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Digital Ecosystems: Principles and Semantics

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Abstract **Digital ecosystems transcend the traditional, rigorously defined, collaborative environments from centralised, distributed or hybrid models into an open, flexible, domain cluster, demand-driven, interactive environment. A digital ecosystem is a newly networked architecture and collaborative environment that addresses the weakness of client-server, peer-to-peer, grid, and web services. In this paper we provide an explanation of digital ecosystems, their analogy to ecological systems, architecture, swarm intelligence, and comparison to existing networked architecture. We then describe how digital ecosystems can benefit from semantic web ontologies and rules. Finally, we discuss issues in the collaboration between semantically neighbouring digital ecosystems.**

Keywords: **Digital ecosystems, swarm intelligence, self-organisation, collaboration, semantic web**

I. The Ecosystem Analogy

We first introduce ecosystems in the biological sense and then proceed to digital ecosystems,

An *ecosystem* is a loosely coupled, domain clustered environment inhabited by species, each proactive and responsive regarding its own benefit while conserving the environment.

Two intertwined types of elements create an ecosystem: multiple species in an environment. *Species* need to interact with each other and balance each other (even though some species may play a leading role at times). The *environment* supports the needs of its species so they can continue generation after generation. Members of a species are called *individuals* and are made up of organs. Each individual can again be considered as an entire ecosystem. Each *organ* carries out its tasks. Organs again need to interact with each other and balance each other (even though some organs are more important than others). The individual supports organ collaboration and communication in order to achieve and maintain a healthy state.

Species, which can be grouped by biological classification through genus, are thus composed of related individuals that resemble one another and are able to live together, cross-fertilise and interbreed. We will discuss four essential aspects of ecosystems: interaction and engagement, balance, domain clustered and loosely coupled, as well as self-organisation.

- *Interaction and engagement*

This refers to interspecies interaction, such as coral polyps, tiny animals that live in colonies and interact with nudibranchs, fish of varying types, turtles, sea snakes, snails and molluscs. They live together in warm, open, clear, shallow waters. They need to interact for social well-being and to engage with each other to find interesting things, and to share the resources. Sometimes they need to unite as a group to defend against threats from human interference, pollution or natural disaster.

- *Balance*

This signifies the harmony, stability and sustainability within an ecosystem. If some species or parts of an ecosystem are getting disproportionally tensioned, dried, overheated, or divided, the whole ecosystem may collapse: 'No benefit or gain, but pain.' However, a single point of failure need not lead to a disaster but may become a contribution to a new balance of welfare for the ecosystem as a whole. For example, when coral polyps die, they become a stony, branching structure as part of a reef and can still provide shelter and maintain the balance of the reef for generations.

- *Domain clustered and loosely coupled*

In an ecological environment, species come to an ecosystem on their own choice. They form loosely coupled groups the members of which share a similar culture, social habits, interests and objectives. Each species preserves the environment and is proactive and responsive for its own benefit. They are thus able to live together and support each other for sustainability.

- *Self-organisation*

This signifies that each species is independent, self-empowered, self-prepared, undertakes self-defence, is self-surviving and undertakes self co-ordination through swarm intelligence. In case of natural disaster they cannot ask 'where is the president', 'what logistics systems are provided' and so forth.

We propose, by analogy to such biological ecosystems, that a *digital ecosystem* be defined as an open, loosely coupled, domain clustered, demand-driven, self-organising agent environment, where each agent of each species is proactive and responsive regarding its own benefit/profit (as detailed below) but is also responsible to its system**.**

'*Agents'* are entities that join an environment or a community based on their own interests. '*Species'* are types of agents. *'Open'* refers to a transparent virtual environment. '*Loosely coupled'* refers to a freely joined, open relationship between agents or species within a virtual community. This term is in contrast to a tightly coupled relationship where each party is heavily dependent on the other, and the roles are pre-defined. *'Domain clustered'* is the characteristic of a colony or a field where species share the same life or interests such as an ocean habitat of a coral reef or exotic tropical plants in a rainforest. '*Demand driven'* is defined as the driving force to join a community - 'push-in' rather than 'pull-in'. Many current collaborative environments are not demand driven because people are told to collaborate or forced to work together, rather than enjoying collaboration arising from a perceived mutual interest of the collaborating parties: There is a lack of consideration about whether there will be a benefit or profit from the collaboration for the collaborating entities. '*Self-organising'* refers to agents being capable of acting autonomously, making decisions and fulfilling responsibilities. *'Agent environment'* is defined as an environment which contains human individuals, information services as well as network interaction and knowledge sharing tools along with resources that help maintain synergy among human beings or organisations. '*Proactive'* is defined as an entity being full of enthusiasm to participate in team work or the community. '*Responsive'* signifies an agent that demonstrates willingness, is cooperative and takes responsibility for its action. *'Benefit'* refers to an advantage that an agent can take without any risks. '*Profit'* refers to social and economic gain.

II. The Basis of Digital Ecosystems

A Digital Ecosystem is: unlike a *client-server architecture*, where the communication is centralised and which acts as a command and control environment; unlike a *Peer-to-Peer architecture*, where, at any time, each agent has a well defined role, i.e. can only be client or server, but not both; unlike a *Grid architecture*, which stitches partners together for resource sharing but cannot avoid counter-free riding; unlike a *Web service network*, where brokers are centralised and service requesters and providers are distributed in a hybrid architecture that does not guarantee trust and QoS. A Digital Ecosystem instead is an open community, and there is no permanent need for centralised or distributed control or for single-role behaviour. In a Digital Ecosystem, a leadership structure may be formed (and dissolved) in response to the dynamic needs of the environment.

An agent in a Digital Ecosystem can be a *client* and a *server* at the *same time*. In the same message, agents may offer a service to others as a Server and request help as a Client. There is no centralised control structure or fixed role assignment. There is no preconfigured global architecture, where the communication and collaboration is based on swarm intelligence: Unlike traditional environments, digital ecosystems are self-organising systems which can form different architectural models through swarm intelligence, where local interactions between agents determine the global behaviour. Occasionally, intelligent agents or entire species may configure into a hierarchical organisation where the communication channels are defined with a leading agent (cf. leading bird or queen bee).. Some intelligent agents or species institute a workflow process with sequentially ordered tasks and predefined flow of operations. Other intelligent agents or species collaborate in a control loop, where each agent is self-coordinated and they put their energy together to tackle issues iteratively.

A *swarm* is a set of agents which have common characteristics and are able to interact and engage directly or indirectly with each other. They collectively carry out a task or share a problem. Swarm intelligence is an important property of ecosystems. We often observe the collective behaviour of agents or species interacting with each other and with the environment, and generate a coherent functional global pattern. Swarm intelligence is now widely researched as it provides a basis to explore collective behaviour for problem solving without centralised or command and control systems, and the provision for flexible, dynamic interactive models.

Let us consider here two aspects of swarm intelligence. *(1) Agent and species*: They are the foundation of intelligence; they can be viewed as an individual or an organisation. Each has its own niche or role to play; each has dual functions or roles. They can be client and can also be server at the same time; each one can carry out bi-directional communication, not just one way. *(2) Leading agent and species*: They emerge through (temporary) hierarchy formation to facilitate, lead and direct collaborative swarms; they may be the representative of the domain cluster in the interaction with other ecosystems. They have the same features and functions as any other agent, but in the current situation have activated the general leadership potential.

Animals, humans, software agents or autonomous robots can all be analysed as agents in the above sense. In this analogy with biological (and social) ecosystems, one may find a better basis for understanding of intelligence and rationality than that provided by traditional AI. Swarm intelligence can help us model intelligent behaviour in relation to, e.g., rational behaviour, goal seeking, task accomplishment, and learning.

III. Semantics for Digital Ecosystems

Individuals in ecosystems need to exchange and process messages to coordinate their behaviour. The information that individuals send to other individuals or broadcast to an entire (sub)system reveals its meaning or *semantics* by a process of interpretation in the receiving individuals. **Biological** ecosystems have developed *shared implicit semantics*, step by step, during their long evolution. **Social** ecosystems have enriched this with *shared explicit informal semantics* (communicated via natural languages) mainly through behavioural and linguistic conventions, regulations, and laws. **Digital** ecosystems should add *shared explicit formal semantics* (communicated via artificial languages) to enable automation with high precision in several areas of business, government and other domains.

Digital ecosystems can benefit from ongoing work in the semantic web, where each entity (e.g., a document) can be globally identified with an Internationalized Resource Identifier (IRI). These IRIs can then be used as reference points of (globally distributed) semantic metadata that enable to search entities with high precision. Metadata (e.g., written in the

RDF language) are descriptions used for entity indexing by categorizing an IRI into classes and attaching properties to them, so that an IRI (and the entity it identifies) can be found through a kind of 'associative' retrieval by querying with a subset of descriptive classes and properties. High precision of such retrieval is enabled by an *ontology* (often modularised into *subontologies*) which acts as the agreed-upon vocabulary of a digital ecosystem. The ontology (e.g., written in the RDFS or OWL language) groups classes (and properties) into a hierarchy, and specifies which (domain) classes can have which properties of which (range) classes. Furthermore, *rules* (e.g., written in the RuleML language) can be used to derive (virtual) properties from combinations of other (stored) properties, to check the integrity of the metadata, and also to process the retrieved information.

The entities described and queried in this highly precise, semantic way, can be arbitrary documents, multimedia objects, web services, etc. that are of use within a digital ecosystem. However, these entities can also be agents or entire (sub)systems, because metadata can act as profiles describing the capabilities of agents, human or machine, for social or digital networking. This means that an agent of a (large) digital ecosystem can semantically search for other agents that advertised themselves using such metadata profiles and that fall into certain classes and fulfil certain properties. Such agent profiles are often written in RDF, using an RDFS-based ontology known as FOAF or the recently proposed SIOC. While existing profiles are fact-based, rules can describe properties conditional on other agents, the time, the location, and so on.

We have implemented the FindXpRT system that applies rule-based social or digital networking to expert finding. The assumed business-service model is the bartering-like exchange of expertise between an expert and a co-expert, where the latter initiates the search using our system. When searching for an expert, in any domain, humans often need to rely on referrals by other experts using their social networks. FindXpRT thus provides both direct searches and referrals, which are both accomplished by applying rules to users' expert queries. We also propose a benchmark suite for expert finding more generally, testing expert-finding systems against expert profiles. This is exemplified with our implemented system, tested against the expertise and co-expertise domains of computer science and music, respectively.

IV. Collaboration Between Digital Ecosystems

The semantics get more complex and interesting when a given individual or (sub)system can be part of multiple *overlapping ecosystems*, hence interact with individuals in any one of them (perhaps at different times). **Biological** ecosystems often develop pairwise overlaps in geographic borderline regions such as the outskirts of a forest or the tidelands of an ocean. **Social** ecosystems typically overlap more freely in various ways such as groups formed around, say, family, profession, and hobby. **Digital** ecosystems may overlap like social ones, but entirely remove the limitations of geographic proximity and can provide tools for cross-system collaboration.

The single-ecosystem case in previous sections can be generalised to this multi-ecosystem case. In particular, 'the' semantic web explained in section III actually is divided into multiple semantic webs serving various digital ecosystems. Even in a 'single' field of knowledge such as medicine there can be 'multiple' semantics such as those of traditional and orthodox medicine (and even for orthodox medicine there exist multiple ontologies such as SNOMED and UMLS). Medicine also overlaps with neighbouring fields such as chemistry, which is reflected by their partially shared digital ontologies and rules. Sometimes such overlaps develop into fields of their own such as the medicine-chemistry overlap of pharmacology.

Participation of individuals in multiple digital ecosystems can obviously help them to reach their goals. Collaboration between entire digital ecosystems can also provide benefits to all ecosystems involved. First, the current borderlines between semantically neighbouring digital ecosystems may not be optimal for any system involved or may indeed be counter-productive, so redrawing or even removing (some of) them may be advantageous to all these ecosystems. The joining of an agent (viewed as a singleton ecosystem) into a digital ecosystem can be generalised to the merger of two digital ecosystems. Second, while a number of digital ecosystems may keep their borders and identities, they might specialise on what they can do best and form 'import/export'-connected components of a higher system as well-known from biological and social ecosystems.

Semantic support for digital collaboration has been studied in the context of semantic web and web service projects under headings such as "semantic information intergration". Since, at least at the start of a collaboration, the ontologies and rules of component systems are usually not (fully) compatible, alignment and mapping/translation techniques have been studied. For ontologies these include Chimaera, PROMPT, and RDFT. For rules, interoperability techniques are being developed, e.g. by the standard bodies OASIS, OMG, and W3C. In particular, like the RuleML Initiative, W3C's RIF Working Group is dedicated to XML- and RDF-based rule interchange via translators to and fro RIF, written in languages such as XSLT.

V. Conclusion

This paper provides an explanation of digital ecosystems, their architecture and comparison with most advanced communication platforms or environments such as client-server, P2P and web services. It also describes how digital ecosystems can benefit from semantic web ontologies and rules, and discusses collaboration issues between semantically neighbouring digital ecosystems. We thus try to bridge between research in digital ecosystem and the semantic web. Government and business application of 'semantic ecosystems' should contribute to international productivity, prosperity and social, cultural and economic balance as well as ecological sustainability. Digital Ecosystems thus move from Darwinian competition to self-interested collaboration.

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