Scientomics: An Emergent Perspective in Knowledge Organization†

Pedro C. Marijuán,* Raquel del Moral,** and Jorge Navarro***

*Bioinformation and Systems Biology Group, Aragón Institute of Health Science (I+CS), Avda. Gómez Laguna 25, Zaragoza 50009, Spain, <pcmarijuan.iacs@aragon.es>
<rdelmoral.iacs@aragon.es>, *<jnavarro.iacs@aragon.es>

Pedro C. Marijuán, Senior Researcher, is the leader of the *Bioinformation & Systems Biology Group* at the Aragón Institute of Health Science (I+CS). Engineer and Doctor in Cognitive Neuroscience (PhD Thesis on "Natural Intelligence," University of Barcelona, 1989). During more than 20 years, he has advanced research on the nature of biological (cellular) information, communication, knowledge, and intelligence. He has covered both intracellular molecular mechanisms and systemic, behavioral (brain), and social realms. He was co-founder with Michael Conrad of FIS (Foundations of Information Science).

Raquel del Moral Bergós, Graduate in Biology, Complutense University of Madrid. Masters in Molecular and Cellular Biology, University of Zaragoza. In 2008, she joined the *Bioinformation Group* of the Aragón Institute of Health Science (I+CS) as Research Assistant. Her main research interest is Neuroscience, but she is also keen on the nature of social information and parallels with biology.

Jorge Navarro López, Graduate in Chemical Engineering, University of Zaragoza. Masters in Physics and Physical Technologies, University of Zaragoza. In 2008, he joined the *Bioinformation Group* of the Aragón Institute of Health Science (I+CS) as Research Assistant. His main research interest is Systems Biology, but also cellular signaling systems, cellular intelligence, and the nature of biological information.

Marijuán, Pedro C., del Moral, Raquel, and Navarro, Jorge. **Scientomics: An Emergent Perspective in Knowledge Organization.** *Knowledge Organization. 39(3)*, 153-164. 47 references.

ABSTRACT: In one of the most important conceptual changes of our times, biology has definitely abandoned its mechanistic hardcore and is advancing "fast and furious" along the informational dimension. Biology has really become an information science; and, as such, it is also inspiring new ways of thinking and new kinds of knowledge paradigms beyond those discussed during past decades. In this regard, a new "bioinformational" approach to the inter-multi-disciplinary relationships among the sciences will be proposed herein: scientomics. Biologically inspired, scientomics contemplates the multifarious interactions between scientific disciplines from the "knowledge recombination" vantage point. In their historical expansion, the sciences would have recapitulated upon collective cognitive dynamics already realized along the evolutionary expansion of living systems, mostly by means of domain recombination processes within cellular genomes, but also occurring neurally inside the "cerebral workspace" of human brains and advanced mammals. Scientomics, understood as a new research field in the domain of knowledge organization, would capture the ongoing processes of scientific expansion and recombination by means of genomic inspired software (like in the new field of culturomics). It would explain the peculiar interaction maps of the sciences (scientometrics) as well as the increasing complexity of research amidst scientific and technological cumulative achievements. Beyond the polarized classical positions of reductionism and holism, scientomics could also propose new conceptual tools for scientific integration and planning, and for research management.

Received 4 November 2011; Revised 6 January 2012; Accepted 12 January 2012

† We thank Francisco Javier Garcia Marco, organizer of IBERSID Conferences, 2011, for very useful comments and suggestions at different stages of this work. We also acknowledge the productive comments of the anonymous reviewers who have helped to improve the present manuscript.

1.0 Introduction: Biological information and new knowledge paradigms

From an information science point of view, the living cell is an astonishing system; it incorporates the highest trove of informational phenomena that one can think of at the molecular scale. It is a micro-world teeming with millions of specific molecular recognition events, genetic codes, transcription and translation processes, molecular machines and self-assembling complexes, signaling systems, messengers, transducers, second messengers, regulators, effectors, connectivity networks, interferences, etc. Conspicuously, the information metaphor has become the natural way of talking about biomolecular phenomena, almost from the very beginning of molecular biology, and even more along the current bioinformatic and "omic" (genomics, proteomics, transcriptomics, etc.) revolutions (Marijuán 2004).

Contemporary biological research factually is answering some of the poignant questions associated with traditionally ill-defined, anthropocentric concepts such as information, knowledge, and intelligence, and is providing new tools to overcome the classical limitations of information theory and other formal procedures applied to the organization of life. The way living cells self-produce, communicate, and collectively organize multi-cell systems becomes a paradigmatic case of informational relationships involving an adaptation to the environment, which is knowledge dependent.

In living systems, there is self-organization plus something else. The crucial distinction of living matter regarding other self-organization phenomena found in inanimate nature is that the complex functions performed by the molecular agents of the living cell (enzymes and proteins) are individually programmed and collectively supported by means of vast accumulations of encoded knowledge in the genome. The "book of life" that characterizes each living species represents the cumulative knowledge obtained along the evolutionary coupling of the phenotype structures and the external environment. Nothing would characterize better the biosphere than the gigantic library containing the whole genomes of all the component species. This new kind of "noosphere" would not merely contain brut collections of DNA sequences, but also a progressive sophistication in the inner organization and developmental use of those sequences. It is an essential trait which parallels the evolution of both biological and social complexity—dramatic improvements in the management and operability of the genomic (or social) knowledge-stocks have been required in order to advance genuinely complex organisms (or societies). And this includes the biological reliance on recombination operations as one of the central engines for the generation of evolutionary novelty (del Moral and Marijuán, 2011).

Thus, although the respective scientific languages are worlds apart, in this paper, we are going to argue that the equivalents of information, intelligence, and knowledge at the human scale might be obtained, or at least approached, along an emerging bioinformational perspective based upon the living cell. It does not mean proposing a new form of informational reductionism, but the creation of a new intellectual resource to develop further insights on the organization processes of other informational entities: human brains, economic organizations, institutional settings, and complex societies at large. Herein, under the scientomics term, we imply that our own understanding of the sciences' dynamics could also benefit from, and cross-fertilize with, the advancements derived from the informational revolution taking place in the contemporary understanding of life

Biological interpretations of human knowledge and social structures are hardly new. After the Darwinian revolution of the 19th century, biological interpretations became a recurrent theme in social sciences, as well as in the economic, politic, and cultural discourses. Different variants of the "survival of the fittest" were applied after H. Spencer's coinage of the term, from Charles Darwin and Alfred Wallace themselves, to different schools of social evolutionism, neo-Malthusianism, utilitarism, etc. More recently, we can also point to social explanations based on ethology (Eibl-Eibesfeldt 1989), sociobiology (Wilson 1975), and memetics (Dawkins 1976). It is quite interesting that, in the 1960s, just after the discovery of the genetic code by Watson and Crick, a new wave of biologically inspired doctrines addressed different relationships among information, cognition, and life. New terms such as self-transcendence, autopoiesis, autogenesis, autocatakinesis, self-production, self-organization, etc., were coined. But, perhaps with the exception of the really brilliant and provocative essay by Jacques Monod (1971), none of those approaches reached a highly multidisciplinary consideration.

Today, the great advantage fuelling the expansion of the bio-information paradigm is that cellular information processes may be defined almost to completion at the molecular scale (at least in the case of the simplest cells). That's not the case, evidently, with nervous systems and the variety of human organizational, cultural, and social developments. Concretely, the crucial evolutionary phenomenon of protein-domain recombination—knowledge recombination—will be analyzed here as a showcase of, and even as a model for, the interdisciplinary and multidisciplinary mixing of the sciences so prevalent in contemporary societies. Scientomics will be proposed as a new research endeavor with potential to be vigorously advanced.

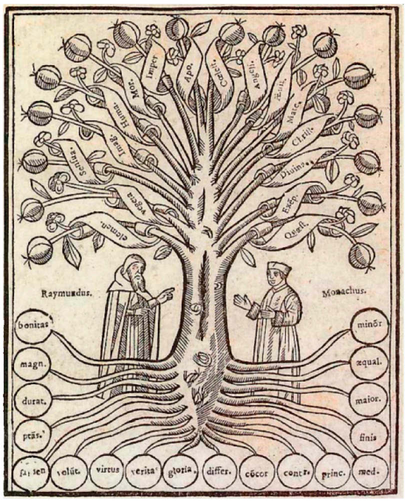
From different sources, pioneering authors have already recognized the multidisciplinary implications of knowledge recombination. At the philosophical and scientific scale, Wilhelm Ostwald's "Kombinatorik" (1929) was notoriously applied not only to nature, but also to knowledge organization and creativity processes (Hapke 2008). In the social realm, James Scott (1998) has discussed how the limitations of human expertise are forcing cognizing individuals to "play" recombination games. In the technological realm, historians have already been aware, at least since Colum Gilfillan (1935), that innovations stem from combinations of what is already known. More recently, the work of Brian Arthur (2009) dealt intensely with the evolution of technological systems through the social organization of "knowledge recombination processes." In the history of science, scholars of interdisciplinarity have been progressively aware of the recombination phenomenon in the relationship between disciplines (Dogan and Phare, 1990); a number of new ideas and projects have also been developed around interdisciplinarity during last two decades (Klein 2004, Gnoli 2008). The ideas that follow, which may be considered as germane or as a rough continuation of some of these previous works, are now drafted from an emerging bioinformational perspective; they put together a new recombinatory "scientomic" sense to be applied upon the inter-multi-pluri-trans-disciplinary games within the sciences.

How might "knowledge recombination" processes be detected amidst the forest of disciplines? As an introduction, we will approach the problem, first, from an historical perspective by looking at the changing ways in which systems of knowledge have been represented along the different epochs. We will move, then, to the philosophical views on the conceptual relationships between disciplines, e.g., reduction, integration, overlapping, multidisciplinarity. After these introductory discussions, the knowledge recombination hypothesis, or better, the discussion about a new scientomics field of research, will be fully developed. At stake is the extent to which the new informational understanding of cellular evolution will give us a useful metaphor to apply to scientific evolution.

2.0 The way representations of knowledge have changed along history

Historically, it is obvious that scientific knowledge has "evolved" and "multiplied" in many different ways. A cursory examination of how each main historical period has contemplated and iconically represented its own structures of knowledge will be quite illustrative. Along the main historical periods, we will roughly focus in the "number" of disciplines, their ordering relationships, and the social-institutional background. Some hints on the relationship between knowledge organization and social complexity will be obtained *en passant*.

From the very beginnings of Western science, the tension between unity and plurality of knowledge was deeply felt. Symbolically, the two main figures of antiquity, Plato and Aristotle, were at opposite extremes—necessary unity versus necessary multiplicity (O'Donell 1998; Lanham 2006). Without diminishing the excellence of the former, the first classification of the empirical sciences belongs to the genius of the latter, undoubtedly with a modern flair: physics, biology, psychology, politics. Somehow, the historical influence of the two authors was projected through very separate channels, Academy and Christian Neoplatonism in one case, and Lyceum and Alexandrian Library cataloguing systems in the other (Wright 2007). Even before the classic Greek period, the tension between unity and plurality was already incorporated into the "tree of knowledge" representation, as used in the Bible from Sumerian and Egyptian sources (Hobart and Schiffman 1998). Figure 1a includes the "tree" representation, face to face with the Roman and medieval system of *Trivium* (grammar, logic and rhetoric) and *Quadrivium* (arithmetic, geometry, music and astronomy) disciplines, in Figure 1b. Actually the origin of this famous medieval system of seven "liberal arts" was due to a late Roman (pagan) intellectual, Martianus Capella (5th Century). It was addressed to the education of aristocracy



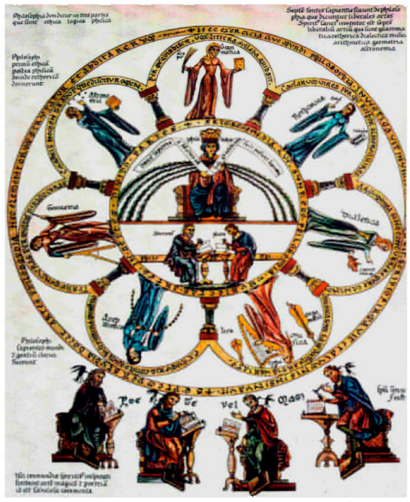


Figure 1a. Left: representation of the *Arbor x scientiae* (1295–1296), as depicted by the medieval "encyclopedist" Raimundus Lullus. ***Figure 1b.*** Right: the seven liberal arts illustrated in the medieval manuscript *Hortus deliciarum* (Herrad von Landsberg, 12th century). In the medieval university, the seven liberal arts were divided in two parts: the *Trivium* (grammar, logic and rhetoric) and the *Quadrivium* (arithmetic, geometry, music and astronomy).

and administrative officers of a crumbling Empire (Noble 1997; O´Donnell 1998). Amazingly, this organization of knowledge was to persist for quite many centuries, even longer than one millennium. Interestingly, during the medieval period, this speculative scheme of liberal arts was complemented with another more practical system, the seven "mechanical arts," undoubtedly due to the strong technological influences emanating from monastic institutions (Noble 1997). Medieval universities kept their focus in the liberal arts, with the exception of medicine and law (Hannam 2009). As Figure 1b implies, philosophy and theology, increasingly separated, were in command of the whole system of knowledge. It was in the 15th century when the printing press shattered this traditional scheme of knowledge, which leaving aside the technological branches, involved only a handful of disciplines, not many more than in classical antiquity (O´Donnell 1998).

With the advent of the scientific revolution, new vistas on the structures of knowledge were framed. Disciplines were "rationally" ordered and caught, almost universally, under hierarchical configurations (Wright 2007). The "tree" representation was occasionally kept, but now highly regular and well-ordered. The emphasis was now in natural and experimental science, accompanied by a dismissal of traditional sources of "authority" and the creation of new procedures to verify the accuracy of knowledge (learned societies, public tribunals, first scientific journals and "laboratories"). The representation of the entire system of human knowledge appearing in *L' Encyclopédie*, Figure 2, makes very clear the absolute rationality of design and the strict order impressed on the system of knowledge. There is now in the order of two or three dozen disciplines, or even more (Hobart and Schiffman 1998). Clearly, the pinnacle of this well-ordered system corresponds to (mathematized) physics, after the phenomenal success of Newtonian mechanics. The motto of the Royal Society, *nullius in verba*, made clear the increasing separation between the natural sciences (as branches of natural philosophy) and the humanities. The "battle of the books" was quite a symptom of the new times and an early crystallization of the two cultures (Lanham 2006).

With the advent of the industrial revolution, the abruptly more complex economic and social systems needed far more specialized work and technical education (Wright 2007). Scientific and technological knowledge started growing at an accelerated pace. University departments and laboratories, polytechnic schools, and industrial companies, were themselves firmly established as the basic institutions providing scientific and technological knowledge. National associations of scientists were created in Germany, Italy, the U.K., the U.S., etc. With successive revolutionary waves, both scientific and industrial, the number of scientists and of scientific disciplines doubled with each passing generation (Landes 1998). The

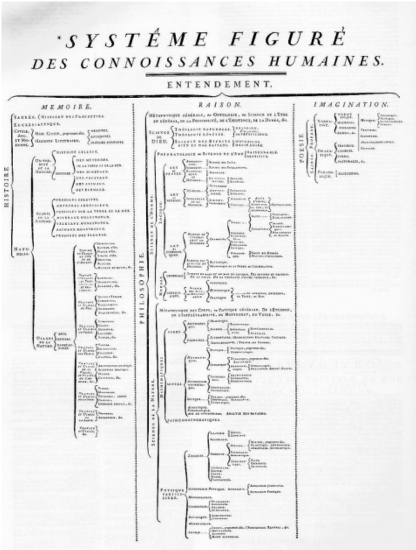


Figure 2. Representation of the entire system of human knowledge appearing in the general encyclopedia "*L' Encyclopédie,*" also known as "*Dictionnaire raisonné des sciences, des arts et des metiers,*" edited by Denis Diderot and Jean le Rond d'Alember, and published between 1751 and 1772 in France.

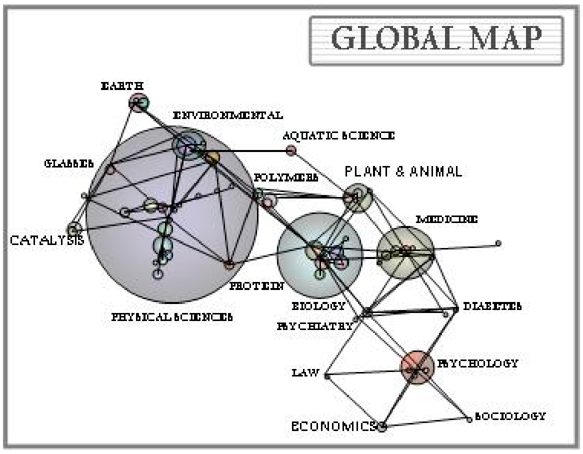


Figure 3. The first global map of the sciences proposed in the 1980s by Eugene Garfield (modified from Small and Garfield 1986).

primacy in this industrial period undoubtedly corresponded to physics, based on mechanics and its expansions (including electrotechnics): classical mechanics, statistical mechanics, fluid mechanics, and quantum mechanics —the "*Four Mechanics.*" The decimal system developed by Melvil Dewey in 1876 (Dewey 1876), covers a system of disciplines ranging now in the hundreds (Wright 2007).

As a representative of the next "post-industrial" period, we have put in Figure 3 the first global map of the sciences by Eugene Garfield produced in the 1980s from citation links (Small and Garfield 1986). It may be taken as a precursor of contemporary network studies, which provide a number of qualitative and quantitative relationships and mappings between scientific disciplines—right in the aftermath of the "information revolution" of the last few decades (Börner 2010). Concerning the number of disciplines, in a very few generations, the system of knowledge has escalated to a new order of magnitude, in the thousands, and the idea of an ecosystem of knowledge has finally replaced the hierarchical views. More than physics, computer sciences and the new biomolecular and bioinformatic fields are commanding a far more complex and interconnected system of knowledge (Noble 1997; Hobart and Schiffman 1998; Lanham 2006).

3.0 The overlapping of disciplines

Perhaps the most conspicuous feature of the historical panorama just described is the accelerated pace of disciplinary multiplication after the scientific and industrial revolutions, roughly at par with the complexification of societies themselves. The discussion of this singular phenomenon, indeed the "big bang" of the science universe, has received only scarce attention in mainstream philosophy of science; perhaps the opposite has occurred in the knowledge organization field (Ranganathan 1967; Dogan and Pahre 1990; Gnoli and Poli 2004), which deals with the practical consequences of the information glut (Wright 2007).

The hierarchical view of disciplines so prevalent during the scientific practice of past centuries was also seminal in the philosophy of science. For instance, the logical-positivist emphasis on reduction between adjacent disciplines was also based in the concept of hierarchy and had established an order of disciplines parallel to the corresponding "material levels" of reality (Figure 4a). The pinnacle corresponded to (mathematical) physics. This simplified arrangement had been endorsed by logical-positivist authors, systems theorists, and post-positivist authors (explicit quotations from Ludwig von Bertalanffy, Kenneth Boulding or from Karl Popper can be pointed out—see for references (Marijuán 1994; Küppers 1990). It is amazing that even antireductionist authors like von Bertalanffy, and, with him, most systems theory scholars, have not discussed this dubious correspondence between scientific and material layers (Bertanlanffy 1956, 8):

> We cannot reduce the biological, behavioural, and social levels to the lowest level, that of the

> constructs laws of physics. We can, however, find constructs and possibly laws within the individual levels. The world is, as Aldous Huxley once put it, like a Neapolitan ice cake where the levels, the physical, the biological, the social and the moral universe represent the chocolate, strawberry, and vanilla layers. We cannot reduce strawberry to chocolate.

In Boulding (1956, 13) the cake contains a few more layers: "Every discipline studies some kind of 'individual'—electron, atom, molecule, crystal, virus, cell, plant, animal, man, family, tribe, state."

A rather different picture could be drawn, however, allowing for the superposition or overlapping of disciplines. Then, two aspects can be highlighted: that basic disciplines overlap their territories—and precisely in these overlaps new disciplines are born—and that real knowledge of any material aggregate or complex system forces us to apply a plurality of disciplinary approaches and to interrelate or integrate them (Figure 4b). The study of objects in the lowest strata shows the highest levels of multidisciplinarity and complexity.

The overlapping or combinatory dynamics at work between the sciences can be observed more easily in the new diagram of Figure 5a. Almost every successive vertical overlapping of disciplines makes sense and corresponds to an existing subdiscipline (Marijuán 1996): chemical physics [physical chemistry], biophysics, psychophysics, sociophysics, biochemistry, psychochemistry [neurochemistry], sociochemistry [toxicology, environmental chemistry], biopsychology, biosociology [sociobiology], psychosociology (numbered in Figure 5b). In that Figure, every number corresponds to an existing subdiscipline formed

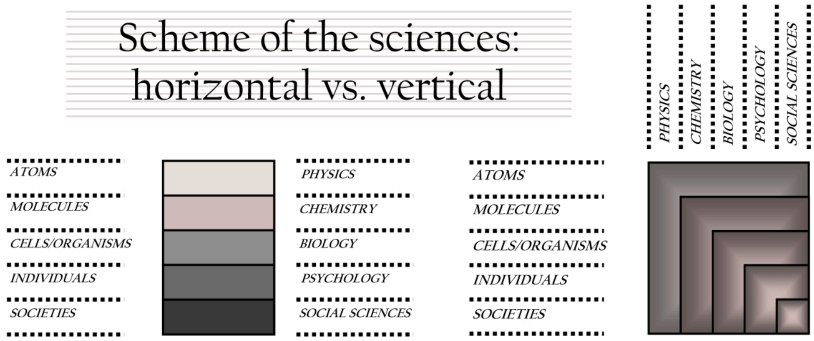


Figure 4a. Left: the horizontal hierarchical representation of the sciences. ***Figure 4b.*** Right: vertical representation allowing for the superposition or overlapping of disciplines.

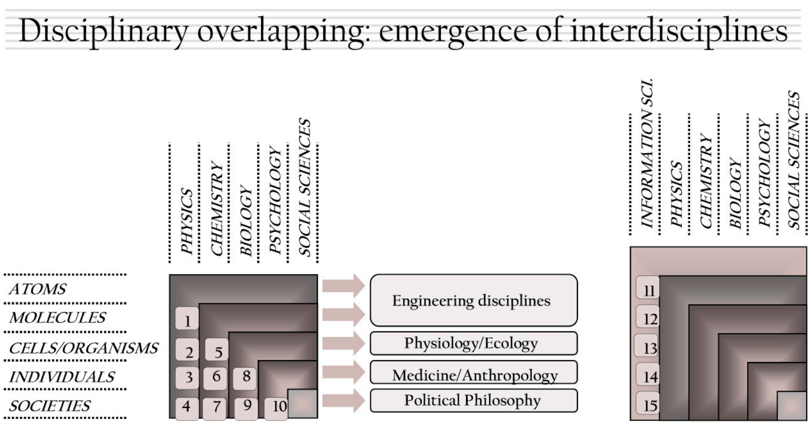


Figure 5a. Left: subdisciplines that emerge from the vertical overlapping of basic sciences. ***Figure 5b.*** Right: the proposed information science and its vertical overlapping with the other basic sciences. Some of the overlaps correspond with recent interdisciplinary explorations (11, information physics; 12, molecular computing; 13, bioinformation and artificial life; 14, neuro-information and artificial intelligence, etc.).

by a basic science working outside its conventional level, e.g., 1: chemical physics, 2: biophysics, 5: biochemistry, 8: psychobiology, 10: psychosociology, etc.

An integrative dynamics can be observed too. A spattering of "object oriented" integrative disciplines emerges in the horizontal dimension of the diagram: engineering disciplines (nuclear, chemical, mechanical, etc.), physiology and ecology, medicine (anthropology), and political philosophy (Figure 5a). These multidisciplinary sciences correspond to the plurality of approaches necessary for understanding their respective objects, now taking into account the whole material, biological, cultural, and social interrelationships in which these objects are immersed. Again, some of these multidisciplinary sciences can be applied outside their own horizontal strata, generating new subdisciplines, e.g., bioengineering, socioengineering, ecosociology.

As an aside from this discussion, let us point out that some authors have speculated in past decades on an enlarged information science, including "informational" aspects of physical, chemical, biological, individual, and social realities (Scarrott 1986; Stonier 1991; Marijuán 1996). In the extent to which the idea of a putative vertical science devoted to information could be cogent, it should create its own spattering of subdisciplines in the overlapping with the other existing sciences: information physics, information chemistry [molecular computing], bioinformation [artificial life], informational neuroscience [artificial intelligence], and socioinformation. Some of these overlaps may be seen in Figure 5b, corresponding with recent interdisciplinary explorations of "informational" nature (11, information physics; 12, molecular computing; 13, bioinformation and artificial life; 14, neuro-information and artificial intelligence, etc.) Information physics was vindicated as a new discipline (Stonier 1991; Haefner 1992). The interdisciplinary attempts of molecular computing, systems biology, bioinformatics, and artificial life might be associated, like artificial intelligence and cognitive neuroscience, with the overlapping of a unitary information science widely conceived, too. Finally, socioinformation might be an adequate label for the pioneer insights of Marshall McLuhan (1964) and for some contemporary elaborations on the information society. In this regard, and without discussing their particular contents, an enlarged information science promotes an elegant alignment of these recent interdisciplinary explorations and suggests a unifying sense for the whole of them.

Summing up, every discipline provides reliable partial information about the external world, but in order to cope with the (non-restricted) real-world problems, it needs integration and overlapping with the extra information provided by the other disciplines. The sciences are continuously mixing and rearranging their contents for the sake of the problems they have to solve, and also as the result of communities of dedicated scientists in a continuous interaction. The realization of this socio-integrative dynamics, in the double inter-disciplinary and intra-disciplinary dimension, becomes the central problem in the praxis of science (the reductionist problem only characterizes a very narrow aspect), as witnessed by the continuous necessity of meetings, means of communication, interdisciplinary flows, creation of new specialties, and so on. The way overlapping processes are realized and generalized across disciplines will be discussed in what follows. Thereafter the knowledge recombination hypothesis will be fully established.

4.0 The inter-multi-disciplinary problem and the knowledge recombination hypothesis

It has been estimated that, after the industrial revolution, the number of scientists and of research fields has roughly doubled with each passing generation (Landes 1998). At the end of the 1990s, more than 8,000 research topics were supported by approximately 4,000 disciplines (Klein 2004). In the extent to which those estimates are cogent, nowadays the number of disciplines could have increased to 5,000-6,000, supporting around 10,000 research fields.

Why such a number of disciplines? How have they emerged? How do scores of different disciplines actually relate within a particular research field? The inconsistencies of institutional discourses involving disciplines, research fields, domains, specializations, etc., do not help, either. In the quest for new, biologically-inspired responses, approaching science from the knowledge recombination point of view looks feasible. We can quote from Brian Arthur (2009, book cover), in his recent approach to the nature of technological change, which is so close to the dynamics of science itself:

> Conventional thinking ascribes the invention of technologies to 'thinking outside the box,' or vaguely to genius or creativity, but this book shows that such explanations are inadequate. Rather, technologies are put together from pieces—themselves technologies— that already exist. Technologies therefore share common an-

> cestries and combine, morph, and combine again to create further technologies. Technology evolves much as a coral reef builds itself from activities of small organisms —it creates itself from itself; all technologies are descended from earlier technologies.

Interesting new ideas on the social nature of scientific knowledge and on social problem-solving are in the making. Apart from the recombinatory approach to technological evolution followed by Brian Arthur (2009), further insights anchoring the social creation of knowledge to biological-evolutionary phenomena have recently been proposed by Steven Johnson (2010), Kevin Kelly (2010), and Tim Harford (2011). Some of their ideas on pluralism, failure, and serendipity may efficiently complement and balance the recombination approach herein followed. Particularly useful are the notions on information eco-system and knowledge growth developed by Yi-Xin Zhong (2011).

The discussion of a real case might be helpful (del Moral et al. 2011). In Figure 6, for instance, we can see how multidisciplinary research in a very advanced field—biomaterial research—is contemplated by one of its leading practitioners (Kirkpatrick 2009). The crowding of subdisciplines and specialties is remarkable; up to 32 different subdisciplines are listed. As we will argue later, it could remind the domain accretion of some large protein of late eukaryotic evolution, as the figure itself suggests by representing specialties in a linear thread of sequential domains. As in the evolutionary process, it makes sense that the most advanced scientific explorations incorporate larger troves of disciplines and specializations. That is particularly true in biomedical research, which has become one of the central and most complex scientific hubs today.

As Figure 6 suggests, all major research fields have to be surrounded by a "cloud" of disciplines in order to convey the necessary scientific-technological knowledge. Concretely, herein we propose the term "domain of knowledge" to the particular collegiums of disciplines surrounding every major research field and potentially contributing to its knowledge recombination processes. It is clear that only some specialties or subdisciplines of each major science are actively involved in the exchange processes of some particular research in the field. Even at the level of one of these subdisciplines, the real granularity of the exchanges concerns a few "modules of specialization" that incorporate theoretical and practical knowledge as embodied by some specialist, researcher, PhD student, etc.

Knowledge is never disembodied, and the fundamental unit that contributes to the multidisciplinary

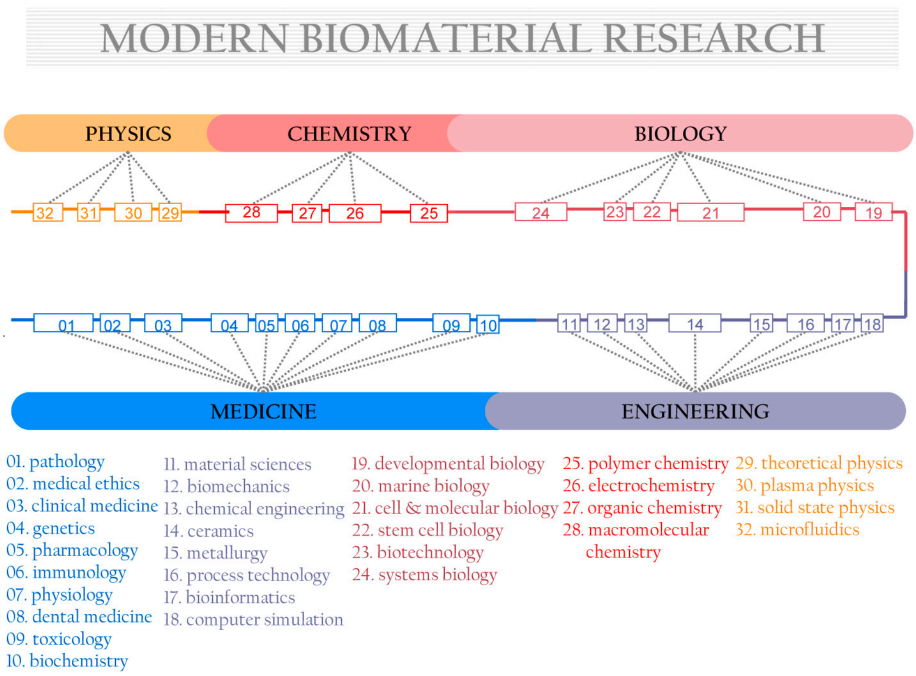


Figure 6. Disciplines involved in modern biomaterial research. The representation is based on the description made by bioengineer James Kirkpatrick (2009) and also del Moral (2011).

enterprise is the individual practitioner—usually working in complex groups and providing expertise on disciplinary grounds. In general, researchers will either need to develop those specialized skills or know enough about them to work with the specialist carrying out those tasks. Thus, it is the specialist who becomes the "module" supporting the different portions accreted in the knowledge recombination process, the equivalent of protein domains at the cellular level. Research fields are but niches of opportunity that attract experts of different disciplines and organize new domains of knowledge; if the research is successful and expectations are fulfilled, new disciplines of inter-multi-disciplinary nature will arise subtended by a new, *ad hoc* research community.

That would be, in synthesis, the basic relationship we propose between fields of research, domains of knowledge, disciplines, subdisciplines, and specialized modules which are at play in the social knowledge recombination process.

For the time being, putting the whole recombination idea to the test might be achieved rather partially. But there might be sufficient room to compare the biological evolution of DNA codes of protein domains, the real "units" of the biosphere, and the social-historical evolution of scientific disciplinary contents. Do cognitive "modules" exist within disciplines that travel to other disciplines and generate new fields there? If so, could the "combinatory" processes in both realms be interrelated? See Figure 7 comparing instances of biological and scientific (mathematical) evolution.

What does the comparison of Figure 7 mean? On the one side, very simple organisms at the beginning of life are counted, with very few kinds of domains grouped in rather short proteins, and then, by way of domain recombination, new families of larger proteins were created along the evolutionary emergence of more complex organisms, producing the "big bang" of the protein universe. While, on the other side, the sciences would also have accreted more and more complex conceptual structures via the entrance, mixing, overlap, or recombination of modules of thought belonging to other disciplines or subdisciplines. Socially, we recognize as "revolutionary" those diffusion processes where a determined core of ideas dramatically alters the existing structures of knowledge in vast areas of science. As we have seen in Section 2, the "scientific revolution" basically meant the diffusion of the mechanical-Newtonian core into many other bodies of knowledge. Many other examples could be drawn from the industrial and scientific revolutions of the 19th and 20th centuries (from thermodynamics to the origins of computers and of molecular biology itself; from biomechanics to bioinformatics and the whole "omic" revolution). Indeed such revolutions have fueled the "big bang" of science evolution during last two centuries.

At the very beginning of science, when a barely distinguishable body of rational knowledge was taking form, mathematical tools such as Euclidean geometry and the algorithmization of ancient arithmetics, together with similar pioneering bodies of logics and philosophy, acted as the founding modules or earliest units of science, the equivalents of those ancient protein domains at the beginning of life. As Figure 7 suggests, those ancient modules have survived historically as smaller components integrated within far more complex modules, in this case of mathematical knowledge, arisen along the "big bang" of recent genera-

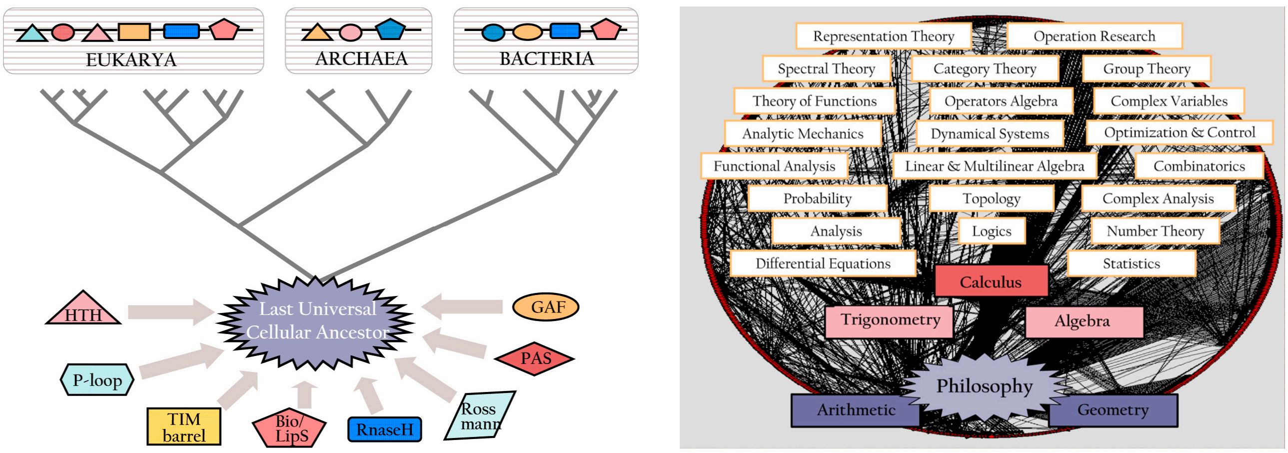


Figure 7. Parallel between recombination events in the evolution of the protein universe and in the evolution of the sciences. ***Figure 7a.*** Left: the "big bang" of protein universe (modified from Koonin et al. 2011) ***Figure 7b.*** Right: subdisciplines of mathematics (modified from del Moral et al. 2011).

tions. In the same way that ancient protein domains and their successive recombination events have been *bona fide* inferred by means of contemporary bioinformatic analysis, a parallel scientomic analysis on the recombination processes of scientific knowledge looks feasible too. In figure 7a, some fundamental domains related to the Last Universal Cellular Ancestor (LUCA, possibly a RNA-centered organism with DNA intermediate in replication) are represented in the bottom; after their evolution by modification and recombination these very modules reappear in more complex proteins of extant life forms, being of particular complexity like those found in eukaryotes. In Figure 7b, some of the main research fields and subdisciplines of contemporary mathematics are represented with an emphasis on the historical founders of modern science (algebra and calculus) and on the most ancient modules (arithmetic and geometry), which have been placed at the bottom.

If scientomics is committed to capturing the big bang of science evolution, "culturomics" might have already paved part of the way. Borrowing the main concepts and techniques from evolutionary biology, Jean-Baptiste Michel, Erez Lieberman Aiden, and colleagues were able to track the growth, change, and decline of the most meaningful published words during recent centuries (Michel et al. 2011). The new term they have coined, culturomics, means the application of "genomic techniques" of high-throughput data collection and analysis to the study of human culture, as sampled in a vast mapping of words from a corpus of digitized books, containing about 4% of all printed books ever published. Further sources might be incorporated to the culturomic stock: newspapers, manuscripts, maps, artwork, etc. Analysis of this corpus enables a new qualitative and quantitative investigation of cultural trends, social and political influences, fashions, and all sort of cultural phenomena.

Thus, the knowledge recombination hypothesis applied to the historical evolution of science, scientomics, might be considered as an evolutionary quest on the combinatory activity of disciplinary modules or domains of theoretical-practical knowledge travelling to other disciplines and changing there the local textures of knowledge, altering the regional maps of science, and the whole complexion of the world of knowledge at large. As we have already argued, influential modules such as Euclidian geometry, Newtonian mechanics, differential equations, genetics, and so on (and a multitude of other minor modules), would have generated the history of sciences, not only "developmentally" inside their own fields, but even more "combinatorially," propelling the multidisciplinary evolution and cross-fertilization among scientific disciplines. In terms of education science, something similar would happen too, for an abridged recapitulation resembling Haeckel's law seems to be taking place in the ontogenetic development of an individual's knowledge, which somehow recapitulates the fundamentals of the social acquisition of knowledge along history. Scientomics appears as a multidisciplinary research-project running in parallel to current achievements of culturomics in the cultural realm, though pointing at some more ambitious epistemic goals. Indeed the creation of a proficient scientomics new field would help to make sense of the historical processes of science, and of human knowledge in action.

One of the many gaps left in this preliminary scientomic approach to knowledge recombination concerns the nature of the individual's creative processes. The social creation of knowledge paradigmatically becomes an informational process, ultimately derived from knowledge recombination processes in the cerebral "workspace" of individuals, as argued by Bernard Baars, Jean-Pierre Changeux, Stanislas Dehaene, Gerald Edelman, and other distinguished neuroscientists (see Dehaene et al. 2001). Indeed, following more recent works by the latter author (Dehaene 2009), a "neuronal workspace" is formed in advanced brains whose main function is to assemble, confront, recombine, and synthesize knowledge. Privileged neuronal projections coming from the evaluation and reward circuits of orbitofrontal and cingulate cortex as well as the subcortical nuclei of amygdala and the basal ganglia participate in this process. This system is further endowed with a fringe of spontaneous fluctuation that allows for the testing of new ideas, related to both the emergence of reflexive consciousness and the human competence for cultural invention. It has been argued (Hobart and Schiffman 1998; Rosen 2000) that the strict conditions put by the scientific method are also efficient protocols that grant the social decomposability of problems. Standards, measurements, mathematical operations, formalizations, and so on become ways and means to export mental operations out of the individual's nervous system and directly interconnect perceptions and actions at a vast social scale. Somehow, the social dynamics of science is recapitulating central aspects of the very cognitive processes of individuals. The success of science in this informational jumping over the individual's limitations has been rationalized as the superiority of the scientific method.

However, there is not much understanding of the underlying "informational" causes, and how cognitive dynamics and strategies are recapitulated from one realm to another "almost by necessity" (see hints in Hobart and Schiffman 1998; Lanham 2006; Wright 2007). Indeed, if the perspective of an ampler information science is cogent, one of its future main goals should be analyzing the abstract convergence of cell-based systems, nervous systems, and social systems on similar knowledge-recombination procedures.

To conclude these brief exploratory arguments on scientomics, the purpose of the new field is to capture the "big bang" of the science universe in a way similar to the genomic and bioinformatic procedures used to capture the "big bang" of the protein universe. This parallel was approximately visualized in Figure 7:

- Scientomics posits an inner structure of major recombination events along science history.
- Scientomics means an epistemic, historic, and scientometric quest on specialized modules of theoretical-practical knowledge that, throughout their knowledge recombination activities, have cross-fertilized other disciplines.
- Scientomics would share a genomics' inspirational parallel with the recent culturomics enterprise and also with a possible future field of "technomics".
- Most of the history of natural and social sciences would have been generated not just "developmentally," but by means of the knowledge recombination dynamics herein postulated.

5.0 Summary

The main purpose of scientomics is to analyze the combinatory processes among the different disciplines that integrate contemporary science in order to ascertain their collective exploratory dynamics as a special form of knowledge-gathering that is crucial for the support of complex post-industrial societies. As stated, the historical expansion of the sciences has re-enacted social cognitive dynamics already realized along the evolutionary expansion of the protein universe, mostly by means of domain recombination processes, and also inside the neuronal "workspace" of human brains. Scientomics captures the ongoing processes of scientific recombination by means of genomics' inspired software, explaining the evolution of scientific maps and the structures derived from contemporary citation networks, as well as proposing new conceptual tools for scientific planning and research management. Philosophically, scientomics implies an efficient alternative to polarized classical positions such as reductionism and holism.

References

Arthur, W. Brian. 2009. *The nature of technology: what it is and how it evolves.* New York: Free Press.

Bertalanffy, Ludwig von. 1956. General systems theory. In Bertalanffy, Ludwig von and Rapoport, Anotol eds., *Yearbook of the Society for the Advancement of GST*. Washington, D.C.: Society for General Systems Research.

Boulding, Kenneth. 1956. General systems theory: the skeleton of science. In Bertalanffy, Ludwig von and Rapoport, Anotol eds., *Yearbook of the Society for the Advancement of GST*. Washington, D.C.: Society for General Systems Research.

Börner, Katy. 2010. *Atlas of science: visualizing what we know*. Cambridge, Mass.: MIT Press.

Dawkins, Richard. 1976. *The selfish gene.* Oxford: Oxford University Press.

Dehaene, Stanislas, Kerszberg, Michel, and Changeux, Jean-Pierre. 2001. A neuronal model of a global workspace in effortful cognitive tasks. *Annals of the New York academy of sciences* 929: 152-65.

Dehaene, Stanislas. 2009. *Reading in the brain*. New York: Penguin.

Dewey, Melville. 1876. *A Classification and Subject Index for Cataloguing and Arranging the Books and Pamphlets of a Library.* Amherst, Mass.

Dogan, Mattei, and Pahre, Robert. 1990. *Creative marginality: innovation at the intersections of social sciences.* Boulder, Col.: Westview Press.

Eibl-Eibesfeldt, Irenäus. 1989. *Human ethology*. New York: Aldine de Gruyter.

Gilfillan, S. Colum. 1935. *The sociology of invention.* Chicago: Follett.

Gnoli, Claudio. 2008. Categories and facets in integrative levels. *Axiomathes* 18: 177-92.

Gnoli, Claudio, and Poli, Roberto. 2004. Levels of reality and levels of representation. *Knowledge organization* 31: 151-60.

Haefner, Klaus. 1992 *Evolution of information processing systems: an interdisciplinary approach to the understanding of nature and society.* New York: Springer-Verlag.

Hannam, James. 2009. *God's philosophers: how the medieval world laid the foundations of modern science***.** London: Icon Books Ltd.

Hapke, Thomas. 2008. Combinatorics and order as a foundation of creativity, information organization and art in the work of Wilhelm Ostwald. Poster at the conference: *Analogous spaces - architecture and the space of information, intellect and action*, 15-17 May 2008, Ghent University, Belgium.

Harford, Tim. 2011. *Adapt: why success always starts with failure*. New York: Farrar, Straus & Giroux.

Hobart, Michael E., and Schiffman, Zachary S. 1998. *Information ages: literacy, numeracy and the computer revolution*. Baltimore, Md.: Johns Hopkins University Press.

Johnson, Steven. 2010. *Where good ideas come from: the natural history of innovation*. London: Allen Lane.

Kelly, Kevin. 2010. *What technology wants.* New York: Viking.

Kirkpatrick, James. 2009. Multi- & interdisciplinarity in bioengineering, biomaterials & nanomedicine. Oral presentation in *CIBER-BBN: networking biomedical research centre for bioengineering, biomaterials & nanomedicine,* Zaragoza 17-18 February 2009.

Klein, Julie T. 2004. Interdisciplinary and complexity: an evolving relationship. *Emergence: complexity & organization* 6n1/2: 2-10.

Koonin, Eugene V., Puigbò, Pere, and Wolf, Yuri I. 2011. Comparison of phylogenetic trees and search for a central trend in the "forest of life". *Journal of computational biology* 18: 917-24.

Küppers, Bernd-Olaf. 1990. *Information and the origin of life*. Cambridge, Mass.: MIT Press.

Landes, David S. 1998. *The wealth and poverty of nations: why some are so rich and some so poor.* New York: W.W. Norton.

Lanham, Richard A. 2006. *The economics of attention.* Chicago: University of Chicago Press.

Marijuán, Pedro C. 1994. Enzymes, automata, and artificial cells. In Paton, Ray ed. *Computing with biological metaphors*. London: Chapman & Hall, pp. 50-68.

Marijuán Pedro C. 1996. First conference on foundations science: from computers and quantum physics to cells, nervous systems, and societies. *BioSystems* 38: 87-96.

Marijuán, Pedro C. 2004. Information and life: towards a biological understanding of informational phenomena. *TripleC* 2: 9-19.

Marijuán, Pedro C. 2011. Knowledge recombination on the informational adaptability of cells, nervous systems, and societies. *Information theories & applications* 18: 3-15.

McLuhan, Marshall. 1964. *Understanding media: the extensions of man*. New York: McGraw-Hill.

Michel, Jean B. et al. 2011. Quantitative analysis of culture using millions of digitized books. *Science* 331: 176-82.

Monod, Jacques. 1971. *Chance and necessity: an essay on the natural philosophy of modern biology*. New York: Alfred A. Knopf.

del Moral, Raquel, González, Mónica, Navarro, Jorge, and Marijuán, Pedro C. 2011. From genomics to scientomics: expanding the bioinformation paradigm. *Information* 2: 651-71.

Noble, David F. 1997. *The religion of technology: the divinity of man and the spirit of invention.* New York: Alfred A. Knopf.

O'Donnell, James J. 1998. *Avatars of the word*. Cambridge, Mass.: Harvard University Press.

Ostwald, Wilhelm. 1929. Kombinatorik und schaffende Phantasie. In *Forschen und Nutzen: Wilhelm Ostwald zur wissenschaftlichen Arbeit*. Berlin: Akademie-Verlag 1978 (2 ext. ed. 1982): 28-30.

Ranganathan, Shiyali Ramamrita. 1967. Prolegomena to Library Classification. *The Five Laws of Library Science*: 1-73. New York: Asia Publishing House.

Rosen, Robert. 2000. *Essays on life itself*. New York: Columbia University Press.

Scarrott, Gordon. 1986. The need for a 'science' of information. *Journal of information technology* 1n2: 33-38.

Scott, James C. 1998. *Seeing like a state: how certain schemes to improve the human condition have failed.* New Haven, Conn.: Yale University Press.

Small, Henry, and Garfield, Eugene. 1985. The geography of science: disciplinary and national mappings. *Journal of information science* 11: 147-159.

Stonier, Tom. 1991. Towards a new theory of information. *Journal of information science,* 17: 257-263.

Wilson, Edward O. 1975. *Sociobiology: the new synthesis*. Cambridge, Mass.: Harvard University Press.

Wright, Alex. 2007. *Glut: mastering information through the ages.* Washington, D.C.: Joseph Henry Press.

Zhong, Yi-Xin. 2011. On information science: an introduction to "principles of information science". In *Proceedings of the 4th international conference on the foundations of information science*, Beijing, China, 21-24 August 2010. Basel, Switzerland: MDPI. Available http://www.sciforum.net/presentation/291.