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Science education for sustainability, epistemological reflections and educational practices: from natural sciences to trans-disciplinarity

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Abstract In this three-part article we seek to establish connections between the emerging framework of *sustainability science* and the methodological basis of research and practice in science education in order to bring forth knowledge and competences for sustainability. The first and second parts deal with the implications of taking a sustainability view in relation to knowledge processes. The complexity, uncertainty and urgency of global environmental problems challenge the foundations of reductionist Western science. Within such debate, the proposal of sustainability science advocates for inter-disciplinary and inter-paradigmatic collaboration and it includes the requirements of *post-normal science* proposing a respectful dialogue between experts and non-experts in the construction of new scientific knowledge. Such a change of epistemology is rooted into participation, deliberation and the gathering of extended-facts where cultural framings and values are the hard components in the face of soft facts. A reflection on language and communication processes is thus the focus of knowledge practices and educational approaches aimed at sustainability. Language contains the roots of conceptual thinking (including scientific knowledge) and each culture and society are defined and limited by the language that is used to describe and act upon the world. Within a scenario of sustainability, a discussion of scientific language is in order to retrace the connections between language and culture, and to promote a holistic view based on pluralism and dialogue. Drawing on the linguistic

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reflection, the third part gives examples of teaching and learning situations involving prospective science teachers in action-research contexts: these activities are set out to promote linguistic integration and to introduce reflexive process into science learning. Discussion will focus on the methodological features of a learning process that is akin to a communal and emancipatory research process within a sustainability scenario.

Keywords Sustainability · Post normal science · Language · Action research · Initial teacher education

Riassunto dell'articolo in Italiano

In questo articolo ci proponiamo di evidenziare alcuni collegamenti tra la prospettiva emergente della 'scienza della sostenibilità' e certi elementi di riflessione critica sui fondamenti epistemologici e metodologici dell'educazione scientifica, proponendo esempi di attività didattiche sperimentate in coerenza con queste riflessioni.

Di fronte alla complessità, all'incertezza e all'urgenza delle problematiche ambientali—che hanno ormai assunto una dimensione globale—la moderna tecnoscienza è oggetto di un approfondito dibattito, e da più parti vengono posti degli interrogativi sulle sue basi epistemologiche e sulle sue relazioni e responsabilità con la società e con i sistemi naturali. All'interno di questo dibattito si colloca la proposta di una scienza della sostenibilità, caratterizzata da una crescente collaborazione (inter-disciplinare e inter-paradigmatica) tra discipline, e dalla scienza post-normale, basata su un dialogo rispettoso tra esperti e non-esperti nella costruzione di nuova conoscenza scientifica.

Una simile trasformazione dell'idea e della pratica della scienza ha implicazioni molto interessanti per l'educazione scientifica, e propone la sfida di trasformare il processo di insegnamento/apprendimento da una comunicazione unidirezionale orientata a trasferire nozioni consolidate, verso una comunicazione dialogica, creativa ed evolutiva, alla quale partecipano con pari dignità insegnanti e studenti. In questo contesto ciascuno è portatore di elementi significativi per la costruzione di una conoscenza condivisa, e diventa più evidente il ruolo del linguaggio con le sue molteplici sfumature (il linguaggio nominale e quello verbale) e canali (iconico, verbale, simbolico…), con i suoi vincoli e le sue potenzialità.

Il passaggio da un contesto educativo polarizzato, in cui l'insegnante è portavoce-neutrale e obiettivo della scienza consolidata, a un contesto dialogico, in cui tutti partecipano al processo di acquisizione consapevole e critica di un sapere dinamico, in continuo mutamento, spesso incerto e talvolta controverso è molto difficile da realizzare, anche perché nella scuola si sono consolidate certezze e abitudini resistenti al cambiamento.

Il nostro approccio, basato sull' idea di scienza post-normale e orientata alla sostenibilità, considera l'ambiente classe come comunità educante, e promuove al suo interno lo sviluppo di un processo dialogico che coinvolge e motiva insegnanti e studenti a costruire insieme elementi di nuova conoscenza scientifica, consapevole dei limiti del sapere umano e in grado di tener conto della complessità e delle interconnessioni tra l'agire umano e il funzionamento dei sistemi naturali, per loro natura in continua evoluzione.

Nella terza parte di questo articolo presentiamo alcuni esempi di attività che abbiamo proposto nel corso di dieci anni a futuri insegnanti di scuola primaria e secondaria: la pratica della ricerca-azione che abbiamo sempre messo in atto ci ha consentito di monitorare i processi di apprendimento in itinere e di valutare il grado di efficacia delle nostre proposte relativamente alla motivazione e alla partecipazione, all'acquisizione di conoscenze disciplinari e trans-disciplinari, all'elaborazione di consapevolezza sui meccanismi di produzione della conoscenza.

> Confined to the existing structures of knowledge generation and transmission, universities find it difficult to do justice to the complexity of contemporary problems.
> Godemann (2008)

The crisis of the human communities on the planet has become acute, both locally and globally. Natural systems seem no longer able to satisfy human needs (WHESA 2011) and violent conflicts are spreading all over the Earth in the face of impending scarcity of land and energy resources (Lambin and Meyfroidt 2011). The current state of emergency requires a profound redefinition of current models of socio-economic development and humanity's demands on the Earth (Sachs 1999). As argued by Amartya Sen (1999) a great responsibility is given to education to promote knowledge, attitudes and behaviours to enable each person equal opportunities of personal development and access to natural services and resources within a limited planet. In order to achieve this aim however, a change of epistemological and methodological conditions orienting the production and use of scientific knowledge for human purposes is also required.

This is the context in which we introduce the conceptual basis of *sustainability science*, as a contemporary framework for orienting knowledge production processes towards a perspective of sustainability. We argue that a redefinition of knowledge categories and methodological approaches in science can be aligned with a creative and constructive disposition towards complexity and uncertainty and the maturation of an inclusive ethical stance. The argument is developed in three main sections. First, we discuss the implications of taking a sustainability view in relation to knowledge processes by introducing the perspective of complexity of natural systems and knowledge integration; the second part will deal more specifically with language processes in the context of interdisciplinary dialogue in science. Finally, the third part provides examples of teaching and learning situations with prospective teachers of primary and secondary education. We draw on a variety of contexts in which science learning was enriched by the linguistic reflection to enable epistemological awareness and a range of social, cognitive, communicative competences that are in line with a sustainability view.

Part 1. Transformations of the environment, transformations of science and the epistemological framework of sustainability science: unsustainable!

Since 1970, we are depleting our ecological budget for the year earlier and earlier; in 2011, the overshoot day was August 21st (Global Footprint Network 2011). Environmental degradation and depletion of natural resources are proceeding at a fast-growing rate, threatening the well being of billions of people (IFPRI 2011) as well as numberless non-human species (Butchart 2010). In this scenario, science and technology are often sought as a means for bringing innovation. The synergy between techno-science and increasingly the private enterprise is expected to boost the economy and help to overcome social problems (DIUS 2008). However science and its technological applications are also the tools for carrying out extensive and unforeseen transformations of socio-eco-systems (Wilk 2010). We are confronted with an uncertain situation whereby the knowledge we produce about the natural world is also the knowledge that leads to problematic situations. It is an ambiguity that is difficult to tackle which requires delving deeper into the complex interaction between ideas of science, representations of nature and the structure of educational processes.

The dominant narrative about science, even in the most rated academic journals, continues to perpetuate the idea that “fundamental knowledge about the natural world will lead to human progress” (Alberts 2008, p. 1435). Quantitative and analytical approaches are fore grounded as the preferred means for scientific inquiry (Enquist and Stark 2007) aimed at penetrating the mysteries of nature and providing the keys for making predictions and achieving control over the natural world. A view of science that produces reliable and objective knowledge has much currency in the current world and it is to this kind of science that policy-makers would often refer to both as the source of innovation and its main evaluator (Ellis 2010).

Similarly, in education, traditional approaches to learning and teaching science contribute to the consolidation of a positivistic idea of science, organised in disciplinary realms and characterised by neutrality and objectivity. As David Orr (1991) remarked “in the modern curriculum we have fragmented the world into bits and pieces called disciplines and subdisciplines. As a result, after 12 or 16 or 20 years of education, most students graduate without any broad integrated sense of the unity of things” (p. 52). Organised in such a way, the curriculum gives little opportunity to appreciate the holistic nature of living systems and their intrinsic faculty to transcend human existence.

While traditional school systems continue to focus on a disciplinary approach to knowledge geared towards the assimilation and memorisation of large quantities of information, the voices of educationalists, psychologists, sociologists of science, anthropologists and science education researchers are converging in an effort to illustrate the inadequacy of this way of teaching science and its negative implications: from the failures of the learning process to the promotion of ways of thinking and doing which have proved unsustainable for both human communities and the environment. In order to start on this inquiry it is to science and associated views of knowledge of the natural world that we have to turn.

Complexity and inclusion at the basis of a new framework

The disciplinary, analytical and quantitative approach characterising scientific research and inquiry allows for the in-depth and refined analysis of selected fragments of reality. This approach is underpinned by a mental process of identification of boundaries, in order to undertake measurements and infer relationships, often followed by a physical process of abstraction or removal of the portion of reality under examination from the rest of the system (van Eijck and Roth 2007). This type of focussed and reductionist thinking has characterised the rise of what Barbara Cartwright (2008) termed *modern science*, a form of inquiry insisting that “we found explanation on experimentally identifiable and verifiable structures and qualities” (p. 81). By means of empiricism, the author maintains, we are only ever able to gain knowledge about what is in the nature of structures to do and in the manner of a dappled picture, as the world is being described through the specific and bounded features of our empirical apparatuses. As such, through the internally consistent, synthetic practices of disciplinary inquiry, reality can be described as a collection of singular objects.

The descriptive and interpretative character of science has further evolved in recent times into a techno-science actively involved in transforming energy, matter and information fluxes all around the world. Over the last 50 years, the intensity and the scale of technological interventions on the natural, cultural and social systems has grown exponentially. From construction projects to intensive food production, a limited number of subjects (mostly international teams supported by large financial and political forces with specific interest) are acting upon the socio-ecological systems with a literally unprecedented power: they are in fact manipulating matter and energy over shorter and shorter time frames. As techno-scientific experiments are no longer confined within laboratory walls, but they consist of open—field experiences on our planet's complex and evolutionary ecosystems, it is no surprise that modern techno-scientific endeavours are interfering locally and globally with the bio-geochemical cycles (Elser and Bennet 2011), bringing some unpredictable consequences. The most striking example is the research, development and large scale farming of genetically modified crops, that are rapidly altering the agricultural scenario worldwide: in 2010 the overall surface area covered by GM crops reached 148 billion hectares, with a market value of 12.2 billions US dollars, which represents 22% of the global seed market (James 2010). Our present ignorance about the genome's physiology prevents us to cope with the unforeseen consequences of the spread of GMO's on biodiversity, general ecosystems' functioning and human health (Benessia and Barbiero 2012).

Confronted with this state of affairs, some authors have looked at modern reductionist science as a forma mentis that appears to be increasingly inadequate to deal with the complexity of natural systems and of our position—as we are ourselves complex wholes—within such systems. Natural systems are constituted of multiple organisational levels, mutually interacting and connected by relationships of non-linear causality. It is impossible to identify clear boundaries between processes and phenomena, even when considering very different time and space scales (Lenton and van Oijen 2002). Indeed, the system displays different properties at different scales, and it is indeed dappled when subjected to disciplinary investigations; however, such properties are in themselves the result of the interactions occurring between parts at multiple levels in a spiral of emergence and creativity (Volk 1998).

In such conditions, while a refutation or a new paradigm for science might still be possible at an intellectual level in the manner anticipated by Karl Popper and Thomas Kuhn (Bloor 1971), the profound transformations that are brought to the natural systems give little or no opportunity to return to a previous situation at a practical level. The system so conceived exists as part of a history of transformations with synchronic and diachronic features posing a challenge to the descriptive power of reductionist science but also to human beings that are required to act in the face of inherent and structural uncertainty.

Embodied cognition

Another emerging perspective feeding into our reflection on scientific knowledge is concerned with the growing realization of the embodied nature of our mind which develops within a sub-system: the body in complex interaction with the natural systems hosting it (Clark 1997). Most importantly, it is the interconnection between the inside and the outside environment of the organism that is fundamental to knowledge. James Gibson (1979) maintained that perception is not simply a passive response of the organism to an outside stimulus much in the manner of a machine recording visual stimuli (cf. Lindberg 1976). Rather, organisms are agents that are actively engaged in sense perception. This idea runs counter to the neural reductionism approach developed in some fields of cognitive sciences which explained sense perception in terms of electrical changes and ion fluxes in neurons and other types of cells. More recently, the works of Erik Myin and Kevin O'Regan (2002) have supported the notion that the organism is involved in shaping the flows of energy and matter in particular ways, thus giving rise to different experiences. Feelings in organisms arise from the exercise of particular skills in interacting, interfacing and thus exploring the world and this will also have to do with intentionality, for “in order to exercise a particular skill, an organism must pay attention to the world in a particular way” (Goodwin 2007, p. 78). In an another context, an elaboration of this idea was proposed by the anthropologist Tim Ingold (2011) in a reflection on the paving of the streets in cities and how it affected–in a coupled way—both people’s behaviours in public spaces and the collective perception of the environment: a culture dominated by the visual took over from an older culture rooted into the dexterous, meshwork of signs, feelings and relationships with the soil and other living forms in one’s own environment.

So, perception is linked to the development of skilful and experientially-based way of interaction with the natural world, through breathing, walking and pacing one’s activities. Additionally, far from being an objective and inarticulate matter, the environment allows for reflexive feed-backs for the organism learns according to the ways in which it shapes his own environment and his modes of interaction with it. Hence, changes in the environment can have profound implications for our behaviours and cultural perception.

Views of the world: continuity between language, experience and thought

Drawing on the fields of neuroscience, evolutionary biology, as well as linguistics and philosophy, George Lakoff and Mark Johnson (1999) expanded on the continuity between *perceptions* and *thought* highlighting the crucial role played by language. The authors refer specifically to metaphors as being embodied linguistic forms. So the organism is part of a natural context continuously crossed over by flows of matter, energy and information which are distributed across a network of psycho-physiological structures (Goodwin 2007). As such, language is a reflection of such embodiment and linguistic expressions and metaphors are expression of this particular embodied way of knowing, thinking and perceiving (Gallese and Lakoff 2005). Thus, language becomes the expression of a way of seeing, sensing and being in the world.

As language is modified over time and across contexts, the present variety of words and meanings that are available to us are also linked to changes of social practices and understandings that have taken place over a longer period of time. So, the appearance of redundancies and indistinctness in language can be paralleled to phenomena of biological evolution, whereby change of biological structures, through the appearance of novelty and ambiguity can be seen an expression of the complexity of interactions between living systems in a context of continuous flux and transformation (Bateson 1972). Therefore, while modern science still aims at objectivity, abstraction, generalisation, universality (Editorial of the Nature journal 2011), it is becoming more and more evident that scientists are deeply embedded within the complex, evolving, and limited contextual reality from which we completely depend (Bateson 1980).

From the perspective of embodied cognition, our knowledge of the world is not simply the result of discoveries but also of inventions, which are evolutionary, technological, conceptual and, ultimately, linguistic (Jablonka and Lamb 2005). Creative thinking (also in science) depends on language, expressing novelty by means of new words, images and concepts and associating them with elements of the existing culture (Konopka 2002). Indeed as reported by Brendon Larson (2011) metaphors are part of the fabric of knowledge production in science and greater sensitivity should be developed to their presence and their implications. Namely, metaphoric ambiguity when productively elicited can be a fertile source of inquiry, allowing for leaps beyond stabilised meanings and opening up new avenues of scientific exploration. This understanding leads to important implications regarding the nature and modes of production of what knowledge about the natural systems.

Contingency of human thought

In the first instance, the contribution of the linguistic dimension allows us to move beyond the image of a single and universal science which eventually uncovers the world as it is and to accept the idea of contingency, temporality and value-ladenness of human knowledge (Dunn et al. 2011). In this context, Jerome Bruner (1991) proceeded on identifying the features of narrative as a form of knowledge production: "It was perhaps a decade ago that psychologists became alive to the possibility of narrative as a form not only of representing but of constituting reality" (p. 5). He signalled the relevance of the inquiring subject, within a context of values, norms and actions.

A similar point was also expressed by Norman Denzin (1989) referring to narratives as thick descriptions with four recognisable characteristics: the context of the act; the intentions and meanings; the evolution and development of the act and the presentation of the act as a text that can be interpreted (p. 33). So narratives emerge from cultural and social practices and their interpretation can provide useful insights into the organisation of knowledge about the world produced by a particular community.

A second, fundamental implication is that there appears to be no distinction between Nature and Culture, culture being the set of languages, norms, behaviours that arise in response of a particular way of directing our attention to Nature and relating to it. The world can be narrated in many different ways and the nature of such relationship is paramount to how we know the world and construct ourselves in a reflexive process. In this view, Western science can be looked at as a cultural narration that can be interrogated on the basis of its values, intentions and means of production in relation to the environment. As reported by Thomas Princen (2010), the notion of laboratory research typical of this Western science is not simply a way of referring to the familiar place in which scientists undertake their empirical investigations, but it is also a powerful metaphor, part of a culturally established consensus on how we conceive of our role of subjects inquiring into the world and how we set boundaries as to which and whom is to be included in the frame. Specifically, the laboratory afforded the possibility of carrying out research in simplified, closed and controlled conditions to produce objectified descriptions that are thin narratives of the natural world (Denzin 1989). Hence an inquiry into the science metaphors is important to retrace complex understandings and what was hidden and revealed behind the formulation of particular metaphors. For example, Larson (2011) produced an extensive list of metaphors used in environmental sciences and conservation biology most of which featuring not only in primary scientific research articles but also in everyday language. Some examples may include alien; flagship; community and many others (p. 5), and they are all terms that retain socio-cultural implications. It suggests that the act of comparison and entering into relationship with other ways of knowing can be fruitful in assessing motives, strengths and similarly also the inherent limitations of scientific descriptions.

This level of epistemological awareness however requires further consideration of the methodological features of a knowledge process that can enable perspective shifts and it is indeed built upon cooperation with other cultures and with nature as a means for dealing creatively and constructively with complexity and uncertainty (Goodwin 2007).

Knowledge, uncertainty and the role of democracy

Many scholars from different fields recognise the idea of complexity as a powerful conceptual tool for rethinking the idea of science and the position of humanity in the world. For example, Sandra Harding (2008) takes a critical stance towards ideas of linear causality and maintains that: "reliability of conventional reliable knowledge has been criticised as producing far too narrow understandings of nature and social relations" (p. 83). Furthermore, she recognises that current problems involving human-nature interactions cannot be captured by singular, disciplinary framings; they trespass traditional knowledge boundaries and escape the control of academic peers. From here the author argues for the intrinsic incompleteness of human knowledge and the acknowledgement of acting in conditions of ignorance whereby we can only know if we put ourselves *in relation* to other ways of knowing.

The theoretical ideas of Harding (2008) find resonance with the work of Silvio Funtowicz and Jerome Ravetz (1999), who formulated the concept of *post-normal science* as a new approach towards doing and thinking about science which extends the practice and conceptions of *normal* science. The awareness that we can only have a partial, incomplete view of the world led the authors to propose a methodology of inquiry that is appropriate for dealing with situations in which facts are uncertain, values are in conflict, the stakes are high and there is a need for urgent decisions. Such a methodology is founded upon the process of open dialogue between all the people who have a right to participate (as they are involved in the problem) and who are expressing the desire to be involved in finding a solution (Funtowicz 2001).

As reported by Sheila Jasanoff (2007), when confronted with the contingent, transitory and uncertain nature of science knowledge, action and decision-making should include a dimension of humility, "about both the limits of scientific knowledge and about when to stop turning to science to solve problems" (p. 33). Furthermore, an attitude of humility may be a fruitful starting point for encouraging an open and creative decision-making process involving experts from different disciplines as well as people carrying their own practical knowledge. Public dialogue is thus offered as a methodology that overtakes the idea of a rigorous scientific demonstration: "Inside the knowledge production process, citizens become both critics and creators. Their contribution has not to be defined as 'local', 'practical', 'ethical' or 'spiritual' knowledge, but it has to be considered and accepted as a plurality of rightful and coordinated perspectives with their own meaning and value structures" (Guimarães Pereira and Funtowicz 2006, p. 35).

Humility and an attitude to respectfully listening are mostly needed in unbalanced situations, such the ones described by Robert Chambers (1997) who suggests not only to put the last first, but also to put the first last; that is to say that experts and powerful people need to become humble with respect to the experiences and framings of the situation that are legitimate for other people. In a paper signed by Carl Folke and numerous colleagues (Folke et al. 2002) who analysed the social and political factors affecting environmental management, the authors underline the need for experts to engage in respectful listening, while the non-experts should gain and develop more confidence in their own abilities to make contributions.

Thus, the notion of responsibility for human-nature interactions is no longer a trade-off between techno-science *speaking-truth-to-power* (Jasanoff 2007) and the political and economical systems acting on the basis of the information received. Instead, we can imagine a dialogical relationship between the stakeholders, each one bringing values and interests in a context of participatory democracy, where the aim is that of making sense of the world by co-producing knowledge, mediation and representation (van der Sluijs et al. 2008).

From epistemic sovereignty to epistemological pluralism

More recently, the ideas of complexity of natural systems and the need to operate in conditions of uncertainty and incompleteness of human knowledge have provided the foundations for the articulation of a *sustainability science* (e.g. Clark, Crutzen and Schellnhuber 2005). Gilberto Gallopin (2004) stresses the evolutionary aspects that characterise both science and the systems that are objects of inquiry: "knowledge of the system is always incomplete. Surprise is inevitable […]. Not only is the science incomplete, but the system itself is a moving target, evolving because of the impacts of management and the progressive expansion of the scale of human influences on the planet" (p. 9).

The literature on sustainability science is continuous expansion with a number of academic journals dedicated to discussing its epistemological and methodological features. The review provided by Mary Thompson-Klein (2004) identifies two main foci of reflection that are interrelated. One is concerned with the nature of knowledge and the move from a homogeneous to a heterogeneous and non-linear form of knowing. The other one is more directly concerned with the ideas of post-normal science, the incorporation of non-disciplinary forms of knowing and the relevant social practices.

Specifically, the notion of incompleteness of knowledge has been taken as a springboard for the promotion of interdisciplinary dialogue. Daniel Sarewitz (2004), for example, declares that, by virtue of its complexity, outside reality can allow for "a science enterprise of enormous methodological, disciplinary, and institutional diversity" (p. 386). Moreover, "the growth of disciplinary scientific methods and bodies of knowledge results in an increasing disunity that translates into a multitude of different yet equally legitimate scientific lenses for understanding and interpreting nature" (p. 390).

However, the pursuit of theoretical pluralism produces debates to arise at all levels, from the more strictly epistemic aspects of how disciplinary integration can occur to broader philosophical stances as to what is to be considered relevant knowledge and the modes and purposes of engaging in joint efforts to tackle problems. To this regard, the analytical framework produced by Malin Mobjörk (2010) outlines a progression from multi-disciplinarity to inter and trans-disciplinarity which exists by virtue of the interplay between a set of three sub-dimensions: collaboration, motives and integration. At a first level, multi-disciplinarity, researchers from different disciplines can come together to complete a task that requires the pooling of knowledge from different disciplines. Collaboration and motives are functional in nature and knowledge integration occurs within the normative boundaries of academic research; it is usually confined to a specific project or problem and it is mainly concerned with the synthesis phase (e.g. pooling of results). At the level of inter-disciplinarity, the coming together of different disciplines is pivotal and it arises from a research process that is jointly established on the basis of a shared problem. The topic of concern is intrinsically an area of intersection between disciplines and normally developing at the interface between social and natural sciences. In addition, within an interdisciplinary approach collaboration may be more or less instrumental or critical; for example, interdisciplinary transfers, such as geography's borrowing models from physics and anthropology, can come from the willingness and awareness of the need to learn from one another and thus enhancing one's own set of conceptual frameworks (Ramadier 2004). Yet, the extent to which researchers draw on and sustain this kind of reciprocal learning and potentially, mutual interrogation of knowledge and perspectives, is dependent upon the level of personal commitment to the topic (motives) and their value-orientations (Nicolescu 1996), a point that was also made earlier by Chambers (1997) and Folke et al. (2002). For example, collaborative work can be sought as a means for seeking solutions to problems as they occur, in the manner of a problem-solving exercise to adjust to given situations. In this context, research may be conducted within the boundaries and contexts of academic work. Conversely, collaboration may be set out to restructure the modus operandi of modern science by facilitating a form of sustained interaction and exchange of knowledge and beliefs. In this case, informal practices of knowledge sharing and personal aspects may be incorporated and pursued. So depending on the nature of collaboration and the level of mutual learning, also the nature of the integration will be different.

Trans-disciplinarity

Mary Thompson-Klein (2004) maintains that a critical stance towards the way we use scientific knowledge is best fulfilled in the context of trans-disciplinarity; referring to the challenges posed by environmental problems to the economic competitiveness agenda of industrialised countries she clearly expressed: "transdisciplinarity raises the question of not only problem solution but problem choice" (p. 518). So, in the first instance, trans-disciplinary research acquires its distinctive features from the nature of the problem that is being investigated, moving from the strict realm of application to the agora of public debate whereby a multiplicity of stakeholders is involved in formulating a problem and contributing heterogeneous skills and expertise. Such change in the range of actors involved is also an important departure from the mix of academic disciplines involved in interdisciplinary work and a move towards trans-sectoriality, whereby science is in with and for society (Kim 1998). Hence, as we move further into post-normal conditions (Funtowicz and Ravetz 1999), the inclusion of other forms of knowledge requires a move towards trans-disciplinarity. For some authors (e.g. Ziegler and Ott 2011) the inclusion of non-scientists and non-strictly scientific forms of knowledge, such as literature and the arts, should be a criterion for quality in sustainability science. The authors point to the necessity to draw upon local knowledge for bringing in thick narratives and contextual elements that can help identify relevant aspects; for eliciting criticality towards scientific assumptions and the limitations of institutionalised ways of communicating and also for being able to welcome novel issues and ideas and respond appropriately to the pressure and urgency of a given problem.

Firket Berkes and Mina Berkes (2009) have analyzed in a systematic way some differences between Western science and indigenous knowledge, underlying the complementary approach of the two knowledge systems: "complex systems phenomena, such as climate change, occur at multiple levels, and there is no one correct level of analysis. The system must be analyzed simultaneously across geographic scale, from the global to the local, but the relative emphasis of science has been at the global level. The fact that indigenous knowledge provides local-level understanding is particularly important because it complements science precisely at the level where information is poor" (p. 11). In this view, trans-disciplinarity combines epistemological reasons associated with incompleteness and contingency of knowledge with political and ethical arguments.

Transdisciplinarity and language

By necessity trans-disciplinarity relies on disciplinary knowledge. However, while multi and inter-disciplinarity continue to rely on disciplinary thinking, trans-disciplinarity challenges it, through the articulation and dialogue between different forms of knowledge. It is a form of research that brings forth and is centred upon an ontology of multiplicity and difference, requiring deconstruction, and the acceptance that "an object can pertain to different levels of reality, with attendant contradictions, paradoxes, and conflicts" (Thompson-Klein 2004, p. 524).

Yet scholars who have had firsthand experience of inter and trans-disciplinary research underline the difficulties emerging within cross-disciplinary encounters. For example, Miller et al. (2008) recognise the need to accept that each single way of knowing is insufficient to understand the issues, to recognise not only the knowledge that is at stake but also the values and aims of the research, and to be able and willing to build internal reflexivity. So, trans-disciplinarity is a process of knowledge production as well as epistemological and personal maturation, and it is profoundly rooted into the interactional and linguistic dimensions. On the one hand, there is attention towards socio-cognitive processes and the opportunities that are offered to stimulate the expression of multiple interpretations, languages and their coming into dialogue. In any case, there is attention towards structures and power relations and thus the extent to which different contexts can allow for inclusion, participation and indeed the building of a community of stakeholders that shares the norms of trans-disciplinarity. As indicated by Edgar Morin (1999), knowledge of complexity requires scientific knowledge to be contextualised and concepts created to play the role of *linking operators*, but it is also a process of intellectual and civic reform towards a broad transdisciplinary culture of critical engagement and cooperation (Mobjörk 2010).

The university as a forum for science-society interactions

Within the scenario of sustainability science, the university is charged with an important role with regard to preparing future scientists and future teachers to engage in democratic dialogue. So the question we ask is what kind of knowledge production processes and what kind of contexts should be devised to promote epistemological maturation and the development of citizens' competences for acting in post-normal conditions? Of particular concern in our case is the preparation of school science teachers and how the linguistic reflection can be used to support scientific preparation that enables understanding of complexity and openness to a multiplicity of views.

Towards a science education for sustainability

By virtue of a traditional idea of science that still prevails, many people identify scientific and technological progress as the most secure way for resolving the global environmental crisis. For instance, the construction of ocean pipes or devices for blocking solar insulation (Keith et al. 2010) fit in with the values and norms of a worldview that separates humans from nature. With consideration of the critical voices arising from different fields of research and inquiry in the sciences, we can argue that the sustainability of human presence on the planet is dependent upon a radical shift of both culture and epistemology. According to Bruno Latour (2007), we need to recognise ourselves as *Earthlings* and move away from the idea of modernization and emancipation from Nature to a concrete scenario of explicit recognition of our dependency upon it.

One level of change therefore is epistemological and concerns the shift from a subject-object to a subject-subject relationship. The power division between those who know (scientists, teachers) and those who do not know (citizens, students) gives way to a dialogical relationship between subjects who are all carrying partial but equally legitimate interpretations. To the extent to which the main research questions are changing, and are increasingly defined by the society at large through democratic processes, also educational priorities are expected to change.

The main goal of the teacher is thus to provide students with reflective skills enabling them to make explicit the dependency of science knowledge from the underlying culture and power relationships (Aikenhead 2003), to understand the complex relationships between ourselves and the natural systems hosting us, and to adaptively cope—through cooperation and self-restrain—with the huge transformations in energy fluxes and matter use within our shrinking, globalised and conflicting world (Martinez-Alier et al. 2010).

In particular, the recognition of a science that is becoming more and more uncertain finds itself in contradiction with educational practices rooted into the delivering of facts, notions, definitions, rules and similarly with research practices looking for fixed understandings (Torbert 1981). Language, dialogue and communication play a central role in promoting a more dynamic and contextualised idea of science (Roth and Lee 2004). Such an approach is not solely confined to dealing with controversial socio-scientific issues or environmental education (Ekborg 2003), but it is located at a more profound level, regarding the interplay between facts and values and the way in which we build and make use of new knowledge.

The second part of the article will now be exploring in more detail the features of scientific language and the different ways of seeing the world elaborated by the scientific disciplines. The linguistic analysis is directed towards the identification of metaphors for enhancing epistemological pluralism and bringing forth a sustainability view. More specific examples of practical applications in action-research contexts will then be offered in the third part.

Part 2. From sustainability science to sustainability education: the methodological foundations of dialogue

Teaching as a communication process

A simple, traditional way to describe human communication is a one-way model, whereby a message is transmitted from a source to a passive recipient in a linear and unambiguous fashion. A more recent model implies an interactive and dynamic two-way communication, in which both source and recipient are engaged in active negotiation of meanings (Resnick et al. 1991).

Reflecting upon the nature of communication has allowed for a deepening of awareness of the multiple components of dialogue and their contribution to making the teaching and learning process more effective and constructive. In the first instance, we note the epistemic and linguistic aspects that include the language we use and its continuous transformations, our interpretive schemes and, more generally, the interpretive lenses adopted by the different disciplines to produce new knowledge.

Secondly, we note the pedagogical aspect: the nature of classroom communication and the importance of building language and communication competences for both teachers and learners (Dodman 2004). There is now a widespread consensus that by offering students an educational context where they can express their own ideas and discuss them with teachers and peers (Klymkowsky and Garvin-Doxas 2008). They are also encouraged to find personal meanings and fulfil a fair role in society and the environment.

Similarly, in science education, the idea that learning science entails a passage from the social to the personal plane through a process of internal reconstruction has constituted the fundamentals of the socio-cultural approach to science learning (Scott, Mortimer and Amettler 2011). Learning is equated to a dialogical process of sharing and integrating different ideas mediated by the use of language. As reported by Valentin Voloshinov (1973): "For each word of the utterance that we are in the process of understanding, we … lay down a set of our own answering words. The greater their number and weight, the deeper and more substantial our understanding will be … understanding strives to match the speaker's word with a counter word" (p. 102).

In the light of previous discussions about language and embodied cognition (part 1), a richness of words and understandings is embraced by complexivist approaches to knowledge. Specifically, children's ideas about natural phenomena not only can be varied but they often differ both ontologically and epistemologically from the descriptions offered by school science. For example, if in the course of everyday experiences we refer to energy as a quantity that *gets used up,* in Physics, energy is a property or state of a system, which is *conserved*. Scientific concepts are products of specific scientific communities and constitute part of the disciplinary knowledge of that community.

Traditionally, one of the goals of socio-constructivist science education has been that of guiding learners to differentiate between everyday knowledge and consolidated scientific views and so for example, "to understand what energy is not (a real substance) just as much as what it is (an abstract quantity)" (Scott, Mortimer and Amettler 2011, p. 6). In this view, the correct scientific description can be identified and transferred, allowing for further integration of different concepts into a hierarchically organised structure (Howe 1996). Links can be established amongst scientific concepts and between scientific concepts and practical experience with clearly stated passages between macroscopic features and theoretical microscopic aspects (Scott, Mortimer and Amettler 2011).

As such, socio-constructivist learning provides the basis for developing the scientific story within a particular discipline, with language being used to set out boundaries of meaning and ideas across disciplinary domains. As indicated in the earlier section, such clarity is important for disciplinary and multi-disciplinary work. However, if science is seen as a subculture (Harding 2008) in linguistic continuity with human thought and experiences across contexts, then we are confronted with the task of re-integrating school science education and its language within a learning process that is both closed and open to conceptual definition (Wittgenstein 1961), in the manner of an ongoing dialogue between partial views. In order to pursue this goal, a discussion of the specific features of scientific language is in order.

Conceptualising reality: nominal versus verbal language

All concepts we formulate and we express by means of language are a manifestation of the interaction between the subject or *knower*, the object of reality and the context in which this is located (Hing 1993). While in some cases we have no difficulty in recognising some concepts as mental abstractions, products of our mind (i.e. the concept of ecosystem), in other cases we are led to believe them as generalisations of real entities (for example, the concept of *cell*). When this occurs, we are led to confound reality with its representation. Language and metaphors in particular account for such difficulty. Metaphor is a key component of intellectual inquiry because it enables us not only to understand one thing in terms of another that is more familiar or close to us but also to think of an abstraction in terms of something more concrete (Larson 2011). So, language is the vehicle that connects abstract and experiential realms; some metaphors have become so established that we are no longer aware of their use (e.g. the leg of a table as a metaphor to talk about the interplay of several qualities such as sturdiness, weight and support). On the basis of such reflection, dedicating attention to the processes of conceptualization can become a fruitful practice for preventing ourselves from *thingifying* nature (Désautels and Larochelle 1998),[1] meanwhile offering the stimulus for developing awareness of the powers and the limits of our mental processes and our language.

All language systems offer two different ways of perceiving, representing and interpreting reality. One is the verbal mode, made up of subjects, verbs and complements. This view of reality corresponds to our view of the world as a *process*, where we can identify agents performing particular actions with specific consequences or processes manifesting themselves through outcomes. Another way of representing reality is the nominal form, which makes prevailing use of nouns and adjectives (Chinn et al. 2008). Agents and processes are no longer visible: what counts is the result. The world is viewed as a product, as something that has already been made and defined. The progress of science and the subsequent specialization of the different disciplines have been closely associated with an increasing use of the nominal language (Dodman, Camino and Barbiero 2008). This type of language allows for the expression of thoughts with high conceptual density by means of a few, selected words (Halliday 2004) but often the connections between such words and their origin or context may not be apparent.

Arguably, it is the increasing gap between the two languages that led to the anthropologists' and sociologists' formulations of *thin* and *thick* descriptions and their different representations in society; one being the abstract, scientific one, and the other one being the culturally embedded human experiences (Jasanoff 2010). An interesting example is the word wetland as opposed to the word swamp that may be more commonly used. One is focussed on the idea of water while the other retains also other connotations such as the intricacy and richness of a swamp area that may trigger images and bodily sensations.

From an educational point of view, to be able to use both languages, recognising their advantages and limitations, is a precious competence (Yore 2008). As reported by Pauline Chinn et al. (2008), "Doing science and building knowledge about nature and naturally occurring events are fundamental to knowing how to facilitate learning about these same ideas; the verb and the noun are intimately connected in the informal and formal learning environments" (p. 155).

Western ways of seeing the world

Throughout the history of Western philosophical thought, the epistemologies and methodologies which have been a long-standing hallmark of our society can be broadly described in terms of three main mental perspectives, which philosophers and scholars have used when looking at the natural world: characteristics, relationships and transformations.

With the notion of characteristics we refer to the distinctive signs through which we can recognise, identify and compare particular objects. Conversely, when thinking about relationships we adopt a way of looking at reality concerned with understanding the

[1] A *thingified* view of the world is currently exacerbated by the loss of nature and experiences of nature in concurrence with a transmissive mode of teaching. It is associated with a sense of exclusion from processes and events to which we are connected and a sense of alienation from topics and problems proposed in the classroom (Désautels and Larochelle 1998).

connections that exist between objects. Finally, when focusing on transformations we direct our attention to the manifestation—over time—of both characteristics and relationships and the changes that occur. A reflection on the elements that structure our ways of thinking and representing reality can be a useful strategy for uncovering similarities between the variously specialised types of knowledge: the *core themes* of every discipline display an association with each one of these three ways of seeing (*characteristics, relationships* and *transformations*). With regard to the study of the natural systems, it is possible to find such perspectives represented in the different *methodological approaches* developed by specific fields of inquiry:

- the *morphological approach* is concerned with the description of forms and structures (*characteristics);* it has been widely adopted by the earth sciences but also for the definition of every living species as *different* and unique, while at the same time recognising the similarities characterising life as a whole;
- the *functional approach* traditionally deals with the processes and dynamic functions characterising the living forms and the conservation of their identity; more generally, a functional view is used to describe the flows of materials and energy throughout a system (living and non living) at different scales;
- the *temporal or historical approach* considers the time span of each transformation, from the micro to the macro scale;
- the *systemic approach* has the task of bringing forth the web of relationships between living and non living forms, shedding light on a hierarchically organised system in which every part is both a whole and a component of a wider system.

Relationships are of crucial importance, for they give both form and meaning to the whole: panarchy (according to Lance Gunderson and Christopher Holling [2002]) and Gaia (according to Volk [1998]).

Every approach is in turn associated with one or more privileged perspectives. In the morphological approach we can recognise an emphasis on characteristics and relationships. The functional and historical approaches are particularly focussed on transformations with different perspectives: time concurrency (synchronic perspective) and time sequence (diachronic perspective). The systemic approach supports a view of dynamic interdependency between characteristics, relationships and transformations (Kay and Schneider 1994).

Epistemological and methodological frameworks: shifting between conservation and flexibility

Tom Bryce (2010) has eloquently reiterated the dilemma that still exists for educators, of being confronted by the "evident strains that exist between teaching approaches which emphasise content (in the conventional sense) and those which try to tackle the contextual complexities" (p. 592). Such duality one may argue is characteristic of scientific knowledge. At the one end, the epistemological body of knowledge of any discipline contains the basis of the discipline itself (expressed with a preferential choice for nominal language) and in the form that is temporarily accepted by the scientific community of the time. At the other end, the methodological framework provides a variety of practices, tools, techniques that are deployed for the exploration of new fields of knowledge. The two ends of the polarity interact with each other and the development of any scientific discipline is made possible thanks to the continuous shuttling between the two.

From an educational point of view, the shift from and to the epistemological and methodological frameworks can be seen from two, very different standpoints. One is the *paradigm of certainty* that describes science as a *building*, a *baggage* or *body* of knowledge

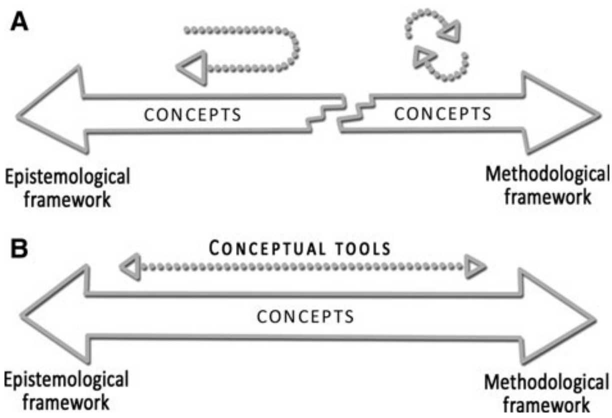

Fig. 1 **a** Fragmented perception of the two polarities of science: products and processes. **b** Restored links between epistemological and methodological polarities of scientific knowledge

that is progressively enriched of new elements provided by the single, specialised disciplines operating through new empirical trials. The teacher adopting this perspective tends to proceeds by means of definitions and consolidated notions to be acquired (epistemological framework), while laboratory and fieldwork (methodological framework) is used to demonstrate and confirm what has already been established. By presenting the consolidated knowledge and the method in an alternative and separate manner (first the facts, then the empirical demonstrations), the idea of science as universal, objective truth is notably reinforced. Students are not encouraged to move along the continuum between the two polarities (Fig. 1a), neither are they enabled to reflect on the processes of thought that occur when they are acquiring new knowledge. Their knowledge is often construed and categorised as divergent from the established scientific view but it is also disconnected from it for alternative conceptions arise and are maintained in the course of their lives.

Alternatively, the teacher can facilitate the shifts between epistemology and methodology by referring to the *paradigm of flux* (Fig. 1b). In this way, aspects of flexibility and the provisional nature of both frameworks are emphasised. Students are encouraged to shuttle between epistemology and methodology and to reflect on the ways in which concepts are modified to gradually disclose new and different interpretations of reality. *Crystallised concepts* (Ostergaard et al. 2008) are useful to provisionally describe the established knowledge, but the same concepts can become powerful tools for the exploration of new ideas; in this way, they can take on new meanings, lead onto new definitions and suggest new questions. As discussed in the first part, Larson (2011) identified metaphors in science that can be used at a gestalt level to stimulate thinking along new paths and thus reframing original questions and boundaries.

From concepts to conceptual tools

From an original epistemological position in which a concept benefits from a well-established definition within a specific disciplinary realm, it is possible to move towards a situation of meaning-making by shifting the same concept along the axis towards the methodological side. During this journey, concepts can change status and functions, to become *conceptual tool* for the exploration of other disciplines, operating at different time-scales and/or organisational levels. During the course of our research and educational practice we have identified two typologies of concepts, which are particularly suited to becoming *conceptual tools.* Some concepts originated from specific disciplines (e.g. the concept of *cell*), others were of more general nature, widely used in everyday communication and in a variety of contexts (e.g. the concept of *boundary*), and for such reasons we have referred to them as meta-disciplinary concepts.

Disciplinary concepts

One example is the concept of ecosystem, which was codified through a definition specifying its characteristics within the particular field of ecology (Tansley 1935),[2] but the concept of ecosystem can be used also for investigating certain properties of the cells, the human body or the biosphere.

Other concepts that proved useful as conceptual tools are, for example, the concepts of organism (Hölldobler and Wilson 1997) and metabolism. When applied to the entire planet (Margulis 1998), the concept of organism can be used to introduce the idea of Gaia (Lovelock 1987). The concept of metabolism has been adopted in recent years by the social and economic sciences to express the complex relationships that exist between human activities and natural systems' functioning (Giampietro, Mayumi and Martinez-Alier 2000).

A concept used outside its original field becomes a powerful tool (Fischer-Kowalski and Amann 2001) for constructing new concepts. Such process makes it apparent that there is no real coincidence between concepts and reality, avoiding the risk of thingifying nature (Désautels and Larochelle 1998), while at the same time encouraging students to make creative use of concepts, by applying them in new realms or inventing new ones and assessing their efficacy.

Meta-disciplinary concepts

As we mentioned before, there is another set of concepts which we have tested over the years as part of our practice. These are concepts of general and familiar use, as boundary, system, cycle, flow, etc. Many of them are metaphors that have become such integral part of our language that their original nature is no longer perceived. For example, the notion of *boundary* can be applied at many scales and can be alternatively used to either indicate a barrier, a divide, or an edge across which exchanges can happen. We can introduce students to reflect on cell boundaries, the boundaries of an ecosystem or (as we will describe later) the boundaries of a gene. Moreover, the process of thinking about the nature of boundaries is a way to tap into the morphological but also functional and systemic approaches, helping us to find the relationships between the three different ways of seeing and thinking about reality (this point will be exemplified later in Part 3 dealing with specific educational activities).

Another example refers to the concept of energy that in science teaching is often associated and dealt with as part of Physics. How to unchain its meaning from the static,

[2] In its original definition, an ecosystem is the entire set of biotic and abiotic components and their relationships found in a given area. An ecosystem is a dynamic and complex whole, a functional unit in stationary state, characterised by flows of matter and energy between its constitutive elements (Tansley 1935).

disciplinary definition of "the capacity of a physical system to perform work"? Thinking in terms of *flows of energy* can help us to move along the polarity between epistemology and methodology, and to overcome disciplinary boundaries: flows of energy can be revealed between cellular structures, between the inside and the outside of a cell, between organism and environment, along the edges of the tectonic plates, between the Sun and the Earth. Furthermore, they can be expressed with different scales and units, from electron Volts, to Calories and Joules. Investigating phenomena by means of this conceptual tool we can reason at different scales, consider the processes and phenomena connecting life with the non living world, and integrate not only different approaches within Natural Sciences, but also Natural Sciences with Physics Chemistry, Technology along interdisciplinary paths.

Some of such concepts can be paired to express complementary, non-mutually exclusive polarities: micro–macro, continuous–discrete, linear–cyclical, static–dynamic, process–product and so on. Such way of moving our thinking between two poles can help to acquire more flexibility in organising thought, and to overcome the hierarchical dualism which features strongly in reductionist thinking—i.e. yes or no, right or wrong, black or white, etc. (Sterling 2001).

Using conceptual tools to promote integration

Drawing on the notion that each science discipline is the result of the application of specific conceptual approaches, each one bringing a particular view on the interpretation of reality, we have drawn the diagram represented in Fig. 2 below.

Our working hypothesis is that if we keep all such approaches separate and we teach the single disciplines, we promote a fragmented view of reality, we reinforce the idea of science as an objective, certain and indisputable description of reality and we contribute to develop a sense of detachment and alienation amongst ourselves and from the natural systems. This hypothesis finds supporters from many realms of literature, both from the fields of environmental education (Tomashow 1996) and sustainability education who are pleading for the development of an integrated vision that promotes a sense of reconnection "of people with their own origins" (Bonnett 2006, p. 271). In addition, the integration at

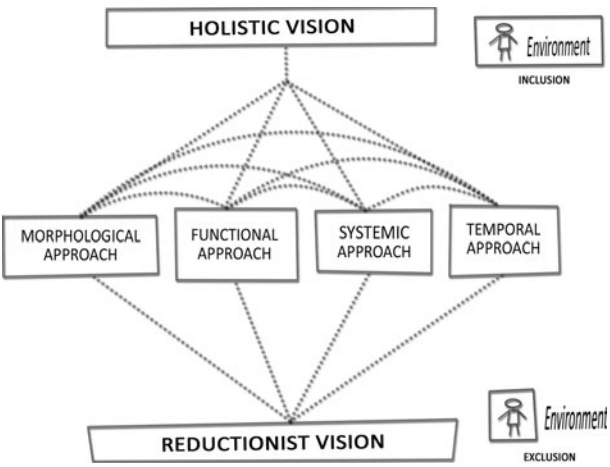

Fig. 2 Integrating disciplinary views may contribute to reconnect with and to feel included in nature

school of the different disciplinary approaches was indicated as the crucial element for dealing with "the interdisciplinary nature of problems in the twenty-first century" (Chamany et al. 2008).

In practical terms, any and each theme in the Natural Sciences realm can be explored through a multiplicity of approaches, and by means of a conscious use of language and conceptual tools, in order to offer a complex, variegated and connected picture of each portion of reality under study. Pillars of such holistic vision are:

- meta-reflective competences: by unchaining concepts from their rigid frameworks, it become easy to highlight the difference between ideas and reality and to stimulate a reflection on one's own ways of thinking. Meta-reflective competences are associated with the development of a fluid type of knowledge, where processes and products, epistemological and methodological frameworks are equally balanced;
- inter and trans-disciplinary knowledge, that derives from the possibility to use conceptual tools to relate the single approaches with one another, recomposing the different disciplinary lenses and connecting them as part of a complex whole. Figure 3 illustrates the potentialities of some conceptual tools for connecting together the different approaches.

Conceptual tools, complexity and education for sustainability

Many of the concepts that we have identified and used as conceptual tools have been recognised as structuring concepts in the field of research in didactics (Giordan et al. 1994). They can also be reconnected to Jeff Bloom and Tyler Volk's (2007) *meta-patterns*. According to these authors, meta-patterns can be used in learning and teaching to promote understanding of systems on a number of different scales and thus to make connections between such scales. A similar idea has been proposed by Walter Reid, Fikret Berkes,Thomas Wilbanks and Doris Capistrano (2006) in relation to establishing connections between different systems of knowledge. Other similarities can be found with Fritjof Capra's (2002) core concepts, referring to webs, nested systems, cycles, dynamic equilibrium, Bateson's idea of mind ecology (Bateson 1972) and Stephen Sterling's (2009) notion of holistic thinking.

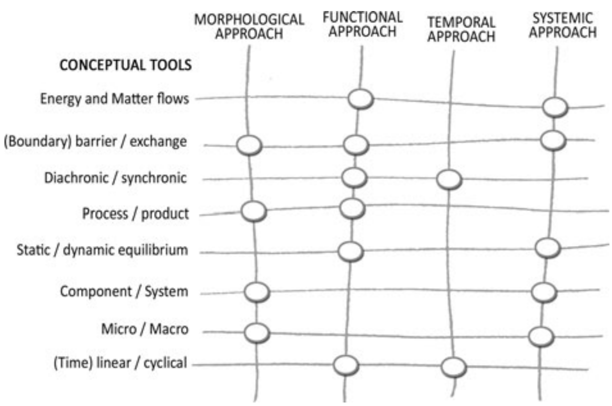

Fig. 3 Conceptual tools help to integrate the different approaches

Making concepts fluid, thinking in terms of polarities, using conceptual tools and connecting different approaches are all strategies for interpretation and internalisation of the notion of complexity. In one sense, we are talking about the complexity of the natural systems (of which we are part) and that requires new ways of thinking. In another sense, we are referring to the complexity of our minds, striving to increase awareness of our own ways of thinking and modes of expression, by means of a more fluid and creative use of the extraordinary power of language, endeavouring to use words not only as constraining heritage but also as energising horizons (Dodman 2007). The notion of complexity and its translation into language processes have profound implications for educational research and practice. It opens the way for a notion of participatory research and learning whereby dialogue and deliberation—in ongoing meaning-making processes—are essential mechanisms for the production of knowledge and awareness of its purposes.

In the following part 3 we address the methodological foundations of research and practice in science education contexts working from a sustainability view.

Part 3. Learning and teaching processes within a dialogical and reflective context: some examples of courses and activities

Context

Over the past 10 years, we have developed a series of educational activities aimed at the integration of the different disciplinary realms of the Natural Sciences and promoting the development of a more fluid form of knowing, open to self-reflection and dialogue. The approach of joint working adopted by the group has been informed on the one hand by the philosophical perspective of complexity in the biological sciences and its critical stance towards the organisation and production of knowledge in science and society. On the other hand, the epistemological reflection has been enriched by the perspective of social constructivism and participatory action-research as a means for bringing science education closer to issues of personal and societal relevance.

Our work developed within a variety of learning and teaching contexts, leading to the production and delivery of a range of courses at the university level, including undergraduate courses in Natural Sciences and teacher education. In particular, here we focus on examples of practice taken from initial teacher education courses for both primary and secondary teachers and offered in the 2000/01 and 2008/09 academic years. In both primary and secondary contexts however the same methodology applied to provide a form of multi-case methodology amenable to the exploration of the use of conceptual tools in science education.

The discussion of the activities and the concluding section will thus focus on the interlinking of different dimensions of the theoretical framework as part of a global view, to illustrate the multi-faceted process of translating the epistemological basis of sustainability science into the educational practice.

The practice and objectives of action-research

A combination of teaching and learning strategies eliciting the sharing of ideas in a context of participatory action-research characterises all courses and each stage of the learning and teaching process (McNiff, Lomax and Whitehead 1996). This way of working allows for a collection of large amounts of data on classroom activity. Most importantly, however, data becomes meaningful as part of a process through which the teacher can be tuned in with his/her own practice and outcomes by means of continuous reflection: "The study of oneself and teachers' educational practices is a complementary research approach which can enhance the reflexive component of action research" (Kitchen and Stevens 2008, p. 4). It is a common form of professional action which has the aim of improving the level of coherence of one's own practice by incorporating monitoring of students' development within an ongoing verification of the formative opportunities that are being offered (McNiff, Lomax and Whitehead 1996).

In particular, by means of the process of action-research, there is an opportunity to produce ongoing feed-backs on the ideas and conceptions that are being expressed, thus making it possible to establish and sustain dialogue between teacher and students and amongst the students themselves (Kemmis 2006). Hence, a particular focus of interest in our case is the quality of the dialogical space. Our attention is devoted to devising educational spaces allowing students to express themselves in a comfortable manner, safely sharing ideas with each other and dealing with the discussion of new concepts, thus making them fluid and deconstructing the existing ones (Goodnough 2003). This is a perspective of participation and emancipation in science and technology related issues (Seiler and Abraham 2009) involving people—in these case prospective teachers—in their different roles and capacities, at the professional, personal and political levels (Noffke 2009). Drawing on one's own experience in the training courses, beginning teachers may feel more comfortable in embarking in the attractive yet somehow fearful enterprise of sustainable education: "The notion of meaning and relevance does not lie just in the conceptual or thematic material itself, but in a context in which there is an interplay between the thematic material, the notions of ownership, and the atmosphere that supports discourse" (Bloom and Volk 2007, p. 63). In practice, the process of action-research leading to the development and implementation of the activities during the course is made of a series of steps involving participants at different times and in different roles, as explained below.

The first step in the process is a planning moment—usually consisting of an activity performed by the members of the research group—which is reframed each year according to previous experiences. In the planning stages, the teacher-researchers share critical reflections about the scientific content of a news or academic article, discussing the cultural framings carried by language, possible misconceptions that may be encountered in the process of understanding the content and the main disciplinary approaches guiding the presentation and assimilation of content.

The planning moment is followed by the drafting of educational activities that are proposed to the students to elicit their knowledge and interpretations. For example, students are asked to answer open questions or questionnaires, make drawings or enter into dialogues with and amongst other participants. Data collected in this form is elaborated and then feed-back to the students in the ensuing sessions, in order to introduce emerging patterns or frames of thinking which are helpful to guide the discussion, unravel misconceptions and inform the development of the topic, introducing interdisciplinary connections. By such means, data are also further analysed and discussed with the participants themselves. This moment usually leads to further deepening of the topic, clarification of doubts and integration of new elements of reflection.

Finally, other data is collected through end of course reflective essays, requiring participants to produce personal accounts on how they approached the themes and the activities of the course. Information from the essay is used to evaluate the course from the point of view of the opportunities given to participants to reflect on their knowledge and ways of learning. One of the objectives of data collection is therefore that of using data as feed-back, to enrich and support the constructive process of restructuring and integration of knowledge an further planning of the course.

Participants and contexts

Each course is attended each year by people with different levels of academic competence and personal motives. Starting from a general draft plan elaborated by the lecturer, the dynamic, open and dialogical features of the activities imply that each course becomes an experience that is by its very nature unique for the particular attendants. Such uniqueness is dependent upon the level of dialogue that is being established, and courses with lesser numbers of students are more amenable to this practice.

The teaching and learning activities described in the following pages refer to four different courses, located respectively within the Undergraduate Programme for Primary Education (course A1) and the Postgraduate Programme for Secondary Teaching (three courses, indicated here as B1, B2, B3). The two programmes account for some important distinctions with regard to participants' prior levels of scientific knowledge, maturity and expectations. In addition, differences in institutional organisation allowed for pragmatic differences in terms of size and length of courses. All courses however were developed by the members of the group by focussing on a particular aspect of disciplinary and inter-disciplinary nature, drawing on a selection of core concepts in the Natural Sciences such as cell, organism, ecosystem, gene and evolution and adopting a shared methodological approach. A brief overview of the different contexts is provided in Table 1 below.

At the end of every teaching and research unit, the data collected is heterogeneous and varied with regard to number of responses and methods used. Through the application of qualitative (Silvermann 2000) and mixed-method (Cresswell 1998) research

Table 1 Overview of teaching and learning contexts

Programme and courses	Focus	Type of knowledge environment
Didactics of the life sciences (A1)	Learning of core concepts in biology by shifting from a disciplinary, analytical view to a systemic and complex view of living things	Disciplinary
Core concepts in biology (B1)	Deconstruction and reconstruction of core concepts (e.g. gene, ecosystem) to open boundaries and transform concepts into conceptual tools	Interdisciplinary within the biological sciences
Flows of energy and matter cycles (B2)	Energy as a conceptual tool for understanding global, socio-ecological issues	Interdisciplinary, across different disciplines in the natural and social sciences
Evolution (B3)	Evolution as a scientific concept that allows for an appreciation of uncertainty, unpredictability and creativity of natural systems and the implicit values embedded in language	Inter and trans-disciplinary. When evolution is understood personally as a process that transcends the individual, there is a possibility to enter in contact with uncertainty and humility as a necessary attitude to knowledge

methodologies it is possible to obtain results that are meaningful and sometimes statistically significant.

So, a first and important aim of gathering perceptions from course participants and include them as part of the research process is not simply to evaluate their knowledge by taking a position from the outside. Rather our attention is placed upon our prospective science teachers' prior knowledge and epistemic content (Quale 2002) and the opportunities offered by the learning environment to uncover discourses about nature, worldviews and to engage with ethical considerations. As mentioned before, data have been collected through a variety of linguistic mediums: drawings, written texts, verbal exchanges and posters. In our methodological framework, such data is used to inform participants' understanding of concepts while introducing a meta-cognitive dimension allowing for considerations about the learning process and its different dimensions: the epistemological level (the nature of science), the methodological level (with particular attention to the variety of languages used) and the ethical level (the quality of interaction between oneself, other people, other living beings). Hence, the aim is not simply that of identifying misconceptions and the degree of accuracy of participants' knowledge with respect to consolidated scientific knowledge, but to organise knowledge according to a framework of emergent complexity and understanding. We are at pains to stress that in this particular paper our concern is to give an overview of the methodological approach by looking across contexts to identify the features of the learning process. By no means have we provided a detailed analysis of knowledge construction processes although this point is discussed in the conclusions and addressed elsewhere (e.g. Colucci-Gray et al. 2010).

The role of the teacher-researcher

The notion of dialogue and participation in learning has important implications regarding the role of the researchers and the management of data. While the action-research activity is located within an experience that is continuous and ongoing, data is by its very nature extracted and isolated as information that can be used to capture moments of this experience, defined in space and time. They can be defined as snapshots of the process of learning and teaching unfolding at a micro-scale, and are linked to cultural processes occurring at a macro-scale (Bloom and Volk 2007), although not in themselves wholly representatives of those. It would thus be inappropriate to extrapolate the general from the situated particular, and this has been a recurrent issue in the discussions surrounding validity and generalisation in action-research (Sumara and Davis 2009).

In such conditions, the traditional role of the teacher-researcher in handling data needs to take account of:

- the participatory nature of the teaching/learning process implying that what is constituted as data is part of an interconnected set of meanings. The researchers in this regard are also teachers, co-learners and actors in the process of meaning-making, aware of their knowledge being partial and subjected to change (Goodnough 2003).
- the creativity of the process: each course and workshop produces new cognitive and relational dynamics, that confine the possibility for confirmation/triangulation (the dilemma of emergence as described by Osberg and Biesta 2007) to contextual aspects.

The process of systematically sharing and discussing with participants not only the data collected, but also the criteria used to organize and classify such data, reduces the risk of super-imposing the teacher-researcher's view. In such a way each issue is presented, discussed, enriched with participants' ideas and conceptions, integrated with inputs drawn from both the disciplinary and educational literature, and finally reviewed in a plenary discussion inviting the expression of multiple and complementary visions and allowing for connections to be made between the different themes and/or perspectives. This is also the methodological choice supporting the presentation of the data later in this section and supports the core idea of a standpoint epistemology that rejects singular narratives to encourage criticality and creativity.

Training courses for primary teachers

The Bachelor of Education programme at Turin University is attended by a large number of students. The number of first year students has progressively increased from a cohort of 30–40 students in 1998 to 571 students in 2008. In many cases, enrolling students often hold very limited knowledge of science (which is assessed through formative opportunities throughout the course), and the structure of the degree is such that over a period of 5 years, there are only three courses (two in the first year and one in the final year) dedicated to science learning and associated preparation to teach science in school. This requires science lecturers to strike a difficult balance between the students' need for basic, disciplinary knowledge and the professional aspects related to using such knowledge appropriately in the primary classroom.

The course of Didactics of Life Sciences (Didattica di Scienze della Vita) (A1)

This course is offered in first year and it is attended by approximately 150 students. With such a large number of students, it is difficult to put into practice learning and teaching approach that is fully interactive, that is, enabling participation and exchanges in a two-way communication process. So the delivery of plenary lectures is by necessity the mode of teaching that is being adopted. Besides, the limited time allocated to science teaching requires making fundamental choices related to course content. One of the goals of this course therefore is that of addressing some of the gaps in students' disciplinary knowledge yet highlighting the educational learning potential (as it was described earlier) of continuously shifting between process and product, verbs and nouns, objects and things (Ingold 2010). In other words, concepts are presented more as tools rather than notions to recover the role of personal interpretation and to allow for conceptual organisation. Content includes unifying and structuring concepts which can be used to interpret and correlate objects, events and processes, bringing together different time and space scales, and from different points of view (Perazzone 2004). In essence, it is a matter of recovering some of the core ideas in Biology, promoting a reflective attitude and organizing concepts within a complex and flexible conceptual web, which can be useful in different situations (Fig. 4).

Within the limitation of the delivery mode, students are stimulated to get involved in a variety of occasions. During the 30 h allocated to the course, we propose brainstorming activities (as it will be shown later with an example) and we encourage students to engage with open questions. In addition, each year we set the students to carry out five, self-directed activities, either individually or in small groups (van Meter and Stevens 2000). The material produced is collected by the teacher-researcher and returned in the following sessions with the aim of generating discussion and reflection on one's own personal conceptions and the factors that sometimes are responsible for turning scientific knowledge into a scholastic object rather than a tool that can be used for understanding oneself and the world (Lewis and Leach 2006). The specific examples reported in the following pages refer to activities dealing with the concepts of organism and cell.

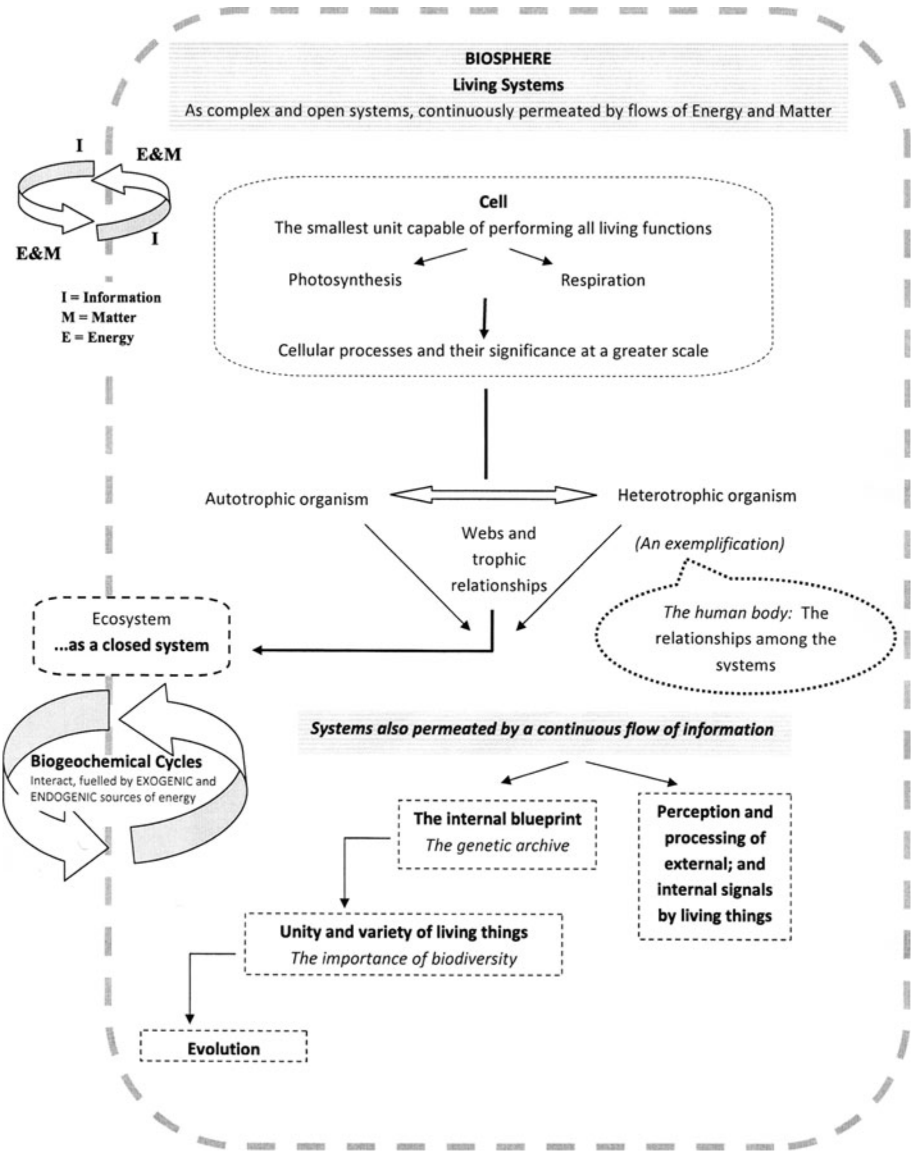

Fig. 4 Integrated overview of the main topics covered in the course of Didactics of Life Sciences. Image modified from Angelotti et al. (2009)

The concept of ORGANISM: from the functional definition to a systemic approach

The concept of organism is in appearance a simple one to grasp as it corresponds to a reality with clearly identifiable structural *boundaries*. This characteristic however is both an advantage and a disadvantage. While we can focus our attention on something that is well defined, we also tend to concentrate on what is on the inside, contained within the boundaries, overlooking the context to which it belongs and thus attributing the organism a

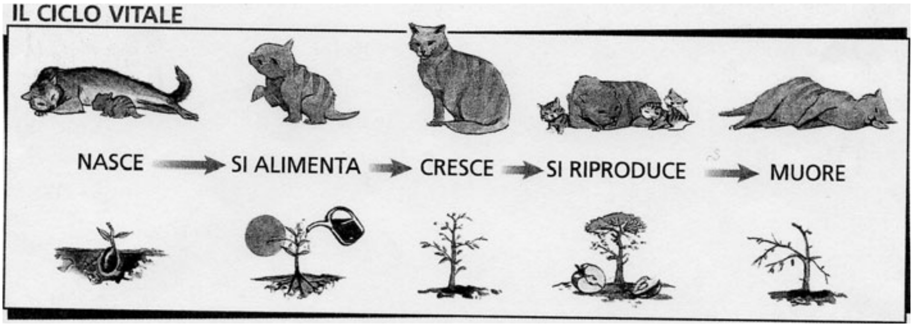

Fig. 5 Pictorial representation of the 'life cycle' of a living organism, extracted from an Italian textbook for primary schools. (English translation: 'The life cycle': it is born; it feeds; it grows; it reproduces itself; it dies)

presumed independence from the rest of the system. This way of thinking often leads to the definition of a living entity as a reality with particular functions (functional approach), overlooking the necessity for this reality to interact with the context (systemic approach). Primary school textbooks as well as many first year primary teachers—holding what is a typically scholastic type of knowledge—define living things by listing a series of actions, that are disconnected from one another, but which are considered to be essential to its functioning (Fig. 5). Furthermore, there is usually no distinction between basic, metabolic functions (feeding, breathing…) and the ones connected to the life cycle (birth, growth, reproduction…). If asked the question "yes… but why do living beings breath?" the answer of many students is predictably: "in order to live!" The living state of an organism is taken as an explanation per se, without the need for further explanations. While this conception is common in everyday talking about living organisms, it is also associated to a lack of a coherent and structured organisation of biological knowledge (Howe 1996). Surely the textbooks written for the upper stages provide more extended conceptions of living things; nevertheless it is the functional definition that is best memorised and remembered and possibly the one that is considered to be essential knowledge in the textbooks and consequently by beginning teachers who will use it with their pupils.

The limitations of the functional approach are evident. However, what can we do to move forward? How can we stimulate students to re-adjust their conceptions so that the concept of organism can become a basic concept upon which to build further knowledge in biology? By means of a simple brainstorming on the concept of living thing, students usually manage to provide a list of functions that are common to all living organisms. The list often contains also a few structural elements, such as the cell or the organic matter composition. It is towards the end of the activity that students mention a property that is generally less well defined and has to do with the response to stimuli from the external environment. This is the starting point for further reflection on one of the essential properties of all living organisms as autopoietic open systems (Maturana and Varela 1987), operating with continuous exchanges of matter, energy and information with the environment in order to maintain their organisation. If all students become aware that there is no reaction, no behaviour and no movement without the presence of a stimulus from the outside environment, it is easier to get them to reflect on the fact that all metabolic functions are determined by an energy/matter flow entering the organism from the external environment and exiting it transformed. By applying the conceptual tools of *system* and *energy/matter flows*, all functions that were previously listed can be essentially subsumed within two main common necessities for all living things (Arcà 1992):

1. to extract, transform and use matter and energy from the environment according to the individuals' own life projects (these are *flows of energy and matter* connected to the functions of breathing and feeding);
2. to perceive and elaborate information from the environment and to respond/behave accordingly (*flows of energy and matter* connected to sensorial perception and movement).

From a systems' perspective, the boundaries of our object of study can thus appear less well defined; in other words, by playing on the two polarities, we can move from the idea of boundary intended as a structural barrier for exclusion to the idea of boundary as a dynamic interface playing a relational function.

This approach can be used as early as primary education, because it does not rely on the acquisition of specialist notions and it offers the advantage of helping pupils to build a model of living organism that is not only more commensurate with scientific ideas but also helpful for making connections with other realms of biological knowledge: from the functioning of a plant or the human body, to the process of adaptation to the ecosystems' internal relationships (Gagliardi 1989). This of course may require stimulating pupils' reflections and thinking beyond the simple memorization of the textbook's definition.

At the end of the course, students are asked for some written considerations about particular aspects of the course, both in terms of content and the methodology used. In relation to the question "Which topics of the course were of particular interest to you? Indicate your reasons", several answers related to the concept of living organism. Students' comments included elements of appreciation but their answers are also indicative of the development of students' epistemic content, and particularly their level of methodological awareness with regard to the organisation and re-structuring of their knowledge (Howe 1996):

a. "Living things, because they were dealt with by a new approach, different from textbooks; I liked the way of looking at things from a systemic perspective" (2007/08);
b. "The approach to living things was nice, I liked the way the reflection was set up… stimulating and interesting" (2007/08).
c. "Living and non-living things and the cell. Topics were dealt with from many different points of view helping us to grasp the different relationships established between living organisms and their environment and the way in which they are made" (2007/08).

In other cases, the level of appreciation suggests that while the course was focussed on disciplinary aspects, students enjoyed making links across disciplines:

a. "The coverage of living things because it provided a more complete idea, less compartmentalised as compared to my previous course of study" (2006/07).

So, at the end of the course students are able to refer to a systemic perspective as an organiser of biological knowledge. They clearly identified the contribution given by lecturer but they also appear to be able to articulate the value of a change of perspective for approaching knowledge in a more meaningful manner. While no claims can be made about the resistance or depth of such understanding, we can suggest that within the limitations of the course it was possible to bring together content knowledge and meta-reflection on one's own way of knowing, enhancing students' own affiliation and confidence with the subject matter (Shallcross et al. 2002).

The concept of CELL: from a component of the organism to a system penetrated by flows of matter and energy. From a structural point of view, all living beings are made by one or more cells and the cell is reasonably considered a component of the organism. The organism however is organised according to hierarchical system levels, from *micro* to *macro*. While the cell can be perceived as a self-contained unit, its characteristics and functions are dependent upon the exchanges of energy and matters occurring both at the levels above and below (Gagliardi et al. 1993). By means of two powerful conceptual tools—*micro/macro*, *component/system*—we can move from the concept of organism to the cellular level and vice versa, thus making explicit the cognitive difficulty of managing

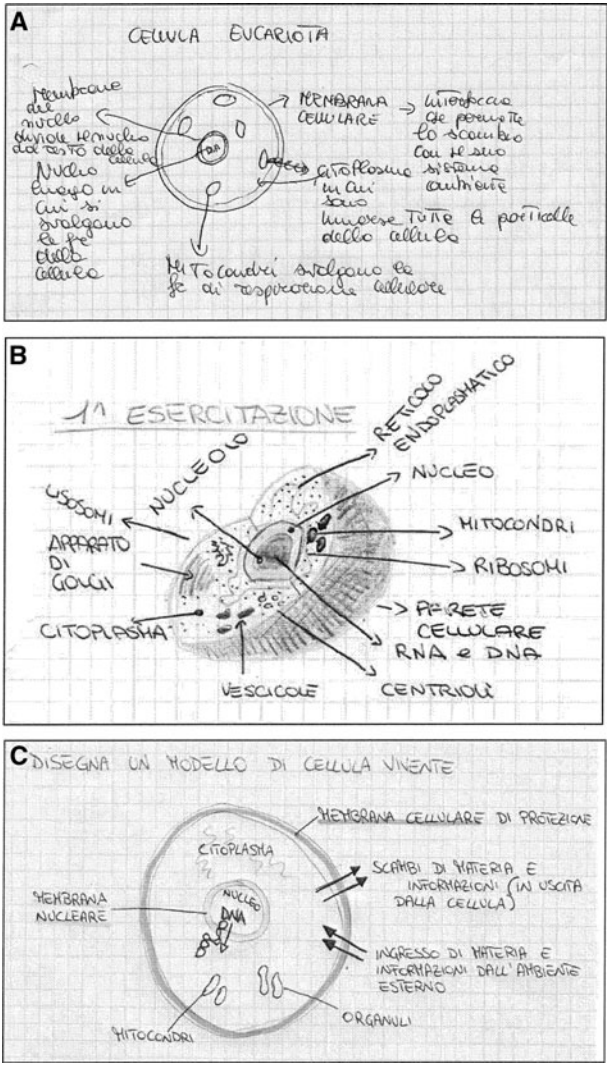

Fig. 6 **a** Drawing of a model of the cell detailing the single components. **b** Drawing of a model of the cell emphasising a structural approach. **c** Drawing of a model of the cell featuring names of components and associated functions (i.e. cell membrane for protection)

changes of dimensional scales–a constant feature in the study of biology (Arcà 1993) and in the sciences more generally (Scott et al. 2011).

If we start to inquire into students' knowledge of the cell by means of a simple drawing task ("represent the model of a living cell"), we find that their knowledge is strongly bounded by the *structural approach.* Every year, about 70% of the students' drawings focus on a structural model. In some cases we recognise meticulous reporting of the names of many cellular parts and also their structures appear to be remembered in detail (Fig. 6a, b).

The other 30% of drawings tend to integrate the names of the structural components with a function label, although often without trying to express the integration between the different components. Only 3% of the students feel the need to represent the cell as part of a context/environment and 2% is able to identify the membrane as a boundary and exchange surface, thus making the cell a relational as well as a functional and structural unit of living systems (Fig. 6c).

Sharing our collective observations about the drawings is the starting point in the learning process. A key element in this process is to give relevance to everybody's contributions; any linguistic expression by definition becomes intelligible through the limitations of a given frame (Wittgenstein 1961), hence whenever we are asked to make a representation we are bound to make a choice, shaped by conceptual and pragmatic reasons. In this view, the use of the structural approach is an immediate and by all means a legitimate choice. The learning opportunity will then be provided by the reflection on the limitations of the prevailing model, by relating it back to what was discussed previously about the concept of organism. At this point, structural and functional approaches can be integrated with the systemic one. More specifically, the link is introduced by means of the concept of *system*, by showing that within a hierarchically organised system, the cell is both a component of the system and a system in itself. As a living entity, every cell is in interaction with the environment and the functions of single organelles carefully labelled by the students are involved in the energy and matter flows occurring across their boundaries, allowing the cell to perform its activities and to reproduce itself.

In the comments gathered at the end of the course we can find some general observations about students' ability to grasp conceptual unity in biology, with some emotional connotations:

a. "I have particularly appreciated the overall aim of presenting an organic view of life. In the past, I received information in solid compartments which prevented me from seeing the big picture" (2008/09).

An emotional dimension also appears which is intra-psychological and related to personal motivation to learn:

b. "I have gained a new interest for the subject" (2006/07).
c. "as well as inter-psychological, pointing to a sense of connection with the world out there and inclusion of oneself within it."
d. "I have managed to connect together old knowledge which did not make much sense to me. [The course] has triggered a sense of wonder towards the living world and its relationships with the environment. For the first time in many years I have developed a holistic view where all the bits I learned are joined up together. I had the impression of being able to gaze at the world around it and embrace it as a whole…. with a growing feeling of marvel" (2006/07).
e. "I have really appreciated the different way of doing sciences, because this is what I believe we have to teach the children and not a list of names" (2007/08).

Students' comments appear to suggest that a change of thinking patterns has occurred, with connections being established between the learning of disciplinary scientific concepts and the grasping of a worldview (quote c), and such learning is bringing psychological, emotional and ethical connotations (Goodwin 2007). Such findings are in line with the theoretical framework of trans-disciplinarity offered by Thompson-Klein (2004) in which scientific knowledge is contextualised within a broader scenario of knowledge, values and emotions. In this way, the course provides students with the preliminary, basic competences for entering a scenario of participation with nature and dialogue with other ways of knowing.

Training courses for prospective secondary school science teachers

The observations and data reported here stem from activities we conducted as part of courses and workshops for prospective teachers of mathematics and science in the lower and upper secondary school[3] and enrolled in the 2 year post-graduate teaching diploma at the University of Turin. All courses are attended by a maximum of 20 students and are characterised by the use of an interactive methodology throughout (e.g. work in small group on given tasks; reflective questions followed by peer and plenary discussions; answering of open questions and exchanges of views with peers). Participants attending courses for the lower secondary constitute a multi-disciplinary audience of math, physics, and chemistry and biology graduates. Hence, the majority of students in these courses tend to have a partial preparation for teaching general science in school. Often in this context, the awareness of one's lack of knowledge seems to be present as a condition shaping the learning climate in the class: students appear are naturally inclined towards engaging with students from other disciplines and they are keen on being part of a collaborative process.

Conversely, in the group of graduate students preparing for the upper stages the basic knowledge competences are well established: all participants hold a first degree in general science and science-related subject or a doctorate on a specific subject. With this group of students, who are holding a much specialised (and sometimes 'crystallised') knowledge, the task of making knowledge fluid is perhaps more difficult, as they are resistant to discuss their body of consolidated knowledge (Zoller and Scholz 2004).

All courses and workshops have the purpose of involving student teachers in testing strategies and suggestions for teaching/learning activities they can bring to the classroom, and stemming from the theoretical premises introduced previously about the use of common concepts as conceptual tools: the purpose is once again that of making scientific knowledge fluid and integrating the different approaches elaborated by the Natural Sciences within a climate of communal exploration.

An overall view

More specifically, the data to which we refer here are drawn from two courses (*Didactics of Life Sciences*—respectively for lower and upper secondary school science teachers) and three workshops: Core Concepts in Life Sciences (for higher secondary school teachers); Energy Flows and Matter Transformations (for lower secondary school teachers) and

[3] In Italy, the two different levels of schooling are catered by two classes of teaching: A059 prepares for teaching in lower secondary school (12–15 years old) and it includes teaching of mathematics and science; A060 prepares for teaching in the upper secondary (15–19 years old) with specialization in the Natural Sciences.

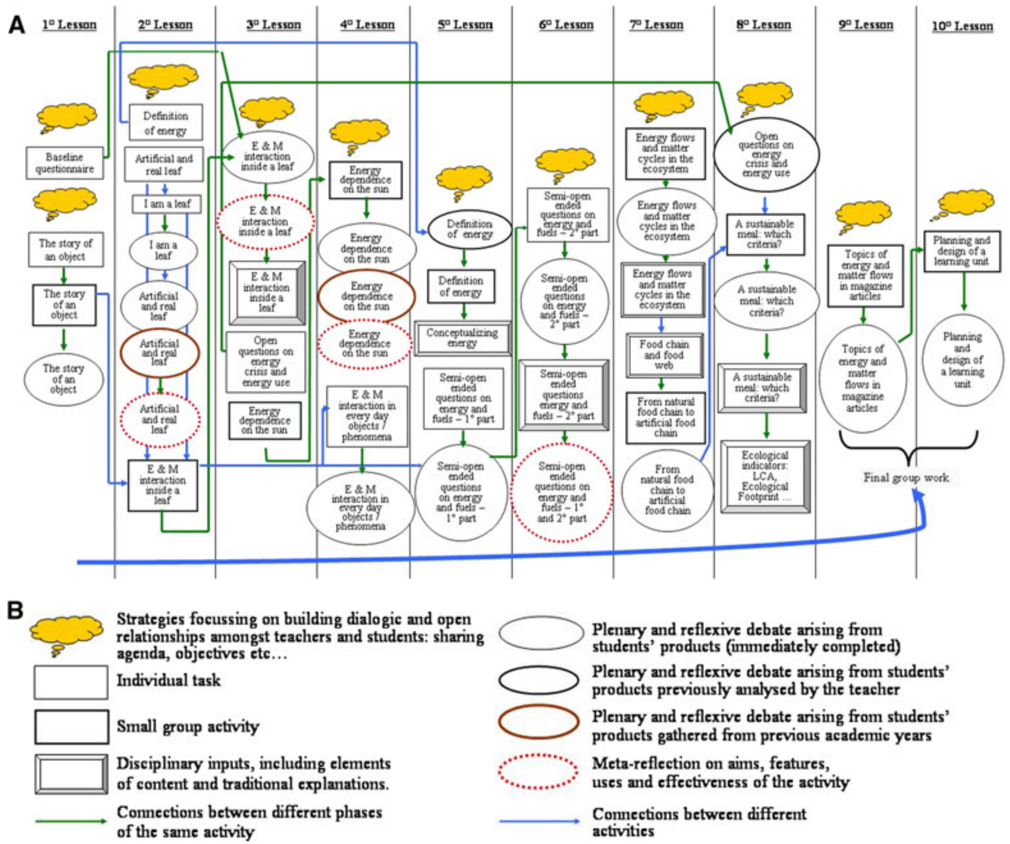

Fig. 7 **a** Map summarizing the sequence and typology of activities carried out during the workshop on Energy flows and Matter transformations. **b** An explanation of the symbols used in Fig. 7a. Arrangement and distribution of activities may change according to subjects, students and context

Ethics and Science (upper secondary school teachers). On the whole, empirical work was conducted on a total of 21 courses and 12 workshops, each one with a time allocation of 25 h, for a total of more than 820 h of action-research practice.

Each course and workshop was developed around specific topics and according to participants' competences and levels of prior knowledge. As indicated in the earlier section on methodology, the activities presented during the courses had the double purpose of eliciting participants' prior knowledge and pre-conceptions and producing information that is then returned to the participants—including the teacher-researchers—as part of the action-research process, to enhance reflection and awareness of changes of ways of thinking. So all proposed activities shared the same aims, working strategies, and assessment and evaluation criteria. Figure 7 contains a map of activities[4] developed for the workshop on Energy Flows and Matter Transformations. The map shows the variety of activities used (from disciplinary inputs to reflections) as well as their sequential arrangement. While there are generic features which are repeated in different courses, the various activities are arranged differently in each course depending on need.

A detailed analysis of the findings from these educational activities and a reflexive evaluation of the overall process have been carried out by one of the members of our Research Group (Marchetti 2008). An analysis of activities regarding a specific issue of biological evolution was carried out as part of a degree thesis by Alessandro Cerutti (2007).

In this article we report some examples of such activities, with the aim of offering experimental, classroom translations of our epistemological and methodological premises.

Core Concepts in Biology (B1)

The concept of GENE "We have often heard it said that genes contain information that specifies a living being. This is wrong for two basic reasons [….]. When we say that DNA contains what is necessary to specify a living being, we divest these components (part of the autopoietic network) of their interrelation with the rest of the network. It is the network of interactions in its entirety that constitutes and specifies that characteristics of a particular cell, and not one of its components. That modifications in those components called genes dramatically affect the structure is very certain. The error lies in confusing essential participation with unique responsibility" (Maturana and Varela 1987, p. 69).

Still now many students hold the idea of genes as objects containing the plans for executing the development of an organism, and they are prone to place structural boundaries around an invisible reality in order to define it as an object of study and to grasp its role and functions. In fact, for a long period of time genes have been referred to as active agents, capable of animating the organism and enacting its construction, while eclipsing the role of the cytoplasmic body (Fox Keller 1995). However, the underlying idea of a one-way communication has been slowly replaced by the expression 'gene activation' that implies a dialogue within the complexity and agency of the organismic body.

So, deconstructing the structural boundaries of the gene helps to reflect in terms of functional boundaries, and to move from a structural approach to a systemic one. This is a way for approaching more current scientific thinking and which goes beyond biology's *central dogma* (Crick 1958). It is an epistemological shift from perceiving the gene as an object which—albeit invisible—can be manipulated (taken apart; moved around), to the

4 For the data presented in Fig. 7 we gratefully thank Dr. Daniela Marchetti, who developed a research on teaching/learning processes in a perspective of sustainability within her PhD thesis (unpublished).

idea of gene as a complex system of relationships (Barbiero 2002), and thus much more difficult to predict and control (Barbiero 2005).

As part of the activities for the class A060, we proposed students to work in small groups to:

a. reflect on the definition of gene;
b. explore the concept of gene by using the different approaches (structure, function, time, system);
c. identify the boundaries of the gene.

These tasks generated interest and discussion, leading to further research in specialised journals and the production of concept maps and reflections that were then reported by the students in their final assignments. For example, in the following extract, one of the students reports on the process of coming to appreciate a different way of looking at the gene. The student appears to become aware of the gene as an epistemological construct rather than a thing or object: "it was difficult to reflect, trying to find a different answer, on what the boundaries of the gene might be. In the first instance, they appeared to us as being certain, defined. Having to consider things from a different perspective has generated a crisis for we had strongly held conceptions and interpretations. In addition, reflecting linguistically on the definition of gene was useful in order to appreciate the new directions of the epistemological reflection. Just like it happened when we did not have information about the DNA, now the epistemology of biology is looking at the gene as concept rather than an object. To adopt this vision for the concept of the gene was much more unsettling than for the concepts of ecosystem and species, given the current possibilities of physically manipulating genes (genetic engineering). We would like to stress that this latter point was indeed the biggest difficulty for us, although it did open up new and wider opportunities for looking at things" (2007/2008).

From the quotation above we are able to infer that the active process of conceptual restructuring operated by language is effective in reverting from an original thingified view of the natural world (Désautels and Larochelle 1998) to a more dynamic view where decontextualisation and transfers of ideas are possible. The student makes comparison with other biological topics (ecosystem, species) and makes reference to the social and ethical implications of scientific activity. So even small entities for which we have no direct experience can be brought part of a dynamic reality of interactions and impacts bringing in a sense of reflexivity and criticality that are more akin to humility than hubris (Jasanoff 2007).

In other cases, the students were able to reflect on their evolving understanding as they engaged with the production of concept maps on the topic. "With our surprise, we realised that the first version of our map was a total…disaster! The word gene did not even feature in the map: albeit involuntarily, the graphical representation placed the DNA as the central element, as if our minds had automatically replaced it with the concept of gene. Our map almost inevitably put emphasis on the structural and functional aspects of the gene, completely overlooking the historical, systemic, ethical and social elements which in actual fact turned out to be of great relevance to the concept of gene. We then tried to revise our mental schemata: time and space are now the background for all concepts. While retaining the structural elements as important and essential parts, the map is open to other epistemological realms, opening up towards the history of life, ethics, relationships with culture, medicine…" (2007/08).

Figures 8 and 9 depict the process of conceptual reformulation underpinning students' revision of their own concept maps.

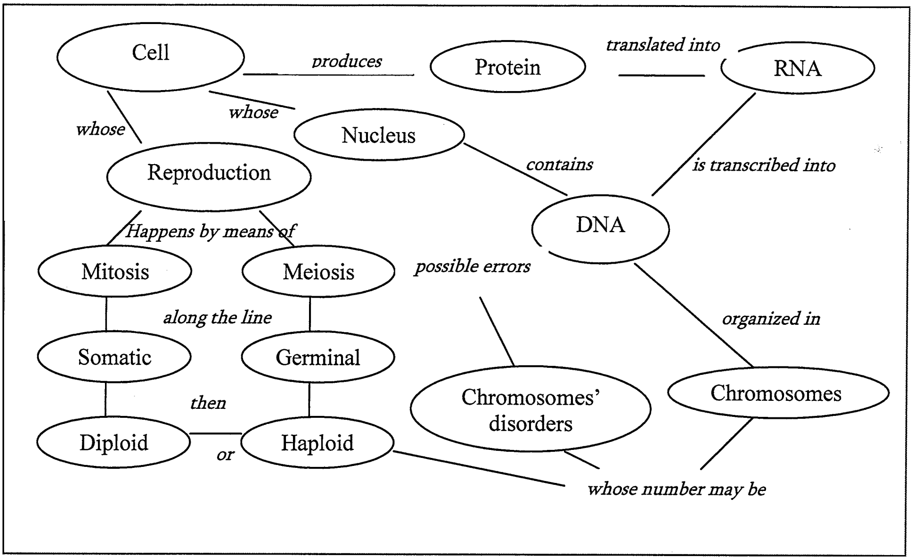

Fig. 8 A collective concept map on the concept of gene

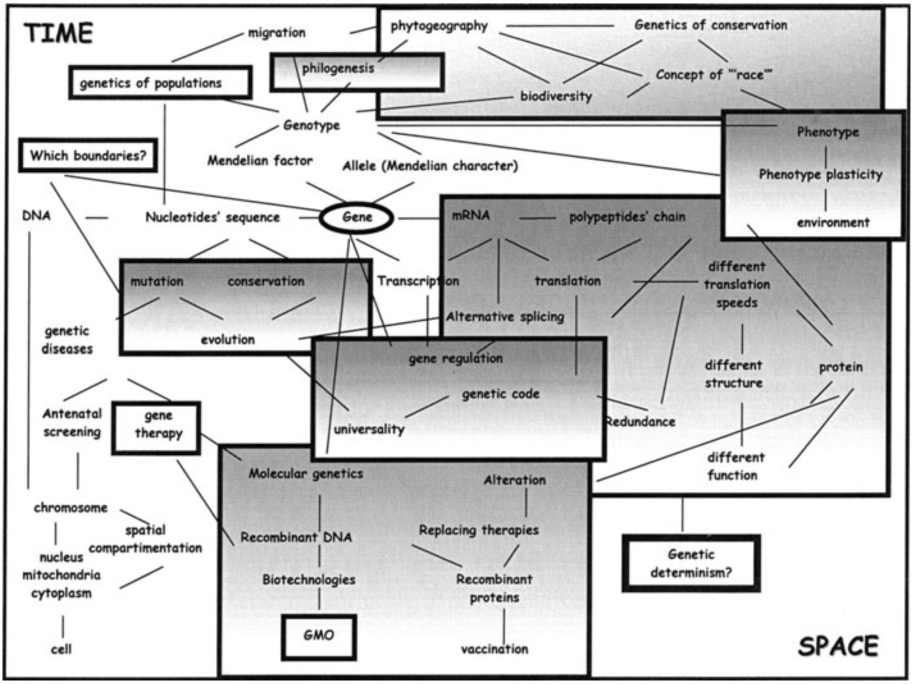

Fig. 9 Progressive transformation of the original concept map following discussion and reflection by the group

In particular in this case, the quotation opens with the expression of a surprise that the student associates with the recognition of having gone wrong. Indeed, concept maps are not meant to be right or wrong: they are tools designed to aid conceptual restructuring as an ongoing process of establishing links between ideas and creating new meanings and ideas. So, perhaps what we observe here is the sense of a realisation of having moved not only from a previous map to a new one that may feel better or right to them, but to a different way of thinking regarding biological processes and organisation. Gregory Bateson (1972) locates this process of shifting perspective and playing with ambiguity at the basis of humour in human communication. Uncovering assumptions can generate rather strong emotional reactions as people discover to have been guided or misled by their implicit notions; hence the humorous situation reaches its climax when the audience is presented with an alternative framework that was unknown or unexpected (Fry 1963). With the introduction of ambiguity and the possibility to approach it as part of science learning we can suggest that students are acquiring a sense of familiarity with the idea of contingency of scientific knowledge (Harding 2008) and the features of an emerging epistemological framework that include the possibility of being wrong (Alles 2008).

The concept of ecosystem The idea of ecosystem which emerges most commonly from preliminary investigations of student teachers' knowledge is that of a limited portion of territory characterised by a complex web of relationships between living systems and non-living components. Also at this organisational level (much in the same way as it was observed when reflecting on genes, cells and organisms) students seek to identify the structural boundaries as a first approach to thinking about an ecosystem. Hence, from here, reflecting on the boundaries of an ecosystem becomes a strategy for reasoning in terms of conceptual tools and approaches.

One way for sustaining the discussion is to start from the reading of selected passages from scientific texts, and for example:

- "An ecosystem is a functional unit. It is not simply a portion of land. When applying ecosystem management, you need to think not only about what's inside the boundary but what's going in and what's coming out." (Interviewing Eugene Odum 1997).
- "Among ecologists willing to draw any lines between ecosystems, no two are likely to draw the same ones. Even if two agree, they would recognize the inherent artificiality of their effort, and probably make the attempt with only a few species in mind. Moreover, one of them might prefer to draw a band or zone of separation rather than a line. Different lines are not surprising, but rather are entirely expected, because of the intrinsic interconnectedness of living systems: the discrepancies between scientists accurately reflect the diversity of the real world" (Corn 1993).
- "Ecosystem processes are scale dependent and, as such, the choice of boundaries for an ecosystem is of profound importance to the conceptualization of an ecosystem and the scope and validity of questions being asked within that ecosystem. The process—function approach […] focuses on processes that influence the flux and flow of energy and materials through an ecosystem. Instead of focusing on organisms, the process—function approach addresses the functional role of constituent parts of ecosystems and, therefore, is often organized around understanding the cyclic causal pathways that maintain ecosystem functions. Energy flow and biogeochemistry are points of focus for ecosystem ecology under this approach." (Post et al. 2007, p. 111).

The functional approach recalled by Eugene Odum, the difference that exists between reality and the methodological choices made by researchers (Corn 1993), the importance of scale and the attention to matter and energy flows mentioned by Post et al. (2007), are considerations which, drawing on a variety of approaches, can help to make fluid the concept of ecosystem. The integration of the different aspects can help towards maturing awareness of the cognitive acts that are involved in enclosing and labelling parts of a natural reality and to reduce somehow its complexity. From this perspective it is possible to observe a key aspect of current globalisation processes: increasing levels of exchanges of information, matter and energy around the globe has resulted into a profound transformation of ecosystems' natural boundaries. These are no longer places of separation and minimum exchange between adjacent environments (according to the classical definition), but they have become sites of conspicuous flowing (both in and out) of objects, people, living beings, energy and information, often with destructive consequences for the natural systems and biological communities. The development of a reflective stance on the notion of ecosystems—promoted with the application of a variety of approaches and conceptual tools (Camino et al. 2002)—helps to reach awareness of the nature of our planet as the only, effectively closed system: this view can disclose crucial opportunities for sustainability education (Bertolino and Perazzone 2005).

Here we report the reflection of a student: "It is indeed thanks to the use of conceptual tools, together with the adoption of a variety of approaches and the use of concept maps, that the study of the concept of Ecosystem could be undertaken. The analysis of the ecosystem required using different approaches which highlighted the complexity, dynamism, interactions and thus the bringing together of all acquired knowledge and their further re-organisation. Furthermore, it helped problematising the relationship between human beings and the environment and considering man's fundamental role as a creator of new ecosystems, at the expenses or in favour of others. From a structural/functional approach focussed on the study of single phenomena (separation of events), we moved to a systemic approach, paying attention to the construction of the whole (re-composition of events)" (2006/07).

The quotation provides a contribution on a similar theme that is to do with the acquisition of a systemic view of ecosystems. Yet the student also indicates how this understanding came as a result of a process of deconstruction by means of conscious application of conceptual tools. The learning process so described involved an active exploration of the complexity of coupled interactions and circularities in complex structures. Particularly in this case we find a mention to the role of human beings, as both inhabitants and creators of the natural world, thus part of the complexity and in continuity with other forms of life. A relational perspective in this case is brought into closer alignment with the ideas of participation in the environment and embodiment outlined by Ingold (2011). From this perspective, an idea of responsibility for one's own actions within a set of interrelationships was also made possible (Jasanoff 2007).

The concept of metabolism In the words of Lynn Margulis (1998): "metabolism, the incessant chemistry of self-maintenance, is an essential feature of life… Through ceaseless metabolism, through chemical and energy flow, life continuously produces, repairs and perpetuates itself" (p. 63).

In our experience, we have found the concept of metabolism to be of value for science education. Perhaps because of the difficulty of associating this term with a precise definition, we are also less prone to thingifying it. Indeed rather than defining the concept of

Table 2 Participants' definitions of metabolism

Combination of biochemical reactions enabling a single or multi-cellular organism, or even organs and tissues, to live, through the modification of resources coming from the outside and transformation of them into energy and matter or waste products.
It is a biological function allowing for an organism to interact with the external environment and guaranteeing its life
With the term metabolism we intend the ability of an organism–animal or plant–to absorb substances from the outside and appropriately transform them to become useful for survival
The global combination of biochemical reactions taking place within a living organism
The global combination of all biochemical reactions taking place within a living organism and allowing for its maintenance and survival
It is the global combination of energy transformations within the organism. It comprises of an anabolic phase of "construction" and a catabolic phase of "destruction"
Combination of reactions enabling living things to absorb and degrade nutritional matter to make them available for use by their organisms
Combination of catabolism and anabolism. Anabolism is the biological activity aimed at "construction", while catabolism is the biological activity that by means of transforming more complex molecules into simpler ones determines the production of energy
The combination of chemical reactions enabling the living organism to transform initial substances into final products. It can be a transformation from inorganic to organic substances (autotrophic organisms) or transformation of organic compounds (heterotrophic organisms)
Combination of reactions inside animal organisms when they introduce solid or liquid food. Transformations generate energy for vital functions (movement, growth, reproduction….)
The process generating the organic compounds constituting living things starting from elementary molecules
The global combination of reactions and transformations taking place in each living organism. Every living thing grows moves, reproduces and is kept alive by means of metabolism

metabolism, people tend to give descriptions of metabolic processes (Table 2) or explanations as to how and why they occur. Generally the idea of metabolism is expressed visually as a large set of coordinated and interdependent, chemical transformations happening simultaneously, within highly organised living structures and mediated by the presence of enzymes. Enzymes are responsible for regulating the intensity, direction and duration of the chemical processes, by responding to flows of information coming both from within (genetic information, cellular self-regulation) and from outside the cell (type of substances, membrane receptors, temperature, pH, and so on).

When talking about metabolism, it is spontaneous to use concepts such as energy flows, structures, systems as we are dealing with transformations powered by energy sources contained within molecules, or developed as electro-chemical gradients across membranes. Altogether such transformations contribute to maintain the structure and organisation of the living organism. Key to metabolic transformations is also the continuous integration of genetic information with environmental information (in terms of matter, energy, information) outside the system. So, it is important to specify the boundaries of energy and matter transportations: by means of metabolic processes, cells and organisms actively manage internal and external energy budgets and they transform matter. Metabolism implies the introduction of molecules, their transformation and further release/production of new molecules either within or outside the system. Matter transformation—guided by a flow of internal and external information—is always associated with a flow of energy in input and an equivalent flow in output. Depending on the selected scale, we can refer to the metabolism of a cell or the metabolism of an organism. Furthermore, as we mentioned

Table 3 An ordered sequence of sentences, following collective discussion amongst participants

1. The global combination of reactions and transformations taking place in each living organism. Every living thing grows moves, reproduces and is kept alive by means of metabolism
2. The global combination of biochemical reactions taking place within a living organism
3. The global combination of all biochemical reactions taking place within a living organism and allowing for its maintenance and survival
4. It is the global combination of energy transformations within the organism. It comprises of an anabolic phase of "construction" and a catabolic phase of "destruction"
5. It is a biological function allowing for an organism to interact with the external environment and guaranteeing its life
6. With the term metabolism we intend the ability of an organism–animal or plant–to absorb substances from the outside and appropriately transform them to become useful for survival
7. Combination of reactions enabling living things to absorb and degrade nutritional matter to make them available for use by their organisms
8. Combination of catabolism and anabolism. Anabolism is the biological activity aimed at "construction", while catabolism is the biological activity that by means of transforming more complex molecules into simpler ones determines the production of energy
9. The combination of chemical reactions enabling the living organism to transform initial substances into final products. It can be a transformation from inorganic to organic substances (autotrophic organisms) or transformation of organic compounds (heterotrophic organisms)
10. Combination of reactions inside animal organisms when they introduce solid or liquid food. Transformations generate energy for vital functions (movement, growth, reproduction….)
11. The process generating the organic compounds constituting living things starting from elementary molecules
12. Combination of biochemical reactions enabling a single or multi-cellular organism, or even organs and tissues, to live, through the modification of resources coming from the outside and transformation of them into energy and matter or waste products

earlier, the concept of metabolism has been used in recent years as a powerful metaphor for dealing with the study of complex systems: hence we can talk about the metabolism of a city (Odum 1988), the metabolism of Gaia (Volk 1998), or social metabolism (Giampietro and Mayumi 2000).

What follows is an example of one activity selected amongst many. First, prior to any explanation of content, participants were asked to write down—individually—a personal definition of metabolism (Table 2). The collection of students' contributions was then taken as the starting point for a plenary discussion aimed at finding a definition that integrated everybody's suggestions.

Table 2 contains a series of definitions that differ for the level of detail and the use of specialist language, such variety being indicative of different levels of knowledge as well as choices made by the students to capture the essence of the process in a given definition.

The next step in this work consisted of finding a means to put such definitions into some kind of mutual dialogue, by recognising and uncovering a prevailing disciplinary view, approach, or scale range (Reid, Berkes, Wilbanks and Capistrano 2006) and identifying possible misconceptions. Further to these initial considerations students are encouraged to work with their definitions, for example by creating a collective conceptual map that is further discussed and used for reflecting on the multi-dimensionality of the concept and integrating new knowledge. Table 3 shows the results of an activity conducted with the students and aiming at organising the definitions into a list showing increasing levels of complexity. We are at pains to stress that the final list is not necessarily the 'right one', and it can be further modified according to new contributions offered from participants.

In reading the contents of Table 3, we point the reader's attention to sentence n. 12, which is placed last in the list. This sentence includes both structural notions (cells, tissues, organs) and functional ones (combination of biochemical reactions), as well as considerations of boundaries and process–product dynamics. Within the new arrangement displayed in Table 3, the last sentence is the culmination of a process of progressive integration between the morphological approach to the concept of organism (i.e. with emphasis on movement, reproduction and so on, sentence 1) and the physiological-systemic one (e.g. sentences 6, 7, 8).

In their reflective assignments, students provided some further insights into the activity. More generally, students made comments about the interdisciplinary way of approaching topics in the Life Sciences: "our reflection started from a static vision of the concept of metabolism, linked to definitions which were strictly associated with biochemistry. It was thus a useful exercise to think first about the concept in terms of structural and functional approaches and then again from a systemic and historical perspectives. This activity enabled us to broaden our views with consideration of many topics of the Life Sciences, approached through the idea of energy exchanges and matter transformations and the self-regulatory systems linked to homeostasis" (2007/08).

In some other cases, students made more explicit comments about the learning methodology being used and the creation of a social climate within the climate that would allow for knowledge exchange and co-construction: "We started from the cell and its compartments, then we considered metabolic processes at the level of the organism, and finally at ecosystem and Gaia levels; those considerations enabled us to find new connections with current issues and to see any given concept from all its multiple facets, thus triggering meta-cognitive reflection on the different processes for knowledge building used by each one of us. Indeed we also became more conscious that not only the contributions expressed within our group but also the wider exchanges with the rest of the class were crucial for finding new connections with current matters and other concepts, thus achieving a socially constructed form of knowing" (2007/08).

More specifically, the students refer to disciplines as 'perspectives' and the opportunity to use such lenses both to deconstruct and recompose knowledge: "Many discussions, during the activity on metabolism, originated from the different backgrounds of the members within our group (we were two biologists and two chemists). It was incredible to see that by studying the same concept from two different points of view (biological and chemical), the same things would appear totally different; this means that different courses of study led to different conceptualizations" (2007/08).

The first quotation makes clear references to cognitive development and the possibility for integrating as well as deepening knowledge of various topics of the Life Sciences and processes that might occur at different scale (e.g. omeostasis of the cell or homeostasis of the organism). It appears that people with specialist knowledge can be encouraged to make links with other areas of specialism and conversely to integrate and build knowledge. In the following quotations we find more explicit references to the process of mutual learning underpinning knowledge building and how this way of learning was ultimately referred to as a crucial aspect for reaching understanding by means of link-making (quote 2) and awareness of different ways of seeing the world (quote 3). So mutual learning in this case can include both a more functional and instrumental dimension to do with furthering one' s own knowledge by drawing on other people's but it is also fulfilling a critical function to enabling the expression of alternative frameworks in the fashion advocated by knowledge creation in post-normal conditions (Funtowicz and Ravetz 1999).

Flows of energy and matter transformations (B2)

Issues of sustainability are characterised by the interconnection of a diverse range of problematic aspects, apparently very different from each other, and occurring at multiple time and space scales. One strategy for making connections between processes and events is that of considering the flows of energy across a living being or through a particular process, being the manufacturing and uses of a product. Unmasking the origin, quantity and types of energy at the basis of material transformations (or deriving from the transformation of matter) is a conceptual strategy for integrating different disciplinary approaches (Doménech et al. 2007), building awareness of energy problems (Trenbert 2009) as well as for overcoming conceptual obstacles (Trumper 1997). This conceptual tool was subject of focussed observation and reflection in a dedicated course addressed to prospective teachers preparing for teaching science in the lower secondary[5] classroom (Colucci-Gray et al. 2010).

During the course, a variety of activities were proposed with the aim of developing participants' competence with using this tool as part of interdisciplinary and trans-disciplinary dialogues. For example, one of the activities required students to reflect on the expression oil eaters (Jones 2001) with its real and metaphorical meanings. Together, we reflected on the flows of energy and trails of energy transformation underpinning the products and production processes and how the production and consumption of oil was implied. Thinking about all mutual interconnections between energy and matter is a way for getting to the heart of societal dilemmas—such as food production and environmental pollution, economic demands and resource scarcity, by helping to find the connections–which are often hidden—between science, technology and value systems: e.g. the meaning of a good life; the meaning of societal progress and development and so on. In relation to this point, Vaclav Smil (2008) makes the following considerations: "I strongly believe that the key to managing future global energy needs is to break with the current expectations of unrestrained energy use in affluent societies (p. 384). … The gains that elevate humanity, that make us more secure and more hopeful about the future, cannot be brought solely by rising energy use. (p. 387)… Equitable sharing would thus provide the world's entire population with enough energy to lead healthy, long and active lives enriched by more than a basic level of education and the exercise of individual liberties (p. 387)*"*.

And here we report some of the participants' comments, written in their final individual reports, in which they were asked to express personal considerations and suggestions on both the content and methodology of the course, and on their own level of involvement and commitment. In the selection of comments provided by the students it is possible to recognise some similarities with the comments provided by the undergraduate students attending the Primary Education Degree Programme. Students point to the development of a way of looking at the living world that has features of connectedness across disciplines and scales:

a. "I must admit I had some reservations about the course and content; I am in the habit of not reading the course guide and personally, the term flows of energy… did not suggest anything good. Discovering this topic bits at a time, the links with all other disciplines and indeed its cross-cutting nature, was a nice surprise […]. I had the pleasure to discover that the terms 'energy' and 'matter' do not only have a meaning in Physics but they extend to broader areas, from the microscopic level (hydrolysis of a

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molecule of ATP, for example) to the macroscopic level; and also it is a topic that relates to the world in its totality, including issues of energy consumption, dispersal and waste, and which can thus be dealt with from many points of view" (2004/05).

b. "From the point of view of content and methodology, this course was a total eye-opener: for example, thinking about the relationships between matter and energy, their close interrelationship and the fact that textbooks would more commonly present them as two separate and separable components, and so there is the concept of energy on the one side and the concept of matter on the other. I also think about the concept of autopoiesis which I had already had the opportunity to discover when reading '*Gaia's body*'; or the concepts of Energy, Exergy and Emergy as possibilities to track energy flows and transformations through matter and more" (2004/05).

In particular, the topics of energy and matter appear related to everyday experiences as a result of a learning journey that enabled them to cross over the boundaries of scientific and everyday knowledge. Indeed as reported in quote a), the student stresses the relevance and importance of generating and recovering a multiplicity of points of view for exploring the topic.

In another occasion, students expand on their description of the learning process by including comments on their psychological and attitudinal development. They point to feelings of mystery and wonder which are associated with the perception of the whole from what is the limited and partial position of human beings.

c. "The course 'flows of energy and matter cycles in the living organisms' invited me to look at reality with a sense of wonder, to take notice and to appreciate life and its mystery. It is quite apparent however that this sense of admiration, or looking at reality with different eyes- and thus giving children the opportunity to similarly develop a sense of wonder about life–is made possible only if concepts are offered, understood and then explained to pupils as something new. Not in the sense of being "new concepts" but in the sense of offering a new way of perceiving them and connecting them together, to conceive them in their uniqueness" (2007/08).

While such quotations are not to be considered per se as final evidence of the ability of students teachers to hold specialist knowledge, they do indicate that the knowledge they built has become integrated within both an epistemological and a methodological framework and this appears to be a common feature across different courses and contexts. From such basis one may infer that student teachers will have acquired a way of looking at things, an organising framework of knowledge and values that can be potentially available to them to filter and organise further knowledge and practice.

Evolution as a frame of mind (B3)

Eva Lövbrand and colleagues specifically refer to the concept of Anthropocene as a geological époque traced back to the latter part of the eighteenth century and characterised by changes in biogeochemical cycles (e.g. global concentration of carbon dioxide in the atmosphere; nitrogen in the soil), transformations of land and sea, loss of biodiversity due to human activity "which has influenced the very dynamics and functioning of the Earth itself" (Lövbrand, Stripple and Wiman 2009, p. 10). So, in a world that is increasingly transformed by human actions, if and how can the evolutionary perspective contribute to the development of behaviours and actions directed towards sustainability? Nowadays, the evolutionary perspective is increasingly applied in fields of research beyond Natural

Sciences, such as the Medical Sciences (MacCallum 2007), Agricultural Sciences and Human Sciences (Futuyma and Meagher 2001). In the light of recent discoveries focusing on the importance of epigenetic inheritance, i.e. traits that can be passed on without changes to DNA sequence, Jablonka (cited by Whitfield 2008) argues: “there are social implications in our approach […] our way of looking at heredity and evolution counters genetic determinism and its political implications”. Douglas Futuyma (1995) recommends educating the public and policy makers about evolution: the worldview in which evolutionary biologists are trained recognizes “that species are genetically variable in almost every respect; that species and their environments are highly complex, sometimes unpredictable systems; that nothing is constant in the fullness of time” (p 42).

Taking into account the evolutionary component further increases the level of complexity which had already been made evident by the systemic approach: evolution is not only a process of the past but it is acting at every moment in the present thus connecting synchronic and diachronic events of Life on Earth. An interdisciplinary and reflexive approach to evolution could thus be a key concept for acquiring a sustainability perspective for it connects the actions of the past with the choices of the present and it is an inherent dimension of our existence as individual beings and as a species.

From these premises, a big picture approach to teaching and learning about evolution encompasses a reflection on common ideas about evolution which are present in the population. In fact, the topic intersects with conceptions about the nature of science and how scientific knowledge is produced, the political, religious and cultural aspects (Alters and Nelson 2002), as well as the nature of environmental systems described by scientific disciplines.

Activities based on verbal and non-verbal language as an opportunity for learning and research In the following paragraphs we present some results obtained from three interactive activities about the topic of evolution that were carried out with future teachers over the course of five academic years (from 2003/2004 to 2007/2008).[6] The activities described below are based on the use of language (in different forms) as a means for generating active engagement with the reality encapsulated by scientific labels. The purpose is that of unravelling contexts, actors and processes and so to grapple with dynamic descriptions of evolutionary processes, along multiple space and time-scales.

The activities included respectively: (a) drawing evolution and (b) reflecting on the meaning of words used in scientific and everyday life contexts.

In line with Mario Bagnoli (2009) and following recent emphasis on the use of communication methods in educational research that are different from verbal answers to given question (such as interview settings), the activities were aimed at generating interpretations and disclosing personal representations. While the activities engaged different cognitive areas (e,g. visual and verbal language; short and long-term memory) they all worked from the same principle of generating data richness: making a drawing or engaging with the search for meaning would not only be a means to elicit students’ knowledge (and possible misconceptions) but also for highlighting the specific qualitative dimensions of evolution that were chosen by each student in order to make sense of phenomena (Weber 2008). What is obtained is a qualitative description which cannot easily be put into words, as it taps into personal knowledge and beliefs unravelling from layers of personal experience. Yet when such representations and descriptions are shared, the process becomes akin to a

[6] For the data presented in this part we gratefully thank Dr. Alessandro Cerutti, who developed a research on teaching/learning processes about evolution as part of his Degree Thesis (unpublished work).

Table 4 Students' drawings of evolution

Types of drawings	N.
Sequential lines of forms: this category includes all drawings which illustrate a linear sequence of forms usually linked together by arrows	44
Phylogenetic tree: it is the representation of the family lines of particular taxonomic groups	19
Conceptual map/diagram: these are usually diagrams in which various concepts are connected by segments or arrows indicating relationships	14
Metaphors (for example ladders or pyramids)	7
Cartesian graphs, constructed with the variable time on one axis, and a parameter expressing the complexity or the anatomical diversity of the organisms, on the other axis	6
Total	90

dialogue that may occur between partial and all legitimate views on a complex phenomenon (Funtowicz and Ravetz 1999) for the purpose of deepening self- awareness and reflection (Primavesi 2000).

Drawing evolution In class, participants were invited to undertake an individual activity proposed with the following question: "Using a graphical device (a drawing, diagram, vignette…), represent the concept of evolution of living beings".

Students were given a form with a blank rectangular space of about 18 × 6 cm and an allocation of 10' to undertake the activity: this was a way to promote spontaneous and concise representations of their ideas of evolution. Similarly to the activities described earlier, the analysis of the drawings was a means for triggering a discussion amongst participants about the content of the representations and to reflect with them on the potential and limitations of any image when describing evolutionary processes.

The drawings collected over 6 years have been organised in categories, and five main typologies of drawings were identified (Table 4):

The category which is most frequently used is the time sequence (Figs. 10, 11 below), whereby evolution is represented as a series of different moments/events of the history of life on the planet.

This representation (Fig. 10) recalls familiar images in textbooks and the common way of writing about life moving from the oceans to the land. It can also be associated with misconceptions: for example the sequence which links dinosaurs with mammals of various groups can suggest a phylogenetic derivation of the mammals from the Tyrannosaurus or Diplodocus forms (the most frequent types in students' drawings). In addition (Fig. 11), the presentation of a different group of organisms at every stage in the sequence (i.e. unicellular organisms, then sponges, etc.) may suggest that at each transition a form is replaced by another form, due to a sequence of extinctions. There is therefore the danger of losing sight of the fact that many living forms have been present on the planet for a very long time (performing amongst other things fundamental roles, as some bacteria which are involved in the planets' biogeochemical cycles).

The drawing of the phylogenetic tree (Fig. 12) focuses on an important aspect of evolutionary theory that is the link between all living beings and the occurrence of processes of speciation. The representation of the tree is also one of the most frequent strategies for illustrating the concept of biodiversity. This kind of drawing features

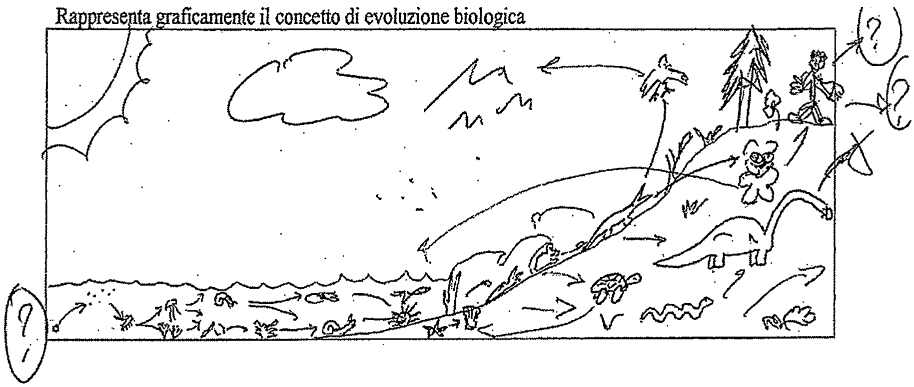

Fig. 10 Example of drawing representing a time sequence

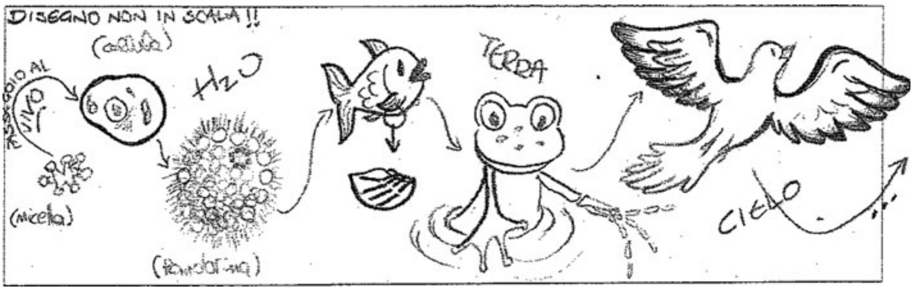

Fig. 11 Example of drawing representing a progression of sequential forms in time

frequently in academic textbooks and we could speculate that student teachers made their drawing by recollecting images they had seen in their books.

Year by year, the analysis of the drawings has provided ideas for further reflection and discussion in the following lessons. By looking at the overall display of the results we can see that:

- 68 drawings out of 90 report information about time, although only 3 drawings make explicit reference to geological time scales.
- 9 drawings contain the idea that evolution is a process which is still ongoing.
- 5 drawings represent the process of extinction, while the drawings which in different ways point to an idea of increase in number and variety of forms are much more common.

The environment as a cause of selective pressures is illustrated in 7 drawings. So, when operating at the level of general ideas, we notice the emergence of an idea of time that is mainly linear and uniform. Evolution appears to indicate progress, as accumulation of life forms and continuous improvement. It is interesting to note that this idea has formed the basis of the modern mindset whereby human beings by means of science can emancipate themselves from nature along a trajectory of continuous growth (Larson 2011).

Alternative representations and misconceptions Some drawings contain ideas or concepts which do not respond to the original request (for example some drawings represent

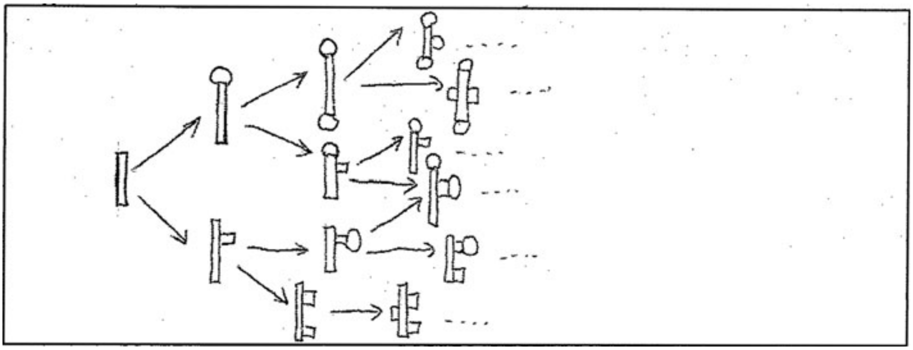

Fig. 12 Example of drawing representing a phylogenetic tree

instances of ontogenesis) or which are indication of possible misconceptions. Some examples include:

- drawings presenting the human figure as being the last one in a sequence of forms: this representation can transfer the idea of a process in which mankind is the final product of evolution.
- drawings presenting sequences of images in which old animal forms are followed by human figures associated to various cultural artefacts (on the horse, then in a car and finally on an airplane…). To some authors, cultural development can be considered as an integral part of biological evolution (Dennett 2006) although for educational purposes it can be useful to reflect on the differences between cultural and biological evolution.
- some drawings convey the idea of a hierarchical organization of living beings. According to many authors this idea needs to be discussed and contextualised, or it can induce misconceptions.

The variety of aspects related to evolution emerging from the drawings is an opportunity for sharing what are the most significant elements for each participant, or which are the aspects which are more readily brought to mind, thus giving the opportunity to link and integrate ideas together.

The language of evolution Since 2004, and for 3 years, participants of one of the courses were asked to individually compile a form with questions and activities about the meaning and use of terms respectively in everyday language and in scientific language (with a total of 42 forms being collected).

The form was designed to make student teachers aware of some problems related to the understanding of evolution which can be associated with the different meanings that some words can have in the everyday context or in the scientific one.

Everyday versus scientific language For example, at the request to write synonyms of the word *evolution* (as found in the everyday language) most student teachers used the terms *change* or *transformation*, which are both neutral. However, it was frequent to find the positive connotation that associates the term evolution with the idea of progress and improvement (22 questionnaires out of 42). It is clear therefore that if the two contexts, everyday and scientific, are not clearly defined, the positive connotation can be associated with the misconception that evolutionary processes are directed towards a positive finality.

Table 5 Students' ideas of evolution embedded in language

	Evolution	N°	Revolution	N°
Speed of change	It features slow and gradual modifications	30	It features sudden, unpredictable, unsettling and often violent changes	22
Relationship with the past	The new situation is in continuity with the previous one	17	There is radical and drastic change which signals a new beginning	27
Trajectory	Idea of progressive rise towards improvement in relation to the starting point	10	It does not always lead to a better situation	3
Where it can be found	It is found in nature	5	It happens to humans; therefore it is located at the socio-cultural level	5

From the analysis of data about synonyms of the word adaptation it emerged that the neutral connotations such as commensurate with (38%) and apt (24%), are the most frequent. However, there are various terms which refer to a characteristic of plasticity (for a total of 21% of the questionnaires) or which contain a value-laden element (correct, in 10% of questionnaires).

Different conceptual domains The second part of the form focussed on the meanings of evolution and revolution. The task was presented as follows: "The words evolution and revolution are both connected to the idea of change. However, they can be chosen to express different kinds of change. Try to formulate two sentences, one for evolution and the other one for revolution, and to explain the difference in meaning."

According to the majority of participants, evolution can be described by a gradual and regular process of morphological change over a long period of time; on the contrary, revolution refers to changes that take place over a relatively short period of time and mainly in the domain of human history. Very frequent is also the idea that revolutions are characterised by stark discontinuities with previous situations, and leading to an entirely new set of conditions (Table 5). In the discussions that followed, it emerged that many student teachers linked the two processes to different time-scales and could not be reconciled.

The linguistic reflection helped to uncover some implicit assumptions held by student teachers about evolutionary processes: slowness and gradualism are commonly linked to the classic formulation of evolutionary theory. What emerges is a Darwinian view of evolution that somehow overlooks later, complementary interpretations, such as that of punctuated equilibria (Eldredge and Gould 1972) that is more akin to revolutionary changes leading to new and unpredictable configurations in the system. Currently the idea of William Eldredge and Stephen Gould (1972) has been further reinterpreted by contemporary system theorists using the notion of *tipping point* (Lenton et al. 2008), whereby a new pattern of relationships and emergent properties appear quite suddenly and in discontinuity with previous conditions.

Is there a hierarchical order in evolution? The third section of the language form was aimed at collecting individuals' ideas for the specific purpose of sparking a debate about the possibility of establishing a hierarchical order of the organisms, on the basis of their adaptations and evolution. The task was given as follows: Try to move from the common use of language to a scientific use that takes into account the modern evolutionary theory.

Table 6 Students' interpretations of language in the context of evolution

Categories of answers		N°
Yes, because…	Organism A is more complex	4
	Organism A is able to perform more functions	2
	Organism A is more specialised	3
	Organism A is older	5
	Organism A has undergone more modifications than the ancestor	5
	Organism A is more similar to mankind	1
	Organism A belongs to a higher evolutionary level	4
	Organism A is more adapted than organism B	4
It is appropriate only…	If organism A is current and B is extinct	1
	For the characteristics of the organisms and not the individuals	3
	If we do not mean that A is better than B	1
No, because…	There is no such thing as measuring a evolutionary level	6
	It does not make sense to compare the evolution of different organisms	3

What does the following expression mean? *Species A is more evolved than species B.* Is it correct to use such expression in a scientific context?

The answers were many and varied. The majority of students reckoned stating different levels of evolution is a legitimate thing to say, but their justifications originated from different types of reasoning, as displayed in Table 6 below:

Student teachers did not reach consensus about the scientific legitimacy of the phrase suggesting that some species can be considered more evolved than others.

In this situation, and as it often happens when a number of different and contrasting ideas emerge from the participants, it is possible to appreciate the close interconnection between collection of data, action-research methodology and pedagogical effectiveness: after the activities described here, almost all student teachers declared they had never addressed the problem before; they participated with great interest in the discussion and contributed to deepening the topic, appreciating the possibility of expressing themselves and discussing the different interpretations.

Conclusions

Ongoing processes of transformations of socio-environmental systems, with rapidly increasing extinctions of species and cultures are well documented by an overwhelming plethora of scientific data as well as personal and collective testimonies. Such processes–that are irreversible at a human scale—are ongoing, shaping the lives of communities in ways that are unknown. Confronted with this scenario, we feel it is reasonable, urgent, and crucial for scientists and educators alike to spark a debate about the worldviews underlying modern science and the aims of current scientific education and to consider their implications and consequences.

So, our research focus is very broad. It responds to the idea that changing a worldview is a gestalt switch, whereby every other aspect—from views of knowledge to the aims and practices of science education— is fated to change.

In this paper we described our experiments with the linguistic reflection to generate learning and teaching contexts aligned with the epistemological framework of post-normal science and sustainability science. This particular epistemological terrain challenges consolidated views of positivistic science to embrace the broader perspective of interconnections between science, technology, society and environment. As indicated in the first part of the article, two main currents of thought converge to characterise knowledge production processes in sustainability science. On the one hand, interdisciplinary dialogue is advocated as a necessity to address current issues of science in society and it is sought as a means for questioning categories of thought, methodologies and focus boundaries. On the other hand, the stream of post-normal science brings forth the necessity of integrating different forms of knowledge in a communal process of knowledge production. Hence the cultural aspects of knowledge become paramount and they interrelate and even subsume the most consolidated forms of scientific knowledge (Harding 2008). Throughout this process however many questions are raised with regard to the procedures for such dialogue to occur. While interdisciplinary conversations can be inspiring and critical to new research, the style and procedures of any one discipline may be seen by scholars in another discipline as cryptic if not irrelevant to their own work (Miller et al. 2008). In addition, there may be disagreements with regard to the opportunity of bringing together different forms of knowledge, which may be perceived to be in conflict or simply alternative and distinctly located in separate realms of human existence. A pertinent example of such debate is the interface between science and religion. In this context, as articulated by Reiss (2010) the nature of scientific knowledge is at stake, for in normal, paradigmatic science, the presence of alternative beliefs systems is very rare. In order to pursue this approach, a different epistemological position needs to be developed. So the objective of our research was to devise settings that were amenable to such investigation and could lead to a more general reflection about pedagogy of science education that would support a sustainability perspective.

In this paper, we provided an overview of the application of conceptual tools in different contexts of teacher preparation. Starting from consolidated scientific concepts, our aim and challenge–within a constructivist and reflexive educational approach–was that of deconstructing concepts in order to focus on their role as conceptual organizers, dynamically evolving together to raise awareness of the complex reality in which we are embedded. From the juxtaposition of the different experiences we derived a series of reflections on the nature and processes of scientific learning involved.

A reflection on knowledge

A first main distinction between the various learning and teaching situations in which we operated was the level of initial preparation in science held by the students, which differed greatly between the primary and secondary context.

While considering these important differences, the data collected from the two cohorts accounted also for some important commonalities in relation to processes of knowledge production in the natural sciences, and in some cases, we would argue, also complementarities. Reflecting on the use of a common strategy in different contexts would thus be helpful to gain an insight into the multiplicity of learning opportunities characterising this particular way of working and particularly, the role played by specialist knowledge.

Starting from the data collected in the primary teaching education context, data obtained from the final assignments pointed to students' growing awareness of their knowledge in biology. More specifically, students' comments pointed to a process of change, that is, from an initial state of knowledge fragmentation to a condition of further integration with the acquisition of a systemic perspective: "*The coverage of living things because it* *provided a more complete idea, less compartmentalised as compared to my previous course of study"* (2006/07—primary education). From a strictly cognitive point of view, such results appear to be in line with the socio-constructive perspective advanced by Howe (1996) and Scott et al. (2011). Activities based on the use of personal knowledge in dialogic settings appear to support the development of meta-cognition and link-making across levels and scales. Hence in our case the deployment of conceptual tools is a means to facilitate acquisition of basic knowledge in biology.

However, an interesting feature emerging from the data across all cohorts and contexts is the students' awareness of the way in which their knowledge is organised. In particular, they refer to the acquisition of a systemic perspective on the Natural Sciences, which is enabled by link-making. For example, within the secondary context, this process is described by the students with a cognitive focus: "…the analysis of the ecosystem required using different approaches which highlighted the complexity, dynamism, interactions*…"* (on page 36).

Within the framework of sustainability science such results can corroborate the idea that conceptual tools can be offered as an educational aid for introducing concepts as linking operators in the manner suggested by Morin (1999). Basic fundamental knowledge in biology can thus be a springboard to structure further knowledge production processes about the natural world in its multiplicity of aspects.

From a knowledge perspective however, there is a distinction to be made between learning science as a description of a reality out there and learning science as a means to connect one's own knowledge with a personal experience, that is by putting in touch the cognitive experience with the state of affairs in the internal world (Reiss 2010). In the case of primary teachers, the realisation of the interconnectedness of the natural world and the position of human beings as part of it is elaborated both at a cognitive and emotional level: "[The course] has triggered a sense of wonder towards the living world and its relationships with the environment. For the first time in many years I have developed a holistic view where all the bits I learned are joined up together. I had the impression of being able to gaze at the world around it and embrace it as a whole…. with a growing feeling of marvel (2006/07–primary education).

So, it appears that what students refer to is not only the acquisition of biological knowledge per se but also an awareness of the pattern or organising structure underlining their learning, and which involves the subject.

Also in the date from the secondary context we can recognise the presence of an ethical dimension: "Furthermore, it helped problematising the relationship between human beings and the environment…" (on page 36). While the expression of gazing at the world and feeling fascinated is suggestive of an attitude of contemplation and openness towards the world with resonates strongly on the inside; the ideas of co-existence and responsibility expressed more formally in the other quotation point to an understanding of relationships with other living forms.

So, knowledge is not simply an accumulation of facts but it affects the way the learner relates to the natural world, conceptually, linguistically, emotionally. Such continuity of learning dimensions can lead to some considerations about the role of specialist knowledge. In all contexts, elements of specialist knowledge are present: they are part of the knowledge of the students but they are also introduced explicitly by the lecturers during the courses. Across all the cohorts however we find the introduction of specialist elements leading to a process of opening up of the learning process to stimulate a range of learning dimensions, to enable connections with other topics (e.g. energy) and openness towards other ways of knowing: "It was incredible to see that by studying the same concept from two different points of view (biological and chemical), the same things would appear totally different; this means that different courses of study led to different conceptualizations" (2007/08, secondary education, on page 39).

Therefore in both contexts, it is possible to appreciate students' acquisition of scientific knowledge alongside an understanding of the incompleteness and partiality of all knowledge, which is an epistemological position more in line with current debates on sustainability (Sterling 2009). An important aspect in this process is also the appreciation that alternative modes of knowing can co-exist, that they are possible and plausible within the scenario of complexity and unpredictability of the natural world.

Knowledge, values and the curriculum

As indicated earlier, students refer to a process of learning in a new way rather than the acquisition of new concepts; equally however in this approach traditional concepts do not disappear: scientific knowledge forms the basis of the process of deconstruction. Besides, as indicated more prominently in the case of the topic of evolution, traditional, consolidated knowledge can be a means to disclose and reflect on cultural representations. Adopting a similar approach in science education has important implications.

In the first instance, we recognise the role played by values which are not separate from science learning but they are part of an active process of knowledge construction. The involvement of the learner at a personal and emotional level may allow for ethical positions to be further expressed and be legitimised as part of the process of how humans learn. This work can thus be offered as a response to the dilemmas outlined by Bryce (2010) with regard to the dichotomy between facts and values that dominates current practices in science education. Equally, it is a position on learning which does not discount the role of specialist knowledge. Rather it departs from an understanding of the legitimacy of all forms of knowledge and ways of knowing, amongst which specialist scientific knowledge plays a contributing part.

Paying attention to students' conceptions and to forms of open dialogue in the classroom—a fundamental point of constructivist education (Gergen 1995)–is a means for students' own values, assumptions, narratives and methodologies to become explicit and recognised. Students' knowledge can be construed not so much in terms of its similarity or divergence from consolidated scientific views (as in many approaches based on the deconstruction of misconceptions), but as a series of coordinated perspectives, all legitimate but all limited (in time, scale, context and so on [Liberatore and Funtowicz 2003]). This alternative perspective on knowledge can be applied to the broader context of science-technology interactions as well as to the smaller scale context of classroom interaction: epistemological pluralism can be practised also within the educating community. A similar point has also been made by Reiss (2010) in relation to the need for science educators to engage more openly with the worldviews of the students and in such way bring the classroom in open communication with the value-base of science communication in society. Indeed, it is within the educating community that both students and teachers can approach value-based issues: from the teaching of socio-scientific issues to the analysis of debates reported in the media but also to engage critically with the worldviews that are implicitly transferred and produced by dominant models of social and economical development. We are arguing for a type of science education that does not discourage people from engaging with the ambiguities and uncertainties of techno-scientific developments and seek to stimulate a variety of points of view.

Further research

The interplay of conceptual knowledge and linguistic reflection by means of conceptual tools can thus make a significant contribution towards the acquisition of a more dynamic scientific competence, evolving within socio-cultural and historical contexts, and to the integration of core science knowledge with social, ethical and cultural dimensions. This type of science education is aligned with the recommendations given by Larson (2011) with regard to the need to prepare students in the natural sciences to become more accustomed to the worldviews accompanying their knowledge and create a classroom climate for the co-construction of shared alternatives and scenarios. In particular here we would like to point out to the need for further and more focussed research on the use of conceptual tools within learning and teaching sequences. For example, an area that requires investigation is concerned with the role and attitudes of the teacher, the types of questions posed (the degree of openness, of inter-disciplinarity and so on), the balance between flexibility and structure in the agenda and more generally the quality of the participatory climate in promoting consciousness about the multiplicity of ways of knowing and relating to the natural systems.

Further research of longitudinal nature might also be required to look at whether elements of epistemological awareness in science would relate to the students' emerging philosophies of practice. A systemic perspective might help students to respond more flexibly towards alternative views, languages and ways of being in the world. Hence further study could focus on the use of conceptual tools as a means to create and evaluate interdisciplinary learning and teaching units in which a variety of learning opportunities–from the learning of basic concepts, to discussion of controversial issues and experiences in the environment is used. In this paper we attempted to provide an integrated framework that could incorporate further experimental units and theories of knowledge.

We are at pains to stress that such research is only at the beginning and it is in the hands of all teachers, teacher educators and researchers who want to embark with experimentations in sustainability. Our hope is to enable students to understand the scientific worldview alongside other worldviews and enter the arena of public communication to produce imagery and attitudes that are more respectful of other people and the environment. As indicated by Sarewitz (2010) "wise democratic guidance will take more than ad hoc panels. A commitment to reflecting on technological futures needs to be integrated into the research and development enterprise" (p. 688). Is science education the key?

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