Collective Adaptive Systems

Expert Consultation Workshop
3 & 4 November 2009

Report

Future and Emerging Technologies

Proactive

European Commission
Information Society and Media

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Executive Summary

The FET Consultation on Collective Adaptive Systems held in Leuven on 3rd – 4th November 2009 brought together a broad range of scientific communities to discuss developments in Collective Adaptive Systems (CAS).

The meeting noted that the number of digital systems and artefacts is increasingly exponentially, such that we are approaching a point where digital entities have ceased to be just technical systems and have become part of the socio-technical fabric of society. This plethora of semi-autonomous, ‘cyberphysical systems’ – which all rely on embedded ICT and are connected to the information ether – will constitute a new kind of physical intelligence.

Examples of these ‘systems of systems’ include city-wide transportation infrastructures, mobile communications networks, and smart energy networks based on micro-production. For our societies to function effectively, we have to learn to identify and give meaning to interactions within these highly complex, cooperative and dynamic systems. This poses severe challenges from both technological and societal perspectives.

Collective adaptive systems differ from current generation systems in two important respects:

1 **Collectiveness:** Systems typically comprise multiple units (often very large numbers), which have autonomy in terms of their own individual properties, objectives and actions. Decision-making is highly dispersed and interaction between the units may lead to the emergence of new and/or unexpected phenomena and behaviours.

2 **Multiple scales in time and space**: Systems are open, in that units/nodes may enter or leave the collective at any time. The nodes themselves can be highly heterogeneous (computers, agents, devices, humans, networks, etc), each operating at different temporal and spatial scales, and having different (potentially conflicting) objectives and goals.

We are still a considerable way from being able to design and engineer true collective adaptive systems, or even of elucidating the principles by which they should operate.

An FET Proactive Initiative on Fundamentals of Collective Adaptive Systems should target the new generation of highly complex, open, multi-level, multi-objective ICT systems now emerging. The Initiative should aim to develop **a theoretical framework for collective adaptive systems** of broad applicability within systems theory, addressing key questions such as:

- How to describe systems which have to deal with multiple scales in time and space?
- What are the principles by which collective adaptive systems operate?
- How can we architect and engineer them ensuring purposeful and secure behaviour?
- How can we design in and exploit emergent behaviour?
- How can we account for their evolutionary nature in development?

While addressing fundamental theory, the Initiative should also have a strong practical orientation, offering new insights on problems of major importance to relevant stakeholders (the research community at large but also industry and policy-makers).

In order to advance the state-of-the-art, the focus should be on the interface between large-scale systems (with a large number of essentially homogeneous entities) and heterogeneous systems, in situations where the human user is both in- and out-of-the-loop.

Key priorities for research are:

1. **Operating Principles:** Research into the principles by which CAS operate, including issues such as: the representation and reasoning about multi-level and multi-scale objectives; the ability to learn, adapt and/or evolve new policies and functionality; ability to reason in the presence of partial, inaccurate and noisy information, and principles of 'lifetime unlimited' systems. Here, CAS provides the opportunity to extend the study of classical problems and classical techniques in control, optimisation and communication in an uncontrolled environment.

2. **Design Principles**: Research into the design and engineering principles necessary to build and manage CAS, including developing: models and design principles that allow for the creation of emergent behaviours; tools and methods that support such development; and principled approaches to incremental development starting from 'legacy' systems.

3. **Developmental Systems:** Research into the evolutionary nature of CAS, including: open-ended (unbounded) evolutionary systems; long-term effects of evolution on the system's level and appearance of self-*; better understanding of trade-off between learning and evolution; principles and effects of replication; and design for emergence.

The Initiative is expected to yield important insights in terms of understanding 'the socio-technical fabric' underlying 21st century society. It will investigate how to design and manage the complex, multi-level systems that characterise increasing areas of our society and economy.

As well as many scientific communities, it will be important to involve social scientists, domain experts and users.

1. Introduction

The ICT Theme's Future and Emerging Technologies (FET) action directs proactive research initiatives in emerging and high-risk areas of ICT. These initiatives, which involve projects clustered around common themes, aim to encourage strategic efforts on foundational long-term research and technological innovation beneficial to the European Union. To identify topics and research areas most suitable for such initiatives, the European Commission periodically engages in focused interaction and consultation with the research community.

To help shape the Work Programme for 2011-2012, the Commission has launched a series of interactive brainstorming events with scientific experts in a number of relevant fields. The meeting "*FET Proactive Consultation on Collective Adaptive Systems*", held in Leuven on 3rd-4th November 2009, brought together a broad range of scientific communities. Participants from existing FET projects were invited to share their views and help the Commission to identify promising strategic areas, especially those going beyond traditional lines of research and presenting novel opportunities for collaboration with other scientific communities.

Participants were asked to suggest key challenges that could be the basis for one or more proactive initiatives to be launched in a 2011-2012 timeframe. Specifically, they were invited to consider the evolution of proactive initiatives in the area of Collective Adaptive Systems (CAS). This is seen as an evolution of two previous/on-going FET initiatives:

- **Pervasive Adaptation (PERADA)** addresses massive-scale pervasive information and communication systems, capable of autonomously adapting to highly dynamic and open technological and user contexts. This includes evolve-able and adaptive pervasive systems, as well as networked societies of artefacts.

- **Science of Complex Systems for Socially Intelligent ICT (COSI-ICT)** addresses key concepts and tools for a data-intensive science of large-scale techno-social systems, i.e., systems in which ICT is tightly entangled with human, social and business structures which, as a result, mutually transform each other, for instance through evolution of acceptance, trust, innovative uses and technology changes.

The intended output of the meeting was a first set of proposals, identifying research challenges, directions or areas that present opportunities for future FET proactive initiatives. These will be used as inputs for the formulation of the Work Programme for 2011-2012.

The invited experts included researchers in software engineering, complex systems science, communications, global computing, and networked and distributed systems. Each of the experts offered a short presentation on the invited theme, which provided the basis for more in-depth, cross-cutting discussions.

2. Context: Towards Collective Adaptive Systems

Autonomic ICT systems have experienced continual evolution over the last twenty years[1]. The first generation of ICT was characterised by connectedness: connectivity technologies (such as web 1.0, GSM and wireless communication) provided an ability to connect literally every-'thing' to every other 'thing'. **Networks of ICT systems** grew up comprised of special purpose computing and information appliances, ready to communicate spontaneously with one another, as well as sensor-actuator based systems able to control devices and modify their environment based on data they collect.

The second generation of autonomic systems, which began around ten years ago, was characterised by awareness. Driven by upcoming context recognition and knowledge processing technologies, these systems were aware of interactions among 'things' (system nodes) and how these interactions changed over time. Nodes became aware of themselves, the situation in which they operated, and the context in which they were being used. Autonomic elements (such as sensors) were able to capture, interpret and predict context in a whole variety of ways, and to self-describe, -manage and –organise with respect to the environment. Thus, **ecologies of ICT systems** emerged, built from collective autonomic elements interacting in spontaneous contexts of time and space.

A third evolution, now underway, builds upon connectedness and awareness by giving **meaning to situations and actions**. The number of 'things' (digital artefacts) with which we are now confronted is truly staggering: upwards of 6 billion humans; over 2 billion mobile phones and a similar number of nodes on the internet; megacities with tens of millions of people; hundreds of millions of videos, images, user profiles and other digital content; and many billions of physical things or goods traded in world markets, many of which are internet-enabled.

As ISTAG has noted[2], in the future there will be a continuum of systems, from the network proper through to 'end systems' – intelligent sensing devices and actuators able to provide information about their environment and their user in a whole variety of settings and respond accordingly. The level of autonomy of the individual system will vary along a continuum of self-determination. This plethora of semi-autonomous, 'cyberphysical' systems - which all rely on embedded ICT and are connected to the 'information ether' - will constitute a new kind of physical intelligence.

Thus, we are approaching a point where digital entities have ceased to be just technical systems but have become part of the **socio-technical fabric of society**. For our societies to function effectively, we have to learn to identify and give meaning to interactions within these highly complex, cooperative and dynamic systems. This poses severe challenges from both technological and societal perspectives.

FET Proactive Initiative on Pervasive Adaptation

Relevant aspects are being addressed under various Proactive Initiatives supported by FET. In particular, the Pervasive Adaptation initiative, launched in 2007, is concerned with massive-scale, pervasive information and communication systems. It focuses on self-adapting software, hardware, protocols and architectures, and on massively scalable systems able to adapt to highly

[1] Position paper of A. Ferscha

[2] ISTAG, 2009

dynamic contexts. Autonomous adaptation strategies (bio-inspired, stochastic, etc.) and multidisciplinary, human-centred research are central features.

Six research projects have been launched under this initiative together with a Coordination Action, PERADA (www.perada.eu). Research areas being investigated include:

- *Evolve-able and adaptive pervasive systems*, able to permanently adjust, self-manage, evolve and self-organise in order to robustly respond to dynamically changing environments, operating conditions, and purposes or practices of use.

- *Networked societies of artefacts* that adapt to each other and to changing needs, collectively harness dispersed information and pursue immediate or long-term goals for context-sensitive service delivery in rapidly changing and technology-rich environments.

- *Adaptive security and dependability:* theories, techniques and architectures, able to cope with the volatile landscape of risks, threats, attacks and context-dependent user expectations for privacy and security in evolving and heterogeneous pervasive systems.

- *Dynamicity of trust:* capabilities for establishing trust relationships between humans and/or machines that jointly act and interact within ad-hoc and changing configurations.

- *Security for tiny and massively networked devices:* efficient, robust and scalable cryptographic protocols, algorithms and other security and privacy mechanisms, including hardware-based ones, as well as collective, biologically or socially inspired ones.

Pervasive adaptive systems are a special case of collective adaptive systems which have specific constraints. The meeting focused on how to extend and build on this research, in particular for systems that span multiple scales (in terms of space, time and abstraction levels) and pursue multiple objectives.

3. Synthesis of Presentations and Discussion

3.1. What are Collective Adaptive Systems?

Each of the experts had prepared a position paper, which was circulated prior to the meeting, and made a short presentation based on this. The papers and presentations (which are included in Annex 2) provided a rich pool of ideas and opinions which were developed in later discussion.

The Experts did not attempt an all-embracing definition of 'collective adaptive systems' (CAS). Rather they engaged in a wide-ranging discussion of their characteristics and features, and the challenges these present for science, technology and society. Specific examples were also advanced (see Section 3.2 below). **Key ideas presented included the following:**

- **Fractal-like properties**: CAS are 'systems of systems' and are fractal in nature[3]. A system consists of many subsystems, each of which can be thought of as a system in itself, such that each part is a reduced size copy of the whole with respect to the general challenges of adapting to the environment. The boundaries between subsystems are fluid: at any time a system (components, devices, group, network, etc.) may be joined to one or

[3] Position paper of E. Hart & B. Paechter

more other systems to form a new system incorporating the goals and context of all. Similarly, something that is a complete system from one point of view (e.g. all the components within a car) might be considered as a single component at another level (e.g. when considering the traffic flow through a city). Thus, system boundaries depend on the perspective being taken, are blurred and change over time.

- **Evolutionary self-organisation**: To be self-aware, a CAS must have an internal self-image; moreover, that image must be dynamic as the system is fluid and dynamic and thus the 'self' is itself changing[4]. Concepts and metaphors adopted from nature could be useful here. These might include: the 'homunculus'[5] – functional images of the body used by the brain and the immunological system; and 'homeostasis'[6] – which refers to an organism's ability to maintain steady states of operation in a massively changing internal and external environment. On the other hand, we should also recognise the limitations of interpreting biological metaphors too literally. Evolutionary computing is <u>not</u> the same as biological evolution: in nature diversity tends to increase through the evolutionary tree, whereas in computing it decreases[7]. Something is missing here and real breakthroughs are needed.

- **Long-term stability in open environments**: Since a CAS is, by definition, dynamic, there is a risk that it enters oscillations or a long sequence of successive adaptations without converging to a stable state that fits the requirements[8] [9] . Existing approaches, from control theory and individual adaptive systems, do not account sufficiently for openness: rather they assume *a priori* knowledge of all possible effects that influence the adaptation process. The co-existence of different autonomous adaptive systems within the same environment, where they are likely to interact with each other (either directly or indirectly) could lead to conflicts and instabilities. New approaches are required. Game theory represents a promising avenue for framing such phenomena in a mathematically tractable form.

- **Controlling emergent behaviour**: Another key feature, linked to the above points regarding evolutionary self-organisation and long-term stability, is that CAS can be expected to exhibit emergent behaviour. This raises a series of important issues from both design and operational perspectives: how do we engineer such emergent behaviour to our advantage?; how do we know with confidence what systems will and will not do?; how should we address security issues in emergent systems?; and how do we avoid developmental drift, so that the system continues to meet its design objectives as it evolves?[10] Such issues have to be addressed for situations both where there is 'user-in-the-loop' and where no human users are directly involved.

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[4] Position paper of S. Kernbach *et al.*

[5] Position paper of E. Hart & B. Paechter

[6] Position paper of J. Timmis *et al.*

[7] Position paper of T. Schmickl

[8] Position paper of K. Herrmann

[9] Position paper of J. Timmis *et al.*

[10] Position paper of J. Timmis *et al.*

- **The data challenge**: As systems become ever larger, data flows increase exponentially until there will be far too much data to process or store effectively. Already there is information hidden in relatively simple data streams that is not utilised: such information leakages can only increase as systems become more dynamic and complex[11]. In many cases, autonomous entities will need to take decisions on the basis of information which may be inaccurate, noisy and partial: an ability to automate reasoning processes in such circumstances is of importance. Furthermore, we have to get the right information to the right place at the right time, which requires an appreciation of its relevance (i.e. the capacity of a system to determine what is important based on an understanding of why)[12].

- **The user and application perspective**: CAS are very, very complex. We should not lose sight of the user in all this complexity. While theoretical breakthroughs are required, it will be important to maintain a strong focus on the role and behaviour of the user within collective adaptive systems[13]. A 'top-down' approach could be useful, based on future application scenarios, so as to understand the potential impact of CAS not only in terms of science but also from a socio-economic perspective[14]. Multi-disciplinary research will certainly be required, bringing in not just scientists, technologists and domain experts, but also social scientists and philosophers[15]. It will also be important to build ethics into any new solutions.

Finding the right language and models: CAS do not fit easily within existing models. In some aspects they may resemble self-similar, scale-invariant fractal systems; in other aspects they may be more like classical systems describable by control theory (using feedback loops); and in yet other aspects they may resemble dynamic systems where individuals can be modelled (using game theory) as entities with varying cooperation strategies, leading to evolutionary dynamics, or emergent behaviours. Often the overall system behaviour only becomes clear and visible when an external (virtual) observer is introduced to the model. We have to find the right language to explore and define the specific issues here, using mathematics where possible[16].

3.2. Examples of Collective Adaptive Systems

Collective adaptive systems occur widely in nature (insect colonies, bird flocks, fish shoals, animal herds), as well as in many areas of human society.

A modern city is one such case[17]. This is a 'system of systems' where decisions need to be taken in a distributed, yet coordinated way. ICT offers opportunities to potentially monitor and control in real-time many fundamental aspects of the modern city, building truly 'cyberphysical' systems. For instance, traffic lights and in-car navigators could be coordinated to optimise traffic flows in

[11] Position paper of B. Benko

[12] Position paper of R. Whitaker

[13] Position paper of N. Serbedzija

[14] Position paper of D. Miorandi *et al*

[15] Position paper of F. Zambonelli

[16] Position paper of H. Bersini

[17] Position paper of D. Miorandi, *et al.*

real-time and reduce air pollution based on current traffic situation and users' needs. Similarly, electricity consumption could be controlled to fulfil user-driven goals while optimising for price fluctuations and minimising environmental impact.

Another example is in mobile communications networks[18]. Mobile systems, mobility management and optimisation algorithms often operate on a local or hierarchical scale but interface to global-scale networked systems. This, together with dynamically changing environmental conditions (wireless medium, connectivity, other nodes competing for bandwidth), mean mobile networks show many of the characteristics of collective adaptive systems and would benefit from self-organising mechanisms.

Other examples include[19]: internet routing in order to assure quality of service; and economic regulation aiming to stabilise prices and reduce inequalities.

3.3. What is Special about Collective Adaptive Systems?

Based on these observations, the Experts agreed that Collective Adaptive Systems were different from current generation systems in two important respects:

1. **The collective nature of CAS:** Collectiveness is a distinctive new feature here, bringing important challenges. By 'collective' we mean:

    - Systems typically consist of **multiple units** (often very large numbers).

    - The units have **autonomy** in that each unit has its own individual objectives and can take actions. This represents a major differentiating factor to existing collective systems research (e.g. swarm intelligence) in which the units typically serve a common purpose without any selfishness. There are also "multi-level objectives" (e.g. at the level of the units and at the global level) that govern the adaptation process and that are not necessarily related to each other.

    - There is **interaction among the units** – both cooperation and competition - that produces a new quality beyond that of the individual units.

    - **Control is highly dispersed** among the units. An adaptation is not controlled centrally and imposed upon the system; instead, it is administered in a decentralised fashion among the units.

2. **Multiple scales in time and space:** As noted above, Collective Adaptive Systems are open systems, i.e., systems comprising different types and numbers of entities, such as computers, agents, humans or even sub-collectives, that may arrive and leave in an unpredictable manner. All such entities should integrate seamlessly with other parts of the system. Both the system itself and the new entities may work on different temporal and spatial scales. 'Space' here refers both to an address space of distributed nodes or agents, and the geographical space within which the collective entities are embedded.

[18] Position paper of K. Hummel

[19] Position paper of H. Bersini

These characteristics – collectiveness and multiple temporal and spatial dimensions – present a number of important challenges from a research point of view.

- **Diversity of components and goals:** A typical Collective Adaptive System is composed of diverse units with different properties and behaviours (e.g. in a traffic control system: humans, cars, traffic lights, etc.). Moreover, these units have diverse objectives which have to be respected in any global scale adaptation. Accounting for the heterogeneous nature of CAS – where the system has to adapt to nodes or complete (sub)systems being added or taken away without notice - represents a novel and demanding aspect.

- **Large and varying scale:** Making coherent adaptation decisions that lead to stable global system configurations is increasingly aggravated as the scale of the system increases. This has to do, for example, with the increasing difficulty of communication and the growing gap between local objectives and global objectives. For example, human-to-computer interaction will work on significantly different timescales than computer-to-computer interaction. Therefore, such systems have to be able to adapt seamlessly to different scales at which operations have to be carried out.

- **Complexity and dynamics of environment:** Not only the units themselves display dynamic behaviour, but also the environment they operate in. It is intrinsic to such systems that they adapt to changes in the environment: these changes become more pronounced as the diversity and scale increase. Moreover, the complexity of the environment can be expected to be high (i.e. the number of ways in which it can change, and the number of aspects within the system that must adapt).

- **Conflicts:** Since there are a large number of units with differing individual objectives in a complex and dynamic environment, conflicts become commonplace. These are situations in which objectives contradict each other and an adaptation has to be found that satisfies all parties.

- **Situatedness:** Collective adaptive systems are situated in the real-world. To solve real-world problems, existing complex collective systems (e.g. the public transport system) have to be equipped with 'adaptation intelligence', possibly by adding adaptation units to the existing architecture, resulting in an overall collective adaptive system. This introduces the problem that such systems cannot be stopped. They have an infinite lifetime over which they have to evolve in order to adapt to long-term changes. Achieving this in a large-scale, diverse system in a complex environment represents a major challenge in terms of lifecycle management, development, and maintenance.

3.4 Beyond the State of the Art

Elements of collective adaptive systems have been studied in various domains from several different perspectives. These include, for example:

- Swarm intelligence, where the collective is essentially homogeneous and the adaptation is derived from interaction with respect to local knowledge and local computation;
- Autonomic computing, where the collective is typically limited and the adaptation is guided by high-level policies with optimisations rather than innovation as the goal;
- Multi-agent systems, where dynamic teams of heterogeneous collectives comprising agents, robots and people have been proposed, but these all operate at the same level of abstraction.

CAS are a form of complex system. As yet ICT researchers have made limited use of complex systems science for designing large-scale distributed adaptive systems. We are still a considerable way from being able to design and engineer a collective adaptive system of the type described above, or even of elucidating the principles on which it should operate. Arguably, such an approach requires a major shift in perspective: from the *design of a system* to the *design of a set of local rules enabling emergence of system behaviours on a global scale* (meta-design).

What distinguishes CAS from other forms of adaptive behaviour is openness. We need to create concepts for enabling autonomous adaptive systems to interact in open environments without ending in conflict or entering unstable behaviour when individual nodes enter or leave the collective. Adaptivity will only be applicable on a large scale beyond closed laboratory environments if this problem is resolved. This is true for all areas of distributed computing and especially for pervasive systems that inherently operate in an open world.

4. Towards an FET Proactive Initiative

4.1 Motivations

An FET Proactive Initiative on Fundamentals of Collective Adaptive Systems should target the new generation of highly complex ICT systems now emerging. Such systems are:

- *large-scale* - composed of very many, diverse nodes;
- *distributed* - the nodes have different and varying goals and control is decentralised;
- *fractal* – the nodes are themselves systems, so that the overall system boundaries are blurred and change over time;
- *open* – the nodes/subsystems can enter or leave the collective at any time and may encounter other systems/collectives with conflicting objectives;
- *collaborative* - there is interaction between the nodes; and
- *adaptive* - goals and behaviours can change and evolve in both time and space as a result of these interactions and other environmental stimuli.

Collective adaptive systems have a strong socio-technical dimension involving humans and technical systems. Such systems increasingly pervade all areas of our society and economy, from transportation, to energy grids, telecommunications infrastructures, eHealth services and social networks. Thus, the challenges relate not just to designing and developing ICT systems, but to shaping the whole **socio-technical fabric**.

Collective adaptive systems will operate under very different conditions and under very different rules to the classical networked systems and adaptive systems we know today. Decision-making will be local rather than global; intelligence will be decentralised rather than centralised; and communication flows will rely on best-effort communication rather than high reliability/minimal delay. All of this amounts to a major shift in terms of system structure, operation and performance.

New research is required into these open, multi-scale, multi-objective systems. The individual human user has personal objectives and expectations with respect to the actions and the performance of the system (e.g. that the system functions according to his personal preferences), while at a global level the system may have additional or even different objectives (e.g. maximization of global efficiency). At the same time, collective adaptive systems must operate over long timescales. More sophisticated adaptation concepts will be required that take into account the tendency for a self-developing system to drift from its original objectives over long periods.

4.2 Aims

The Initiative should aim to develop **a theoretical yet practicable framework for collective adaptive systems** of broad applicability within systems theory. Key questions are: How to describe systems which have to deal with multiple scales in time and space? What are the principles by which such systems operate? How can we build them? How can we evaluate them? How can we design in and exploit emergent behaviour? How can we account for their evolutionary nature in development? While addressing fundamental theory, the Initiative should also have a strong practical orientation, offering new insights on problems of major importance to relevant stakeholders (the research community at large but also industry and policy-makers).

In order to advance the state-of-the-art, the focus should be on the interface between large-scale systems (with a large number of essentially homogeneous entities) and heterogeneous systems, in situations where the human user is both in- and out-of-the-loop.

Research should be directed at three main areas:

1. **Operating Principles:** Research into the principles by which Collective Adaptive Systems operate, including issues such as control, interaction and communication. Aspects would include:
    - The representation and reasoning about systems that span multiple scales and have multi-level objectives;
    - The ability to learn, adapt and/or evolve new policies and functionality;
    - The principles of 'lifetime unlimited' systems, i.e. systems which have a lifespan and lifecycle beyond the intentions and expectations of system designers;
    - Strategies for adapting individual and/or institutional behaviours, rules and policies in computational economies or electronic institutions;
    - Strategies for reasoning in the presence of partial, noisy and inaccurate information;
    - Strategies for information dissemination and semantic interoperability across multiple boundaries of scale, time, and geography.

Here, CAS provides the opportunity to extend the study of classical problems and classical techniques in control, optimisation and communication in an uncontrolled environment.

2. **Design Principles**: Research into the design and engineering principles necessary to build and manage Collective Adaptive Systems. Aspects would include:

    - Developing design principles for CAS that allow for the creation of emergent behaviours;
    - Developing tools and methods that support such development (e.g. templates);
    - Developing principled approaches to let CAS emerge from the incremental development of 'legacy' systems;
    - Developing tools and methods to support the validation, control and argumentation structures regarding emergent behaviour in such systems;
    - Exploiting the inherent parallelism in CAS for computation based on relevant principles and methodologies.

3. **Developmental Systems:** Research into the evolutionary nature of Collective Adaptive Systems. Aspects would include:

    - Open-ended (unbounded) evolutionary systems (fitness-driven vs concept-driven evolution; and global fitness vs local fitness);
    - Better understanding of long-term effects of evolution on the system's level and appearance of self-* (self-identification, self-repairing, self-monitoring and other self-* functions);
    - Better understanding of trade-off between learning and evolution;
    - Principles and effects of replication, including non-software components (e.g. 'artificial chemistries' taking inspiration from chemical and physical processes);
    - Design of emergence (design of interaction) by using self-organisation and evolution.

4.3 Expected Impacts

The Initiative is expected to yield important insights in terms of understanding 'the socio-technical fabric' underlying 21st century society. It will investigate how to design and manage the complex, multi-level systems that characterise increasing areas of our society and economy.

While the main focus should be on probing fundamentals and elucidating a theoretical framework, these objectives will be best achieved through being grounded in application scenarios that provide demonstrable references for the theory. Possible scenarios could include:

1. **Integrated urban transportation:** Urban transport is a good example of a collective, adaptive system: many autonomous interacting units, changing boundaries and objectives, etc. Collective adaptive strategies could be applied to optimise the performance of the urban system as a whole according to a number of criteria (energy consumption, avoiding congestion, optimising connections, minimising pollution and waste, weather conditions, etc.). This would take account of factors such as:

    - Patterns of behaviour (both individual and collective)
    - Semantics of information

- Community based control
- A combination of locally-centralised and non-centralised control
- Optimised routing and navigation
- Support for different grouping patterns (socio-techno).

2. **Micro-energy production:** Energy systems are undergoing fundamental change, with factors such as deregulation, energy security and climate change leading to systems that are two-way (i.e. individual residents and factories being producers of energy as well as users). This new generation of energy production will rely on diverse micro-level entities, such as houses, buildings and other potentially small energy collection points. This would provide a collective effort for power generation with resources being locally “prosumed” – both produced and consumed by individuals. Such a scenario would be a complex adaptive system, characterised by openness, multi-level goals and different levels of scale (e.g., houses, neighbourhoods, cities and regions). Adaptation would be needed to satisfy demand against possibly unknown and changing objectives.

Trust and security, which includes privacy and protection of personal data, is an important consideration in both these scenarios. Such aspects should be built in from the start rather than added later as a ‘bolt on’.

4.4 Disciplines and Stakeholders Involved

Many communities worldwide, and especially in Europe, are working on various aspects of collective systems. These communities include those concerned with: adaptive and bio-inspired systems; evolvable and reconfigurable hardware; biological and bio-synthetic systems; software-intensive and distributed systems, as well as various branches of networks and network-based approaches. Joining the efforts of several such communities around the foci of ‘collective’ and ‘adaptive’ will allow the formulation of common problems, challenges and solutions , as well as increase impact in the field of information and communication technologies.

In addition, as noted above, since this is essentially a societal issue as well as a technological one, it will be important to involve social scientists, domain experts and users.

4.5 Implementation

The research agenda here is still being defined and in implementing the Initiative the Experts recommend that the Commission should show as much flexibility as possible. ‘STREPs’ are an appropriate mechanism, provided they are of a sufficiently long duration (say 4-5 years) and the ability is retained to adapt their workplans during the lifetime of the project.

PERADA – a central coordination mechanism between complementary projects – was thought to be a useful model. A mechanism similar to either the Networks of Excellence or the COST Actions should also be considered as a way of involving representatives from industry and public services in the sectors identified for the application scenarios. This would be a ‘thinktank’ or ‘collective’ with 30-40 partners that would support the projects as they progress and work towards sample applications.

Annex I: List of Participants

Chair:

Ben Paechter	Edinburgh Napier University, UK
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Hugues Bersini	Université Libre de Bruxelles, Belgium
Gusz Eiben	Vrije Universiteit Amsterdam, the Netherlands
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Klaus Herrmann	Universität Stuttgart, Germany
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Support:

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Commission Observers:

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Annex II: Terms of Reference

Consultation meeting:
Fundamentals of Collective Adaptive Systems
3-4 November 2009, Leuven

FET (Future Emerging Technologies) acts as a pathfinder for the information and communication technology programme of the EU by fostering novel non-conventional approaches, foundational research and supporting initial developments on long-term research and technological innovation. FET structures research in a number of proactive initiatives, which typically consist of a group of projects funded around a common theme. The themes are shaped through interaction with the research community, and focus on novel approaches, foundational research and initial developments on long-term research and technological innovation.

To help identify new research challenges and opportunities for the future, FET has launched a brainstorming process involving interaction with research experts who can help the Commission define new proactive initiatives. The aim is to look beyond traditional lines of research in order to recognise future and emerging areas as well as opportunities for collaboration with other communities. The final results will contribute to establishing the work programme for 2011-2012.

In this context FET launched a consultation entitled "*fundamentals of collective adaptive systems*" on 3 and 4 November in Brussels. This particular brainstorming session is done in collaboration with the PerAda Coordination Action. The report resulting from this meeting, will act as a key input to the drafting of future FET proactive initiatives.

1. Short Presentations

To get discussion underway, each participant is asked to give a five-minute presentation summarising their vision of emerging research. The objective is not to validate existing research but identify topics, challenges and ideas for new proactive initiatives. The series of five-minute "previews" are meant to act as a discussion starting point and participants will have full opportunity for expansion of their ideas in later discussion. The following is suggested as a focus for presentations and discussion.

- **Challenges / new areas** - *why are these an opportunity?*
- **Research topics –** *why and how are these different than existing research*
- **Impact** - *what potential impact on information processing and communication from a breakthrough in this area ?*
- **Suitability for ICT and FET** - *what makes this suitable for ICT and FET as opposed to the mainstream programme? Is it vision-driven and high-risk, embryonic or foundational?*
- **Communities** - is this topic addressing an existing or new community?

Participants are also invited to prepare a short (1- 2 page) position paper inspired by some of the issues below:

Adaptive systems

- What are metrics? How to validate or compare?
- What is the ideal mechanism? What about choice between fitness-driven versus concept-driven?
- Relation learning – self-organisation – evolution

Collective systems

- How does cooperation emerge? (alignment, imitation, sharing, anticipation)
- How does semiotics or language emerge?
- How does behaviour emerge?
- What are driving forces of controllability of long-term developmental processes?
- Controllability and predictability of self-* properties
- Developmental drift due to emergence of artificial culture
- How do separate species arise in biological and artificial context?

2. Agenda

Tuesday 3 November 2009

11:00	Welcome and introduction
11:30 – 13:00	Short presentations by participants (ideas for new proactive initiatives)
13:00 – 14:00	Lunch
14:00 – 16:00	Discussion on challenges/new areas/research topics
16:00 – 16:30	Coffee break
16:30 – 18:00	Discussion on impact of future research
19:00	Dinner followed by informal discussion

Wednesday 4 November 2009

09:00 –10:30	Break-out session: discussion on new opportunities
10:30 – 11:00	Coffee break
11:00 – 12:00	Discussion: new proactive initiatives
12:00 – 13:00	Presentation of results

3. Useful links

The FET website http://cordis.europa.eu/fp7/ict/fet-proactive/, gives details of the proactive initiatives, in particular you can see the scope and composition of the proactive initiatives portfolio, and an overview is included in the attached document. In addition, the previous consultation report "shaping the future" is as ftp://ftp.cordis.europa.eu/pub/fp7/ict/docs/fet-proactive/press-07_en.pdf