The International JOURNAL of SCIENCE IN SOCIETY

Volume 1, Number 1

The Great Scientific Domains and Society: A Metascience Perspective from the Domain of Computing

Paul S. Rosenbloom

COMMON GROUND

www.scienceinsocietyjournal.com

THE INTERNATIONAL JOURNAL OF SCIENCE IN SOCIETY
http://science-society.com/journal/

First published in 2009 in Champaign, Illinois, USA by Common Ground Publishing LLC
www.CommonGroundPublishing.com.

ISSN: 1836-6236
Publisher Site: http://science-society.com/journal/

THE INTERNATIONAL JOURNAL OF SCIENCE IN SOCIETY is peer-reviewed, supported by rigorous processes of criterion-referenced article ranking and qualitative commentary, ensuring that only intellectual work of the greatest substance and highest significance is published.

Typeset in Common Ground Markup Language using CGCreator multichannel typesetting system
http://www.commongroundpublishing.com/software/

The Great Scientific Domains and Society: A Metascience Perspective from the Domain of Computing

Paul S. Rosenbloom, University of Southern California, California, USA

Abstract: The concept of a great scientific domain spans the traditional distinctions of science versus engineering, research versus applications, and quantitative versus qualitative methods. It focuses on understanding and shaping the interactions among a coherent, distinctive and extensive body of structures and processes. It not only includes the traditional sciences and engineering, but also mathematics, the humanities and the "professions", such as medicine, law, business and education. There are three traditional great scientific domains – physical, life and social – but there is now also a fourth domain that deserves the appellation: computing. Based on an earlier analysis of the computing domain, the Metascience Expression (ME) language has been developed to aid in understanding the structure of, and relationships among, great scientific domains. For computing, ME yielded a novel multidisciplinary organization capable of spanning its cacophony of subfields. Here, ME is applied – along with key themes from the study of science in society and results from ME's use in computing – to provide new insight into the relationship between science and society.

Keywords: Great Scientific Domains, Computing, Society, Multidisciplinary, Metascience

FOR ROUGHLY A decade (1998-2007) I led *new directions* activities at the University of Southern California (USC) Information Sciences Institute (ISI), a large academic research institute with a focus across much of computer science and engineering. ISI's new directions activities were highly interdisciplinary during this period, spanning not only computer science and engineering but also their interactions with many other disciplines and society as a whole. Notable examples included automated building construction, biomedical computing, technology and the arts, blending computing and entertainment for military training, community earthquake modeling environments, and responding to unexpected events. I began reflecting on this experience several years ago in an attempt to descry any latent coherence that might exist across such disparate topics. The result was a new multidisciplinary perspective on computing as a whole that revealed significant structure lurking behind the inventory of topics that typically define the field (Rosenbloom, 2004). A recent return to, and extension of, these earlier reflections has led beyond the boundaries of computing to a perspective on the structure of science and engineering as a whole, with a particular focus on the relationships among its various parts. The results of these further reflections, and their initial implications for the study of science in society, are presented here.

Broadly, this article can be viewed as an exercise in *metascience*; that is, science about science. Normally metascience proceeds under such traditional disciplinary banners as philosophy of science or sociology of science, but metascience can be based on any number of scientific perspectives. I am a computer scientist by profession, rather than a philosopher or sociologist of science, and thus have approached this exercise in metascience from the

The International Journal of Science in Society
Volume 1, Number 1, 2009, http://science-society.com/journal/, ISSN 1836-6236

distinct perspective, and body of expertise, that characterizes the domain of computing. But the fact that this therefore has been done in isolation from the more traditional metascience approaches means that this article should be viewed more as reflections from a computer scientist than as a deeply scholarly article within an existing tradition. In keeping with this, the number of citations has been kept to a minimum.

The first section of this article introduces the concept of a *great scientific domain* as a unifying notion across the traditional sciences, engineering, the humanities, mathematics, and the professions (such as medicine, law, business and education); and then reapportions most of these topics across three great scientific domains: physical, life and social. The second section builds on this by proposing a fourth great scientific domain that is distinct from, yet just as important as, the traditional three: computing (Denning and Rosenbloom, 2009). The third section takes an analytical approach to understanding the great scientific domains, yielding a mathematical language for characterizing these domains and how they can interact in arbitrarily complex, multidisciplinary, ways. The fourth, and final, section applies this framework and language to improve our understanding of science in society.

Great Scientific Domains

Our starting point is two core human intellectual activities: *understanding* and *shaping*. Understanding is the process of comprehending the nature and significance of things. Shaping is the process of creating and giving particular form to things. The former is primarily an analytic activity while the latter is predominantly synthetic. They are closely related to the more familiar concepts of science and engineering, but differ crucially for our purposes here. Paradigmatic science and engineering presuppose particular experimental, theoretical, and computational methods, and limit themselves to subject matter that can be investigated via these methods. Deriving the meaning and significance of the works of Jane Austen is, for example, clearly an act of understanding, but it is not part of science. Similarly, medicine and education shape our bodies and minds, but are not traditionally part of engineering.

Understanding and shaping, when considered together, resemble the Roman god Janus in being two closely interlinked faces of the same activity. The world is often shaped during the process of understanding, and to shape effectively one must understand. In a domain such as computing these two aspects are so closely intertwined that even professionals in the field have trouble distinguishing between them, and in fact too often get it wrong. For example, the true distinction between the disciplines of computer science and computer engineering is one of software versus hardware rather than science/understanding versus engineering/shaping.

A *great scientific domain* involves both understanding *and* shaping of some significant body of phenomena. The term “scientific” here is used not in the narrow method-limited manner discussed above, but in its most general sense, as “a particular branch of knowledge” (dictionary.com). It captures the concept of a major domain of investigation without the normal barriers that separate science from engineering, research from applications, and quantitative from qualitative methods. Not every domain that combines understanding and shaping in this way has the richness and scope to be termed a great scientific domain though. In full, a great scientific domain can be defined as: the *understanding* and *shaping* of the *interactions* among a *coherent*, *distinctive* and *extensive* body of *structures* and *processes*. Let's look at this definition in pieces.

The task of *understanding* the world is traditionally partitioned into three scientific domains. The *physical sciences* study physical, non-living systems, from the smallest subatomic particles to the immensity of the universe. It is comprised of disciplines such as physics, chemistry, astronomy and geology. The *life sciences* study living organisms, whether unicellular (e.g., bacteria), multicellular (e.g., plants and animals), or non-cellular (e.g., viruses, which exist on the margin between living and non-living). It comprises the various disciplines that fall under the broad rubric of biology. The *social sciences* study human behavior in individuals and groups, both past and present, and whether organized or not. Its disciplines include psychology, sociology, economics, and history.

The task of *shaping* the world is less well structured, at least in academia. Engineering is traditionally considered the analogue of science in the context of shaping, but it concentrates on a quantitative/mathematical approach to shaping the physical world (mechanical, electrical, civil, chemical, nuclear, etc.). People also shape the non-physical world, and via a range of quantitative and qualitative methods, just under different banners, such as the professions of medicine, law, business and education. Humans shape the living world through a range of activities that create, alter and destroy plant and animal life. It is studied in traditional schools of (human and veterinary) medicine and agriculture, and in newer disciplines, such as synthetic biology and genetic engineering, which develop new biological functions and organisms. Humans shape the social world through education and training, child rearing, propaganda and psychological operations, governing, advertising, counseling, and much of speech, discussion, and argumentation. Such topics are typically studied in schools of education, law, public policy, and business, but all focus on shaping the social world.

It should not be surprising that the three obvious candidates for great scientific domains are: physical, life and social. They not only are preeminent domains of understanding, but of shaping as well when their full scope is acknowledged. As we shall see, these three also meet the other requirements for a great scientific domain. What they lack, though, is exhaustiveness. For example, three significant human intellectual endeavors that don't fit well within these traditional great domains are the humanities, mathematics, and computing. As we will see, only one of these additional intellectual endeavors – computing – deserves affirmation as its own great scientific domain. Both the humanities and mathematics will find their appropriate niches as parts of other great scientific domains rather than existing as domains of their own.

To continue with the definition of a great scientific domain, consider the notion of *structures*; that is, the "things of interest" in the domain. In the physical sciences, a partial list of structures would include particles and energy, atoms and molecules, stars and planets, rocks and soil, rivers and atmosphere. In the life sciences we see everything from organic molecules to cells, organs, organisms, and (non-human) social groups. In the social sciences the structural focus is on people: the contents of their minds, the groups they form, and the articles they produce and use. (Human bodies are within the domain of life, at least according to the conventional boundary between the social and life sciences.) *Processes* then play a role in altering structures over time. In the physical sciences we see elementary forces and their consequences, such as chemical reactions, the birth and evolution of the cosmos, and the creation and erosion of landmasses. In the life sciences we see the creation, evolution, life and death of both organisms and their constituents. In the social sciences we see individual and group cognition; learning; and various forms of emotional, past, monetary, legal, and group behavior.

There is a richness and vitality in each of the great scientific domains that arises from the *interactions* among its structures and processes. Processes cannot exist without structures on which they can operate. However, there are important intellectual domains with significant structure yet little to no process. The humanities are a prime example. They are "Those branches of knowledge, such as philosophy, literature, and art, that are concerned with human thought and culture" (dictionary.com). They clearly involve both understanding and shaping of structures – books, paintings, statues, etc. – but there is little process to interact with these structures. What process does exist in the humanities is largely the human creation of structures, which is properly part of the social domain. Without processes, the humanities yield a *static* domain that falls short of the scientific fertility produced by *dynamic* domains in which processes are also central components. Without processes, there is little or no need for experiments or models. Analysis and theory have roles in a static domain – as they do in the humanities – in dissecting and explaining the domain's structures, but experiments and models exist to illuminate the inner workings of processes and their interactions with structures.

What about mathematics? People refer to the mathematical sciences. Yet, like the humanities, mathematics is all about structure. Dictionary.com defines it as "the systematic treatment of magnitude, relationships between figures and forms, and relations between quantities expressed symbolically." There is process in mathematics, *proof*, which generates new structures (proved theorems) from existing structures (axioms and theorems), but proof is a process engaged in by mathematicians – or occasionally by computers – rather than being a process in the domain of study itself. Mathematics may also be used to model processes, such as the flow of water in the physical domain, but the processes themselves are still not part of mathematics. Descriptions of processes (models) and products of processes (proofs) are part of mathematics, but they are static descriptions – structures – rather than processes. Thus, by definition, mathematics is not a great scientific domain. It is a static domain largely lacking in both processes and experiments.

Beyond interactions among structures and processes, the definition also demands coherence, distinctiveness and extensiveness. *Coherence* is straightforward. The domain must consist of a related body of material rather than a disparate amalgam of topics. For the three traditional domains, their coherence is succinctly reflected in single-word names: physical, life and social. *Distinctiveness* requires that the domain possess a core of structures and processes that are different from those studied by the other great domains. This does not imply that they must be completely disjoint – in fact, overlaps among domains are a key topic in this article – but that their core questions and methods should be sufficiently distinct from each other. Without this, two domains are best considered jointly as a single domain rather than as distinct domains.

Here we see a second problem with the humanities as a great scientific domain. They engage with products of human behavior that comprise a subset of the social domain's structures rather than a distinct body of material. Taken together with their lack of a significant process component – their processes also belong to the social domain – the obvious resolution is to classify the humanities as part of the social domain; in particular, that part focused on cultural artifacts. We will reach a similar conclusion about mathematics in the next section, and for similar reasons place it within the domain of computing. This placement of the humanities and mathematics within other great domains is in no way intended to denigrate the centrality or importance of either domain, only to locate them conceptually where they appear to belong.

To complete our analysis of the definition of a great scientific domain, *extensiveness* requires that a domain's core body of distinct material be sufficiently large to justify the appellation of "great". Without it, the domain would be relatively insignificant scientifically. All three of the traditional domains satisfy this in addition to the other criteria for being a great scientific domain. In the next section we will show that there is a fourth domain – computing – that does so as well.

Computing as a Great Scientific Domain

To establish that computing comprises a fourth great scientific domain, we will provide a working definition of computing and then inquire into its status with respect to the stated requirements. There is no generally accepted definition of computing so we will work here with one simple but useful variant: Computing is the domain concerned with the *transformation* of *information*. Within its scope are both computer science and engineering, and information science and technology.

Information can consist of bits, binary elements that can be 0 or 1; numeric values and measurements, such as a checkbook balance or seismic data from an earthquake; strings of characters covering everything from short nonsense strings, such as "ax5q", to web pages and books; on-line audio and video files encoded in a format such as MP3; knowledge about the world, such as the generalization that "all men are mortal"; models of how things work, such as a Computer Aided Design (CAD) model of an airplane or car, or a model of atmospheric circulation; or programs specifying sequences of operations to be performed by computers. Information can be about our world – and be more or less accurate in the process – about imaginary or virtual worlds, or about no world at all.

Transformation consists of the execution of computational operations that alter this information. Such operations could increase the balance in a checkbook by crediting a deposit, predict the climate later in this century, convert an audio file into signals capable of driving speakers, or conclude by reasoning from the general rule concerning mortality and the fact that I am a man that I am mortal. Transformations, as specified by programs (software) and executed by computers (hardware), provide the core processes underlying computing.

The core of computing comprises *understanding* and *shaping* of the *interactions* among *structures* (information) and *processes* (transformation). The domain is *coherent*, as evidenced by its simple definition. It is also *distinctive*. The structures and processes embodied by computing can model the structures and processes from other domains – as in a computational model of climate change – but such models are tools for domain scientists rather than objects of study within those domains themselves. Information and its transformation is simply not a core object of study in the physical, life or social sciences. Computing does overlap with these other domains, as with the physical substrate of computing (hardware) or the basics of human information processing (cognitive modeling), but these overlaps reflect relationships between computing and these other domains – as will be discussed in the next section – rather than being part of any single domain's core material.

The structures underlying computing *are* similar in their representational nature to those in mathematics, but computing is inherently a dynamic domain in which processes are at least as important as structures. Thus, in analogy to how the humanities were treated, mathematics is best situated as part of the computing domain. It becomes a major component of computing theory, concerned with the deep understanding of informational structures.

If computing lacked *extensiveness*, it would be inappropriate to place it on a par with the other great domains. But consider all that computers currently do, and all that they can potentially do. They are ever more central to communications, business, entertainment, socialization, education, manufacturing, and all other science and engineering. They are capable of reproducing (or at least simulating) much of the extent of the other great domains, such as the forces that bind atoms together, the dynamics of weather systems, cellular and ecological processes, and human thought and behavior. In fact, computers are *universal* in a precisely definable sense.

The notion of computable functions has been developed within computing theory to characterize what computers can in principle do. The generally accepted but still unproven Church-Turing thesis states that there is an abstract class of machines – Turing machines – capable of computing any computable function. Within the overall class of Turing machines there are specific instances, called universal Turing machines, that can emulate – that is, imitate or "act as if" – they were any other Turing machine. This unlimited ability of a single device to emulate arbitrary Turing machines – and thus to compute any computable function – is the basis for modern stored-program computers. Computers read programs stored in memory – while also reading and writing data in other portions of their memory – to "act as if" they are those programs. The resulting (almost) unlimited plasticity is what enables computing to yield not just a limited variety of concepts and tools, but instead the (almost) unbounded potential and extensiveness of phenomena required of a great scientific domain.

Analyzing the Great Scientific Domains

As mentioned at the beginning, this article can be considered as an example of metascience. It may not fit the narrow definition of science – although this section does introduce a mathematical language – but it does fit naturally within the broadly construed social domain as an attempt to understand and shape the interrelationships among the sciences and society.

Since metascience is simply a form of science, albeit turned in on itself, it should be possible to identify the structures and processes involved in this enterprise. The structures are straightforward. They consist of the four great domains themselves, the disciplines within these domains, and the structural relationships that exist among them. The canonical structural relationship for scientific domains/disciplines is *part of*. It yields taxonomies of science in which a subordinate discipline's subject matter is a subset of its parent discipline's; for example, chemistry covers a subset of the materials of the physical domain, while physical chemistry in turn covers a subset of chemistry. Not so obvious at first blush is the nature of the processes in this metascience. However, an analysis of computing has uncovered two active across-domain relationships – *implementation* and *interaction* – that act as metascience processes.

In the rest of this section these two metascience processes are presented and their interactions with the corresponding structures are explored via a mathematical language – the *Metascience Expression (ME) language* – that helps in understanding the structure of the individual domains, the interactions across the domains (and across disciplines within a domain), the overall landscape of multidisciplinary science (both existing and potential), and the relationship of science to society.

Generically, to *implement* is to "put into effect" (dictionary.com). A computer scientist implements an algorithm by getting a computer to act according to the algorithm; that is, by writing a program that causes the computer to behave according to the algorithm. Electronic circuits implement computing by providing a physical device – a computer – capable of computation. Quantum computing also provides physical devices capable of computation, but based on quantum rather than electronic principles and components. A computer can in fact be implemented by any combination of structures and processes, from any domain, that interact to yield the transformation of information.

More broadly, one domain implements another domain if structures and processes from the first domain combine to create elementary structures and processes in the second domain. The physical domain implements the biological domain – as studied in molecular biology – by defining the basic molecules and processes underlying life. The biological domain implements the social domain – as studied in cognitive neuroscience – via the brain's provision of the basic structures and processes of thought. And the computational domain implements, or at least simulates, the social domain – as studied in artificial intelligence and cognitive science – through computational provision of the basic elements of thought. In all such examples, the first domain either "puts into effect" the second domain or a model of it. Although there are critical differences between implementation and simulation/modeling, concerning whether they produce a true instance or only an imitation or approximation, for the purposes of this article it will be fine to conflate them.

Interaction involves "reciprocal action, effect or influence" (dictionary.com). When a dog fetches a ball, the physical and life domains are interacting. When a person tells the dog to "sit", the social and life domains are interacting. In human computer interaction, people use their standard sensory and motor systems (eyes, hands, etc.) in conjunction with computer input and output devices (keyboards, screens, etc.) to interact with computers. Brain computer interaction is much like human computer interaction in purpose – enabling people to interact with computers – albeit rather more novel and exotic in bypassing the normal human sensory and motor systems and instead attempting to interact directly with the brain. In general, we can think of interaction between any two domains as involving communication, or any other form of direct influence, between them.

In (Rosenbloom, 2004) there is a 4x3 table that maps out much of the domain of computing as a cross product between metascience structures and processes. The space of structures was kept simple, including just the four great scientific domains, without distinguishing their subdisciplines or structural relationships. Three processes were included – implementation, interaction and embedding – but embedding was later reformulated as a composite of the other two, so we will not attend to it further here. Each cell in the table represented computing combined with one other domain – which may have been computing itself – via one of these three processes. The surprising result was that most of the computing domain, whether considered a priori to be multidisciplinary or not, fit neatly within the twelve cells of this table. Hardware was the physical implementation of computing, artificial intelligence was computing implementing thought, human computer interaction was people interacting with computing, networking was computing interacting with itself, compilers and interpreters were computing implementing itself, and so on.

What didn't fit were true instances of computing in isolation – aspects of theory and algorithms – or complex topics embodying multiple processes and domains, such as ubiquitous computing (multiple humans interacting with a network of computers that is pervasively embedded in the physical world) or multi-player on-line gaming (multiple humans interacting with each other in a complex, networked, virtual world). The Metascience Expression language was developed to span all of computing, whether involving one, two or more domains.

Although ME was motivated by work in computing, there is nothing in it specific to computing. As its name suggests, it should be applicable across all of science. Still, given that it was developed from an analysis of computing, and that it has not yet been explored systematically outside of computing, it is possible that additional processes may prove necessary to cover all of science.

ME is based on five symbols each for structures and processes. Structures are represented by the four domain initials (P, L, S and C) plus "*" to represent all sciences (the taxonomic parent of the four great scientific domains). As in prior work, we will not delve below the level of great scientific domains in defining ME, but will then use ME to characterize disciplines within the domains. Implementation is represented by the division symbol (/), separating the domain being implemented from the domain doing the implementing, such as C/P for the physical implementation of computing and P/C for computing implementing/simulating the physical domain (as in weather modeling/forecasting). Beyond computing, we can, for example, talk about molecular biology as the physical domain implementing life (L/P), cognitive neuroscience as life implementing thought (S/L), or even about the physical implementation of everything (*/P).

Interaction is denoted by an arrow (↔, → or ←) indicating the direction of the influence(s). We can use S↔C for human computer interaction, C↔C for computer networking, and C←P for computerized sensing of the physical world. For the special case where there are many instances of the same domain mutually interacting we can use an exponential notation – such as C^n for computer networking – just as if symmetric interaction were repeated multiplication. Beyond computing are such examples of interaction as ecology being concerned with the interactions between life and the physical environment (L↔P) and sociology being focused on groups of interacting people (S^n).

In addition to the symbols for implementation and interaction, there is also the addition symbol (+) to serve as a generic over processes; enabling, for example, P+C to represent all possible combinations of the physical and computational domains. The + and ↔ symbols are commutative: P+C is the same as C+P and S↔L is the same as L↔S. The other symbols (/, → and ←) are not, but → and ← mirror each other, so L→C is the same as C←L.

For clarity and simplicity in complex expressions, two additional notations have been added to ME: commas "," to separate unrelated domains, and parentheses "()" to delimit sub-expressions. With these additions, a computer that senses both the physical and living worlds can be represented as (P,L)→C, denoting that both P and L individually affect C but without any relationship being noted between P and L themselves. Or consider the topic of neural prostheses, where a computational device is embedded within the brain to replace damaged functionality. In ME, this can be represented as L/(L↔C), signifying that the brain is implemented by interactions among computational and living (neural) elements.

With ME we are able to characterize arbitrarily complex combinations of domains and processes. Consider the *Spore* game from Electronic Arts (www.spore.com), in which players dally with species creation and evolution in a complex implementation/simulation of a physical, living and social world. The essential multidisciplinarity of Spore can be represented in ME as S↔((($(S/L)^n$ ↔P)/C). As a second example, consider complex mobile devices such as Apple's iPhone, which interact directly with a human user (both mind and body) as well as with a broader physical, social, and computational world over a wireless connection. This multidisciplinary topic can be represented as (S/L)↔(C/P)↔(P,S,C^n). As a final example, consider human-induced global warming, where people alter the physical environment, which in turn affects both humanity and the other forms of life with which we share the Earth. It can be represented as S↔P→L.

With ME we can not only represent arbitrary combinations of domains and processes, but can also generate the space of all possible domain combinations by starting with the four individual domains and systematically adding more domains and processes one at a time. If the domains and processes form a complete set, this space should include all of science. One long-term hope is to exploit this generative capability to identify areas that are still unarticulated and unexplored yet have untapped potential for the future.

Science in Society

Given an understanding of the four great scientific domains and the expressive power of ME, we now have a basis for discussing science in society. Science, broadly construed, is simply represented as * in ME. Society is a group of people thinking, behaving, and interacting; and as such is part of the social domain that can be represented as S^n. Combining these together via the generic process symbol (+) yields *+S^n as an abstract representation of science in society. But can we say anything more concrete and useful about this combination? The simple answer is “yes”. As justification, we will expand on this answer via two related approaches.

The first approach is to shed additional light on what is meant by “science in society” through an ME-based analysis of the key themes of the 2009 International Conference on Science in Society (*http://y09.cg-conference.com/*). In brief, the “social impacts of science” reflect how science influences society: *→S^n; the “values and ethics of science” concern the impact of pursuing science on scientists (i.e., people who mentally implement/conceptualize science): *→(*/S)^n; the “pedagogies of science” focus on the transmission of knowledge about science, as implemented/conceptualized in the minds of teachers, to society: (*/S)^n→S^n; the “knowledge making processes of science” consist of scientists creating new knowledge about science for science: (*/S)^n→*; the “politics of science” concerns scientists (people who implement knowledge of science) interacting with each other and with the rest of society: (*/S)^n↔S^n; and the “economics of science” is a bidirectional interaction among scientists, science and society: (*/S)^n ↔*↔S^n.

As an early attempt at characterizing these subjects via ME, these expressions are all open to improvement and refinement; however, even as is, they yield two important messages. First, the expressions formalize and illuminate the interactions covered by the key themes. They involve both unidirectional and bidirectional interactions, as well as three varieties of participants: science, society and scientists (including teachers of science). In toto, the key themes turn out to provide a complete set of interactions: science and scientists influencing society, society and scientists influencing science, and science and society influencing scientists. Second, the expressions reveal that all of the key themes implicate interaction as the dominant process, even when implementation is included (generally to reflect human knowledge as the implementation of part of a domain by a person). What would it mean for society to implement science or for science to implement society? One aspect of this is discussed as part of the second approach to expanding on our “yes” answer.

This second approach is to systematically generate and analyze all possible ME expressions that include society (S^n) as a component, much as was begun in prior work for computing. This full enterprise is beyond the scope of both this article and my expertise, but we can make a start within these constraints by: (1) exhaustively covering all binary combinations of computing and society ($C+S^n$); and (2) highlighting a few noteworthy multi-domain combinations.

Bidirectional interactions between society and computing can be viewed as forms of on-line social networking and groupware – $S^n\leftrightarrow C^n$ or $(S\leftrightarrow C)^n$ – in which computation facilitates interactions and collaboration among people. This includes everything from the World Wide Web to video conferencing and social networking sites (such as Facebook and Twitter). A unidirectional interaction from society to computing – $S^n\rightarrow C^n$ – can be viewed, perhaps a bit more darkly, as the computational monitoring and analysis of society. The computer industry also sits here, although embodying the active influence of society on computing rather than the passive monitoring of society by computing. The inverse interaction – $S^n\leftarrow C^n$ – is one aspect of the societal impact of science, representing both how computers and computational thinking (Wing, 2006) affect society.

Computational implementation/simulation of society – S^n/C^n – is studied in areas such as artificial intelligence and computational sociology, where models are built of societies of (virtual) humans. The reverse direction, in which society implements computing – C^n/S^n – is the domain of Wizard of Oz experiments and Mechanical Turks, where people implement, or substitute for, computation that is otherwise unavailable.

Beyond such binary combinations is a fascinating, and occasionally disquieting, space of more complex possibilities that involve society, computing and additional domains. Examples include large groups of people "living" much of their lives as avatars embedded in online virtual environments and games: $(S^n\leftrightarrow P)/(S^n\leftrightarrow C)$; groups of people with brain-computer interfaces interacting thought-to-thought, possibly at great distances, through these links: $((S/L)\leftrightarrow C)^n$; and groups of intelligent robots, perhaps performing specific service functions or just living out their own lives, comingling freely with people in the real world: $((S/C)\leftrightarrow(L/P))^n\leftrightarrow S^n$. The future of science in society will be increasingly interesting and challenging as more and more of these complex domain combinations approach, or become, reality.

Acknowledgements

This work was made possible by sabbatical support from the USC Viterbi School of Engineering. I would like to thank Peter Denning for a series of interactions that have helped to shape and clarify several of the key ideas presented here.

References

Denning, Peter J. and Rosenbloom, Paul S. (2009). Computing: the fourth great domain of science. *Communications of the ACM*, 52: 27-29.

Rosenbloom, Paul S. (2004). A new framework for computer science and engineering. *IEEE Computer, 37*: 31-36.

Wing, Jeannette M. (2006). Computational thinking. Communications of the ACM, 49(3): 33-35.

About the Author

Prof. Paul S. Rosenbloom
Paul S. Rosenbloom is a Professor of Computer Science at the University of Southern California (USC). He received a B.S. degree from Stanford University in mathematical sciences in 1976 (with distinction) and M.S. and Ph.D. degrees in computer science from Carnegie Mellon University (CMU) in 1978 and 1983, respectively. Prof. Rosenbloom spent twenty years at USC's Information Sciences Institute (ISI), most recently as its Deputy Director. He has also served as Chair of the Association for Computing Machinery (ACM) Special Interest Group on Artificial Intelligence (SIGART) and as a Councilor of the Association for the Advancement of Artificial Intelligence (AAAI). Prof. Rosenbloom was a co-developer of the Soar cognitive architecture, and co-PI of the interdisciplinary, multi-university Soar Project from 1983 until 1998. He was elected a Fellow of the AAAI in 1994. Prof. Rosenbloom is currently writing a book on the structure and scope of computing in a multidisciplinary context, grounded in reflections on his ten years leading new directions activities at ISI.

The International JOURNAL of SCIENCE IN SOCIETY

COMMON GROUND