No old actors in the network were deleted after implementing the DEAL and one new node (IITK, the implementer) was added to the network. What was observed was that several weak links were introduced between existing nodes, signifying greater interaction (and hence social capital), and a deepening of community relations. Thus, the ICT intervention has led to the enhancement of social capital (Granovetter 1985, Coleman 1988). Another indicator of this increased interaction is the group reciprocity measures which increased from 0.3585 in pre DEAL to 0.7745 in the post DEAL scenario.

[32] PNU – Pant Nagar University is a technological and agricultural university of India
[33] IIPR – Indian Institute of Pulses Research, is a pulses research institute of ICAR

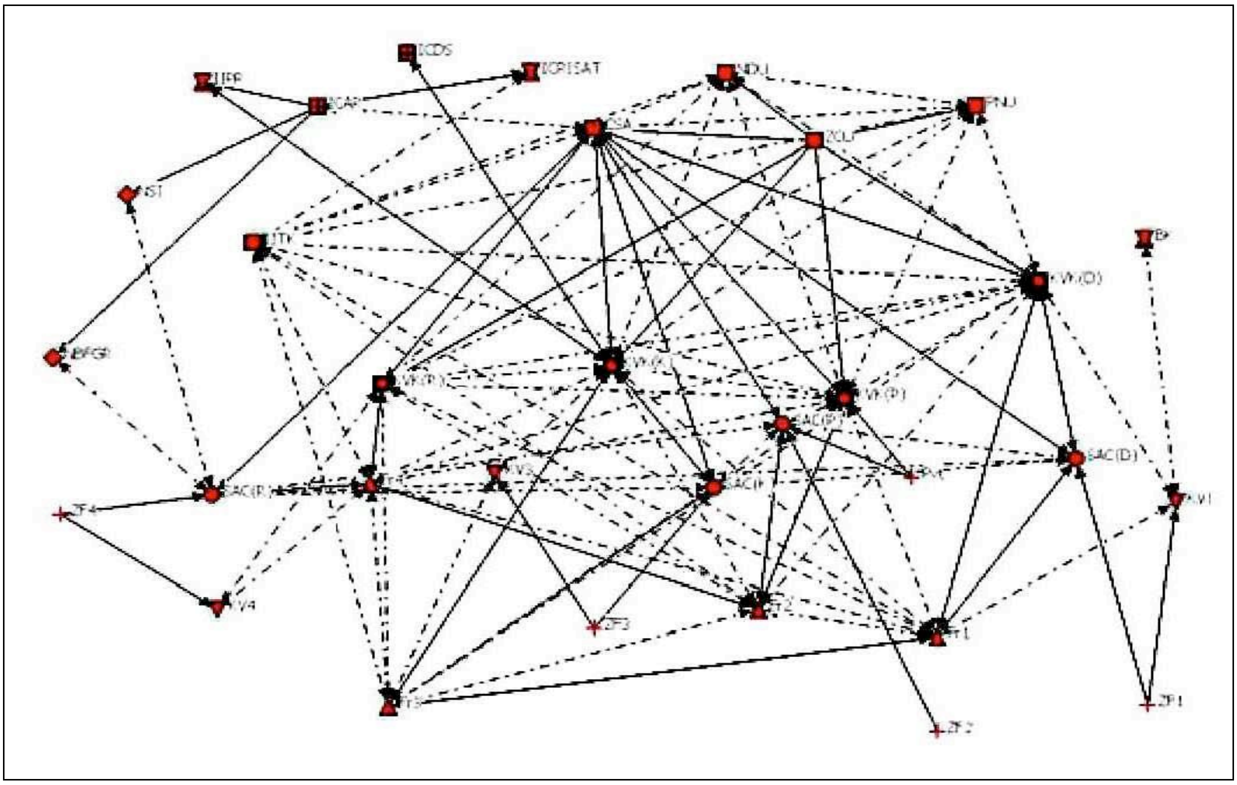

Figure 3.7: Network ties after DEAL

3.6.4 Agents and Horizontal Networks – Pre DEAL Scenario

Our study shows that, in the absence of proper channel to facilitate communicative interaction most of the scientist of the KVK operate in isolation and hardly have any opportunity to gain the information and knowledge about other scientist working in her/his area in another district even at the local level. Within their respective KVK the scientist also have information sharing with other scientist in a limited arena.

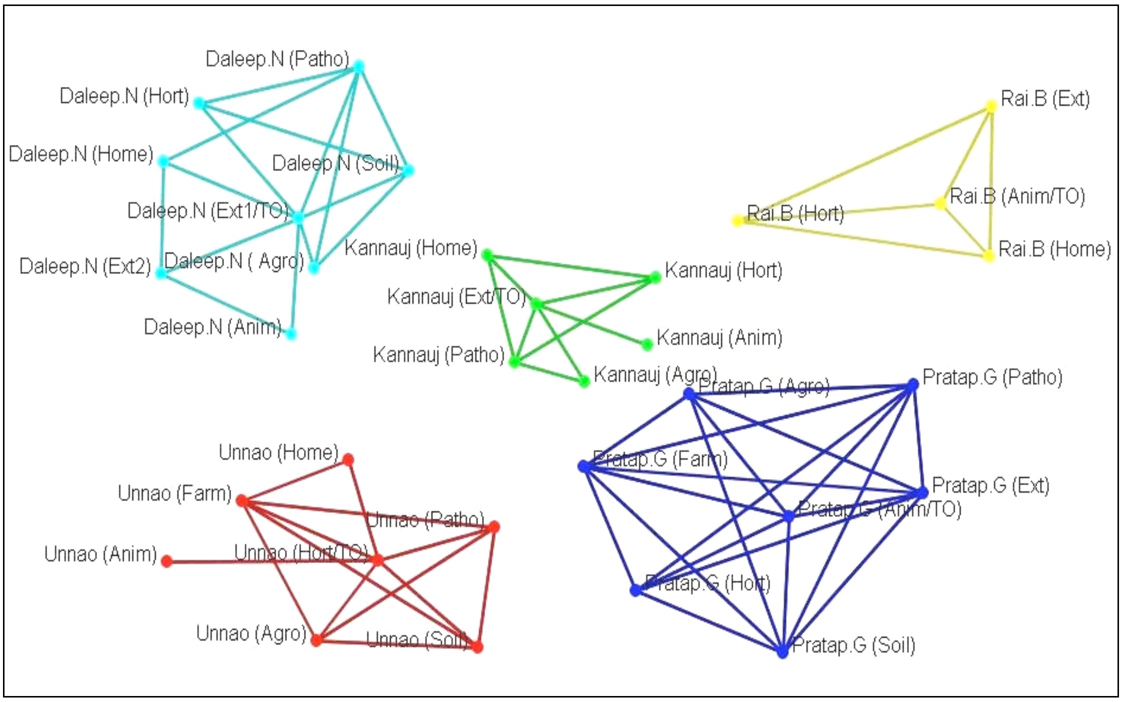

Figure 3.8: Network for Information Sharing among KVK Scientists in the Absence of DEAL

For example in the earlier discussed KVK at Dhaura all the scientist working in the KVK shared reciprocal relationships with the SMS of Horticulture as he was the administrative head of the KVK, where as in terms of actual information sharing hardly they have any reciprocal relation with another scientist (Figure 3.8). It is important to note that the network density for pre DEAL scenario is .1199; total number of links in the interactional space is 119. In pre DEAL scenario SMSs of animal husbandry and home science are most isolated in the interactional domain of information sharing, where as agronomist, plant protection (plant pathology), farm manager and soil scientist have unitary mode of network relations. These forms of relationships hardly meet the rising need of the information resources of the scientist in the present context of the rapid changes that occurs in agricultural technology. The lack of reciprocity among SMS of different KVKs also reflects the current top-down approach of information dissemination in Indian agricultural extension system.

3.6.5 Agents and Horizontal Networks – Post DEAL Scenario

Studies in network architectures suggest that centralized networks are ineffective modes of interaction for information sharing (Fahey and Prusak, 1998; Markus, 2001). In contrast to it a participatory bottom-up approach allows information sharing and communication more effectively. This is where the DEAL has played a crucial role.

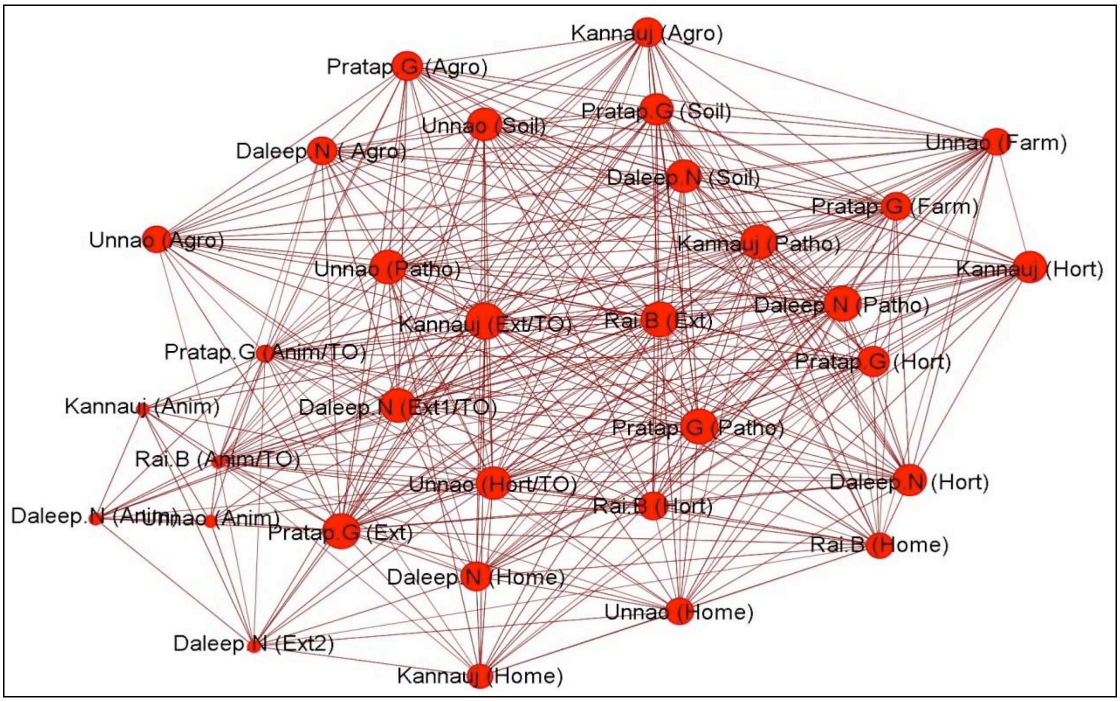

Fig 3.9: Information Sharing among Scientists in a Post-DEAL Scenario

The DEAL aimed to create network among different Subject Matter Specialist (SMS)[34] of KVK by linking each of them to other through digitally facilitated knowledge architecture. The DE design of the system places special emphasis on voluntary participation, and as more members access the network the number of ties increases, and as these ties are mutual and voluntary (Chatterjee, Pattanaik, and Sarkar, 2008). Figure 3.9 shows the network relations developed among various scientist in a post DEAL scenario. The network density for post DEAL scenario is .6279; and total number of links in the interactional space is 628.

Literature in knowledge management and communities of practices suggest that normally people in a structured Communities of Practice (CoP)[35] come from background having shared knowledge or

[34] SMS – Subject Matter Specialist is an agriculture experts as well hey are the field level extension agent of the KVK-ICAR system

[35] CoP – Communities of Practice

shared belief system. In these kinds of structural arrangements often people gets benefit of the facility that is available through structural resources and positions (Baalen, Bloemhof-Ruwaard and Heck, 2005). In contrast to it on the other hand information and communication can build a different kind of network i.e., a network of practice (NoP)[36] by challenging the established normative structure through discursive interaction of different language communities (Chatterjee and Pattanaik, 2008a).

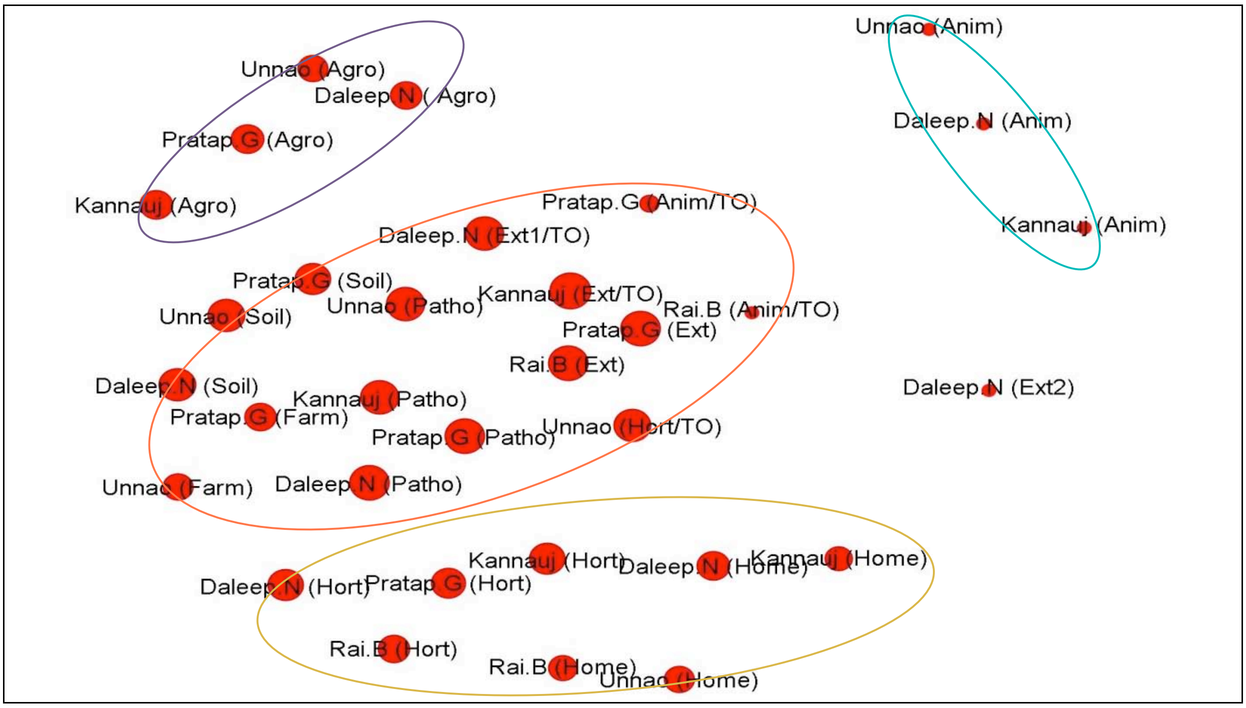

Figure 3.10: Structured Interaction in Language Communities - Post DEAL Scenario

A knowledge portal such as DEAL under these conditions facilitates the process of autopoietic mode of language reproduction by filing the structural holes through generation of social capital in trust-relationship based framework. DEAL as a socio-technical mediator facilitates the bottom up approach for knowledge sharing to the people from different organizations. A network of conversions exhibit inherent circularities and self amplifying feedback loops. The closure of the network results in a shared system of beliefs, values and possibly praxis, a context of meaning, which is continually sustained by ongoing conversation (Chatterjee and Pattanaik, 2008a). The DEAL has able to create a network of relationship among various scientists for information sharing. There is a constant information flow among both within the groups and between groups both at horizontal and vertical level. This has been done by creating a platform for different KVKs to share their extension experiences with each other through hosting a website for each of them. One Such socio technical architecture is the *Kisan blog* at DEAL portal.

3.7 A Note on Kisan Blog

Kisan Blog is a Web 2.0application for farmers to share knowledge in audio format at the portal. The purpose of the audio blog named as *Kisan blog* is to capture and digitize local/tacit knowledge at real time without distortion of the information (Pattanaik and Sarkar, 2008). The interface of the *Kisan blog* is based on audio interface of a blog portal. A person interested to put up any question, can do the same either by recording it in an electronic device or directly through a microphone attached to a computer linked with internet.

[36] NoP – Network of Practice

Figure 3.11: Interface of the Kisan Blog

At the top of the page a link is provided containing information on how to use the blog. For posting any query the user has to log on into the page. It can be done by clicking on the option login at the webpage. It has a fixed login and a password for common user which is given at the bottom of the login page. Each participating KVKs has been allotted with separate logins. This has done to ensure their identity.

Once a user login to the page he can post his query either directly or can upload a file already recorded on an electronic device. The usual time period for direct recording is 250 sec, for upload the audio file has to be below 2mb in size. Figure 3.12 shows the recording procedure step 1 at the Kisan blog. After the recording is done, the user can check the same for quality, clarity etc. by clicking in the option play.

There are additional features to improve the quality of recording which can be accessed by clicking the right mouse button. Once the recording is done the user can submit the same by clicking the submit button. Hence a new page appears where the user can give a title to his audio clip and any other additional information relation to it on text format. An on screen key board (in Hindi) is available for the same purpose. He also can provide identity such as name, place etc in text format. This supplementary information appears at the blog in text format along with the audio clip when it is transmitted in air. When this is done it is automatically stored at the server of DEAL.

However to be on air it requires an administrators permission. The administrator has separate login id and follows the same login procedure. He filters the relevant question and puts them on air. Currently the filtering is usually done by the agricultural experts of DEAL. This has been done with an intention to ensure that the questions asked and the answers provided are valid. Once on air the query appears on the blog site with title, identity and the audio. Users interested in answering the query can do so by clicking on the option 'number of suggestions' which appears at the bottom left of the query.

Figure 3.12: Recording Procedure 1

To answer a query one can follow the same recording method. However answering a query does not require any login. The names of the most recent users who provide suggestions along with associated information related to their designation, expertise, etc. are categorized and appear at the top of the main page of the *Kisan blog*. This ensures authenticity of the suggestion as well as acts as a form of intrinsic reward in the form of recognition to the person.

Figure 3.13: Recording Procedure 2

Kisan Blog holds three possibilities for the upcoming web technology and use in agriculture and rural livelihood domain. (a) It allows capturing the tacit knowledge in its pure form. The distortion of the knowledge does not occur as it is mostly in audio format and is directly added to the portal. (b) It is

based on easy to use and easy to learn mechanism. (c) It ensures collaborative practices for knowledge generation and reuse through intrinsic rewards (Pattanaik and Sarkar, 2008).

3.8 Lessons for Future Research

The DEAL has been able to create a network of relationship among various scientists for information sharing. There is a constant information flow among both within the groups and between groups both at horizontal and vertical level. This has been done by creating a platform for different KVKs to share their extension experiences with each other through hosting a website for each of them. One interesting application is the Kisan blog at the DEAL portal. Contemporary web 2.0 has empowering effects if it is used as a tool for communication and cooperation in civil society. In this sense DEAL as a web 2.0 application has contributed in restoring the lost voices of the ordinary rural farmers in Indian society. It has enlarged the sphere of voices and issues that other wise have remained marginal (Pattanaik and Sarkar 2008). The DEAL experience in expanding the IAES knowledge network and the self catalyzing characteristics exhibited by several applications like the '*Kisan blog*' inspire new research interests regarding the role of participative digital communication as enabler for innovation in large complex socio-technical systems. This research project has also renewed our interest in *Gemeinschaft* and *Gesellschaft* (Toennies, 1957) paradigm to realize as to how Digital Business Ecosystem and Digital Knowledge Ecosystem differ and converge as socio-technical innovation systems.

4. A Study List for Sounding[37] the Epistemological Foundations of the Knowledge Economy in Support of the Practical Introduction of Digital Ecosystems in Argentina[38]

Chapter Authors: Paolo Dini and Lorena Rivera León (LSE)

In this chapter we shift the focus to examine the interface between economics, biology, and physics. We will in particular attempt to reconcile some key concepts that have cross-fertilised these three disciplines in the form of metaphors. We will pay more attention to the metaphors that are relevant to socio-economic development, noting that they tend to be characterised somewhat differently depending on which disciplinary discourse one relies on. We will also compare some of these concepts to how they have been presented and characterised by complexity science. Armed with a more precise semantics of cross-disciplinary relevance we will critically analyse a particular body of economics research that has applied some of these concepts to the Argentinean context, and will offer suggestions for how these strands of discussion can be reconciled with our own research on digital ecosystems and with its potential applicability in Argentina.

This chapter therefore tries to do several things. Starting from the assumption that we are generally unaware of the epistemology we rely upon when engaged in dialogue, it raises the awareness of language use in interdisciplinary contexts and relates it to the relevant underlying epistemology(-ies). We believe this can lead to more fruitful discussions of concepts that span different disciplines, by highlighting the differences in meanings that these concepts can acquire depending on which epistemology they rely upon. Having set up the analytical context in this reflexive manner, the chapter discusses the use of physics language and concepts in biology and economics in order to point out some of the positive and negative consequences of the interdisciplinary discourses that have been conducted in these fields over the past couple of centuries. It then uses these insights to discuss a paper by Yoguel, Erbes and Robert (2008) that applies complexity science to development economics in the Argentinean context. By comparing the theory presented in this paper to digital ecosystems theory and methodology, the chapter then goes on to propose that a complexity science epistemology struggles to represent the reflexive dimension of the hermeneutics tradition within a context of democratic processes and discourses. Representing metaphorically the crossing of this boundary as entering 'inside' the system that has so far been described from the 'outside', the remainder of the paper serves as a case study on two levels: firstly, at the level of the language of applied socio-economics discourse the protagonists are shown to be people who act, speak, and make decisions; secondly, at the level of case study reporting the last two sections of this chapter recount our experiences in Argentina during a research visit in which we presented the digital ecosystems ideas and methodologies to different communities of stakeholders in and near Buenos Aires, thereby providing an example of 'social science in action'.

4.1 Meta-causality, metaphors and history

The overarching aim of this chapter is to begin to discuss a conceptual space whose main dimensions reflect some of the more important epistemological[39] perspectives that have emerged in a number of disciplines over the past few centuries around problems of social development and economic growth. The need for this exercise arises from the fact that we are not generally inclined, or trained, to question

[37] Echo sounding is the technique of using sound pulses directed from the surface or from a submarine vertically down to measure the distance to the bottom by means of sound waves. (www.wikipedia.org)
[38] Based on a paper presented at EULAKS Latin American and European Perspectives on the Social Science-Policy Nexus in the Knowledge Society Conference, Vienna, 8-9 June 2009. (www.eulaks.org)
[39] In Latin countries epistemology is generally associated with the philosophy of science. In the rest of Western philosophy the original Greek meaning has been retained, which is based on the root `episteme' or `knowledge'; hence, epistemology is the study of knowledge or the process by which knowledge is constructed. In this paper we use this latter meaning. See also a similar definition at the beginning of Chapter 3 in this same report.

the specific type of ontological[40] and epistemological assumptions upon which we rely to make sense of the world. Thus, we are seldom aware of the fact that the inference and causal frameworks we routinely use to draw rational conclusions could lead to different conclusions if we 'plug in' different ontological assumptions and epistemological machinery. Taking inspiration from Rosen (1991), Aristotelian causal categories can help reify the elusive and transparent character of ontology and epistemology within a functionalist research framework:

$$\text{ontology} \xrightarrow{\text{epistemology}} \text{methodology}, \qquad (1)$$

where ontology here plays the role of Material Cause, epistemology that of Efficient Cause, and we have taken considerable poetic licence in extending the semantics of 'methodology' to encompass 'reasoning', 'rationality', etc. Because different ontological and epistemological choices lead to different ways to make sense of the world and because, furthermore, we tend not to be aware of having made any such choices, when attempting to communicate across disciplinary boundaries we often fail to understand each other – but we do not know why. Therefore, in this chapter we wish to begin to build a 'dictionary' that can help interdisciplinary researchers understand each other by helping them become aware of their own epistemological machinery and make it explicitly accessible to their collaborators. The depth and complexity of this set of meta-theoretical questions implies that we can only begin to scratch its surface in this short chapter.

We believe a historical perspective is an essential 'meta-methodological' ingredient in the process of translation of concepts between different epistemologies. Metaphors that emigrate to different disciplines, in fact, crystallise upon arrival to form epistemological structures that preserve the 'customs' of the time the migration took place, maintaining thereby the discipline of origin in a state of suspended existence, detached from the 'cultural context' from which it originated and that will continue to develop along its own path. In this chapter we argue that this appears to have happened to Newtonian mechanics in its adoption by biology and economics, and we begin to explore the positive and negative consequences of this historical event.

A historical perspective additionally makes the benefit of hindsight explicit. For example, since the time in the 18th Century when sociology began to acquire its own disciplinary identity as it grew out of physics, it took more than a century for the research community to realise that sociological discourse could be based on different epistemological viewpoints, and that most of these were quite different to the objectivist and realist epistemology of physics. Hence we can likewise infer that current interdisciplinary barriers are most probably symptoms of a similar need to develop deeper meta-theoretical foundations than we have been able to muster so far.

4.2 Study list and chronological map

The body of economic theory, physics and biology over the past 2 centuries that needs to be studied and absorbed in support of this discussion is considerable. In this chapter we indicate a 'wish list' only some of whose items represent areas with which we are currently familiar. Thus, during the course of the OPAALS and EULAKS projects these topics will necessarily be revisited and the discussion begun in this chapter will be extended to reach more complete and operationalisable conclusions.

Some of the topics that populate our study list include:

- institutional and new institutional economics
- economic sociology and gift economy
- neoclassical economics and general equilibrium theory
- evolutionary economics
- Newtonian physics and non-linear dynamics
- development and industrial economics (in this chapter: in the Argentinean context)

[40] Ontology also comes from Greek and means the study, or definition, of what 'is'. Cfr definition in Chapter 3.

- cell biology
- statistical physics and critical phenomena
- non-equilibrium thermodynamics
- autopoiesis and systems theory
- social constructivism and language

Why is this study list relevant to OPAALS and EULAKS research? Because in order to realise the DE vision we must be able to understand and communicate how all the components of a digital ecosystem fit together, at an abstract as well as at a practical level, across all the underlying disciplines, of which the above are some of the salient ones. As stated, this chapter uses Newtonian mechanics as a running thread that strings together the more theoretical aspects of the discussion, for two reasons. Firstly, because the mechanical metaphor has received such bad press in the last few decades that we feel it is important to highlight that it still has valuable things to offer, even in the presence of Rosen's profound and fascinating 30 year-long critique of Cartesian causality. In the development of a theory of bio-computing, in other words, we are advocating that we not throw away the baby with the bath water. Secondly, because a similar critical attitude of the Newtonian mechanistic approach has arisen within Economics, which is one of the core areas of concern of digital ecosystems research.

The next two sub-sections will therefore present a critical discussion of the role played by the Newtonian mechanistic metaphor in these two disciplines.

4.3 Rosen's excursion into the mathematical foundations of circular causality

In 1958-59, as part of his PhD thesis under Nicolas Rashevsky (Rosen, 1958a, 1958b, 1959), Robert Rosen proved a theorem that we have analysed and discussed elsewhere (Dini et al, 2008b) and that is briefly discussed in the conference paper included in the Appendix of this report (Schreckling and Dini, 2009). The significance of this theorem is that it provided a proof of the invertibility of *the cell metabolism repair function performed by the DNA*, offering the mathematical feasibility of *the DNA repair function performed by the cell metabolism*. Thus, it appears that the cell is 'self-sufficient' or self-contained, in the sense that it does not need any information residing outside itself to repair itself – and therefore to maintain its organisation. This has more recently been described (Cornish-Bowden and Cardenas, 2008) as an example of Maturana and Varela's **operational closure**, a concept discussed in D1.2 (Dini et al., 2008a) that was not yet available when Rosen proved his theorem.

4.3.1 The meaning of Life

Interestingly, Rosen took this theorem as a point of departure for a 30-year long theoretical and philosophical excursion into the basis of causality and of the epistemology of biology, following Rashevsky's programme for a Relational Biology as an alternative to the reductionist methodology[41] prevalent to this day (Rosen, 1991). In essence, Rosen provides a convincing argument for the limits of the mechanistic causal model of Newtonian physics, and offers a broader and more general framework founded on the inclusion of an additional Aristotelian causal category: Immanent Cause, or "cause from within". This is equivalent to what we just said about different parts of the cell entailing each other or depending on each other, which can also be stated more formally as the system being closed to efficient causation. From this we can see that Efficient Cause can be intuitively understood as a mapping from a set of inputs to a set of outputs: the mapping that Rosen proved is invertible and hence achieves the closure of the functional interdependence of cellular components. From this Rosen arrives at a definition of life itself as, "A material system is an organism if, and only if, it is closed to efficient causation" (Ibid: 244). This conclusion seems to be quite relevant to OPAALS bio-computing research agenda, since

[41] As discussed more fully in Dini et al. (2008b), reductionism here refers to breaking the cell down to its chemical and physical components, and attempting to explain global cell behaviour in terms of the interactions between it elemental and molecular parts.

> Biology becomes identified with the *class of material realizations* of a certain kind of relational organizations … Biology becomes in fact a *creative* endeavour; to fabricate any realization of the essential relational organization (i.e. to fabricate a material system that possesses such a model) is to create a new organism (Ibid: 245, emphasis in original)

Although Rosen's theory warrants further study, as exemplified in a recent series of articles in which it is still being vigorously debated (Chu and Ho, 2006, 2007a, 2007b; Louie, 2007; Wolkenhauer, 2007), we are left wondering about an apparent omission: in presenting his theory Rosen does not discuss non-linear systems. Non-linear systems are founded on circular causality and feedbacks, so at first this might seem like a very odd omission. To be sure, Rosen goes to great lengths to provide a rigorous definition of a "mechanism" – and of a more restricted family of systems which he calls "machines"[42] – and relates them to linear models (Ibid: 153). So he is certainly aware of the concept of non-linearity. Furthermore, he cites the three-body problem of planetary motion, a famous unsolved problem that is unsolvable in general precisely because of the non-linear character of Newton's universal law of gravitation and the non-linear coupling between the three bodies that it implies.

Thus, although what Rosen says about linear deterministic causality and the Cartesian machine metaphor certainly rings true, there are still some aspects of the story that are unaccounted for. Rosen appears to have relied on an understanding of physics methodology and epistemology that dates back to when Newtonian mechanics was originally developed to model the motion of the planets around the sun in an immutable and reversible solar system. To a practicing physicist Rosen's perspective on what is generally referred to as Classical Mechanics seems a little reductive and not quite up-to-date, even for the 1950s.

However, it is true that non-linear systems generally are not solvable explicitly within the current epistemology of mathematics, in the sense that in most cases their behaviour cannot be expressed as an explicit function of time that would enable quantitative predictions. So perhaps Rosen's deep theoretical results are the other side of the non-integrability medal for systems of non-linear differential equations. Rosen's work is not likely to change the non-integrability properties of many non-linear systems, but perhaps it will open the door to new ways of thinking about such systems, helping us pose different kinds of questions about them.

4.3.2 Structure, function, and abstraction hierarchies

To explain the difference between the reductionist and the systemic viewpoints Rosen (1972) compares the physico-chemical approach, which since the discovery of the structure of DNA in 1953 had been hugely successful at understanding the inner workings of the cell, to his approach:

> The first step in conducting any structural study of a biological system is to abstract away the organizational properties of the system, leaving behind a purely structural residue to be studied entirely in structural (that is, physicochemical) terms. (Rosen, 1972: 219)

In reference for example to the many kinds of cells present in the human body, he notices that

> systems of the utmost structural diversity, with scarcely a molecule in common, are nevertheless recognizable as cells. This indicates that the essential features of cellular organization can be manifested by a profusion of systems of quite different structure. … What we shall do, in effect, is to begin by *abstracting away the structure* (that is, the physics and the chemistry) of the system, leaving behind only the functional organisation, which then can be characterized and studied abstractly. (Ibid) (emphasis in original)

From the above it may seem at first that Rosen has convincingly argued for the *independence* of structure and function in biology. The argument sounds plausible, but we also know about many examples where structure and function are intimately related in biology. For example, the same cells that Rosen is talking about require different structure to perform their specific functions: nerve cells

[42] Rosen relates machines directly to algorithms in a Turing machine (Ibid: 191, 203), but that is a different thread of discussion to the one we are pursuing in this paper.

need to be extremely long and thin (aspect ratio of 10^4 or more), skin cells are localised (aspect ratio close to 1) and have tough walls, brain cells (neurones) have yet another geometry, and so forth. To resolve this point we need only highlight that ‘function’ can take on different meanings depending on the level of abstraction. Where Function refers to cellular organisation, Rosen is quite right and Structure and Function are independent. At lower levels of abstraction, however, where a cell is meant to perform some function within the operation of the organism, its physical structure and geometry matter a great deal for the enablement and carrying out of its function.

So the challenge we see is to be able to reconcile two valid but apparently contrasting views: on the one hand, the study of systems theory, which is “… the study of organisation per se, divorced from material embodyment” (Rosen, 1991: 14); on the other hand, the study of systems as machines whose state transitions are triggered by their interactions with other machines. In biology the latter perspective cannot ignore the physical structure and substrate that ‘carries’ the various states of the system and enables its functional semantics. We contend that both views can coexist peacefully as long as we allow each to apply, independently, to a different level of abstraction of a system’s Function.

Although the concept of organisation is very general and broadly applicable to social science, the above distinction opens extremely interesting questions for bio-computing research. By contrast, we now look at how a similar debate in Economics has evolved along a different path, arriving at a collection of views and ideas that are very valuable to the social science aspects of DE research.

4.4 Hodgson on Evolutionary Economics

In this section we provide a brief discussion of some of the conceptual and theoretical challenges Economics has faced in the last two centuries from a viewpoint of an institutional economist, Geoffrey Hodgson, who has spent a great deal of effort in the past 20 years critiquing the theoretical framework of Economics and especially its overlaps with Evolution. We will in particular focus on his first major work in this area, *Economics and Evolution* (1993). Hodgson’s stated purpose in writing this book is “to question the very roots of modernist science, as applied to economics, in the philosophy of René Descartes and as exemplified by the mechanistic tradition of physics founded by Galileo Galidei and Sir Isaac Newton” (Ibid: 9). Thus, like Rosen, Hodgson feels the need to deconstruct the Newtonian apparatus and replace it with a new framework, in this case built largely around evolutionary thinking rather than around the operational closure of the cell.

Figure 4.1 shows a first draft of a map of economics authors and concepts arranged in approximately chronological order from left to right, meant as a reference and conceptual aid in the discussion. This map was drawn while reading Hodgson’s book, but a similar map could probably be produced from any number of other books. We will in fact continue to develop it over the next few years as we continue to expand the body of economics literature upon which our research relies.

Hodgson begins his discussion by noting that Descartes’s dualism between mind and body, also known as ‘Cartesian boundary’, “… created a dichotomy between rationalism and empiricism” (Ibid: 14). As in other key areas of discussion covered by the book, polarisation is not deemed to be helpful. Another ‘grand dichotomy’ that we have examined before and that we continue to grapple with within OPAALS is between agent-oriented individualism and system-oriented structuralism as the basis for explaining socio-economic action. The manner in which Hodgson proposes an institutional economics perspective as a way to reconcile these polarities within a discussion informed by evolutionary ideas is most interesting. Our objective in this section of the chapter is therefore two-fold: on the one hand, we wish to analyse critically Hogson’s characterisation of the Newtonian mechanistic metaphor, in order to provide a more insightful discussion of the dialogue between complexity science and economics; on the other hand, we wish to highlight conceptualisations from evolutionary economics that can be particularly useful in contextualising digital ecosystems in the economics literature in general and in the Argentinian development case in particular.

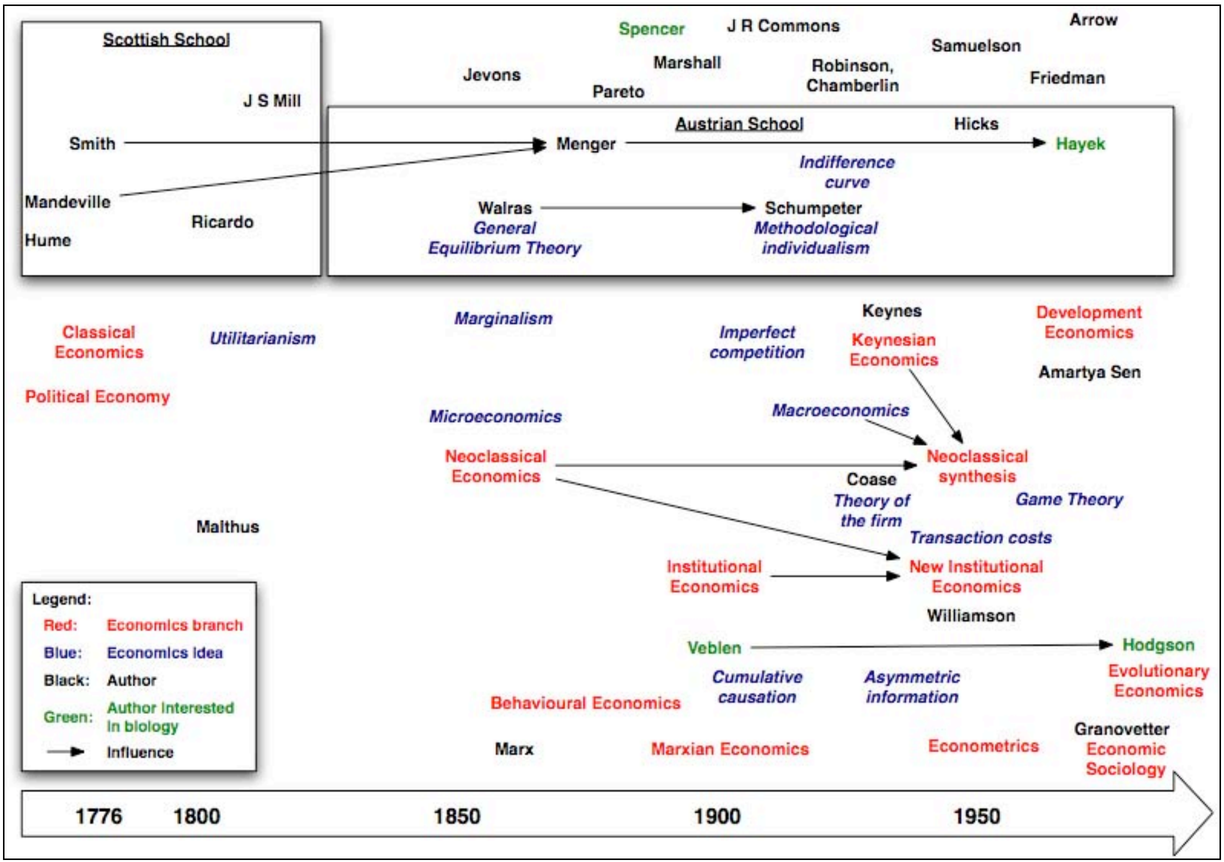

Figure 4.1: Approximate chronological map of economics

4.4.1 Context

In approaching biology and evolution, Hodgson is careful to clarify that

> There are parallels between the natural and the human worlds, but they have to be drawn with care. One of the biggest errors, committed by the Social Darwinists long ago, was to see the individualism and greed of modern competitive capitalism as universal in both spheres. By seeing capitalism in nature, the capitalist system was thus deemed to be 'natural'. (Ibid: 31)

Aside from the obvious pitfalls of Social Darwinism, which has been thoroughly discredited and has not posed a problem in social science for a long time, Hodgson is concerned with showing how biological thinking has informed economic theory since the time of Darwin, creating tension with the entrenched modelling and conceptual frameworks inherited from Newtonian physics. To create some order, Hodgson proposes a taxonomy of evolutionary ideas that provides a very useful reference framework for our discussion and that we reproduce in Figure 4.2.

Hodgson starts from the Latin root of Evolution as *volvere*, which means " 'to roll' but is often used in Latin in a broader sense to refer to the general idea of motion" (Ibid: 37). Interestingly, and somewhat ironically, the term 'evolution' was appropriated by the physics of the 16^{th} and 17^{th} Centuries in reference to the motion of planets around the Sun. In physics, to this day, it denotes 'change (of some variable or parameter) with respect to time'. The governing differential equations of planetary motion, thus, are called the 'evolution equations', and the solution or behaviour of a dynamical system is often referred to as its 'time evolution'. When this term was appropriated again by biology, it carried with it this very clear connotation of 'change', and in particular 'change with respect to time'.

Biology in the 19^{th} Century, even more than today, was still very much under the spell of physics, as was indeed also social science. We could describe the persistence of physics metaphors in the

languages of these disciplines as 'metaphorical inertia' (itself a physics metaphor!), or the consequence of language and culture becoming dependent on the words they acquire, which causes words to be retained in the collective and codified written or oral memory through many generations. Hence it does not seem implausible to claim that the taxonomy shown in Figure 4.2 reflects these different historical layers of the meaning of this gravid word. Of course, the great majority of the speakers of the 'discourse of economics', who are not likely to be experts in either biology or physics, will not necessarily be aware of the subtle and not-so-subtle differences in meaning that different metaphors might carry. Usage breeds new associations, such that fairly quickly a new specialised vocabulary emerges whose words appear identical to the same words used in other disciplinary contexts but that, however, rest on rather different networks of semantic associations. Once the semantic networks in the two disciplines become decoupled in this manner, the evolution of word meanings in the discipline of origin has a small and decreasing influence on the evolution of the meanings of the same words in the new discipline, which is driven by entirely different cognitive – and even epistemological – processes.

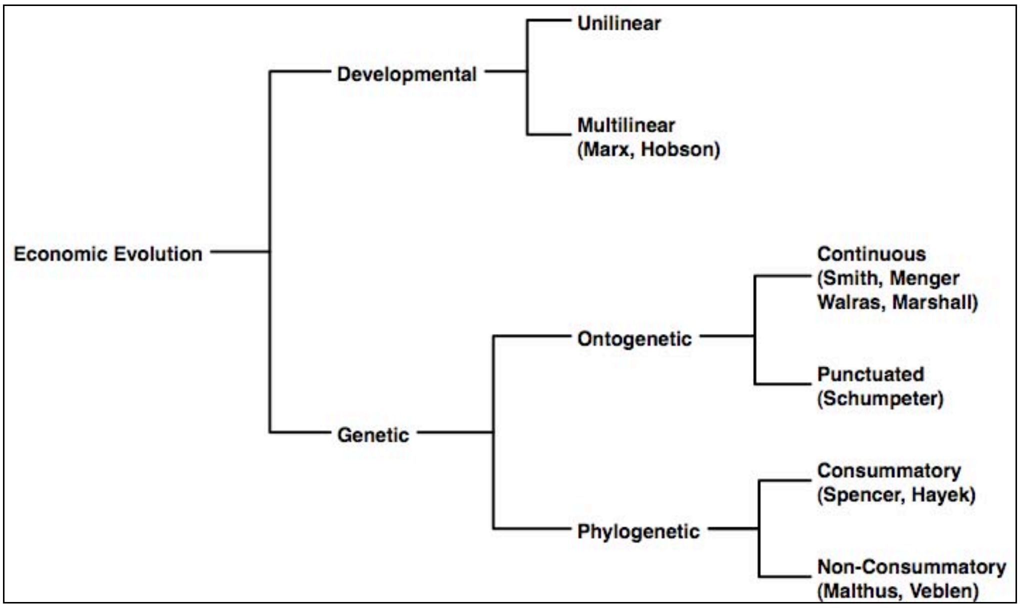

Figure 4.2: Taxonomy of economic evolution meanings (reproduced from Hodgson, 1993: 39)

For example, what Hodgson calls Developmental Evolution does not have much to do with biology at all, but is much closer to the prior physics meaning of the term, such as

> … the Marxian idea that history is progressing – whether deterministically or not – through a series of stages, from 'primitive communism', through classical antiquity, feudalism and capitalism, to socialism and communism in the future. … In contrast, when historical movement is made to proceed in terms of Darwin's biological principles it is impossible to predict the character and form of social change. (Ibid: 41)

Another example is the juxtaposition in the figure above of the terms Developmental and Genetic. In biology the former is synonymous with Ontogenetic, so in the taxonomy above they would fit better together as a sub-category of Genetic. Further, whereas there is nothing wrong with the term "ontogenetic evolution" in English, or from a physics point of view, in the specialised language of biology such usage is generally avoided since the *development* of the individual organism from the fertilised egg according to the DNA blueprint (ontogeny) is a distinct conceptual category from the *evolution* of new species through the mutation, recombination and selection of heritable morphological and behavioural features across many generations of populations (phylogeny).

So even though the taxonomy above is very helpful for understanding the history of economic thought from the particular perspective of evolutionary ideas, a physicist or biologist arriving in the Land of Economics will experience a sense of disorientation because the implicit networks of associations upon which the above taxonomy relies will differ from his or her own. It will be difficult for the traveller to make sense of the knowledge of the new discipline. This is one example of what we mean by a difference in epistemologies.

4.4.2 Herbert Spencer (1820-1903): The first systems theorist

Spencer was a contemporary of Darwin's and is credited with coining the term "survival of the fittest" (Ibid: 81). We find his work particularly interesting for OPAALS since "he proposed a unified system of science, spanning both natural and social phenomena" (Ibid). Further, "Spencer can be regarded as one of the early architects of general systems theory" (Ibid: 83). In DE research systems theory is seen as a holistic perspective that contrasts reductionism. Although Spencer's universalist tendencies brought him close to a systems theory perspective 60 years before Bertalanffy, it is ironic that they also motivated him to develop a physics-inspired theoretical framework for economic dynamics that is actually in contrast with Darwinian evolution and that supported the emergence of the neoclassical model – which today is regarded as the most reductionist understanding of economics. The ground is therefore fertile with lively contradictions. What epistemology could we use to tell the grain from the weeds? We think Hodgson does an excellent job towards the end of his book, which we will discuss below. First, we propose that a physics epistemology may be a good starting point in picking apart the physics metaphors that Spencer so freely mixed.

According to Spencer's use of the energetics metaphor (known today as conservation of energy), equilibrium is attained through optimisation under constraint (Ibid: 86). To a physicist this apparently innocuous phrase could mean a great many different things. Some light is shed when Hodgson explains that Spencer conceived of evolution as

> having its outcome in perfect equilibrium and harmony. Change comes about as units adapt to the pressures of their environment. Motion ceases in the state of equilibrium when each unit has reached the most satisfactory possible state. … The engine of change becomes vaguely subsumed under his Law of Evolution – the move towards increasing differentiation and progress. (Ibid: 86-87)

From a physics perspective and in modern physics terminology, Spencer's law of evolution seems to indicate the intuitive conflation of three natural phenomena: minimisation of energy, maximisation of entropy (these two together give minimisation of free energy), and exponential growth of linear instabilities. These are all indeed spontaneous processes that are relevant to ontogeny, although not directly to evolution. So it seems that Spencer's intuitive awareness of some genuine physical phenomena influenced his conceptualisation of socio-economic processes that were clearly dynamic and superficially analogous to them. We contend that this is a case of very complex socio-economic phenomena being force-fit into an epistemology that is plainly too 'tight' and inadequate.

It is however also worth remarking that these same physics concepts were being discovered and formalised by the physics of the second half of the 19th Century (Bolzmann, etc), and were not as well understood as they are today. So even if the relevance of some of these concepts is uncertain, engagement with concepts outside economics led to a body of work that could serve as a reference, to agree or refute, for subsequent theoretical developments. Nobody could easily disagree with the statement that Spencer's ideas played an important role in the history of economic thought.

In addition to the confusion suffered by 19th Century economics, for better or for worse, even today Hodgson provides further evidence that physics metaphors in economics continue to drift to different meanings. In discussing whether Spencer's ontological standpoint is organicist or atomist, he says:

> Consider, for example, modern general equilibrium theory in economics. Its metaphor is mechanistic, and each part – the individual – is an atomistic and self-contained unit. It is 'organic' only in the limited sense that everything may impinge on everything else – like billiard balls on a table or gas molecules in a jar. … Society is addressed in mechanistic terms. It is regarded as no more than the interplay of self-

> contained individuals pursuing their own ends, plus the social arrangements connecting them. The social system is seen as the complex interplay of atoms rather than as an organic whole. (Ibid: 88)

But to a physical scientist the above characterisation of 'mechanistic' is very limiting! 'Mechanistic' here is taken to refer to the ideal gas metaphor of atomism. The interactions are taken to be collisions rather than, for instance, time-dependent potentials (i.e. non-linear coupling). The profound complexity of the n-body problem (n > 2) is entirely lost. One cannot help but point out that non-linear coupling and the n-body problem are both entirely within the 'Newtonian mechanistic model' – according to the physics interpretation of the term.

Thus, the problem is not that general equilibrium theory is not reductionist or mechanistic. General equilibrium theory is both these things. But 'mechanistic' means *much more* than the ideal gas law. The problem is that in the 19th Century understanding of Newtonian physics this was not fully appreciated. Today we know that the whole of Chaos Thoery lives happily within the Newtonian paradigm, and that by taking the limit to large numbers of particles the whole of statistical physics, phase transitions, and critical phenomena can be easily reached by extrapolating Newtonian physics.

As we will discuss below, current work that explores the possible relevance of applying complexity science to economics is proposing interesting and valid ideas. Oddly, however, the merits of the new science are extolled by juxtaposing it to the 'bad' Newtonian mechanics, which must be duly ostracised. Our point is that this is both unnecessary and unfair. It is also self-defeating since more confusion is created – although, in fact, nobody seems to mind. Why is that? As already hinted, when concepts leave the haven of physics objectivism they become vulnerable to re-elaboration and re-interpretation through language and cognitive processes that are not dependent on experimental data, or at least not in the same way. Observed social or economic phenomena are compared to conceptual structures that are partly subjective and that partly rely on other concepts present in the culture, and all these processes are mediated by language – which continually begets new conceptual structures. 'Verification' therefore becomes a process that is relative to a context that is stable only insofar as the participants in the discussion agree on its characterisation and share the same inferential system, but that could drift to new interpretations as the shared understanding shifts. This is what we understand by an inter-subjective and social constructivist epistemology, an example of which is briefly discussed in the next section.

4.4.3 Shedding the metaphors: Institutional economics

Hodgson spends a couple hundred pages in an illuminating analysis and discussion of many of the authors and topics depicted in Figure 1. Most significantly, he devotes a significant amount of time to a discussion, and eventual refutation, of Hayek's methodological individualism and of the reductionism of microeconomics. Having deconstructed a great deal of the economics canon, and much of Newton too in the process, in the last chapter of his book he takes off on his own, for better or for worse finally free of all the excess baggage handed down from physics and, upholding Veblen's tradition, defines institutions as units of analysis:

> Among the preliminary tasks of scientific analysis are taxonomy and classification, involving the assignment of sameness and difference. Classification, by bringing together entities in discrete groups, must refer to common qualities. For classification to be enduring, it must be assumed that the common qualities themselves must be invariant. … the relatively invariant unit is the social institution. We may define institutions in broad terms. They refer to the commonly held patterns of behaviour and habits of thought, of a routinized and durable nature, that are associated with people interacting in groups or larger collectives. Institutions enable ordered thought and action by imposing form and consistency on the activities of human beings. … Institutions are seen as both outgrowths and reinforcers of the routinized thought processes that are shared by a number of persons in a given society. (Ibid: 252-253)

The language above is self-sufficient, self-contained, and clear. It needs to apologise to no other discipline and depends entirely on the shared understanding of basic terms such as "people", "habit", "activity", 'thought process", "group", etc to build up the more complex and abstract concept of "institution". As long as the shared understanding of the basic terms does not change, the meaning of

the term "institution" will remain stable. Thus we can see the importance of the cultural and historical context for providing a stable foundation below everything else.

Interestingly, the construction of semantic hierarchies appears to be recursive. In fact, with the elemental concept clearly defined, larger concepts such as macroeconomics can be described, and it is also easier to open up to complexity science and even autopoiesis:

> The macroeconomic system may be treated as a legitimate unit and level of analysis only if it has its own intrinsic set of institutional structures. To be regarded as an autopoietic or self-organizing system, these constituent institutions and structures must be partially autonomous and strongly self-reinforcing. (Ibid: 263)

Hodgson concludes his book with the vision of a hierarchical ontology, where each level of the system is not entirely determined by the level below (microeconomic reductionism) or above (Marxist structuralism), but "… because the levels are connected, assumptions made about a particular level cannot be arbitrary, and attempts must be made to render them consistent with other assumptions or results, at lower, hither, or equivalent levels" (Ibid: 266).

In this sub-section our purpose has been to show how a well-respected scholar, who is generally regarded as a 'heterodox economist' and who has invested a significant in building a useful bridge between economics and evolutionary theory, arrives at a conceptualisation of socio-economic structures that is at once firmly rooted in social science discourse, without needing any physics, and evocative of complexity science themes such as nested hierarchical structures. In the next sub-section we switch gears to a different strand of heterodoxy built around the work of Cristiano Antonelli, who is an important reference for our Argentinean partners in the EULAKS project.

4.5 The Rich Discourse of the Economics of Complexity

This section touches on two sources: Cristiano Antonelli's latest book on the economics of complexity (Antonelli, 2008), and a paper on the application of complexity science to development economics in the Argentinean context (Yoguel, Erbes and Robert, 2008). As in other parts of this chapter, this discussion should be considered only a first step in a longer, broader, and deeper study of these themes.

Antonelli defines localised technological change in the context of complexity theory as follows:

> Localised technological change is the endogenous outcome of the induced creative reaction of firms exposed to unexpected changes but able to change their technology. … The basic apparatus of microeconomics is retained, and yet the appreciation of the complexity of decision making in a world characterised by irreversibility, localised knowledge, creativity and social interactions leads to understanding of the dynamic variety of outcomes that are possible at both the aggregate and the disaggregate levels, where learning agents are supposed to be embedded in a collective and localised context of action and able to try to change intentionally their technologies. (Ibid: 1-2) … The merging of the theory of complexity and economics contributes to the buiding of an economic theory of complexity based upon non-ergodicity, social interactions, phase transitions and emerging properties. The notion of path dependence as the specific form of complex dynamics applied to understanding economic systems as evolving systems makes it possible to integrate into a single and coherent framework a number of relevant and complementary contributions (David, 1988, in Antonelli, 2008: 3)

The limit of the frequency distribution of an infinite series of random samples taken from a non-ergodic system does not equal a Gaussian. In other words, the Central Limit Theorem, or the 'law of large numbers', does not apply in such systems. In physics, these tend to be open systems that fall outside the laws of equilibrium statistical mechanics. Prigogine (1996) has developed a theory of non-equilibrium thermodynamics to deal with such systems that shows how their distance from equilibrium is a necessary condition for them to exhibit (one particular class of) self-organising behaviour. Now, that's a mouthful, and we have not defined self-organisation or emergence yet. What

could phase transitions possibly have to do with socio-economic systems? Phase transitions are global changes in the properties of large systems arising from changes in the regime of local interactions between their microscopic elements. Socio-economic agents certainly interact, so at a metaphorical level it seems plausible that one could make this kind of analogy.

We could go on explaining in turn the precise physics meaning of each term. However, this does not appear to be necessary. An engineer/physicist/mathematician who has become acquainted with social science[43] cannot help noticing a difference in the way in which the meanings of these terms are handled in these two disciplinary domains. Although one can argue that mathematics and physics are just 'texts' or that they are just languages that are as socially constructed as everything else, the social construction takes place at the level of axioms and of choice of deductive and inference rules for theorem proving, which henceforth provides a stable epistemological backbone for these disciplines. On the other hand, in spite of the fact that within social science there are many and markedly different philosophical currents and epistemological frameworks, from the vantage point of the 'hard' sciences one notices a significant overlap in the characteristics of the discourses of social science, namely a significantly greater reliance on language processes than on theorem proving processes. Social science discourse, therefore, cannot help relying on what to an outsider look a lot like social constructivist processes – even for disciplines such as economics that would recoil at such a label!

Thus, while on the one hand a precise definition and integration of the above complexity science terminology within a *theorem-based* modelling framework of socio-economic relevance would require an immense amount of work, if it is even possible, on the other hand we notice that we do have an *intuitive* idea of what these terms mean and how they might apply to socio-economic systems and actors. Thus, whereas a physics epistemology would not be able to cope with making sense of such systems, we observe from the literature that a social science epistemology is much more comfortable using these terms liberally and relating them to social science ways of making sense of things, such as qualitative empirical research and quantitative economic data.

It is on the strength of the many publications that have been produced in this way that we now proceed with a brief discussion of Yoguel, Erbes and Robert's paper (henceforth YER).

4.5.1 An analytical framework within the Economics of Complexity discourse

The objective of YER's paper is to examine the process of economic development at different scales of description and from the point of view of complexity science applied to economics:

> In this approach, the economic structure can be understood as a set of systems and sub-systems defined at different levels of aggregation. These structures interact among themselves within a framework of temporal irreversibility, radical uncertainty, disequilibrium and nonlinear path dependency

From this perspective the time evolution of economic systems is guided by two emergent processes: self-organisation and adaptation. Broadly speaking, self-organisation can be understood either through incremental memory-based processes such as ant colony pheromones or Darwinian evolution, where the DNA is the 'memory', or through more dynamic processes driven by the fall towards equilibrium. When the latter occurs in open systems we have the interesting fact that a constant energy flow maintains them away from equilibrium; such an energy flow, however, does not prevent the system from continuing to fall towards equilibrium. Hence spontaneous self-organising behaviour continues indefinitely, until the energy flow stops (lack of food) or something in the system breaks (sickness). Thus we can see that in biology

$$\text{Equilibrium} = \text{Death} \tag{2}$$

The more dynamic variant is of course the basis of ontogenetic evolution already discussed, which however integrates nicely with Darwinian evolution as soon as we allow reproduction of the organism

[43] The first author of this chapter fits this description.

to different generations. Adaptation requires either preprogrammed flexibility to a range of inputs or environmental contexts, or structural change across generational boundaries, i.e. evolution again.

Whereas these meanings are quite constraining, it is clear that YER have a much more powerful and dynamic process in mind, where the central role of human agency is an indispensable starting assumption. Hence, the emerging discipline of complexity science applied to economics necessarily combines physics ideas and concepts with conceptualisations of system 'components' at much higher levels of abstraction, i.e. human beings and the institutions they generate through socio-economic and cultural processes. As long as we are able to recognise that the epistemology of the Economics of Complexity is bipolar, the discussion can be very interesting, illuminating, and effective.

Hence, YER explain that this approach enables descriptions of economic systems based on

> (i) diversity and heterogeneity of skills and routines of its components, (ii) temporal irreversibility, as a result of a dynamic driven by a non-ergodic path dependence, (iii) disequilibrium interactions among system components, and (iv) the presence of institutional rules, learning, discoveries and space of selection operating as coordination mechanisms that potentially enable change and reduce radical uncertainty.

They explain that radical uncertainty in this case refers to the unavoidable and irreducible ignorance about future outcomes that economic agents have to face whenever they need to make an economic decision.

Thus, it is clear from the above that the complex systems perspective is utilised to provide an inferential framework that enables explanations through a conceptual vocabulary that is more attuned to the classical physics of the 19^{th} and 20^{th} Century than to the classical physics of the 17^{th} and 18^{th} Centuries. In either case, however, by relaxing the constraints of the objectivist epistemology of origin, the discourse of complexity science can be 'stretched' to accommodate the description of phenomena that originated in the hermeneutics tradition and that can therefore already be clearly expressed through, for example, the discourse of social constructivism.

For example, the level of development of an economy is explained by the CAS concepts of self-organisation and adaptation,[44] which enable "processes of creative destruction, structural change and appropriation of quasi-rents on the one hand, and absorptive and connectivity capacities on the other, at different levels of aggregation". In particular, YER posit a causal dependence of the former on the latter, in the sense that "the level of skills and linkages of economic agents (are) the key element for understanding the generation of knowledge and appropriation of quasi-rents" (Yoguel et al., 2008). Further, their research shows that connectivity capacity is influenced by absorptive capacity, where 'capacity' is a metaphor that combines the concept of potential energy with the concept of geometrical volume to connote 'ability to engage' and 'scale or intensity of engagement'. But connectivity acts as a feedback since it enables further absorption.

By contrast, when such feedbacks occur in physical systems, they are modeled and represented through quantitative relationships between the measurable variables in which the variables appear as functions of time that are multiplied together, rather than only being added or subtracted, and/or with power other than 1. This is why they are called non-linear.

For example, if connectivity depends on absorptive capacity, but absorptive capacity is, in turn, enhanced by the connectivity it enables, we can write

$$\text{absorption} \rightarrow \text{connectivity} \rightarrow \text{more absorption}, \qquad (3)$$

where the arrows denote a causal link. Looking at the first arrow, one of its possible reductionist interpretations is that the connectivity is proportional to the absorption:

[44] See Chapter 1.

$$\text{connectivity} = k \cdot \text{absorption}, \quad (4)$$

where k is the assumed constant of proportionality. Notice that the absorption variable appears with power 1, so Eq. (4) is linear. The second arrow implies a change in the absorption variable, which is plausible and convenient to express with respect to time:

$$\frac{\text{d(absorption)}}{\text{dt}} = h \cdot \text{connectivity} \quad (5)$$

This equation is also linear. Because connectivity depends, in turn, on absorption (we are traversing the causal chain in Eq. (3) in reverse), what's actually happening according to this very simple model is that

$$\frac{\text{d(absorption)}}{\text{dt}} = h \cdot (k \cdot \text{absorption}) = h \cdot k \cdot \text{absorption} = j \cdot \text{absorption}, \quad (6)$$

where $j = h \cdot k$ is just a new constant. This is a linear differential equation whose solution is the familiar exponential function (which is itself non-linear). In the presence of more complicated causal interdependencies, for instance

$$\frac{\text{d(absorption)}}{\text{dt}} = \text{absorption} \cdot \text{connectivity} \quad (7)$$

we obtain

$$\frac{\text{d(absorption)}}{\text{dt}} = \text{absorption} \cdot (k \cdot \text{absorption}) = k \cdot (\text{absorption})^2, \quad (8)$$

which is a non-linear differential equation. This leads to even faster growth, as might be intuitively clear. In general there is no limit to how complex the mathematical model could become, leading very quickly to problems that are not solvable and where the system's behaviour cannot be expressed in terms of elementary functions of time. More importantly, a more complex model is not necessarily more explicative, accurate, or useful.

Leaving aside extremely reductionist mathematical models such as these, YER are interested in characterising econometrically the relationship between absorptive and connectivity capacities between 359 firms from different production networks in Argentina (automotive, steel, apparel, services related to oil industry, agricultural machinery, metal mechanics and ship building). Complexity science helps, them and us, conceptualise the behaviour of self-reinforcing processes, for example, where the entity can be an institution, a network, or a capacity. Where the entity cannot be measured or quantified directly, it is generally possible to measure a related variable in order to extract some relevant information, thereby making the analytical approach workable at a practical level – even if not necessarily fully representative of the socio-economic phenomenon.

Like Hodgson, YER point out that there are different schools of complexity science thinking: one inspired by Marshall and Schumpeter is inspired by ontogenetic processes, whereas a second that they identify with the Santa Fe Institute is inspired by Darwinian evolution. Of course as we have seen it is not so easy to make clean separations, because in the Complexity of Economics metaphors from biology are usually borrowed freely without worrying too much about isomorphic faithfulness to the original ontological and epistemological context. Thus, Schumpeter's creative destruction includes also selection mechanisms. Be that as it may, YER side with the former as providing a framework for the construction of order from dynamic interactions that appears to be easier to relate to the dynamics of socio-economic systems. In digital ecosystems research we try to reconcile both views (see Chapter 5 in this report) but it does seem that the ontogenetic viewpoint offers slightly easier similes and metaphors to work with in developing explanatory theories for socio-economic systems. The clearest

example of this is probably how the concept of interdependence applies equally well to the agents in a market, the species in an ecosystem and the components of the cell. By contrast, as discussed by Hodgson the determination of the unit of selection and of the analogue to DNA in socio-economic systems remains a challenging theoretical problem.

According to YER, order is created "from the absorptive and connectivity capacities of its components, (which) make it possible to exchange knowledge and energy with the environment, which externalises the production of entropy whilst constructing order internally to the system" (Yoguel et al., 2008). This is a bit of a stretch, because it is difficult to assess to what extent such a close analogy to biological construction of order through free energy minimisation can apply to the behaviour of socio-economic systems, or indeed what entropy means in such contexts. In any case, YER do offer a broad framework over multiple scales that characterises the dynamics of agents through the interaction of absorptive and connectivity capacities and relates it to the meso and macro-level dynamics through the complex systems properties of self-organisation and adaptation. At the macro level the dynamics is dominated by processes of creative destruction, appropriation of quasi-rents, and structural change. The presence of a mechanism that couples the micro to the macro levels is most interesting and warrants further epistemological analysis of the kind we have indulged in in this chapter. As this will be pursued in our future work towards D12.10, we now turn to YER's discussion of their empirical findings.

4.5.2 Empirical findings from Argentinean industrial production networks

YER performed a quantitative empirical study of the links between the following socio-economic actors: firms, intermediates institutions like chambers of commerce and consultants, and academic and research institutions. On the other hand, absorption capacity was measured by looking at the quality management, training activities, work organisation, and the presence and kind of R&D teams. They found low levels of connectivity and absorption capacity, implying also weak feedbacks. The study showed absence of a correlation between skills and linkages between firms, which YER think is consistent with the context of Argentina as a developing country. Second, thesholds in absorptive capacity were shown to be necessary for accessing links with intermediate institutions. Third, also the links with universities were poor and were found to depend on a similar threshold.

YER then compare these results to their analogue from developed countries and draw inferences about the development potential of countries like Argentina in terms of the quantitative indicators of the study. The inference relies on the complex systems properties to connect the data at the micro level to the performance at the macro level. However, rather than a tight deductive process, as would be required in the physical sciences, the discussion is broader and punctuated by references to data and to other similar studies, to produce an interesting and convincing account of a wide range of complex socio-economic phenomena relevant to the discourse of economic development.

The paper ends with a section on policy remarks that benefits from the thorough econometric analysis and synthetic framework just built, in the sense that intervention at the micro level to increase the connectivity and absorptive capacities of Argentinean socio-economic actors seems like a plausible lever point based on the foregoing.

4.5.3 Comparison with the digital ecosystems approach

The digital ecosystem approach has relied from the beginning on an alternative epistemological framework founded on the hermeneutics tradition and on the phenomenology of Heidegger which was inspired by the work of Winograd and Flores (1985), who were among the first to claim that computers are not about *computation*, they are about *communication*.

As discussed more extensively in Dini (2007), in the DE community the prevalent understanding has been that the motor of socio-economic action arises from social constructivist processes founded on intersubjective understandings of social and economic institutions mediated by language processes. Following Winograd and Flores (1985), DEs are seen as socio-technical systems whose main function is to facilitate communications. Thus, technology is seen as both a social construction that cannot

afford to claim value-neutrality, consistently with Feenberg's (Marxian) critical theory of technology (Feenberg, 1991, 2002), as well as a catalyst of socio-economic interactions that can accelerate the same processes that underpin socio-economic development.

However, we cannot risk being perceived to say that technology will solve everything simply because it accelerates all the socio-economic processes it mediates. This would be worse than technocentrism, which is intrinsically limited by its objectivist and realist ontology. We must highlight that social constructivist processes can lead to both 'positive' as well as 'negative' outcomes, depending on the reference framework and starting assumptions a particular community or social group adopts. Thus, a good part of our work has focussed on exploring the foundations of the "principles of digital ecosystems" that have appeared in various publications over the past 7 years (Nachira, 2002; Dini et al., 2005; Dini and Nachira (2007); Dini (2007); Nachira et al., 2007; Darking et al., 2008; Dini et al., 2008) in an attempt to explain them and legitimise them in terms of agreed objectives. This is a big task that is still on-going and that we cannot properly do justice to in this chapter. We can summarise the main points and leave a more thorough and complete discussion to our next deliverables in the 'foundational' series of OPAALS, D12.10.

Digital ecosystems research is by design meant to adapt to the context in which it is instantiated. Taking inspiration from, among others, Moore's work (1996), the 'European instantiation' of DEs was originated by Nachira (2002) around two main objectives:

- Achieving sustainable socio-economic development led by SMEs and catalised by ICT
- Strengthening the European software industry, esp by strengthening European software SMEs

These two high-level objectives were assumed to be most easily reachable through three high-level principles:

- Avoiding single points of control and failure in the distributed software architecture and in the economic models supporting B-B interactions (i.e. avoidance of centralised servers and monopolies)
- Adopting an Open Source approach for the infrastructure in order to foster collaboration and shared responsibility through shared ownership
- Defining the area of policy intervention at the EU regional/local rather than national scale

A more thorough analysis and re-elaboration of these fundamental objectives and principles is the object of research of many researchers in the OPAALS project and in other related projects, as can be seen also in all the chapters of this report. Our discussion in this chapter and in this section can in particular be seen as a further elaboration of Section 1.2 on the fundamental social science research questions, including some of the possible answers. We are also working on it in the EULAKS project, currently as a draft available at www.eulaks.org (Rivera-León and Dini, 2008). We can also utilise Figure 4.3 to show our current understanding of what makes a socio-technical-economic system a digital ecosystem, which relies on this working definition:

> A Digital Ecosystem (DE) is any autonomous, distributed, adaptive, and open source socio-technical-economic system that fosters the emergence of properties of self-organisation, interdependence, sustainability, and scalability and is inspired by natural ecosystems, evolutionary processes, and autopoiesis. If we place less emphasis on the technical or economic dimensions, a DE can also be viewed as a collaborative community based on democratic and multi-stakeholder processes, and reflexively organised around language and language processes. It is composed of multiple, independent individuals and/or organisations (enterprises) sharing structural concerns related to the avoidance of centralised points of control or failure in the architecture and in the socio-economic organisation as assumed preconditions to facilitate and enable just socio-economic development (Iqani and Rathbone, 2009).

As one of the points of relevance of complexity science, digital ecosystems research seeks to realise the vision of self-organising software that incorporates and exhibits both ontogenetic and phylogenetic properties. This requires an in-depth study of the foundations of computer science and how they may need to be modified to achieve adaptive and evolutionary behaviour. DE research, therefore, needs to work also with biologists in order to discover together some aspects of cellular organisation and the best modelling methodology to be followed. A hypothesis that we do not have the space to discuss here but that we plan to examine in greater depth in future work is that the best strategy to achieve bio-computing (knowledge flow from biology to computer science) is to develop simultaneously models that are relevant to computational biology (knowledge flow from computer science to biology). The paper in the appendix by Schreckling and Dini (2009) gives an idea of how far we are along this path.

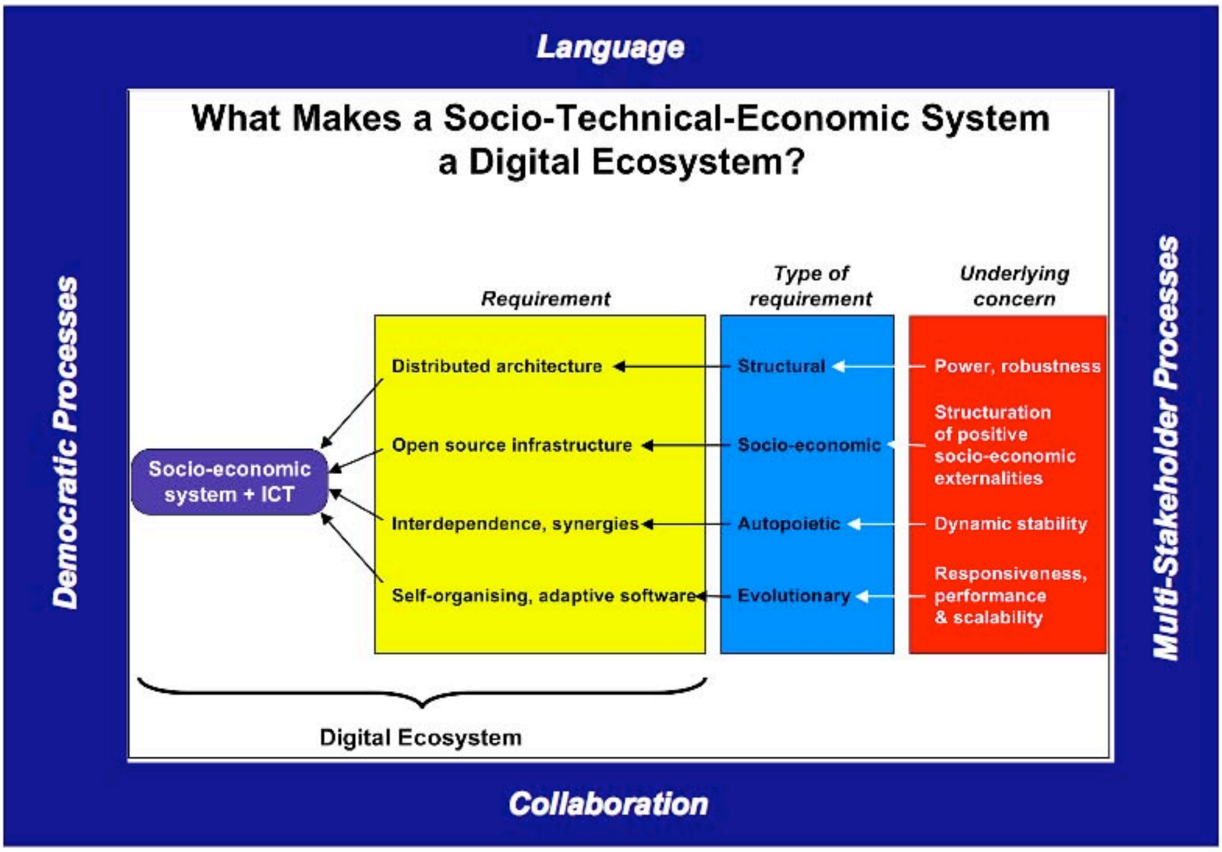

Figure 4.3: Reconciling the diagrammatic view of DEs with the underlying social and democratic processes without which a DE cannot be realised.

Although as can be seen from the chapters of this report we find significant value and interest in applying the complexity science, biological, and autopoietic perspectives to economics and to social systems in general, we also feel that we need to be vigilant about the bedrock upon which any sustainable socio-economic system must be built. The assumption in DE research from the beginning has been that the bedrock of *sustainable* socio-economic systems is a framework that clarifies the role of democratic processes in addressing issues of power aggregation and distribution, accountability, and trust. For the construction of this framework we feel that social science does not need any help from physics or mathematics in stating the problem and in working, through a multi-stakeholder process, towards possible solutions.

In fact, although we fully support in the need for debate and consensus-building in the 'democracy of ideas', we think that the complexity science viewpoint carries significant hazards when approaching themes of power and democratic process, because its epistemology does not account for concepts such as reflexivity, individual expression, and power relationships as effectively as, for example, the

hermeneutics tradition of social science. This hazard is the principal reason for maintaining an open mind about when complexity science ought and ought not to apply in digital ecosystems research, and for continuing to critically analyse it and, where possible, extend it (this will be the focus of Deliverable 12.10). In other words, just as technology development cannot afford to be agnostic about the cultural values the technology embodies, digital ecosystems research cannot afford to be agnostic about the ontological choices its epistemology embodies.

Figure 4.3 can be used as a significantly simpler but still useful example of what we are trying to say. The central area of the figure with white background is a conceptualisation of what a DE is that inherits from the model-making tradition. It is a formalised depiction of what a DE is that is itself a 'system' of interrelationships between abstract concepts outside ourselves. The central part of the figure objectifies a DE as a system and DE research as a workflow. The blue frame is a humble attempt at reminding ourselves that without a multi-stakeholder process, without collaboration, without language, and without democratic processes – without, in other words, rolling up our sleeves and starting at least to talk about it – DEs are just another pipe dream. This exactly mirrors our experience in the field through many meetings with regional stakeholders, Regional Catalysts and SMEs in the past 6 years: DEs became alive more through direct engagement by and among the stakeholders than through ivory tower elaborations of rational or epistemological frameworks. The big insight in DE research is that we are all stakeholders: consistently with the insights of 2nd-order cybernetics, *we are a part of the digital ecosystem*. It therefore becomes important to be able to immerse ourselves among the future users of digital ecosystems with a perspective and a language that they can understand.

Without taking anything away from the value of complexity science in offering new and interesting conceptualisations of socio-economic systems, the following sections provides an illustration of how DEs are approached *in practice*., as a record of our recent trip to Argentina where we met several regional stakeholders in different municipalities of Buenos Aires. The following section can thus be taken as a case study of what the DE conceptual framework looks like 'from the inside'.

4.6 Theoretical deliberations and practical discussions in the case of Argentina

In the framework of the EULAKS project, a research visit was organised to the Province of Buenos Aires (cities of Buenos Aires, San Fernando and Morón) in order to start a research dialogue and to establish the framework of the development of a Pilot Case Study on Digital Ecosystems in Argentina.

The purpose of the research trip was twofold. At the theoretical level, the objective was to promote dialogue on how Digital Ecosystems research and principles fit the research agenda of the *Instituto de Industria* (IDEI) in *Universidad Nacional del General Sarmiento* (UNGS) in order to find research synergies around the modelling of economic systems, for example through a complexity science perspective; whereas at a more practical level the aim was to enable discussions on how to develop a methodology to disseminate the Digital Ecosystems concept to existing knowledge-intensive sectors in the Argentinean context.

Meetings were organised with regional stakeholders in academia and public bodies regarding the different approaches for disseminating the Digital Ecosystems approach for sustainable development at the regional level as well as the different phases for planning their deployment. Introducing the DE concept to these stakeholders was not an easy task, and it usually involved two types of introductory dialogues:

- An Overview of DEs research at the theoretical level. Giving a summary of the evolution of the technical aspects of the DE infrastructure, and in general a high-level overview of the OPAALS project. Discussing at a high level an epistemological framework by which social science can be organised, culminating with a possible interpretation of the self-reinforcing feedbacks between technology production and social processes (Autopoiesis of Media).

Broadly, it is important to define a digital ecosystem, highlighting which properties set it apart from other socio-technical-economic systems.

- An introduction to DEs from a socio-economic perspective. Presenting DEs as an enabler of local development, discussing its benefits, principles and main characteristics. Other more practical elements include discussing the concept of a Regional Digital Ecosystem and the methodological framework for planning the deployment of a DE at the regional level based on European experiences (i.e. Aragón, the Midlands, Cambridge-Peterborough, province of Trento, DEAL project in India, etc), as well as the variables that affect the deployment process. Other concepts such as the Regional Maturity Grade, the Digital Ecosystems Impact Index, and the existing networks or regional stakeholders in support of DEs in Europe (i.e. REDEN and DEN4DEK).

4.6.1 The choice of a case study for DEs deployment

Two towns were identified as options for developing a study case on DEs in Argentina: the city of San Fernando and the city of Morón, both in the province of Buenos Aires. The two possible study cases had different and particular characteristics and specific needs.

- San Fernando is a town located in the centre-east part of the province of Buenos Aires, just north of the city. The town's economic activity is characterised by a large number of manufacturers, sellers and service suppliers of the nautical industry. More recently the municipality had recognised and supported the emergence of the retail sector as a second economic component. The municipality's main technology-related initiative is the introduction of a Digital Agenda in the support of the business sector and citizens through the establishment of several community technology centres. After an interactive introduction of the DEs concept, the municipality showed great interest in the approach of DEs for local development, expressing great openness and willingness to collaborate in developing a pilot case study, arguing among other things that the municipality has accurate and recent statistical data for the business sector that would facilitate a preliminary and exploratory analysis. An initial sector of interest for deployment was the nautical sector and the retail sector.
- The municipality of Morón is located in the western part of the province of Buenos Aires. One of the main projects of the Municipality is to centralise all of the administrative and regulatory processes digitally, through a 'One window' portal service for SMEs. The municipality is also known for its extremely efficient articulation between public administration, university and industry associations. The representatives of the local government with whom we met showed special interest in applying the DE approach to the mechanical machinery industry. Studies developed by UNGS in Morón had highlighted the importance of the mechanical machinery industry in the economic structure of the municipality, accounting for 20% of total SMEs therein. A recent study developed by UNGS has shown that businesses in the industry are weakly linked with intermediate actors that would otherwise facilitate their incorporation into value chains (i.e. chambers of commerce, trade unions, etc.). After a 4-hour meeting of interesting and interactive discussion, the Municipality expressed its keen interest in collaborating with the DE team for developing a pilot case study.

In the scope of the EULAKS project, Morón was selected as a case study for analysing the feasibility of the municipality to adopt DEs at all levels. For the team involved in the deployment planning process, there were two main reasons for this selection. First, there are strong communication channels and a history of trustful relationships between the municipality and the research team in Argentina (i.e. UNGS), which enables dynamic interactions and the access to information. Second, Morón collaborates closely with industry and academic institutions at the local level. This articulation is extremely important when planning a deployment of DEs, since all the relevant stakeholders need to be linked and share common objectives.

Generally, the same introductory definitions, descriptions, and presentations are given to every region interested in the DEs approach for sustainable development. Nevertheless, the responses to and

acceptance of the approach tend to be very different from one region/locality to another. For example, whereas San Fernando showed great interest and openness in knowing more about DEs, Morón went further and questioned the study team on the different steps needed to make the deployment happen in reality, and seemed generally more engaged and proactive.

These differences could be explained by the fact that the process of deploying a DE is user-specific, sector-specific and context-specific. No deployment strategy will be exactly equal to another given strategy, because the reality and positions of the people involved in the process are always different. This is indeed one of the main characteristics of this approach to development. The technology, the processes and the applications are adaptable to any context, and are built by the stakeholders involved in the deployment process based on their 'development needs'.

The following section develops in more detail the practical deliberations and definitions used for introducing the DEs concept among policy-makers, decision-makers and regional/local key stakeholders.

4.6.2 The introduction of the Digital Ecosystems concept for sustainable development: the case of Argentina

Introducing the concept of Digital Ecosystems to policy-makers, decision-makers and regional/local key stakeholders is not an easy task. DEs are a novel approach for the catalysis of sustainable development driven by networks of economic agents, enabled by ICT services and intelligent technologies that offer cooperative solutions that are affordable, trustworthy, adaptive and evolutionary.

Digital Ecosystems are also described as an enabler (tool) of development. From an economics empirical perspective, a DE is two things:

- A socio-technical system
- A link between the 'micro-economy' and the 'macro-economy'

The latter definition requires further explanation. DEs minimise transaction costs within clusters at the regional/local level through knowledge integration and sharing within the regional/locality, and thus through more dynamic Regional Innovation Systems. DEs maximise the benefits to enterprises in participating to Global Value Chains because, when referring to SMEs and distributed markets, more collaboration leads to better competition.

The findings and results on deployment of the DBE project confirmed the above considerations that there are some differences in regional needs, requirements and opportunities for DEs. Typically, the regional variations reflect the differences in regional innovation capability, in regional enterprises' ICT capability, and in the social capital of the region. Nevertheless, regions interested in the deployment of DEs are typically characterised by their commitment to regional development and by their support to regional innovative capabilities.

More precisely, regions interested in the implementation and deployment of a DE are characterised by:

- A strong focus on the development of the regional business sector
- An interest in mechanisms for sharing and for open diffusion of knowledge within local clusters, supported by the interaction and Europe-wide cooperation between regional networks.
- A need for easy-to-use services with high user value
- A shared interest and support for Open Source
- An interest for the promotion of the knowledge "embedded" within local territories, and the recognition of the importance of knowledge sharing and best practices through regional innovation programs and plans

Based on the practical experiences of deployment in the DBE project, the DBE Lazio Project and the OPAALS project, an identification of different uses and applications of Digital Ecosystems emerged for the regional level of intervention. So far, four different typologies have been identified within a Regional Digital Ecosystem (RDE): Digital Business Ecosystems (DBEs), Digital Ecosystem for Public Administration (DE-PA), Digital Ecosystems for Researchers (or DEs of Knowledge – DEK), and Digital Ecosystems for the Labour Market (DEW). Figure 4.4 is self-explanatory for understanding the co-existence of different DEs (with different objectives and purposes) within a RDE. Once again, how the RDE will evolve and with which ecosystems is context-specific.

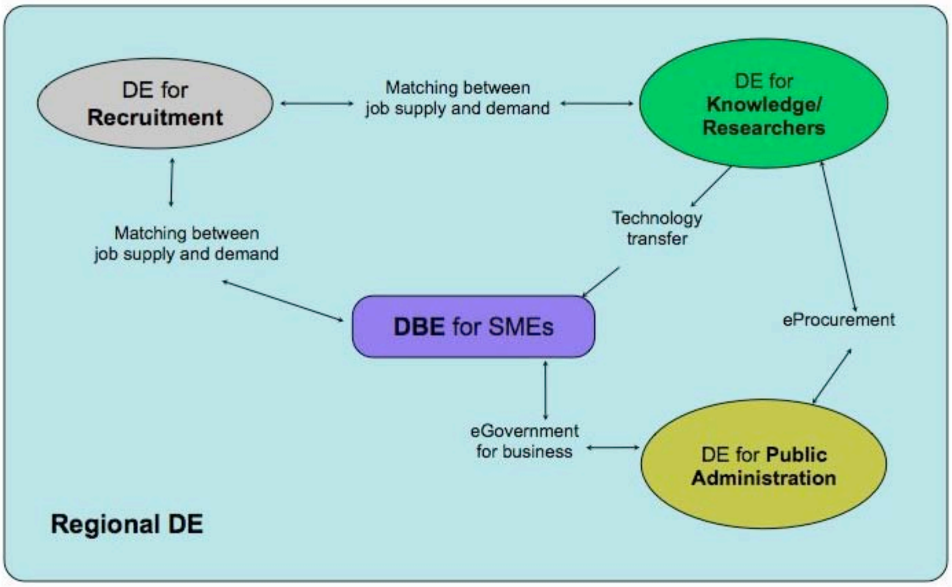

Figure 4.4: A Regional Digital Ecosystem (authors, based on Passani, 2008)

DE technologies are adaptable to different regional applications and needs, and they are thus not exclusive to the business sector. Each region has the opportunity to shape DE technologies to fit regional priorities best. This is why understanding the regional needs and actors is a priority exercise for planning the deployment of DEs. The following section deals with the tools for achieving a clearer understanding.

4.7 Planning the deployment of Digital Ecosystems at the Regional Level

The following paragraphs discuss different strategies for the introduction of the DE concept at the regional level, with a focus on practical issues, difficulties and key success factors.

4.7.1 Understanding the background: the Regional Maturity Grade[45]

The Regional Maturity Grade (RMG) theoretical framework was initially introduced in the DBE project. Since then, different regions have used it. The Morón case in Argentina will develop its RMG during 2009. RMG studies serve as a tool for regional analysis and they are usually done as a second step in a 'public-sector driven' deployment strategy. The RMG is a theoretical framework used for interpreting innovative processes at the regional level. It is formed by different techniques of analysis, qualitative and quantitative, that give a complex description of the real context, thus becoming a useful instrument for planning and policy interventions.

The RMG function is composed of three key elements: Social Capital (SC), Innovation Capacity (IC), and the relation between SMEs and ICT (ICT). Figure 4.5 syntheses the variables and indicators analysed in each of the key elements. The RMG describes the region from a socio-economic point of view and measures the dynamics and modifications resulting from a development intervention. It is

[45] Based on CENSIS (2006)

useful for understanding the regional background and it is usually undertaken within feasibility studies of DE deployment.

4.7.2 From Regional Maturity Grade to the Digital Ecosystems Impact Index

One of our research activities within the OPAALS project deals with the more practical aspects of the process of developing a multi-stakeholder policy framework. This process hinges first on the development of a methodology for assessing the socio-economic impact of Digital Ecosystems deployment, through what we call the Digital Ecosystems Impact Index (DEII).

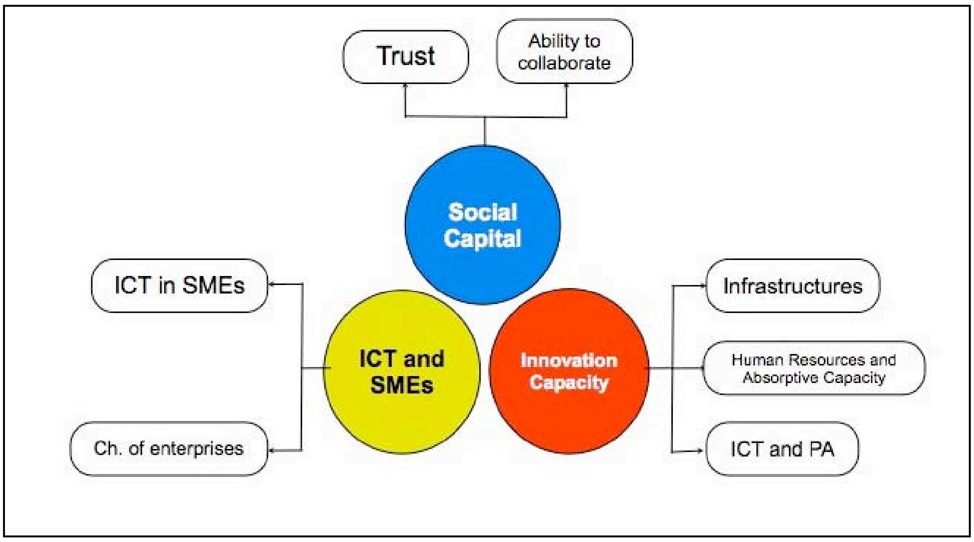

Figure 4.5: The Regional Maturity Grade – key elements (Passani, 2008)

The DEII takes the form of an aggregated composite indicator, formed by four evaluation accounts: financial, user, economic development and social. It is an open and scalable tool for assessing the socio-economic impact of DE deployments at local/regional level. The DEII wishes to be not only an instrument for quantifying the effective impact of DE implementation (this needs real and well established DE implementation at local level), but also as an instrument able to advise policy-makers what they need to do in order to be ready for the DE implementation. In this sense, the DEII would represents an updated and more sensitive version of the Regional Maturity Grade developed by CENSIS during the DBE project and further developed and tested in the Lazio region. The DEII thus gives support to policy-makers in developing policies able to support the DE implementation and, more generally, local sustainable development.

As stated, the impact analysis framework envisaged includes four different accounts:

- Financial account (studying the expected revenues and expenditures from DE implementation)
- User/consumer account (studying the net benefits to users and direct beneficiaries of DE implementation)
- Economic development account (studying theoretically microeconomic and macroeconomic relationships and impacts related to incremental effects at the regional/local or sector level from DE deployments)
- Social account (studying the impact on social intangible variables such as social capital, knowledge flow, social inclusion, region's public image, entrepreneurship, innovation incentives, etc).

The Digital Ecosystems Impact Index (DEII) will thus be built from these four accounts. The impact analysis methodological framework will be used for the compilation of a synthetic policy framework useful for regional stakeholders interested in the deployment of DEs

4.7.3 The role of policy-makers in DE deployment

The tools discussed above are supposed to provide policy-makers with evidence on which trade-offs to expect at the regional/local level from DE deployment. The role of policy-makers is thus central, and once again, context-specific. De Gier (2000:109) identified four interacting factors as the basis for the public policy process: interests, ideologies, information and institutions. This results in three different kinds of possible utilisation of the feasibility studies of DE deployments by policy-makers:

- Instrumental use for DE deployments. This will happen when there is a political consensus between policy goals and the DE net benefits provided by the region, as evidenced through the RMG or DEII. Additionally, the capacity (financial and operational) to implement/deploy has to be available.
- Conceptual use. The DEII and/or RMG introduce ideas and theories that might influence the political agenda and discourse. In this case, the tools will provide an important contribution for more effective policy-making, helping to strengthen policy areas that are difficult to accept or are unclear from a social and political point of view. It can be seen as the preliminary step to instrumental use when there is no political consensus between policy goals and the DE net benefits as per the DEII/RMG.
- Warning use**.** The tools might be used to move items up (or down) in the political agenda. In this case, the DEII/RMG will draw policy-makers' attention at an earlier stage, concerning possible criticisms of a given issue related to the regional/local development process. 'Warning use' is required when Instrumental use applies, but the capacity (financial and operational) is not present in a given setting.

In all these three cases, the DEII and RMG can be seen as a tool for 'evidence-based' policy-making. The argument is that while being able to map the value of the net benefits related to DE deployments, policy-makers will find it easier to decide on a *use* within the referred territory. In order to understand the type of use, one has to understand the implicit and explicit motivations of policy-makers to turn to a DE-based regional knowledge economy through the DEII/RMG.

4.8 Conclusion

In this chapter we have ranged over a wide array of concepts and ideas. Our purpose has been to highlight the importance of exposing the epistemological machinery we generally take for granted in constructing our arguments when engaged in interdisciplinary dialogues. We could call this process one of 'epistemological reflexivity'. We have attempted to make this point through the deliberate use of several rather different 'discourses' whilst, at the same time, tending to the business of the continued development of the digital ecosystems concepts at theoretical and applied levels, and relying on our experiences in Argentina as a reference case study at all these levels. We find that complexity science, if used with care, can provide an enriching vocabulary and useful insights for many discourses of social science, but that we should not forget about a hermeneutics epistemology to keep in focus the role of reflexivity and the fragile and never-ending quest for democratic processes.

In the next and final chapter we develop the concept of Community Cloud Computing. Similarly to the discussion of the Argentinean DE case study, the process of software engineering conceptualisation i*n practice* does not necessarily need to rely on a particular theoretical framework or other. Thus, as we enter the community cloud as a software-ecosystem-in-the-making we can draw from any of the theories presented so far to make sense of what we see.

5. Digital Ecosystems in the Clouds: Towards Community Cloud Computing

Chapter Authors: Gerard Briscoe (LSE) and Alexandros Marinos (Surrey)

Cloud Computing is rising fast, with its data centres growing at an unprecedented rate. However, this has come with concerns of privacy, efficiency at the expense of resilience, and environmental sustainability, because of the dependence on Cloud vendors such as Google, Amazon, and Microsoft. Community Cloud Computing makes use of the principles of Digital Ecosystems to provide a paradigm for Clouds in the community, offering an alternative architecture for the use cases of Cloud Computing. It is more technically challenging to deal with issues of distributed computing, such as latency, differential resource management, and additional security requirements. However, these are not insurmountable challenges, and with the need to retain control over our digital lives and the potential environmental consequences, it is a challenge we must pursue.

The recent development of Cloud Computing provides a compelling value proposition for organisations to outsource their Information and Communications Technology (ICT) infrastructure (Haynie, 2009). However, there are growing concerns over the control ceded to large Cloud vendors, including the lack of information privacy (Armbrust et al., 2009). Also, the data centres required for Cloud Computing are growing exponentially (Hayes, 2008), creating an ever-increasing carbon footprint, raising environmental concerns (Mckenna, 2008, Kaplan et al., 2008).

The social paradigms and technologies of Digital Ecosystems, including the community ownership of digital infrastructure, can remedy these concerns. So, Cloud Computing combined with the principles of Digital Ecosystems provides a compelling socio-technical conceptualisation for sustainable distributed computing, utilising the spare resources of networked personal computers to provide the facilities of a virtual data centre to form collectively a Community Cloud.

5.1 Cloud Computing

Cloud Computing is the use of Internet-based technologies for the provision of services (Haynie, 2009), originating from the cloud as a metaphor for the Internet, based on how it is depicted in computer network diagrams to abstract the complex infrastructure it conceals (Scanlon and Wieners, 1999). It can be seen as a commercial evolution of the academia-oriented Grid Computing (Foster et al., 2008), succeeding where Utility Computing struggled (Foremski, 2006, Orlowski, 2005). It is being promoted as the cutting edge of scalable web application development (Armbrust et al., 2009), in which dynamically scalable and often virtualised resources are provided as a service over the Internet (Gruman and Knorr, 2008, Haynie, 2009, Gartner, 2008, Gaw, 2008), with users having no knowledge of, expertise in, or control over the technology infrastructure of the Cloud supporting them (Danielson, 2008). It currently has significant momentum in two extremes of the web development industry (Armbrust et al., 2009, Haynie, 2009): the consumer web technology incumbents who have resource surpluses in their vast data centres[46], and various consumers and start-ups that do not have access to such computational resources. Cloud Computing conceptually incorporates software-as-a-service (SaaS) (Turner et al., 2003), Web 2.0 (Oreilly, 2008) and other technologies with reliance on the Internet, providing common business applications online through web browsers to satisfy the computing needs of users, while the software and data are stored on the servers.

Figure 5.1 shows the typical configuration of Cloud Computing at run-time when consumers visit an application served by the central Cloud, which is housed in one or more data centres. Green symbolises resource consumption, and yellow resource provision. The role of coordinator for resource provision is designated by red, and is centrally controlled. From the figure, it can be seen that coordination and resource provision are centrally controlled, even if the central node is implemented as a distributed grid, which is the usual incarnation of a data centre. Providers, who are also the

[46] A data centre is a facility, with the necessary security devices and environmental systems (e.g. air conditioning and fire suppression), for housing a server farm, a collection of computer servers that can accomplish server needs far beyond the capability of one machine (Arregoces and Portolani, 2003).

controllers, are usually companies with other web activities that require large computing resources, and in their efforts to scale their primary businesses they have gained considerable expertise and hardware. For them, Cloud Computing is a way to resell these as a new product while expanding into a new market. Consumers include everyday users, Small and Medium sized Enterprises (SMEs), and ambitious start-ups whose innovation potentially threatens the incumbent providers.

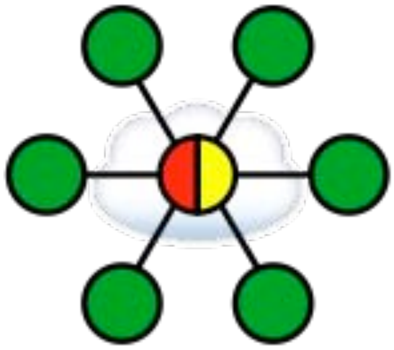

Figure 5.1: Cloud Computing: Typical configuration when consumers visit an application served by the central Cloud, which is housed in one or more data centres. Green symbolises resource consumption, and yellow resource provision. The role of coordinator for resource provision is designated by red, and is centrally control led.

5.1.1 Layers of Abstraction

There is a significant buzz (Worthen, 2008) around Cloud Computing, but there is little clarity about which offerings actually qualify and their interrelation. The key to resolving this confusion is by realising that the various offerings fall into different levels of abstraction, as shown in Figure 15, aimed at different market segments.

Infrastructure as a Service (IaaS) (Newmanet al., 2008)

At the most basic level of the Cloud Computing offerings, there are providers such as Amazon (Amazon, 2009) and Mosso (Mosso, 2009), who provide machine instances to developers. These instances essentially behave like dedicated servers that are controlled by the developers, who therefore have full responsibility for their operation. So, once a machine reaches its performance limits, the developers have to manually instantiate another machine and scale their application out to it. This service is intended for developers who can write arbitrary software on top of the infrastructure with only small compromises in their development methodology.

Platform as a Service (PaaS) (Buyyaetal., 2008)

One level of abstraction above, services like Google App Engine (Google, 2009) provide a programming environment that abstracts machine instances and other technical details from developers. The programs are executed over data centres, not concerning the developers with matters of allocation. In exchange for this, the developers have to handle some constraints that the environment imposes on their application design, for example the use of key-value stores[47] instead of relational databases.

Software as a Service (SaaS) (Turner et al., 2003)

At the consumer-facing level are the most popular examples of Cloud Computing, with well-defined applications offering users online resources and storage. This differentiates SaaS from traditional websites or web applications which do not interface with user information (e.g. documents) or do so in a limited manner. Popular examples include Microsoft's (Windows Live) Hotmail, office suites such as Google Docs and Zoho, and online business software such as Salesforce.com. To better understand Cloud Computing we can categorise the roles of the various actors. The vendor as resource provider has already been discussed. The application developers utilise the resources provided, building services for the end users. This separation of roles helps define the stakeholders and their differing

[47] A distributed storage system for structured data that focuses on scalability, at the expense of the other benefits of relational databases (Bain, 2008), e.g. Google's BigTable (Chang et al., 2006) and Amazon's SimpleDB (DeCandia et al., 2007).

interests. However, actors take on multiple roles, with vendors developing services for the end users, or developers utilising the services of others for their own. Yet, within a Cloud the role of provider, and therefore controller, can only be occupied by a single entity, the vendor.

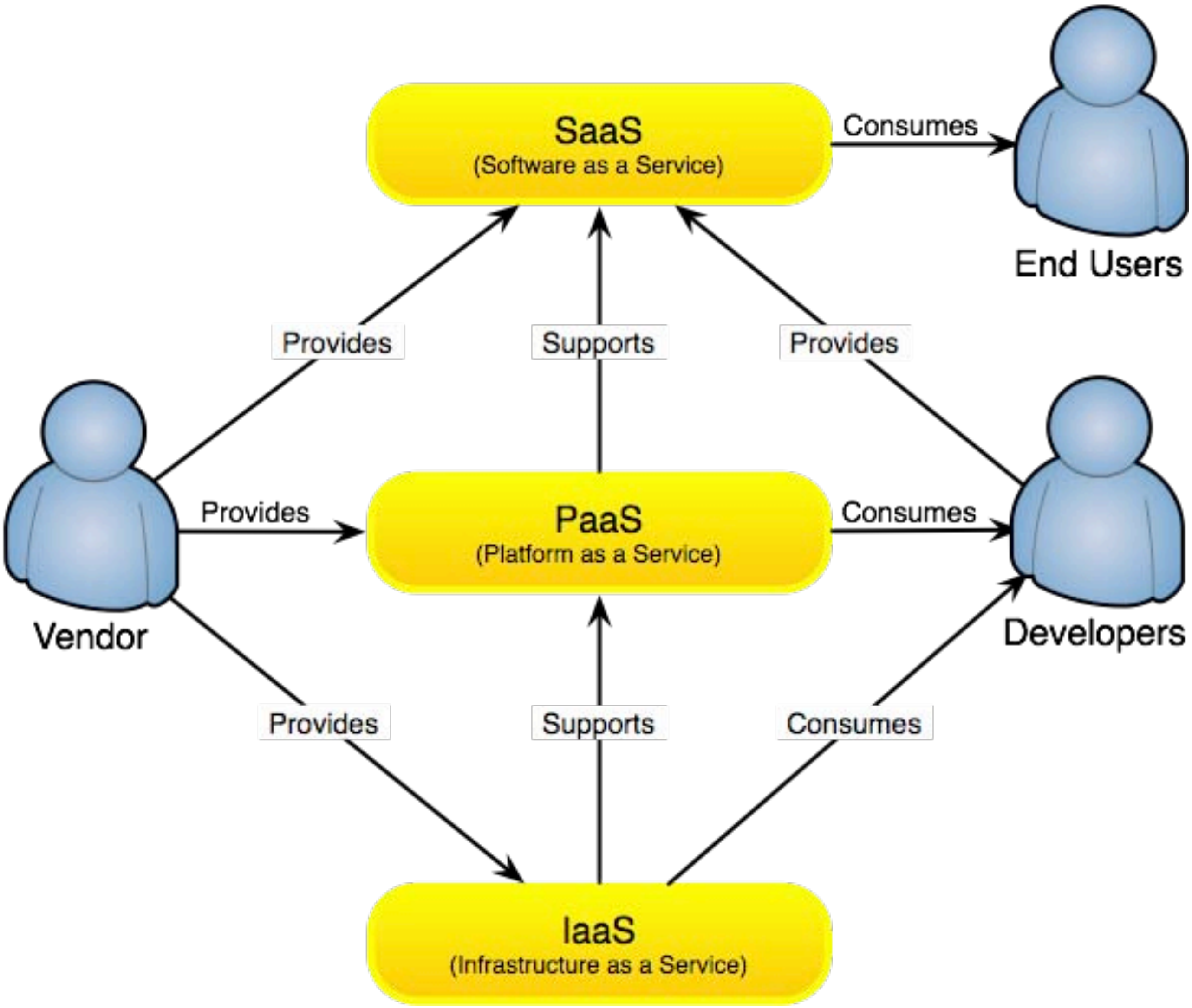

Figure 5.2: Abstractions of Cloud Computing: There is a significant buzz (Worthen, 2008) around Cloud Computing, but there is little clarity about which offerings actually qualify and their interrelation. The key to resolving this confusion is by realising that the various offerings fall into different levels of abstraction, aimed at different market segments.

5.1.2 Concerns

The Cloud Computing model is not without concerns, as others have noted (Johnson, 2008, Armbrust et al., 2009), and we consider the following as primary:

Economics of Failure

The uptime[48] of Cloud Computing-based solutions is an advantage, when compared to businesses running their own infrastructure, but often overlooked is the co-occurrence of downtime in vendor-driven monocultures. The use of globally decentralised data centres for vendor Clouds minimises failure, aiding its adoption. However, when these failures do occur it has a cascade effect, taking down organisations depending on the Cloud. This was illustrated by the Amazon (S3) Cloud outage (Modine, 2008), which took with it several other dependent businesses. So, failures are now system-

[48] Uptime is a measure of the time a computer system has been running, i.e. up. It came into use to describe the opposite of downtime, times when a system was not operational (McCabe, 2007).

wide, instead of being partial or localised. Therefore, the efficiencies gained from centralising infrastructure for Cloud Computing will increasingly be at the expense of the Internet's resilience.

Convenience vs. Control
The growing popularity of Cloud Computing comes from its convenience, but also brings vendor control, an issue of ever-increasing concern. For example, Google Apps for in-house e-mail typically provides higher uptime (Montgomery, 2008), but its failure (Perez, 2007) highlighted the issue of lock-in that comes from dependingon vendor Clouds. The even greater concern is the loss of information privacy, with vendors having full access to the resources stored on their Clouds. In particularly sensitive cases of SMEs and start-ups, the provider-consumer relationship that Cloud Computing fosters between the owners of resources and their users could potentially be detrimental, as there is a conflict of interest for the providers. They profit by providing resources to up and coming players, but also wish to maintain dominant positions in their consumer-facing industries.

Environmental Impact
The other major concern is the ever-increasing carbon footprint from the exponential growth (Hayes, 2008) of the data centres required for Cloud Computing. With the industry expected to exceed the airline industry by 2020 (Kaplan et al., 2008), this raises sustainability concerns (Mckenna, 2008). The industry is being motivated to address the problem by legislation (Kaplan et al., 2008, EPA, 2007), the operational limit of power grids (not being able to power any more servers) (Miller, 2006), and the potential financial benefits (McIsaac, 2007, Kaplan et al., 2008). Their primary solution is the use of virtualisation[49] to maximise resource utilisation (Talaber et al., 2009), but the problem remains (Brill, 2007, Brodkin, 2008).

While these issues are endemic to current Cloud Computing, they are not flaws in the Cloud conceptualisation, but of the vendor provision and implementation of Clouds (Google, 2009, Amazon, 2009). There are attempts to address some of these concerns, such as avoiding vendor lock-in through a portability layer between different vendor Clouds, called a meta-Cloud or a Cloud-of-Clouds (Metz, 2009). While this would avoid vendor lock-in to an extent, it will not alleviate the other concerns raised. Also, there is an open source implementation of the Amazon (EC2) Cloud (Amazon, 2009), called Eucalyptus (Nurmi et al., 2008), which allows for a data centre to execute code compatible with Amazon's Cloud, providing private internal Clouds. This would avoid vendor lock-in and provide information privacy, but only for those with their own data centres, and so is not really Cloud Computing (which by definition is to avoid needing one's own data centre (Haynie, 2009)). So, vendor Clouds remain synonymous with Cloud Computing (Gruman and Knorr, 2008, Haynie, 2009, Gartner, 2008, Gaw, 2008), while our response is an alternative model for the Cloud conceptualisation infused with the principles of Digital Ecosystems.

5.2 Community Cloud

Community Cloud Computing arises from concerns over the control of vendors in Cloud Computing and the observation that analogous concerns drive Digital Ecosystems research. It aspires to combine the principles of Digital Ecosystems with the use cases of Cloud Computing. Replacing vendor Clouds by shaping the underutilised resources of user machines to form a Community Cloud, with nodes potentially taking on all roles, consumer, producer, and most importantly coordinator , as shown in Figure 5.3.

5.2.1 Conceptualisation
The conceptualisation of the Community Cloud draws from Cloud Computing (Haynie, 2009), Digital Ecosystems (Wikipedia) and Green Computing (Harris, 2008). It is a paradigm for Cloud Computing in the community, without dependence on Cloud vendors, such as Google, Amazon, or Microsoft.

[49] Virtualisation is the creation of a virtual version of a resource, such as a server, which can then be stored, migrated, duplicated, and instantiated as needed, improving scalability and work load management (Wolf and Halter, 2005).

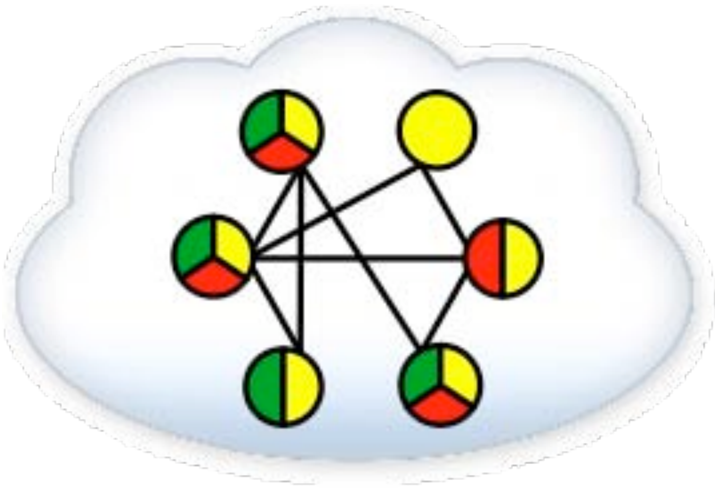

Figure 5.3: Community Cloud: Created from shaping the underutilised resources of user machines, with nodes potentially taking on all roles, consumer, producer, and most importantly coordinator. Green symbolises resource consumption, yellow resource provision, and red resource coordination and administration.

Openness
Removing the dependence on vendors makes the Community Cloud the open equivalent to vendor Clouds, and therefore identifies a new dimension in the open versus proprietary struggle (West and Dedrick, 2001) that has emerged in code, standards and data, but has not until now been expressed in the realm of hosted services.

Community
The Community Cloud is as much a social structure as a technology paradigm (Benkler, 2004), because of the community ownership of the infrastructure. This community ownership carries with it a degree of economic scalability, without which there would be diminished competition and potential stifling of innovation as risked in vendor Clouds.

Graceful Failures
The Community Cloud is not owned or controlled by any one organisation, and therefore not dependent on the lifespan or failure of any one organisation. It will be robust and resilient to failure, and immune to the system-wide cascade failures of vendor Clouds, because of the diversity of its supporting nodes. When occasionally failing it will do so gracefully, non-destructively, and with minimal downtime, as the unaffected nodes compensate for the failure.

Convenience and Control
The Community Cloud, unlike vendor Clouds, has no inherent conflict between convenience and control, because its community ownership provides for democratic distributed control.

Environmental Sustainability
The Community Cloud will have a significantly smaller carbon footprint than vendor Clouds, because making use of underutilised user machines will require much less energy than the dedicated data centres required for vendor Clouds. The server farms within data centres are an intensive form of computing resource provision, while the Community Cloud is more organic, growing and shrinking in a symbiotic relationship to support the demands of the community, which in turn supports it.

5.2.2 Architecture
The method of materialising the Community Cloud is the distribution of its server functionality amongst a population of nodes provided by user machines, shaping their underutilised resources into a virtual data centre. While straightforward in principle, this poses challenges on many different levels, but many are aligned with currently active research topics in Digital Ecosystems (Krause et al, 2008).

5.2.2.1 Core Infrastructure

Before proceeding to the resource exchange and service composition, the nodes will be deployed as isolated virtual machines, forming a fully distributed peer-to-peer network, providing support for distributed identity and coordination.

Virtual Machines (VMs)
Executing arbitrary code in the machine of a resource-providing user will require a sandbox[50] for the guest code, a VM[51] to protect the host. The role of the VM is to make system resources safely available to the Cloud in a measurable manner. Fortunately, feasibility has been shown with heavyweight VMs such as the Java Virtual Machine and Common Language Runtime, and with the lightweight JavaScript VMs present in most modern web browsers. Furthermore, the age (Geer, 2005) of multi-core processors [52] has resulted in unused and underutilised cores being commonplace in modern personal computers (Posey, 2007), which lend themselves well to the deployment and background execution of Community Cloud facing VMs.

P2P Networking
At this most fundamental level, nodes will have to be interconnected to form a peer-to-peer network. It will have to be specifically engineered to provide high resilience while avoiding single points of control and failure, which would make a decentralised super-peer based control mechanism (Risson and Moors, 2006) insufficient. A completely distributed peer-to-peer network is required, immune to super-peer failure.

Distributed Identity/Trust
The performing of tasks beyond the networking requires nodes to identify each other and keep historical context. This identification must be performed in a fully distributed manner, which has implications as most identity schemes are based on an identity provider controlling provision. Additionally, trust should be tracked as a multi-dimensional variable, including considerations such as uptime, performance characteristics, and reputation.

5.2.2.2 Resource layer

As the networking infrastructure is now in place, we can discuss the first consumer-facing uses of the virtual data centre of the Community Cloud. At its core, Cloud Computing is about using resources from the Cloud. The Community Cloud will offer the usage experience of Cloud Computing on the platform-as-a-service (PaaS) layer and above. Utility Computing (Rappa, 2004) scenarios, such as access to raw storage and computation, will be made available at the PaaS layer. Access to these abstract resources for service deployment will then provide the software-as-a-service (SaaS) layer.

Distributed Computation
The field has a long history of successful incarnations in its centrally controlled form. However, Community Cloud Computing will need to take inspiration from Grid Computing (Berman et al., 2003) to provide distributed coordination of the computational capabilities that nodes offer to the Community Cloud.

Distributed Persistence
The Community Cloud will naturally require storage on its participating nodes, taking advantage of the ever-increasing surplus on most[53] personal computers (Daley, 2009). However, the method of information storage in the Community Cloud is an issue with multiple aspects. First, information can

[50] A sandbox is a security mechanism for safely running programs, often used to execute untested code, or untrusted programs from unverified third-parties, suppliers and untrusted users (Bishop, 2004).
[51] A virtual machine is a software implementation of a machine (computer) that executes programs like a real machine (Craig, 2006).
[52] A multi-core processor is an integrated circuit to which two or more processors have been attached for enhanced performance, reduced power consumption, and more efficient simultaneous processing of multiple tasks (Zelkowitz, 2007).
[53] The only exception is the recent arrival of Solid-State Drive (SSD) in personal devices, popular for mobile devices because of their lack of moving parts, and whose use is growing as their size and price reach traditional HDD (Mellor, 2009).

be file-based or structured. Second, while constant and instant availability can be crucial, there are scenarios in which recall times can be more relaxed. Such varying requirements call for a combination of approaches, including distributed storage (Yianilos and Sobti, 2001), distributed databases (Garcia-Molina et al., 2008) and key-value stores (Bain, 2008). Information privacy in the Community Cloud will be provided by the encryption of user information when on remote nodes, only being unencrypted when cached on the user's node, allowing for the secure and distributed storage of information.

Bandwidth Management

The Community Cloud will probably require more bandwidth than vendor Clouds, but can take advantage of the ever-increasing bandwidth and deployment of broadband (wal, 2008). Also, peer-to-peer protocols such as BitTorrent have made the distribution of information over networks much less bandwidth-intensive for providers, accomplished by using the downloading peers as repeaters of the information they receive. Community Cloud Computing will have to adopt such approaches to ensure efficient use of available network bandwidth, to avoid fluctuations or sudden rises in demand (e.g. the Slashdot effect[54]) burdening parts of the network.

Community Currency

An important theme in the Community Cloud is the notion of nodes being contributors as well as consumers, which will require a community currency[55](redeemable against resources in the community) to reward users for offering valued resources. It will also allow for traditional Cloud vendors to participate, by offering their resources to the Community Cloud to gather considerable community currency, which they can then monetise against participants who cannot contribute as much as they consume (i.e. running a community currency deficit). To avoid predicting or hard-coding the relative cost of resources (storage, computation, bandwidth), their prices can fluctuate based on market demand.

5.2.2.3 Service Layer

Cloud Computing can be said to represent a move from service-oriented (Newcomer and Lomow, 2005) to service-driven architectures, making services explicitly dependent on other providers instead of building on self-sufficient resource locations. Community Cloud Computing makes this more explicit, breaking down the stand-alone service paradigm, with any service by default being composed of resources contributed by multiple participants. The following sections describe the core infrastructural services that the Community Cloud needs to provide.

Distributed Service Repository

The repository of the Community Cloud must provide persistence, as with traditional service repositories (Papazoglou, 2003), for the pointers to services and the semantic descriptions of services. To support the absence of principal (service-producing) nodes during service execution, there must also be persistence of the executable code of services. Naturally, the implementation of a distributed service repository is made easier by the availability of the distributed storage infrastructure of the Community Cloud.

Remote Service Execution

When a service is needed to fulfil a request, but is not currently instantiated on a suitable node, a copy should be retrieved from the repository and instantiated as needed. This allows for flexible responsiveness and resilience to unpredictable traffic spikes. Nodes are naturally interested in executing services as their purpose is to gather community currency for their users. A developer should note the resource cost of a service in its description, allowing for pre-execution resource budgeting by nodes, and post-execution community currency payments by consumers. It is in a developer's own interest to mark resource costs correctly, because over-budgeting will burden their

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[54] The Slashdot effect, also known as slashdotting, is the phenomenon of a popular website linking to a smaller site, causing the smaller site to slow down or even temporarily close due to the increased traffic (Adler, 1999).

[55] In economics, a community currency is a medium (currency) for exchanging goods and services within a community, that is not backed by a central authority (e.g. national government) (Greco, 2001), and which need not be restricted geographically despite sometimes being called a local currency (Doteuchi, 2002).

users and under-budgeting will cause premature service termination. Additionally, developers could add a subsidy to promote their services. Remote service execution must be secured against potentially compromised nodes, because while unable to access a complete traffic log of the services they execute, they could potentially access the business logic of the services they execute. Otherwise, we would be replacing the vendor looking in problem, with an anyone looking in problem.

5.3 Wikipedia in the Community Cloud

Wikipedia suffers from an ever-increasing demand for resources and bandwidth, without a stable revenue source for support (Heebie Blog, 2009). Their current funding model requires a continuous influx of monetary donations for the maintenance and expansion of their infrastructure (Modine, 2009), the alternative being contentious advertising revenues (Heebie Blog, 2009), which has caused a long-standing conflict within their community (Roelf, 2007). While it would provide a more scalable funding model, the fear is it would compromise the public's trust in the content (Leslie, 2007). Alternatively, the Community Cloud could provide a self-sustaining scalable resource provision model without risk of compromising the content, because it would be compatible with their communal nature (unlike their current data centre model), with their user base accomplishing the resource provision they require.

Were Wikipedia to adopt Community Cloud Computing, it would be distributed throughout the Community Cloud alongside other services, which in this context can be as simple as a webpage or as complex as necessary. Participants in the Community Cloud will have a node on their machine, which when active accumulates community currency by providing resources to fulfil service requests from other nodes. These service requests can be as simple as instantiating a simple HTML page or executing a server-side script, the core operations of Wikipedia. Participants can then use their amassed community currency to interact with Wikipedia, performing a search or retrieving a page. More complicated tasks, such as editing a Wikipedia page, will require an update to the distributed storage of the Community Cloud, achieved by transmitting the new data through its network of nodes, most likely resulting in an eventual consistency model (Vogels, 2008).

We have discussed Wikipedia in the Community Cloud, but the latter is not limited to not- for-profit organisations, being just as beneficial to for-profit businesses. Its organisational model for resource provision moves the cost of service provision to the user base, effectively creating a micro-payment scheme, which dramatically lowers the barrier of entry for innovative start-ups.

5.4 Conclusions

We have presented a socio-technical conceptualisation for sustainable distributed computing, the Community Cloud. The Community Cloud is an alternative to Cloud Computing, created from blending its usage scenarios with the principles of Digital Ecosystems. Community Cloud Computing utilises the spare resources of networked personal computers to provide the facilities of data centres, such that the community provides the computing power for the Cloud platform they wish to use. Furthermore, we hope that the Community Cloud will encourage innovation in vendor Clouds, forming a relationship analogous to the creative tension between open source and proprietary software.

6. CONCLUSIONS

6.1 Visually mapping a complex, adaptive field of theory

This deliverable has offered a wide-ranging set of theoretical insights and empirical explorations, both of which emerge from a foundational conception of digital ecosystems as complex and adaptive systems. In a research area defined by interdisciplinary collaboration and a wide array of theoretical and applied expertise, it is to be expected that the theoretical framework developed will in itself be complex and open to adaptation and evolution as the research progresses and its boundaries shift. The following diagram offers a snapshot in the life of the evolution of this theoretical framework. It is helpful to think of core concepts represented in the diagram as a collection of concepts, which although not necessarily reconcilable, all contribute a unique perspective to the theorisation of digital ecosystems.

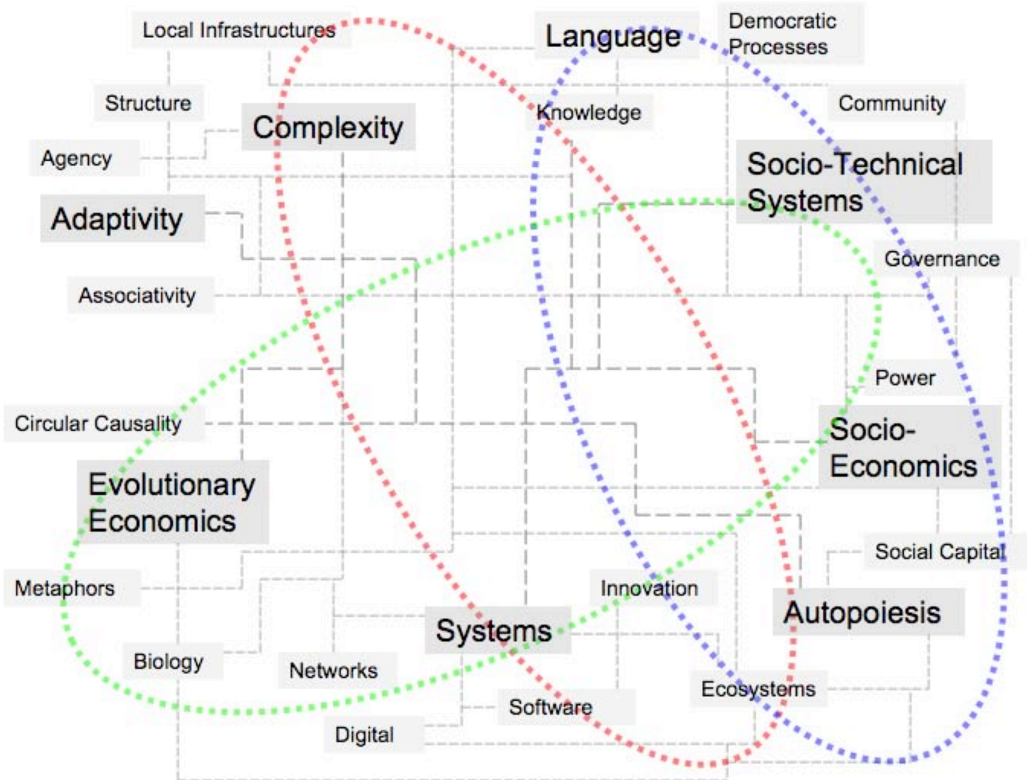

Figure 6.1: Graphic representation of Theoretical Framework as a distributed, interdisciplinary network of concepts

Figure 6.1 takes the core concepts as addressed in each chapter and distils them into keywords, framed in shaded boxes, which can be used as anchors or flashcard entry points to the deeper, complex, exploratory discussions which take place in each chapter. In this sense the diagram should not be seen as an eliminating summary of the entire deliverable, but rather as an invitation to access elements of the discussion at a deeper level whilst providing a bird's eye view of the constellation of core theories addressed in the entire deliverable. Only theoretical keywords are included in the diagram so as to create an abstracted, and therefore more broadly applicable, view on the current status of the theoretical framework.

The lines represent not dependencies but complex, theoretical paths of association between the keywords. As indicated by the many intersections and junctions, there are a variety of routes that can be travelled from one concept to the other: those represented here are certainly not eliminating. We do not use arrows so as to avoid deterministic suggestions of flow direction, instead, the flows should be conceptualised as multiple and moving both ways along all paths. The lines are dotted so as to represent an openness and permeability, and to make it clear that the flow paths represented here are neither definitive nor static. In this way, the diagram itself represents a complex and adaptive model of a range of theoretical possibilities, not integrated, but instead dynamically arranged so as to facilitate coherent, yet creative and dynamic analytical thinking.

The coloured ovals represent each case study, approximating the conceptual terrain that they explore through the empirical ground covered. The blue oval represents the DEAL case study (echoing the use of blue within the OPAALS project to represent social science). The red oval represents the Cloud Computing case study (echoing the use of red within the OPAALS project to represent computer science). The green oval represents the DE in Argentina case study (echoing the use of green within the OPAALS project to represent natural science). These colours should not be considered definitive, as there will be elements of each disciplinary perspective present within each case study, to some degree or another. Furthermore, the boundaries of these shapes should not be considered definitive – as the flows of relationships between the concepts represented by the lattice of dotted lines show, although specific keywords may not fall within the ovals' boundaries, *routes* to almost all of them do. The superimpositions of the ovals is intended to illustrate how specific parts of the theoretical framework have been addressed by the case study, but also imply that a broader set of relationships exists, and wider extrapolations and theoretical connections should be presumed to be present.

6.2 Juxtaposing theory and practice

The juxtaposition of theoretical perspectives and applied approaches through the chapters in this deliverable illustrates the broader relationships between theory and practice which define the research work of OPAALS. Chapter 1 addressed complex adaptive systems theory in the context of digital ecosystems, and then took the perspective of local infrastructures in order to consider the centrality of the former to the applied scenarios of digital ecosystems in regional contexts. Chapter 2 provided a conceptual and theoretical discussion, informed by a computer science epistemology, of the characteristics of digital ecosystems. Chapter 3 centred its theoretical discussion on an explication of autopoiesis within the social sciences, and then applied this to the empirical case of DEAL in India. Chapter 4 focussed on the challenges of inter-epistemological discourse and attempted to show how such a dialogue can be improved, leading to increased understanding, by acknowledging and explicating rather than glossing over epistemological differences. The chapter applied this approach to theories of evolutionary economics and then reinterpreted these within the practical context of the introduction of a digital ecosystem in Argentina. Chapter 5 put this knowledge into practice through an instantiation of cloud computing to digital ecosystems in the form of Community Cloud Computing, assessing its relevance to digital ecosystems principles.

Overall, therefore, the deliverable has exhibited a steady and rhythmical shift between theoretical and practical concerns, and with finding and mapping the relationships between each. In this sense, it builds the next level of groundwork necessary for the epistemological and social science theoretical framework which will be articulated in Deliverable D12.10, as a result of all of the lessons of practice and theory that have been learnt in the duration of the research project. This deliverable has provided a picture of the complexity of the research being undertaken by the OPAALS consortium, and illustrates the difficulties inherent in any attempt to integrate the theoretical traditions which inform the various strands of our research. Nevertheless, the deliverable has also succeeded in illustrating the ways in which these strands are interlinked and interdependent. The ongoing work of the OPAALS consortium is aimed at continuing to weave these strands together, parallel to the practical pursuit of the research objectives, such that, by the end of the project, a more closely-knit version of the theoretical

framework can emerge as a result of both empirical and conceptual work, abstracted to the degree that it can be considered applicable to other DEs as well as OPAALS.

The theoretical framework put forward in this deliverable is built from the concepts addressed in each chapter, which are in turn interrelated within the broader context of interdisciplinary research. The deliverable is helpful in terms of the ways that it catalogues both theoretical and empirical insights into the types of concepts, and applications thereof, relevant to digital ecosystems research. In other words, it is a "context-setting paper", which highlights themes and topics of importance to the field of digital ecosystems research and illustrates some of the ways in which those concepts can be operationalised in a productive and enlightening manner. The "garden" of theories, concepts and empirical studies provided in this deliverable will be further extended and deepened in the third and final deliverable of this series, D12.10.

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8. Appendix: Distributed Online Evolution: An Algebraic Problem?

Distributed Online Evolution: An Algebraic Problem?

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***Abstract*— Evolutionary computing in general and distributed online evolutionary computation in particular are hard problems in terms of monitoring, evaluation, generating functionality, and performance. We strive to complement current approaches and develop mechanisms which do not require the ex post effort of controlling the outcome of the computation. Instead, the goal of our research agenda foresees techniques which allow evolutionary and distributed computing to solve the problems above a priori. To support such an intrinsic system we make use of the powerful tool of algebra. Thus, this paper sheds some light on algebraic theories which allow the establishment of strong connections between biological concepts, automata theory, and the algebraic theories associated with them. We compile various contributions from different areas of research of the last few years discussing the algebraisation of biological systems and functions and their relation to automata theory and algebra. We highlight the role of category theory and abstract algebra and outline why these concepts are highly relevant for computational approaches inspired by biological mechanisms.**

I. Introduction

This research is motivated by the fundamental question whether an ecosystem could be used as a model from which to derive self-organising and self-healing properties of software. This research question is premised on the assumption that such biological properties can increase the effectiveness of information and communication technologies (ICTs) in various application domains, from ubiquitous computing, to autonomic communications, to socio-economic processes aimed at regional development, simply on the basis of their greater and spontaneous adaptability to user needs. We refer to distributed socio-economic-technical systems as 'digital ecosystems' [1]. Thus, this paper addresses some of the non-functional requirements of the underlying technology.

Unlike physical systems, software systems do not have an interaction energy and operate at zero Kelvin – because they are abstract. Furthermore, the successes of statistical physics are not readily transferrable to software due to the absence of the concept of temperature in the latter. Of course, the wealth of probabilistic methods based on uniform and non-uniform probability distributions do a good job at achieving an analogous effect; but such effect is contrived in the sense that it is imposed on the digital information which, if left to its own devices in the absence of deterministic instructions, would forever lie still in the 'current state'.

However, the users provide a constant input of information, which we can regard as analogous to the Sun's energy as the fundamental driver of the biosphere. Thus, even if we do not have a proper 'temperature', we do have a constant flow of information through the system and a constant poking and prodding by the users that can be seen as analogous to a certain level of thermodynamic 'mixing'. If we abstract a complex distributed computation and communication system as a set of coupled finite-state machines, user inputs become 'waves' of signals that propagate through the system, carried by the interactions between the state machines. The puzzle of self-organisation and autonomic behaviour, thus, could be cast as the problem of deriving appropriate constraints in the execution paths of the state machines that would lead to the construction of ordered structure and behaviour by harnessing the 'energy' flowing through the (open) system.

In biological systems such constraints arise from the underlying physical laws. Because in software there are no such underlying laws, over the past 6 years our recommendation has solidified into leveraging computer science for what it is strong at, that is, formalisation The methodology is to use mathematics, and algebra in particular, as a common link between physics and computer science. In its most abstract sense, algebra can be used to formalise the regularities in structure and behaviour, or 'symmetries', of biological systems, which are then expressed as constraints on the formal objects of computer science: automata and logic formulas.

Clearly the problem posed in this manner is not trivial. In the DBE EU project we therefore developed an Evolutionary Environment in parallel with the more mathematical research [2] [3] [4]. Although we were able to achieve some level of optimisation of the distribution of services in the ecosystem through a neural networks-based Distributed Intelligence System [5] [6], the evolution of the services to satisfy a particular user request was not achieved. It appeared that using services as the atomic units of evolution was not sufficiently granular to respond adequately to different contexts. On the other hand, breaking services down to apply genetic algorithms to the code itself is still too difficult for engineering applications.

The problem seemed to be a lack of understanding of the structural and dynamical features of ecosystems that need to be satisfied in order to support an effective evolutionary framework. Put simply, because evolution is a weak and slow process that, in order to avoid instabilities (death of the phenotype), can only make extremely small modifications to a given genotype, the ecosystem itself must already be

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highly performant, in the sense that its 'components' must already be quite compatible with one another and must already be close to satisfying a given fitness requirement. This implies the need for a holistic approach, whereby the ecosystem is in some sense 'bootstrapped' *all at once* through a massively parallel process in which hundreds if not thousands of requirements are satisfied simultaneously and compatibly with one another.

Our objective, therefore, is to find a balance between evolutionary computing and what we are calling *interaction computing*. We seek an integration of the two approaches that is analogous to what DNA has been able to achieve: the same molecule is a carrier of hereditary traits across generations whilst also guiding the morphogenesis and metabolism of the individual organism. Based on our experience in the DBE, OPAALS, and BIONETS EU projects, we feel that the problem of interaction computing must be solved first, before we can hope to achieve effective evolutionary behaviour.

After a very brief discussion of related work the paper focuses on three topics: an extremely simplified model of the cell from the point of view of category theory, a discussion of the decomposition of finite automata, guided by a simple example, and a broader discussion of category theory and logic. Conclusions and future work complete the paper.

II. Related Work

Our current and recent work [7], [8], [9], [10], [11], [12] started from a perspective informed by statistical physics and non-linear dynamics and has gradually migrated towards a perspective informed by algebra. We are currently investigating these questions from two points of view: the formalisation of cell metabolic and regulatory pathways through algebraic automata theory, which we can call a local perspective; and the characterisation of the mathematical properties of the cell as a whole through category theory, which we can call a global perspective. The local perspective is inspired and guided by the work of Nehaniv and coworkers [13], [14], [15], [16], [17], which builds on the original work from the 1960s on the prime decomposition of transformation semigroups [18]. We are only at the beginning in the building of a global perspective. In this section we summarise informally some of the pioneering work of Robert Rosen [19]. We have recently become aware of the work of Cornish-Bowden and Cardenas [20], and of Nomura [21], [22], [23]. In addition, it is worth drawing attention to a controversy that has arisen around Rosen's work [24] and that is documented in a series of articles in *Artificial Life* [25], [26], [27], [28], [29].[1] As we are at the beginning of our research programme we do not feel we can adequately address all these references and recent discussions here. However, since Rosen's "central theorem" was motivated by one of his early results that we *do* discuss, we hope that our work can begin to make a positive contribution towards clearing up the controversy.

[1]We are grateful to one of the anonymous reviewers for pointing this out.

Lie groups methods for the solution of low-dimensional dynamical systems modelled as sets of coupled non-linear differential equations is a third strand of activity that appears to be tantalisingly close to the other two, as exemplified by the Lie algebra structure of DNA [30]. This work was only begun in the DBE project [8] and its continuation is planned for future projects and publications. It is interesting that the algebraic object 'Category' is almost identical to the algebraic object 'Transformation Semigroup' (or in fact Monoid), and that the latter as the mathematical representation of automata can be mapped to discrete dynamical systems, which are also amenable to symmetry analysis.

The (descriptive) theory of autopoiesis is concerned with providing a conceptual framework for understanding the organisation of living things. Its emphasis is therefore on the characterisation of whole systems rather than on the structural decomposition and analysis of individual parts [11].

In the 1960s the work of several mathematical biologists whose ideas were compatible with autopoiesis acquired a greater visibility partly because of the general growth of the system theory or 2nd-order cybernetics movement. The work of these mathematical biologists acknowledged the importance of interactions of the system with the observer. For example, Rosen [19] drew a distinction between structural decomposition and functional organisation, and started elaborating a mathematical theory of relational biology, as one of the first applications of category theory.

III. Modelling Biological Systems

Parts of this section have already appeared in [31], [12].

Having noticed that systems of extremely diverse structure still qualify as instances of the same recognisable entity, the biological cell, Rosen's starting point is to say that "What we shall do, in effect, is to begin by *abstracting away the structure* (that is, the physics and the chemistry) of the system, leaving behind only the functional organisation, which then can be characterized and studied abstractly. [emphasis in original]" [32]. Here, he uses the word structure in very concrete biological terms, as in the shape, extent, and material composition of different cells. In mathematics, on the other hand, 'structure' can mean something much more abstract, as in 'algebraic structure' or 'smooth manifold structure'. Our work in applied mathematics is very much based on using abstract mathematical structure to help and to guide our intuition for unravelling how biological process might work.

A. Conceptual Model of the Cell

We stress that what follows is mainly a *conceptual* discussion, since in this early stage of our research we are mainly interested in developing new perspectives in the conceptualisation of biological systems and of their possible 'homomorphisms' to computer science constructs.

Rosen argued that since the lifetime of the cell by far exceeds the lifetime of any of its parts, the cell must implement a mechanism to repair itself [32]. As expressed in a much more recent article [20], this characteristic raises

a major theoretical regression problem caused by a recursive interdependence between different repair systems.

We notice that that the cell is made of two parts: the cytoplasm and the nucleus. We regard the cytoplasm as the site where the metabolic (in truth, also catabolic) activity takes place, whereas the nucleus is the site that implements (among other things) the repair mechanism. The cytoplasm and the nucleus can be seen as two separate but coupled input-output systems. In point of fact, this is not entirely correct. Whereas the metabolic system can indeed be regarded in this way, the repair system is a little different. Figure 1 [19] shows that it consists of components (red circles) each of which is paired to a metabolic component. Of course in nature things are rather more complicated, but notice how even the simple block diagram employed here can already express a fair amount of complexity. For example, the signal that M_6 should be rebuilt does not come from M_6 itself, but from M_5. Such a signal does not have to follow from a 'call for help' from M_6, it could arise at some time after M_6 has stopped functioning. It could be caused indirectly by this fact, or it could simply be something M_5 does periodically. In any case, notice that in this particular model the R-components do not depend on each other, something that's different to the M-components. In other words, epigenetics, which is concerned with dependence between genes, does not appear to be modelled by this theory.

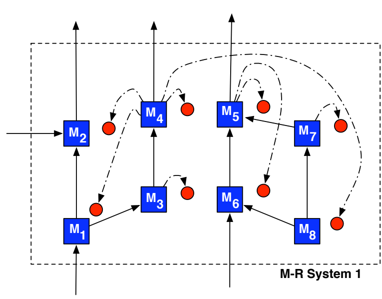

Fig. 1. **Block diagram of a metabolism-repair system**

The repair function relies on the continual synthesis of basic units of metabolic processing (enzymes), in response to inputs provided by the metabolic activity itself. The inputs are shown as curved 'dot-dash' arrows in Figure 1, which in this extremely simplified model could be seen to carry a 'stress signal' from a damaged M-component to its R-component, or as we said more generally from any M-component to any R-component whose job is to replace its M-component with a new version.

Figure 2 shows how this simple model reflects the 'bare bones' of internal cellular organisation. The metabolic input-output system is embedded in the larger M-R system (the cell), which includes also the repair system (the nucleus).

B. *Mathematics of M-R Systems*

This simple model of a cell can be translated into mathematical language. Each metabolic M-component receives inputs and generates outputs. Thus, it can be seen as a function (or map, or mapping) from a set A of inputs to a set B of outputs, where the subscript i refers to a particular component:

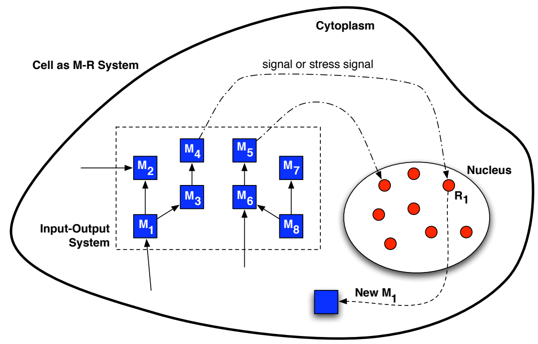

Fig. 2. **Metabolic input-output system and repair system as part of M-R system**

$$f_i \in H(A_i, B_i), \tag{1}$$

which reads, "f_i belongs to the set of mappings from the set A_i to the set B_i". H denotes such a set of mappings. Each repair R-component receives a signal from an M-component, and generates a new copy of the same or of a different M-component. Hence it can be seen as a function from a signal $b \in B_i$ to another function, where B_i is the set of signals associated with the output of metabolic component i:

$$\varphi_i \in H(B_i, H(A_i, B_i)). \tag{2}$$

As will be discussed below, the fact that a particular M-component could be replaced as a result of a trigger originating from a *different* M-component is captured by using the Cartesian product of all the possible B_i's, although this is not shown explicitly in the above equations.

The simplest M-R system that captures these relationships is composed of a single metabolic and a single repair component, which can be written as follows:

$$(A \xrightarrow{f} B) \xrightarrow{\varphi_f} H(A, B) \tag{3}$$

Whereas M-components are being replaced or *repaired* by R-components, we have not addressed the replacement of R-components. As mentioned before, this risks to lead us to an infinite regress of repair components that repair other repair components, ad infinitum. Rosen makes the bold claim that the solution to this riddle is that category theory embodies all the necessary 'machinery' to enable the self-replication of the R-components. The 'self' in 'self-replication', however, refers to the whole M-R system rather than to an individual R-component replicating itself. This means that the M-R system is able to perform this replication. Rather than providing a mechanism, Rosen proves its mathematical feasibility, in two steps:

- first he recasts the repair map (Eq. (2)), which is a map from the set B to the set $H(A, B)$, as a map from the set of all possible repair maps to $H(A, B)$, which we can loosely write as $\varphi \to f$
- then he shows that this map is invertible: $f \to \varphi$

With this proof Rosen shows that M-R systems are self-contained, or metabolically closed using the Cornish-Bowden terminology, or operationally closed using the Maturana and Varela terminology, by proving that φ and f can generate each other. Please see [12] for the complete proof.

The fact that DNA is routinely repaired by the cell gives us pause. We already knew this and did not need category theory to tell us as much. However, the result of Rosen has a unique depth of significance because it highlights how the two repair systems, which we had no special reason to believe were related, may actually be very closely linked. How closely depends on how we interpret the meaning of 'invertible'. But there is no question that this result introduces an important aspect of the conceptualisation of the cell and of its possible mathematical modelling. Could this be an example of how the organisation of the metabolic activity mirrors in some way the structure of DNA? Could this be an example of what 'information contained in the environment' means?

The possibility that the same cell metabolism has an 'outward-facing' function to carry out the job of the cell and an 'inward-facing' function to repair DNA brings us to the concept of multi-functionality.

C. Multi-functionality

Cornish-Bowden and Cardenas share our view of the importance of the multi-functionality of the components of self-organising systems: "A major principle that has emerged from studies of the circular organization of metabolism is that the circle of efficient causation can only be closed if some (and in reality probably many) of the catalysts used by organisms fulfil multiple functions. Multifunctionality, or 'moonlighting', is increasingly observed, but it is much more than just an interesting observation about living organisms, because it is essential to their survival." [20].

Multi-functionality could, for example, enable an M-component to double up its function to map elements of the set of inputs A to the set of outputs B with the function to generate its φ – the same φ that will then generate f when it receives the right signal, as discussed. Nomura captures the analogous and nested functional structure of the simplest M-R system very succinctly [23]:

$$\left\{ \left[A \xrightarrow{f} B \right] \xrightarrow{\varphi_f} H(A,B) \right\} \xrightarrow{\Phi_f} H(B, H(A,B)), \qquad (4)$$

which shows how the M-R system we have been talking about so far, on the left and in curly brackets, can itself be considered analogous to a 'metabolic component' of a larger M-R system which repairs the R-components. This highlights Rosen's point that there is an "equivalence between the metabolic and genetic activities" [19].

In this section we have only scratched the surface of an important area of mathematics for the modelling of cellular processes, category theory. In the next section we begin to address the formalisation of computational structure as the fundamental bridge between biology and computing.

IV. Automata Theory and Biological Models

A. Automata

This section is chiefly motivated by [14], as follows. The interactions between the DNA and cell metabolism are formalised through a complex web of interlinked biochemical processes. If we choose a subset of these that is relatively autonomous, we can derive a Petri net from the chemical reaction equations. Such a Petri net is a subset of a much larger automaton, whose algebraic structure can be analysed through Krohn-Rhodes theory [18]. Hence, we need to develop an in-depth understanding of algebraic automata theory in order to be able to discover and interpret appropriately the computational structure of cell metabolism.

We rely mainly on [33] and [16] and define an automaton as the quintuple $\mathcal{A} = (A, X, O, \delta, \lambda)$, where A is a finite set of states, X is a finite input alphabet, O is a finite output alphabet, $\delta : A \times X \rightarrow S$ is the next-state or transition function, and $\lambda : A \times X \rightarrow O$ is the output function. The next state of an automaton is determined by the input symbol that is fed to it. To a succession of input symbols there corresponds a succession of states. The concatenation of arbitrary numbers of input symbols from X defines a set of admissible input sequences. Because such a set is then closed with respect to concatenation and because concatenation satisfies the associative property ($x(yz) = (xy)z = xyz, \forall x, y, z \in X$), this set forms a semigroup with the operation of concatenation, denoted by X^* and called the *free semigroup* on X.[2]

The above definition of semigroup is analogous to the axiomatic definition of group. Just as the rotational symmetry groups of geometrical figures provides a tangible example of a set of elements upon which a permutation group could operate, the set of states of an automaton provides an analogous concrete set of elements upon which the free semigroup can operate. We therefore see a very close parallel between permutation groups acting on sets of elements and a new mathematical object called a *transformation semigroup* acting on the set of states of an automaton. In fact, the only difference between the two is that in the latter an inverse is not defined for each member of X^*. If every input sequence also had an inverse then X^* would actually be a group. In this section we discuss briefly some aspects of an automaton derived from a permutation group [12].

1) The DFA of the rotational symmetry group of the tetrahedron: Figure 3 shows the deterministic finite automaton (DFA) obtained from the rotational symmetry group of the tetrahedron, whose periodic structure is very evident.

2) Partitions and hierarchical coordinates: In addition to acting on the individual states of the DFA, the transformations r and s can be seen to operate also on a 'coarser' version of this DFA. In other words, they operate on subsets of states, as shown in Figure 4. We now develop some mathematical formalism around this concept, following [33].

[2]In truth, X^* also contains the identity element, which is the empty sequence Λ, and therefore it is really a monoid. However, the use of the term 'semigroup' is more common even when it contains the identity.

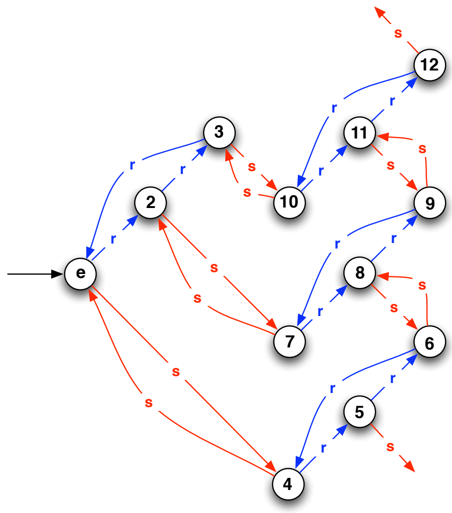

Fig. 3. DFA derived from the rotational symmetry group of the tetrahedron

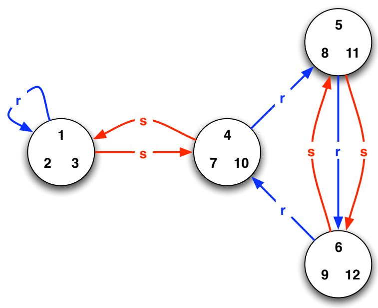

Fig. 4. Lower-resolution coordinate of tetrahedron DFA

A *partition* π on A is a collection of disjoint subsets of A, called 'blocks', whose union is A:

$$\pi = \{B_\alpha\} = \{B_1, B_2, ..., B_n\} \tag{5}$$

The block B of partition π that contains element a is designated by $B_\pi(a)$. Thus, the blocks of partitions are conceptually analogous to the cosets of rings and fields (see [9] for more on rings and fields). More precisely, "If R is an equivalence relation on A, then the set of equivalence classes defines a partition on A, and conversely every partition π on A defines an equivalence relation R on A whose equivalence classes are the blocks of π" ([33]: 4). We will need the following definitions and operations:

$$a = b(\pi) \quad \text{means that } a \text{ and } b \text{ are in the same block of } \pi\text{: } B_\pi(a) = B_\pi(b) \tag{6}$$

$$a = b(\pi_1 \cdot \pi_2) \iff a = b(\pi_1) \;\wedge\; a = b(\pi_2) \quad \text{(the blocks of } \pi_1 \cdot \pi_2 \text{ are the intersecting blocks of } \pi_1 \text{ and } \pi_2\text{)} \tag{7}$$

$$a = b(\pi_1 + \pi_2) \iff \exists \text{ a sequence in } A\text{: } a = a_0, a_1, ..., a_n = b \quad \text{such that } a_i = a_{i+1}(\pi_1) \;\vee\; a_i = a_{i+1}(\pi_2),\; 0 \le i \le n-1 \tag{8}$$

Whereas Eq. (6) is just notation and the product of two partitions (Eq. (7)) is easy to understand intuitively, Eq. (8) is much harder to unpack. However, it is not difficult to grasp intuitively either. What it says is that where the blocks of two partitions overlap (i.e. contain some of the same elements) the sum of the two partitions will have blocks that are the union of such overlapping blocks. Where the blocks do not overlap, they will remain separate also in the sum.

Given a machine $\mathcal{A}$ such as the one given in the definition above, we say that a partition π on A has the *substitution property* (SP) if and only if

$$a = b(\pi) \quad \Rightarrow \quad \delta(a, x) = \delta(b, x)(\pi), \quad \forall x \in X, \tag{9}$$

which means that a partition has the SP iff two states belonging to the same block implies that all their possible next states *also* belong to the same block. Notice that 'same' here could also mean the block they both start from in addition to a block that is different to the starting block, which is perhaps the more natural interpretation.

The SP carries an additional, powerful implication, which motivates the work we are about to do with it. If π has the SP, it is clear that $a, b \in B_0$ will be mapped by δ to some other block B_1, for an input x_1. If we now take a third element $c \in B_0$, by construction $a = c(\pi)$. Therefore, since π has the SP, $\delta(a, x_1) = \delta(c, x_1)(\pi)$, and c is also mapped to B_1 by δ, for the same input x_1. Repeating the argument for other elements of B_0, it is easy to see that by induction the SP implies that the input x_1 maps the *whole* of B_0 into B_1. Most generally, under δ each input x_i will map B_0 to a potentially different B_i. Hence, since δ determines unique block-to-block transformations for SP partition π, we can think of these blocks as the states of a new finite state machine defined by $\mathcal{A}$ and π. This is the main concept behind the decomposition of finite automata.

We are gearing up to the development, and eventual application, of a rigorous framework for the analysis of automata. Let's therefore use the tetrahedron DFA as a simple example we can analyse completely in order to understand all the relevant concept completely.

Another key concept we need is that the partitions of a set A form a partially ordered set, or 'poset' (see [9] for more on posets). Therefore, all the partitions of the state set of an automaton can be arranged as a Boolean lattice, which we call L. In order to do this for the tetrahedron DFA we need to calculate all of its partitions, and we also need a criterion to order them.

If π_1 and π_2 are partitions on A, we say that $\pi_1 \le \pi_2$ iff every block of π_1 is contained in a block of π_2.

To build a lattice we also need to identify and/or construct the least upper bound (l.u.b.) and the greatest lower bound (g.l.b) for any two given partitions:

$$\text{l.u.b.}(\pi_1, \pi_2) = \pi_1 + \pi_2 \tag{10}$$

$$\text{g.l.b.}(\pi_1, \pi_2) = \pi_1 \cdot \pi_2 \tag{11}$$

A consequence of the above definitions is that the l.u.b of the whole set of partitions on a set of states A =

$\{a, b, c, d, ..., z\}$, called the *supremum*, is denoted by the identity symbol I[3] and is given by (following [33], blocks are indicated by an overbar):

$$I = \{\overline{a, b, c, d, ..., z}\} \tag{12}$$

The infimum, on the other hand, is

$$\mathbf{0} = \{\overline{a}; \overline{b}; \overline{c}; \overline{d}; ...; \overline{z}\} \tag{13}$$

We can now proceed with the computation of all the SP partitions of a state set. This involves starting with all the smallest partitions, and combining them through sums to obtain larger partitions. This takes quite a bit of work, so the motivation for doing this is to understand the structural characteristics of this automaton in greater depth, hoping that our understanding will be more generally applicable and hoping also to recognise any opportunities to automate the process (e.g. through symbolic algebra programs such as *Mathematica*).

The 7 minimum SP partitions are (see [12] for the details):

$$\pi_1 = \{\overline{1,4}; \overline{2,5}; \overline{3,6}; \overline{7,12}; \overline{8,10}; \overline{9,11}\} \tag{14}$$
$$\pi_2 = \{\overline{1,9}; \overline{2,7}; \overline{4,11}; \overline{3,8}; \overline{5,12}; \overline{6,10}\} \tag{15}$$
$$\pi_3 = \{\overline{1,11}; \overline{2,12}; \overline{4,9}; \overline{3,10}; \overline{5,7}; \overline{6,8}\} \tag{16}$$
$$\pi_4 = \{\overline{1,2,3}; \overline{4,7,10}; \overline{5,8,11}; \overline{6,9,12}\} \tag{17}$$
$$\pi_5 = \{\overline{1,5,10}; \overline{2,6,11}; \overline{3,4,12}; \overline{7,8,9}\} \tag{18}$$
$$\pi_6 = \{\overline{1,6,7}; \overline{2,4,8}; \overline{3,5,9}; \overline{10,11,12}\} \tag{19}$$
$$\pi_7 = \{\overline{1,8,12}; \overline{2,9,10}; \overline{4,5,6}; \overline{3,7,11}\} \tag{20}$$

Now we find that the sums $\pi_1 + \pi_2$, $\pi_1 + \pi_3$, or $\pi_2 + \pi_3$ all equal the same partition:

$$\pi_8 = \{\overline{1,4,9,11}; \overline{2,5,7,12}; \overline{3,6,8,10}\}, \tag{21}$$

whereas *any* other sum between any of these 8 partitions equals I. Hence we have found all the partitions of this DFA. The state transition charts of π_8 and π_1 are shown in Figure 5, whereas π_4 already appeared in Figure 4. Figure 6 shows the Boolean lattice for all the SP partitions, which shows the different resolution levels of the various sub-automata.

3) Is the glass half-full or half-empty?: SP partitions can be seen from the point of view of ignorance or information. We know that a state in a particular block is mapped to other blocks along with the other states in its own block. If we regard our knowledge of which block a state belongs to or is mapped to as a certain level of information we possess about the system, then we could regard the fact that we can resolve the location of that same state only up to which block it belongs to as our corresponding level of ignorance about the same system.

The implication of this view is that the largest partition of all, I, corresponds to the greatest ignorance level and to the least information we can have about that state: it belongs to the automaton $\mathcal{A}$ and that's all we can say about it. Conversely, the smallest partition, $\mathbf{0}$, corresponds to the

[3]We use a different symbol to e in order not to cause confusion with the identity transformation of a group or semigroup.

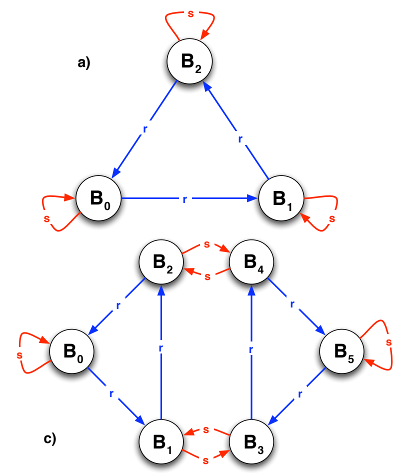

Fig. 5. State chart of a) π_8 and c) π_1

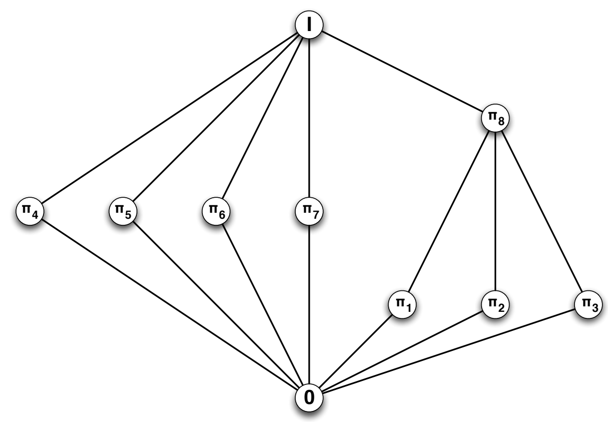

Fig. 6. Boolean lattice of tetrahedron DFA's state set partitions

smallest ignorance level and greatest information: we know exactly where our state is in the state transition graph of $\mathcal{A}$. SP partitions do not change our level of ignorance or information as any initial state is mapped to subsequent blocks.

B. Categorical view

In its main features, category theory is a highly abstract way to look at mathematics. It provides a formalism able to describe general characteristics of similar structures and to formalise transformations from one type of structure to another. We usually know mathematics from a rather *structure-internal* point of view, i.e. we look at a set of elements and define the operations we can perform on them. Category theory takes one step back and looks at the collection of these definitions from an *external* perspective. Thus, it does not discuss the elements of the internal structure but the structure described by the elements and their definitions. Using functors it can also put these structures into relation or transform one structure into the other. From this point of view, this complex theory perfectly fits our way of looking at biological processes and their formalisation. Assuming familiarity with a number of introductory textbooks ([34],

[35]), we aim to show why Category Theory is becoming increasingly relevant to our research.

All types of algebraic structures can form categories. One obvious question that we need to answer is whether we can also apply category theory to automata or transition systems in general, i.e. whether we could use the powerful tools of this theory to compare the results we get from discussing systems or models of real systems in biology, physics, etc. with systems or models in automata theory. Even more relevant for our research: Can we directly map automata or even any kind of system into category theory? Partially, these questions have already been answered. Permutation groups, which are also monoids, are objects and thus can be mapped into a category. A permutation group or monoid underlies an automaton. Thus, the simplest category representing, e.g., a finite state machine is a category consisting of one object, the set of all elements of the monoid. The arrows of this category are the transitions of the automaton. This mapping is very easy but it does not reveal much about the structure of the automaton. However, a more structured mapping can be chosen, such as in [36].

From a semigroup G, representing automaton $\mathcal{A} = (A, X, \delta)$, a small category $\mathcal{G}$ can be derived. It basically represents the *input processing* of our automaton. Thus, we know *what* the automaton processes. To clarify the internal structure of our automaton, i.e. *how* it processes the input, the category $\mathcal{S}$ of all sets together with a functor with domain $\mathcal{G}$ and codomain $\mathcal{S}$ can be considered. It maps each object $u \in \mathcal{G}$ to set S of the automaton and each arrow $z \in \mathcal{G}$ it associates with the corresponding mapping $\delta^*(z)$ defined by the original signature of the automaton. With this functor we are able to separate the structure of the automaton – the state transitions – from the set of objects it is working on. Thus, the functor can be interpreted as an automaton. Hence, the functorial view also allows us "…to distinguish the automaton's structure and those mathematical objects on which this structure is realized." [36]. We can further interpret each of these functors as an object and construct a more abstract category $\mathcal{S}^{\mathcal{G}}$. Morphisms between objects of this category, i.e. automata, would then be natural transformations. They allow us to compare different automata, construct new automata by combining functors, and to define different transformations from one automata into another etc.

C. Coalgebraic view

Another important concept in Category Theory is duality as it allows us to also involve the complement of algebraic automata theory in our discussion: *coalgebra*.

With regular algebra we can describe an automaton starting from its internal structure. Its definition is based on the carrier set A (also called the set of states). Together with a transition function $\delta : A \times X \rightarrow A$ it describes the behaviour of the automaton. In categorical terms we can reformulate this presentation and form an F-algebra (A, α_A) with the endofunctor $F : \mathcal{S} \rightarrow \mathcal{S}$. Here, α_A is a morphism with $\alpha_A : F(A) \rightarrow A$. This very general definition allows us – depending on the type of functor F – to describe many different classes of automata, e.g. with $F(A) = X \times A$ we are able to describe a state machine with a fixed input alphabet X. Important principle to note: In abstract terms F-algebras describe how to construct new elements in A, i.e. full knowledge about the construction of A is available.

The dual to F-algebras, F-coalgebras [37], allow us to reverse this principle: in order to obtain full knowledge about A the operations defined by the coalgebra have to be applied. This is achieved by simply generating the dual of α_A which is $\beta_A : A \rightarrow F(A)$. (A, β_A) then describes the F-coalgebra.

The study of automata in this bialgebraic framework has several advantages. Many observations made in the domain of algebras already hold in the domain of coalgebras by the principle of duality. Additionally, each domain provides separate insights. Some properties are easier or better to describe in one domain compared to the other. Similarly, some solutions to particular problems become easier to solve in the dual domain. Finally, F-coalgebras and F-algebras with a specific functor F form so called topos [38]. Observations in this category can help to get a deeper understanding of the class of automaton, e.g. finding isomorphisms.

Therefore, the combination of *universal algebra* and *universal coalgebra* using the "glue" category theory is a powerful tool to formally describe a large variety of static and dynamic systems in computer science, including programming language semantics, finite and infinite or recursive data types, transition systems, concurrent programming languages, dynamical systems, etc.

Among the various results which have been presented in pertinent literature we would like to mention the results from Gabriel Ciobanu and Sergiu Rudeanu [39]. Using category theory they translated existing links between Mealy, Moore, and Rabio-Scott automata into isomorphisms of categories, which did not only show equivalences between single automata but between different classes of automata. Based on the work of Varacca [40] who combined non-deterministic and probabilistic systems, Jacobs [41] used coalgebras to describe traces in such systems which is important for validation and verification purposes. Finally we mention Badouel and Tchendji [42], who use principles of coalgebras to ensure consistent update mechanisms of hierarchically organised documents whose parts – considered as subsystems – are fragmented in highly distributed computer networks.

The young research domain of coalgebra is just conquering the various fields of its application. Coalgebraic logic and automata specification, which we will briefly discuss in the following section as important building blocks for our future research, are two of them.

V. Implications for Evolutionary Computing

To gain a better appreciation for the motivation that underlies such an investment of energy and resources, we should clarify that until the 1960s the general consensus was that semigroups were too unstructured for anything useful to be done with them. This perception was radically changed by the Krohn-Rhodes theorem published in 1965 [18], which

proved the existence of a much greater amount of structure in semigroups. The relevance of semigroups to automata has then made this mathematical theory of increasing interest to computer science over the past 40 years. For our purposes, finally, we remark how the non-linear character of automata ([43]: 8) suggests that they could be the right instrument to model the enormously intricate feedback loops of discrete cellular processes.

The non-uniqueness of K-R decomposition and the sheer complexity of semigroups and their algebra have maintained this area of mathematical research 'current' up to the present day. More importantly, the computational power we now have at our disposal has recently made it possible to develop tools in computational group theory that are beginning to make the exploration of semigroups more feasible. Some branches of current research in computational systems biology ([15], [13], [14]) address specifically the formalisation of cellular pathways as automata. It is our hope, therefore, that the analysis of the algebraic structure of such biologically derived automata will afford us some useful insights on the correlation between the algebraic structure properties of these automata and the observed self-organising or autonomic behaviour they enable. In the remainder of this section we are going to sketch how the analysis of three of these correlations may impact evolutionary computing.

A. M-R Systems Again

Let's start by looking at component M_1 in Figure 1. If we take out this component, M_2, M_3, and M_4 will cease to function. M_4 will also fail to send a signal to R_8, thereby preventing M_8 from being replaced. As a consequence, the whole system will eventually stop functioning. If we take out M_2, something else happens. The rest of the system continues to function and eventually M_2 will get replaced when an appropriate signal from M_4 reaches R_2. Components like M_2 are called *reestablishable*, whereas components like M_1 are called *non-reestablishable*. M_1 is also called *central* because the whole system depends on it. Rosen states and proves in [32] that every M-R system must contain a non-reestablishable component. Additionally he concludes that a single non-reestablishable component in an M-R system must be a central component.

Based on this theorem we can say a few interesting things about the cell model developed by Rosen [19]. If we regard a cell as an M-R system, there must be one or more metabolic components whose loss or injury is not repairable by the system. One may think that minimising the number of non-reestablishable components would be desirable, i.e. down to 1. However, the smaller the number of non-reestablishable components the more central they become, i.e. their loss causes greater damage to the whole system. Thus, it should be interesting to see whether evolution has selected for a relatively large number of non-reestablishable components, such that the loss of each of these might not cause too great damage to the cell. It is also worth asking how these considerations might relate to the online evolution of, e.g. software. Is it possible to use this knowledge to improve the fitness function for increasing the resilience of individuals which are highly dependent on different interacting components?

B. Algebraic Specification

Section IV showed how it is possible to describe a system by simply using an algebra. The same algebra or a subset of it can be used to specify a system, e.g. in terms of what the system must or must not do. This branch of research is called *algebraic specification*. It defines a formal and thus mathematical model of a system in order to be able to verify certain properties. With the help of category theory we are able to refine, combine, or analyse these specifications. Additionally, by duality, category theory induces the field of coalgebraic specification. As a consequence we can choose specifications according to our needs. For algebraic specifications we can choose a specification 'language' which uses the state space, such as complete traces. In the case of a coalgebraic specification the internal state of the system is not important but the operations on the state space which transition the system into new states are.

Of course, the type of specification does not only depend on the property to be specified but also on the type of system it is determined for. In fact the logic used to specify a particular system property strongly depends on the system description [44]. In [45], we have listed a small choice of logics and how their expressiveness can be used to specify a system. They are perfectly feasible to specify properties in classical algebraic systems. But it is also desirable to be able to use temporal logic for reasoning about systems defined by coalgebras. After all, for the purpose of specifying requirements or constraints some type of logic is essential. Coalgebraic logic [46] closes this gap. It defines general modal logics interpreted on coalgebraic systems.

So why are category theory and (co-)algebraic specification so important for distributed online evolution? We are striving towards a deeper understanding of how we can couple automata specifications and their logical equivalent. Assume that we can develop a logical specification language in which the system description has direct impact on the semantics and structure of an automaton. Further assume that we can show that this coupling of specifications and their respective automata induces a special class of category such as is done in classifying categories. In this case we might be able to represent automata with special characteristics, such as certain security or resilience properties, or simply a certain fitness, etc., as a subcategory of the category of all possible automata the interaction computing framework defines. Such a specification will not only restrict the type of automata to particular structures but it may also intrinsically limit the number and type of combinations or modifications, e.g. which might be applied by mutation or cross-over operations in genetic programming, with other automata. In our framework, combinations and modifications may then be presented as natural transformations. Current research – to our knowledge – has not been able to show yet whether the theory of F-coalgebras can be developed in its corresponding functor F and natural transformations

applied to it. Fortunately, active research in the area of modal logic and the efforts of trying to discover a direct relationship between the coalgebraic logics and their respective systems represents a viable alternative.

Our research direction is also confirmed by recent findings in the field of trace semantics which yield a description of traces in the framework of coalgebra. Why is this? Traces are known to be an important means to identify system properties, e.g. for security. When used for specifying properties particular traces can even be combined in order to express more complex properties. It will be interesting to study the impact of the framework of coalgebra on systems using traces, e.g. as presented by Mantel in [47] who specifies information flow properties. We think that these traces may yield a particular category, probably a subcategory of the more generic traces presented by Hasuo et al. [48].

VI. Conclusion

The main conclusion we can draw from the material discussed in this paper is that, in addition to the challenges to be found in each of the disciplines discussed, we are also facing the very difficult interdisciplinary challenge of integrating these different theories into a single framework of general applicability. The following observations summarise our current understandings towards such an integrative framework.

A. Structure and Behaviour

We wish to emulate biological behaviour. But biological behaviour is strongly dependent on structure.[4] Thus, if we want to emulate biological behaviour in software we also need to understand structure formation in biology and the interdependence between structure and function. In fact, evolution could be described as the trial-and-error process by which the most adequate structure or morphology is selected for a given environment or ecosystem.

But natural selection does not act alone. Like a sculptor it acts to find the best 'shape' to fit a particular task, defined by a set of environmental constraints, but unlike a sculptor it does not work with inert marble. The marble of evolution is alive, and embodies an inner force of self-organisation within each species that like a powerful geyser pushes against other species in the ecosystem in ruthless competition for the limited resources, the whole ecosystem holding itself in balance through the scalpel of natural selection.

In spite of infinite flexibility, some structures remain invariant, or at least quite stable, for two reasons: either they reflect a constant feature of the environment (most animals' ability to metabolise oxygen reflects the stable presence of oxygen in the earth's atmosphere throughout its history), or they represent an optimal solution given the available materials (e.g. gray matter). In either case we can't help noticing a great deal of structural regularity, where the meaning of 'structure' should be taken in the most general and abstract possible sense: from physical structure to abstract mathematical structure. The latter, in particular, applies just as easily to the former as to the formalisation of dynamical behaviour. The emphasis on automata and on an algebraic perspective in our work is motivated by the algebraic structure of both physical and dynamical regularities.

B. The Link to Dynamical Systems

Aptly, dynamical systems theory has uncovered quite a bit of inner structure in the dynamical behaviour of non-linear systems. This is relevant since cellular processes are strongly non-linear (rich in feedback loops). Grafting in an evolutionary framework enables the system to respond at a deeper structural level and over longer time scales to changes in the 'environment', of which the users are the principal part.

In its simplest form, an automaton is composed by a set of states and by a set of transformations that operate on the set of states. The set of transformations has additional structure and therefore we call it a semigroup. Thus,

$$\begin{aligned}\text{Automaton} = {} & [\text{set of states}] + [\text{semigroup of trans-} \\ & \text{formations operating on this set}] \end{aligned} \tag{22}$$

A dynamical system can be seen as a continuous manifold and a set of continuous transformations operating on this manifold. So we can write down a similar 'equation':

$$\begin{aligned}\text{Dynamical system} = {} & [\text{manifold in phase space}] + [\text{Lie} \\ & \text{group of continuous transformations} \\ & \text{operating on this manifold}] \end{aligned} \tag{23}$$

Thus, we notice that dynamical systems share a similar algebraic structure to automata, but that, in addition, they also have a continuous analytic structure [49].

Now the strange and surprising thing is that, whereas in an automaton the transformations are aligned with the time axis, in the case of dynamical systems the time evolution of the system along the solution curve is not actually the focus of attention of Lie groups-based analytical methods. Rather, the transformations are 'perpendicular' to the time axis. This is because whereas the time dimension is measured *along* a solution curve, the transformations of a Lie group map a solution to an *adjacent* solution. We are investigating the possible connections between the 'temporal symmetries' associated with the semigroup structure in the direction of computation with the 'spatial symmetries' associated with the topological structure of the manifold that hosts the solution trajectories.

Mathematical research in semigroups is very advanced and semigroups in general are extremely difficult objects to work with. While this is a little daunting, at the same time it provides a certain level of reassurance since it suggests that the theoretical framework we are developing may be of sufficient sophistication to match at least the simplest aspects of the overwhelming complexity of the 'computation' performed inside the cell. It is this perception, therefore, that motivates us to build a body of codified and formalised

[4]This is a strong and wide-ranging statement that needs to be qualified. For example, in Section III we mentioned how the internal organisation of cells is *independent* of their structure. In spite of this fact, there is undeniably a strong interdependence between structure and whole classes of biological behaviour.

knowledge that will hopefully serve as a bridge between the roles of DNA in metabolism and in evolution.

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