From Metaphor towards Paradigm - A Computing Roadmap of Digital Ecosystems

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***Abstract*—Metaphors from biological ecosystems emerge in a wide range of leading computing areas and applications of digital ecosystems. The diversified use of these metaphors in different application domains of digital ecosystems varies between computing areas and shapes their interventions. This paper reviews these application interventions of various computing areas as a qualitative approach to outline a roadmap of digital ecosystems from a metaphor towards a mature scientific paradigm. This roadmap is illustrated through five propositions to current practice. The proposed roadmap envisions digital ecosystems as a collaborative coordination environment and platform for computing interventions.**

I. Introduction

Social, technological and business systems emerge to large-scale, decentralized, open, heterogeneous, adaptive, loosely coupled and complex digital ecosystems that experience major computing interventions [4], [12]. However, the term 'ecosystem' cannot be justified by simply using it as a metaphor to raise ungrounded and naive analogies between the complexity of computing and biological environments. Transforming the notion of a digital ecosystem to a mature scientific paradigm requires the introduction, integration and diversity of those emergent computing properties that do match with properties found in sustainable biological ecosystems and even go beyond them.

The notion of digital ecosystems used in literature as a metaphor or a paradigm remains unclear. A wide range of bio-inspired computing areas, such as peer-to-peer computing, autonomic computing and organic computing, define and describe digital ecosystems from different angles, yet with a high degree of overlap in their concepts and contributions. This paper classifies these computing areas to two classes of metaphors and reviews their interventions in application domains as a qualitative approach to evaluate the potential of digital ecosystems to evolve from a metaphor towards a mature scientific paradigm.

Despite the wide theoretical applicability of various proposed computing frameworks, each computing area actually focuses on specific application interventions with certain assumptions and specializations. For example, some of the most important contributions of autonomic computing concern the power management of large data centers with an emphasis on software. In contrast, interventions of organic computing appear in the area of embedded control systems. Despite the major theoretical overlap between autonomic and organic computing, their interventions appear almost independent.

This paper aims to identify and discuss some of the links between these computing areas and draw a roadmap of digital ecosystems towards paradigm. This paper supports this roadmap based on five propositions that are justified by the illustrated literature review of various relevant computing interventions. The propositions of this paper illustrate digital ecosystems as a potential unifying collaborative environment and platform of computing interventions in a wide range of application domains.

The rest of this paper is organized as follows. Section II provides background information about the use of metaphors and paradigms in science. Section III illustrates a classification of different computing areas of digital ecosystems based on the use of metaphors. Section IV includes a detail discussion about the interventions of different computing areas. Section V introduces five propositions to the current practice that form a roadmap towards the paradigm of digital ecosystems. Finally, Section VI concludes this paper.

II. Computing Metaphors and Paradigms

Metaphorical concepts, such as biomimicry [45], have always been used throughout the developments and advancements of computing systems. The abstract nature of computing systems, especially the one of software systems, is a challenge for the generation, evaluation and acceptance of new conceptual ideas compared to other scientific disciplines, e.g. biology, that are based on physical observations and interpretations. Metaphors provide (i) inspiration, (ii) intuition, (iii) educational value and (iv) concepts that can be shared between different computing areas and communities. When studying complex, large-scale, decentralized, open and heterogeneous computing systems, the introduction of metaphors inspired by biological ecosystems provides a new source and research framework of knowledge.

From a different viewpoint, cognitive sciences use metaphors to acknowledge the critical role of prior knowledge in acquiring new knowledge from real-world problems [6]. Computer scientists use metaphors as a representation, recognition and evaluation of research applications or solution interventions. In other words, metaphors in a culture of scientific research, have merits for building pragmatic solutions and supporting researchers to claim the interventions of these solutions. Therefore, metaphors facilitate a collective initiative for establishing mature scientific realities that make a difference in social and organizational contexts. For example PolyWorld [47] is a computing model of living organisms that attempts to integrate key components of living systems through a visual perceptive mechanism that helps foster and simplify complex ecology.

Social networking is also an example of a paradigm that emerged from various computing areas and their metaphors. Such transformations and enrichments are one of the visions of this paper for digital ecosystems. However, metaphors may result in oversimplifications, misconceptions or conceptual problems related to (i) arbitrary primitives, (ii) describing real metaphor phenomena and (iii) non-empirical formalism [6]. 'Metaphorical displacement' describes metaphors that move between two scientific disciplines, for example neuroscience biological metaphors in bioinformation and neuroscience bioinformation metaphors in biology [36].

Moving towards a mature scientific paradigm of digital ecosystems requires a structural review of the related computing areas and their adopted metaphors as a means to minimize their drawbacks and emerge their aforementioned benefits.

III. Computing Areas of Digital Ecosystems

There is a range of computing areas that use metaphors of biological ecosystems. This paper identifies a distinction in the way these metaphors are used and introduces a classification to *metaphor-inspired* and *metaphor-defined* computing areas.

Metaphor-inspired computing areas usually have clear technical foundations in their terminology and concepts but introduce methodologies and applications inspired by ecosystem metaphors. A metaphor in a metaphor-inspired computing area indicates an analogy of an algorithm or a computing system with a biological phenomenon or process. Such a metaphor provides an intuition and a better understanding of computing problems and motivates solutions that successfully apply in biological ecosystems. However, the main artifacts, terminology and concepts of a metaphor-inspired computing area remain technical and computing-based.

In contrast to metaphor-inspired, metaphor-defined computing areas engage metaphors more explicitly and have a more dominant role in their foundations. More specifically, the artifacts, terminology and concepts of metaphor-defined computing areas are related to the self-* properties, evolution and sustainability of biological ecosystems.

This section classifies a number of computing areas relevant for digital ecosystems in these two classes. Note that it is not the purpose of this paper to cover all of the related computing areas that use metaphors related to biological ecosystems. Nonetheless, the discussed computing areas serve the supporting arguments of the propositions illustrated in Section V and the proposed computing roadmap of digital ecosystems towards a scientific paradigm. Future work aims at a more complete and in-depth coverage.

A. Metaphor-inspired Computing Areas

Biological principles are mainly introduced in distributed algorithms and systems. Some of these biological principles [14] and patterns [1] are related to diffusion, replication and stigmergy, and appear in swarm intelligence of social insects, firefly synchronization, activator-inhibitor systems, immune system, epidemic spreading, cellular signaling etc.

1) Peer-to-peer computing: Peer-to-peer systems are decentralized computing systems that are based on a large number of computing hosts (peers) that provide and consume resources in a balanced and 'fair' manner. Peers need to search, aggregate and load-balance their resources without centralized intervention. To meet these requirements, peers form self-organized overlay networks to manage this complexity. One of the challenges in peer-to-peer searching is when to exploit and explore new information. Ant algorithms are used for this problem to model query routing and data replication [29]. Epidemic protocols are used for fast information dissemination and aggregation [1].

2) Cloud computing: Cloud computing refers to a distributed environment in which users can store and access resources remotely using any of their personal computing machines with network access to the cloud. The metaphor of a cloud ecosystem inspires both business models [3] and techniques for efficient resource allocation and scheduling by ant colony virtualization frameworks [48].

3) Agent-based computing: The notion of an agent is multidisciplinary as it appears in many scientific areas and contexts. Agents-based methodologies have always been inspired by biological metaphors from the level of the cell up to the level of ecosystem populations and species that dominate and extinct.

4) Grid computing: Grid computing focuses on high-performance applications that distribute computational load in a computing infrastructure. A wide range of optimization algorithms, such as genetic algorithms, perform resource allocation and scheduling [25].

B. Metaphor-defined Computing Areas

Biological concepts, such as self-organization, self-healing, evolution and sustainability pose as principal concepts in metaphor-defined computing areas. Applications are an actual computing specialization of these biological concepts. For example, self-healing properties in a Smart Grid are instantiated by monitoring and fault-detection/tolerance mechanisms [7].

1) Autonomic computing: Autonomic computing is an IBM initiative that envisions systems designed with properties of the human autonomic nervous system. Autonomic computing emphasizes on self-* properties that make systems more robust, reliable, and efficient to resemble the sustainability of biological ecosystems. These properties are realized by various proposed frameworks [23], [27], [43] that are based on utility functions and adaptation via feedback control loops.

2) Organic computing: Organic computing overlaps conceptually with autonomic computing. Self-* properties are also the core of its foundations. However, self-organization, decentralization and emergence are the key properties for organic computing that are regarded crucial for future computer systems and cyber-physical systems [33].

3) Evolutionary computing: The concepts of Darwinian theory build the foundations of evolutionary computing. These concepts guide the design of iterative optimization processes that search for solutions in computational problems [15]. Reproduction, mutation, recombination, selection and fitness are some of these concepts that model evolutionary algorithms.

4) Green computing: Green computing [34] describes a set of goals about (i) how computer systems can make our environment more sustainable and (ii) how computer systems can be designed and operate in a most sustainable and environmental-friendly manner. Computing systems in green computing favor or optimize environmental factors. Therefore, sustainability plays a dual role: It is an ecosystem metaphor that defines the computing area and it is also the one that benefits from green computing. The reduction of energy consumption and carbon footprints by personal computers and data centers, recycling, the usage of renewable energy sources for powering computing systems, the usage of environmental-friendly materials and other actions that have a multidisciplinary scientific background are some research efforts of green computing.

IV. Different Computing Interventions

This section provides an overview of application interventions for each computing area illustrated in Section III. Due to the vast scale and range of research work in these areas, this section does not illustrate technical methodologies but (i) outlines a representative high-level overview of the interventions of each area and (ii) reviews their key properties. Figure 1 summarizes the computing areas of digital ecosystems.

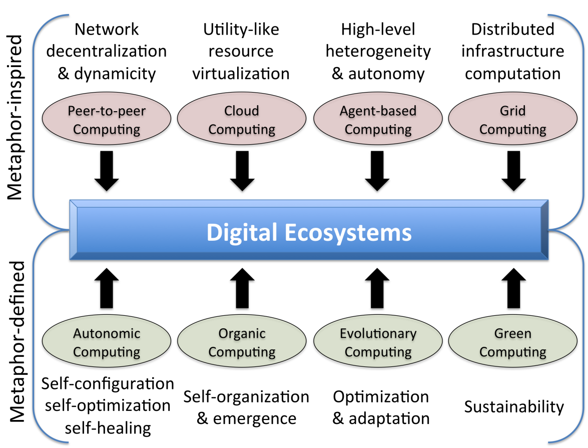

Figure 1. Computing areas and properties of digital ecosystems.

Peer-to-peer computing has made some major interventions on the Internet with 70% of the Internet traffic coming from peer-to-peer applications [49], such as file sharing [19], multimedia multicasting [41] and massively multiplayer games [26]. Furthermore, peer-to-peer computing influences the evolution of the Internet by emerging new business relationships between the ISPs [8]. These interventions have a major impact on the complexity and the power-law topology of the Internet [13]. Similar power-law systems govern biological ecosystems [4].

However, the interventions of peer-to-peer computing are limited to the Internet. This is because peer-to-peer overlay networks require an underlying communication infrastructure that performs the actual routing using standardized protocols, e.g. the OSI protocol stack. Despite the efforts to apply peer-to-peer computing in other domains, such as the Smart Grid [40] and Organic Grid [7], there are certain technical and conceptual problems related with interoperability and the high heterogeneity of the physical and software infrastructure [17].

Cloud computing introduces significant interventions in Internet-based and service-oriented business models [3]. A cloud ecosystem provides on-demand services and computing resources as utilities, in a similar fashion as electricity providers [5]. Cloud computing has also an environmental impact as the virtualization of data centers addresses requirements for lower carbon footprints. However, various technical and policy issues [3], [5] related to security and privacy are dependent on specific vendors e.g. Google, Amazon, or Microsoft resulting in closed business environments that challenge their sustainability.

A wide range of interventions appear in the area of multi-agent systems [2]. Application domains such as electrical power management [40], intelligent transportation systems [20], and telecommunications [44] engage multi-agent systems to achieve autonomy and decentralization. Multi-agent systems provide services such as search, scheduling, aggregation and decision-making that are crucial for the operation of applications in such complex heterogeneous application domains. Despite the efforts for software compliance and standardization among multi-agent platforms, interoperability between multi-agent systems cannot be verified or tested in practice [38]. Furthermore, multi-agent systems experience emergent phenomena that are hard to predict and handle [21].

Evolutionary computing appears in a plethora of optimization problems that require the discovery of an optimum or sub-optimum solution. The domains of structural design and civil engineer [24], manufacturing [35], robotics [46], music [30] and electrical power management [16] are some examples of this broad applications spectrum. Performance metrics such as convergence time and computational cost are design aspects of evolutionary algorithms. Because of this performance-driven approach, it is challenging to model user requirements and design generic fitness functions for different computational problems [39]. Furthermore, most evolutionary algorithms are computationally centralized and require a high number of iterations to converge.

The key contributions of autonomic computing concerns the management and optimization of large data center ecosystems [27]. IBM, as the initiator of autonomic computing, has played a key role in the contributions of this area. Self-* properties introduced via intelligent architectures based on adaptation, feedback loops and utility functions [23] achieve an intelligent resource utilization that maximizes performance and minimizes the energy costs and environmental impact [43].

Note that the majority of the autonomic computing interventions have two features [42], [28]: (i) They focus on the self-healing, self-protection, self-configuration and self-optimization properties and to a lower degree on self-organization. (ii) They focus on large computing systems such as mainframes rather than large-scale dynamic networks. The increasing decentralization motivates research towards networking interventions [42] and other domains such as automated vehicles [10] and telecommunications [22]. In contrast to the significant overlap of concepts between autonomic and organic computing, their interventions differ. Organic computing seems to cover the self-organization gap of autonomic computing interventions with an extension to ubiquitous, embedded and cyber-physical networked systems [31]. Traffic light control, network management, robotics and elevators control are some application examples of organic computing. However, the challenge of modeling, control and management of emergence is regarded a key for the further development and interventions in this computing area [33].

Finally, green computing focuses on goals of transforming digital ecosystems to sustainable and viable systems able to coexist in harmony with natural ecosystems [34]. Although the usage of IT standards and regulations that define environmental-friendly materials are crucial tools to achieve these goals [34], the actual computing interventions overlap with the ones of autonomic, organic, grid and cloud computing. For example, power management, virtualization, lower carbon footprints and power consumption in large data centers are means addressed by other illustrated computing areas.

V. Propositions to Current Practice

This paper introduces five propositions that underline the current state and practice of digital ecosystems. These five propositions form a computing roadmap that shows how the metaphor of digital ecosystem can be transformed to a scientific paradigm. Figure 2 depicts this roadmap derived from the five illustrated propositions.

The need for such a scientific paradigm is the alignment and coordination of the interventions of all computing areas that engage metaphors of biological ecosystems. In this sense, digital ecosystems can play the role of an unification 'umbrella' over significant, challenging and visionary computing approaches that emerge in parallel.

A. Digital ecosystems are more (and less) than biological ecosystems

A mimicry [45] of biological ecosystems is not adequate to capture the complexity of digital ecosystems. Common properties and complexity laws, such as the power law [4], govern a wide range of ecosystems with agents competing

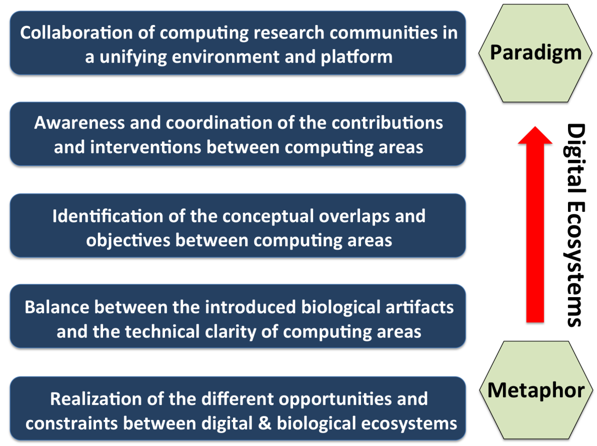

Figure 2. A computing roadmap of digital ecosystems.

and cooperating for shared resources. Inspiration and drive by these properties and laws are a knowledge transfer and scientific enrichment. Nonetheless, digital ecosystems require an adaptive design and runtime that meets a wide range of dynamically evolving user requirements. These requirements expand to many dimensions such as performance, efficiency and other more complex requirements such as security, privacy and environmental sustainability that green computing addresses. Therefore, digital ecosystems are dynamic environments of evolving and emerging objectives, constraints and trade-offs [4]. Biological metaphors, concepts and laws cannot always address such artificially generated complexity.

Moreover, a digital ecosystem that is fully self-managed, self-controlled and decoupled from any human intervention is not a realistic goal and even if this was technically possible, its adoption in critical application domains would be avoided in practice. Digital ecosystem should not be designed more complex than they need to be. Simplicity is an added value in digital ecosystems and therefore, moving all the observed complexity of biological ecosystems to the digital ones does not contribute to their viability in socio-technical environments [47].

B. Digital ecosystems require both metaphor-inspired and metaphor-defined computing areas.

The metaphor-inspired computing areas discussed in Section III-A introduce new concepts from biological ecosystems as an effort to (i) handle their technical complexity, (ii) compose novel computing methodologies from well understood biological processes and (iii) make their contributed knowledge accessible to a wide range of research communities. However, it is unavoidable that introduced biological metaphors in technical computing areas may raise misconceptions and issues of clarity and consistency.

In contrast, the principal concepts of metaphor-defined computing areas are based on the key properties of biological ecosystems, such as self-* properties, evolution, sustainability etc. Therefore, these computing areas are based on ecosystem artifacts and contexts based on which the contributions and interventions can be compared, evaluated and validated [37]. However, replacing or enriching technical artifacts from mature computing areas with artifacts from biological ecosystems is challenging. For example, self-organization is a property hard to measure, describe and attribute to a computing system. This challenge may result in naive and ungrounded analogies between computing and biological systems.

The synergy of metaphor-inspired and metaphor-defined computing areas is crucial. Digital ecosystems need mature artifacts and concepts from biological ecosystems that explain complex adaptive systems. However, these artifacts and concepts should not be intrusive in the sense that they influence the technical clarity and consistency of mature methodologies developed in the area of distributed computing.

C. There is a major overlap in the concepts, objectives, contributions and interventions of computing areas of digital ecosystems.

Section IV illustrates computing areas that may solve similar problems but from a different angle. Green computing [34] emphasizes on the reduction of energy consumption and carbon footprints of large data centers. However, one of the most significant contributions of autonomic computing is exactly in this area [27]. Furthermore, autonomic and organic computing define similar concepts and properties, e.g. self-* properties, that their systems should have. Their difference is not clear and should be motivated more in future work through the distinct interventions they focus on. Similar issues have been raised in literature for peer-to-peer/agent-based [32] and cloud/grid computing [18].

D. Digital ecosystem require a self-awareness and coordination of computing contributions and interventions

Awareness of the contributions and interventions in computing areas is crucial to minimize their overlap. Reviewing and classifying the current state of the art is one approach to gain this awareness. Related computing research communities to digital ecosystems need to coordinate their actions and efforts to increase the impact, reflection and interventions of their research contributions.

Coordination and awareness can shape a research problem. For example, the following questions may be raised in the design of an efficient and environmental-friendly data center: Which machine types are required to form an environmental-friendly data center (green computing perspective)? How important is decentralization and point-to-point communication (peer-to-peer computing perspective)? How can the system self-organize its interactions (organic computing perspective)? Is software able to self-manage trade-offs between performance, energy consumption and carbon footprints (autonomic computing perspective)? Which methods can be applied for an efficient computation of these trade-offs (grid computing perspective)? Which software models realize these methods (agent-based computing perspective)? Are the achieved solutions optimum (evolutionary computing perspective)? How does the user access the services of such a data center (cloud computing perspective)? Therefore, coordination is required for the integration of solutions [11] emerged from different computing areas on the same or similar research problems.

E. Digital ecosystems can potentially become a collaborative research environment or platform of computing areas

Digital ecosystems can potentially stand as collaborative research environment or platform if relevant research communities promote the concepts of self-awareness and coordination in joint research projects. It is crucial that such a collaboration begins at the level of single universities and extends to geographically dispersed academic and industrial institutes [9].

VI. Discussion and Concluding Remarks

This paper illustrates a computing roadmap towards transforming digital ecosystems from a metaphor to a paradigm. This roadmap is based on five propositions supported by a literature review of intervention in computing areas that engage metaphors of biological ecosystems. Achieving precision, clarity and realism (analogy) within a specific metaphor based on a single viewpoint or model is practically and empirically not possible [36]. The same holds for the metaphor of digital ecosystem and its usage by different computing areas. Digital ecosystems have the potential to emerge to a collaborative coordination environments of computing areas that engage metaphors of biological ecosystems. Metaphors should be used wisely, without raising wrong expectations or naive and ungrounded analogies about digital and biological ecosystems.

Future work should provide a more in-depth review of metaphor models and theories applicable in computing areas of digital ecosystems. Bridging the gap between theory and practice will have an impact on the interventions of digital ecosystems and their computing areas.

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