Knowledge Capture through the Millennia: From Cuneiform to the Semantic Web

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ABSTRACT
As we celebrate twenty-five years of knowledge capture research we can view it from a short-term perspective as a substantial component of the sixty-year development of digital computing technologies, or from a long-term perspective as part of the most recent segment of the hundred millennia evolution of recorded knowledge processes that have shaped our civilization.

We can trace the development of knowledge capture processes similar to those we now study: from the Neolithic origins of our civilization; through the Babylonian development of mathematics and writing; Greek innovations in logic, ontology and science, and their medieval elaboration; the development of formal logics, metaphysical systems and sciences stemming from the scientific revolution; to the computational implementation of knowledge representation, capture, inference and their ubiquitous application in our current information age.

This presentation outlines major events in the trajectory of knowledge capture processes over the millennia, focusing on those relevant to where we are now and where we may be going. It encompasses: the evolution of civilization from archeological, economic, socio-cultural and systemic perspectives; highlights in the formalization of knowledge capture processes through the ages; trajectories of the development of knowledge technologies supporting its representation, capture and use; to projections of expected major issues and advances in the next quarter century.

Categories and Subject Descriptors
I.2.6 Learning – *knowledge acquisition.*

General Terms: Human Factors

Keywords
History of knowledge acquisition, expert systems & artificial intelligence; role in evolution and civilizations; place in infrastructure of information technology; future projections.

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KNOWLEDGE ACQUISITION RESEARCH
A quarter century ago the first Knowledge Acquisition Workshop (KAW) took place in Banff in a wave of enthusiasm—120 papers submitted, 500 applications to attend from 30 countries. After intensive refereeing, 42 papers were accepted and 60 researchers invited to attend. The trigger for the workshop was the explosion of industrial and academic interest in the potential of expert systems as evidenced by the attendance of over 7,000 at the previous year's joint IJCAI/AAAI Conference at UCLA.

The three largest tracks were: *Learning and Acquisition* with 31 papers; *Expert Systems* with 28; *Natural Language* with 28. Some 36% of the 245 papers presented were on these themes that came to dominate the KAW meetings worldwide, but the unexpectedness of this is illustrated by the conference planning where none of the 4 keynotes and only one of the 12 panels addressed these themes.

Evolution of Artificial Intelligence Research
The significance of this growth of interest in expert systems may be seen in terms of the history of artificial intelligence research which took off in the late 1950s with the *Dartmouth Summer Project* [1] in the USA and the *Mechanization of Thought Processes Symposium* [2] in the UK. These occurred as computers came into their second generation, before the advent of computer science as an academic discipline, and when the artificial intelligence metaphor might well have become the core of such a discipline. There was a crisis in the 1970s as computers came into their fourth generation and embryonic computer science departments had to vie with nascent artificial intelligent departments in their requests for major funding to purchase the next generation of computers such as the DEC PDP10.

In Britain the conflict led the Science Research Council to commission a distinguished applied mathematician not associated with the contending applicants to report on the state of the art and future potential of artificial intelligence research. The infamous *Lighthill Report* [3] damned both in sarcastic terms, and undermined the funding of AI research in the UK and USA for seven years—the first so-called *AI winter* [4].

It is ironic that the report only briefly mentions the recognized achievements of DENDRAL [5], overlapped Winograd's [6] doctoral thesis on SHRDLU which marked a major advance in natural language understanding, and was shortly followed by Shortliffe's [7] doctoral thesis on MYCIN that provided the foundations for expert systems research and application. Whilst the immediate impact of the Lighthill report was highly negative for AI research funding, the effect was alleviated in 1980 when MITI in Japan announced its national program for the development of a fifth generation of computers targeted on *knowledge-processing systems* [8-10].

The Japanese program triggered a competitive response in governments around the world: in the USA DARPA's *Strategic Computing Program* (SCC); in the UK the *Alvey Program*; and in the EEC the *Esprit Program*. Major corporations funded their own internal programs and through the 1980s artificial intelligence boomed as never before, particularly that associated with expert system development. The AAAI annual conference had continuing attendances above 5,000 with very large accompanying commercial exhibitions—the call for sites for the 1988 conference estimates attendance at 6,500 and exhibition space at 80,000 square feet.

However, the failure of the Japanese program to produce any meaningful outcomes led to the SCC, Alvey and Esprit programs being discontinued in the late 1980s, and the MITI sixth generation program [11, 12] attracting little interest. A second *AI winter* [13] commenced in 1987 as the associated technology bubble burst and commercial interest in expert systems waned, but had surprisingly little effect on the KAW and other specialist AI communities world-wide.

The reduction in the hype and excessive expectations provided breathing space to reflect on fundamentals, continue to develop and refine techniques and tools, and integrate frameworks from the diverse fields relevant to knowledge acquisition. It had been obvious all along that available information technology provided the means to support and amplify human intelligence, rather than replace it, and we needed to understand the requirements in greater depth and match the technology to them—a slow process of incremental improvement rather than dramatic breakthrough.

Evolution of the World Wide Web

At the 1994 KAW Tom Gruber drew attention to the potential of Netscape's development of interactive protocols for the World Wide Web (web), and set the KAW community the challenge of porting its knowledge acquisition tools to the web. In 1995 the commercialization of the web led to an explosive growth of web-based applications that continues until this day, and the knowledge acqisition community began to play a significant role in the development of what has come to be called the *semantic web*.

Journal publishers' digitization of the bulk of the scientific literature, the growth of mutual help mailing list archives, blogs and wikis encompassing all aspects of human life, and the ongoing project of digitizing all the world's literature, led to an explosion of digitally encoded knowledge in textual and other media becoming not only almost universally available but also a widely accepted and utilized resource in a very short span of time.

It also created a massive information overload that was eventually tamed through Google's indexing technologies [14], and similar developments in the content-based indexing of all materials on corporate and personal computers. In parallel with these new technologies many of the problems that had been targets in the early days of AI, such as text and speech recognition and machine translation, were quietly solved to the extent of become routinely useful, as much through the continuing exponential growth in computing power as through improvements in understanding the nature of the problems and solution techniques.

Web Technology in Knowledge Capture

Web technology is providing access to a high proportion of human knowledge available through contextual indexing in a manner that seems to match well the processes of human memory [15], and provides much of the support for human knowledge processes that had been expected from expert systems. It does so largely through document-retrieval techniques based on content and human-generated linkages with little use of the logical methods and knowledge structures that have dominated AI and KAW research. It 'gives advice' and 'answers questions' by finding relevant pre-existent material that provides the information to enable the human users to infer possible solutions to their problems. DeepQA/Watson [16] does use logical ontologies for some inferences but its answers are based in large part on massive information retrieval and probabilistic evidence combination from many diverse sources.

This raises questions about the integration of the techniques developed in twenty-five years of knowledge acquisition research, most of which have logicist foundations and many of which have been successfully deployed, with techniques of information retrieval and natural language analysis and generation. Will the *semantic web*, based on description logics and formal ontologies to support machine understanding of the information stored on the web, actually become a significant component of the evolution of the web, and, if so, what is the most effective research agenda for its development?—all this against a well-argued background that information technology is moving towards *alien intelligence* [17] and a *singularity cusp* [18] where human and computer intelligences merge.

The historian, White [19], has emphasized the plasticity and metaphorical power of historical accounts—we construct histories for ourselves that both empower and constrain our futures. Setting the history of the KAW/KCAP community within the framework of artificial intelligence and expert systems studies may not provide an appropriate ethos for our current and future research in the much wider context of the semantic web and its role in human society.

The remaining sections frame our activities within a much broader context of the evolution of the human species and human civilization. What are the human needs that the web addresses; what is its place in our biological evolution; how does our current ethos relate to those of our ancestors over the millennia; and how did the intellectual technologies that we bring into play evolve, and why?

These are not normal topics at KAW/KCAP—we have been a specialist community focused on knowledge capture for computer systems that emulate the roles of expert human advisors—but, perhaps, every quarter century we should review our activities within a broader framework.

ROLE OF KNOWLEDGE IN EVOLUTION

Where to start?—*the big bang*—Ayres, a well-respected technological forecaster, wrote a remarkable book, *Information, Entropy and Progress: A New Evolutionary Paradigm*, that provides a coherent systemic model of physical, geological, biological, social and economic evolution, and models skilled activity such as manufacturing as an information process that, for example, creates an automobile by imposing information on matter.

If we conceive of knowledge abstractly as the information we impute to a system to account for its behavior then Ayres' framework shows knowledge processes playing a far wider role than any we normally envision. If we characterize living systems abstractly as *autopoietic* [20] in actively creating conditions for their own persistence, then Ayres' informational formulation allows us to model the fundamental processes of life as being those of knowledge creation, capture and transmission.

Cybernetic/systemic models of such broad scope are fascinating and inspiring but too abstract to have a direct impact on the diverse disciplines they encompass. However, in the past twenty years advances in molecular biology have made DNA sequencing technologies available to archeologists and anthropologists, and enabled information-flow models to be used to expose not just the systemic commonalities but also the mutual constraints coupling genetic, cultural and behavioral processes in living systems.

Oyama's *Ontogeny of Information* [21] is arguably the first such analysis to become widely influential through the *developmental systems theory* community. Jablonka and Lamb's *Evolution in Four Dimensions* [22] provides a unified model of the transmission of variation between living systems encompassing genetic, epigenetic and behavioral sub-systems and their interactions.

From a knowledge capture perspective, we can see such unified models as providing a detailed account of how:

- genomes adapt to the environment through random search, encoding and propagating information that may ensure the fitness of future generations;
- epigenetic processes manage the expression of particular capabilities encoded in the genome 'library' to more rapidly propagate adaptations to major environmental change [23];
- behavioral adaptations are propagated through reinforcement and mimicry, both intrinsically and through pedagogy [24];
- symbolic representations of the information involved in all these processes may be used to facilitate them, amplify their effect, and enable them to be widely diffused through both space and time [25].

The exchange of information between all levels and partitions of living systems provides a common framework for biological symbiosis, psychological foundations of sociocultural systems and, through the symbolic signaling system of 'money,' for economic models of those systems.

Physicists have set a realistic target of a unified *theory of everything* in the physical sciences, but those facing the complexities of the biological and human sciences have felt it foolish to even dream of such for their disciplines. However, quite suddenly, as an outcome of advances in molecular biology and the human genome project, such unification is occurring without it ever having been an envisioned target.

EVOLUTION OF KNOWLEDGE CAPTURE

Where to start?—*out of Africa*—our species, *homo sapiens sapiens*, diverged from *homo erectus* some 500,00 years ago, from *homo sapiens neanderthalis* some 300,000 years ago, developed some form of language some 50,000 years ago, was reduced by environmental catastrophe to a population of some 3,000 in Africa some 50,000 years ago, and through migration commencing in the Levant expanded worldwide, developing community infrastructures and agriculture some 10,000 years ago, defining the Neolithic era of modern humanity. The details are contested in a massive research literature, but the overall framework is widely accepted [26-29].

For most of our history, genetic, epigenetic and behavioral processes dominated our evolution as they do in other animal species, but at some time in the past 100,000 years information came to be communicated and captured symbolically to an extent that gradually came to differentiate us from all other species—"humans became behaviourally modern when they could reliably transmit accumulated informational capital to the next generation, and transmit it with sufficient precision for innovations to be preserved and accumulated." [30, p.809].

The capability to capture and transmit knowledge is generally taken in the archeological and anthropological literatures to be the major factor in the explosion of the human population. Whereas the rate of unconstrained population growth in other species is proportional to the population size, and hence exponential, for the human species it is proportional to the square of the population, and hence hyper-exponential (until 1962 when the population growth rate dramatically declined [31]). The additional multiplier is attributed to the generation and diffusion of knowledge being proportional to the size of the population [31].

Human population growth does not show a smooth growth over recorded history. There have been major die-offs due to climatic factors such as the ice ages, and diseases such as the black death, but the overall trend has been hyper-exponential. One can discern a pattern of trends encouraging the generation and diffusion of knowledge, such as the development of communities around population centres, which also increase the risk to life, for example, by facilitating the development and spread of disease [32, 33].

Note that language and knowledge are not intrinsically 'survival traits'—Bickerton [34] notes that one possible outcome of the power of intelligence is species destruction—Wojciechowski [35] models the growth of knowledge as process whereby more knowledge must be continuously created to combat the adverse side-effects of the application of prior knowledge.

Early Knowledge Capture

The major problem with tracking the evolution of symbolic knowledge capture is that the media used have limited lifetimes, and often do not survive decades let alone millennia [36]. Archeologists are left with a biased sample of the few originals that survived, and historians with the residues of the transcription and copying processes that have attempted to preserve the content as the medium decays. That situation continues in our era as our computer media all have short life expectancies and rely on continuing backup processes for the preservation of their content. However, effective digitization procedures can now guard against transcription errors and ensure exact copying [37].

The earliest examples of knowledge capture where we have a substantial body of material is Babylonian cuneiform writing on clay tablets from some 5,000 years ago. Modern scholarship has decoded many tablets which originated to keep track of trade transactions and inventories [38] and were repurposed to capture mathematical and military procedures [39, 40]. We can also see the beginnings of scientific data collection and modeling in the Babylonian materials where astronomical and weather phenomena are tracked and used to predict political and economic events [41], possibly with some partial success in both cases since the weather affects harvests and prosperity which in turn affects the popularity of rulers.

There was probably some diffusion into later Greek astronomy but overall the outcome appears to be what Burnet [42] in his comments on early Greek science terms one of the *periodical bankruptcies of science*. In this respect knowledge evolution parallels biological evolution in that most innovations end in failure and only a few propagate to become assimilated into the 'genome' of science.

There are strong parallels between the Babylonian development of cuneiform writing and later developments of knowledge capture technologies, including that of computers. What is common is the addressing of timeless human needs with the best available technology of each era:

- The environmental stress of warfare was addressed with cuneiform tablets detailing siege techniques—the first digital computers were developed under the stress of the Second World War for purposes of code breaking and ballistics computations.
- The cuneiform tablets supported administrative record keeping—IBM adopted computer technology postwar to enhance its existing card-based census and business record-keeping systems.
- Cuneiform tablets captured the surprisingly sophisticated mathematical algorithms of that era—computers made operational those of our era.

And so on—the most powerful approach to technological forecasting is to identify the primary social needs of an era and assume that major social resources are being applied to develop and apply effective technologies to address them.

In the era immediately after Babylonian innovations in knowledge capture we find civilizations in India and China making major advances in mathematical, scientific, medical and legal knowledge [43] and capturing them in a variety of scripts on a range of media such as animal hides [36]. The developments that had most impact on western civilization were those of the Greek enlightenment some 2,500 years ago when Euclidean geometry, Socratic dialectic, Platonic philosophy and Aristotelian logic, metaphysics, science and ethics provided the foundations of modern mathematical, scientific, medical, ethical and legal systems [44].

Early Greek civilization captured knowledge primarily in the brains of people and propagated it through an oral tradition that probably extends back at least one hundred millennia but cannot be tracked because it left no record other than brief historical accounts in the later written record. However, by the time of Plato knowledge was being captured in written form using an alphabet deriving from an earlier Phoenician script [45] that continued in a variety of forms thereafter, including an Etruscan variant in Rome that constitutes our current Latin alphabet.

The first major library of which we have detailed accounts are those of Aristotle some 2,400 years ago, collected despite the sarcastic comments of his peers because he regarded it as important to understand the ideas of others in developing his own. A succession of national leaders also saw the importance of collecting the world's knowledge of their era, forming national libraries such as that of Ptolemy at Alexandria some 2,400 years ago where Kallimachos developed techniques of cataloguing and indexing library materials that are similar to those in use today [46].

The preservation of written knowledge was erratic until the invention of printing facilitated the wide dissemination of many copies of major works making it probable that some copies would survive local catastrophes [47]. Aristotle's library was passed to three generations of successors but then stored under conditions where much material was severely damaged [48]. The library at Alexandria was completely destroyed. The Greek knowledge base that provided the intellectual foundations of modern science only survived in substantial part because several later societies attempted to collect and capture it for their own use, notably the Arabic translation movement in Baghdad some 1,300 years ago that both captured the material in Arabic and stimulated an industry of making additional copies of the Greek originals for translation purposes [49].

One can continue the story of knowledge capture and translation, but not within the scope of these few pages—the relevant literature constitutes a substantial component of national libraries. The account above is sufficient to show how major roles now being played by the web have their parallels through the ages:

- The web provides a compendium of human knowledge fulfilling the role of the library at Alexander and its later formulations such Diderot's *encyclopedia* [50] and Wells *world brain* [51]—both of which were seen by their proponents as socially egalitarian and liberating, much as the web is seen today.
- Discussion in the Athenian agora is emulated by mailing lists and interactive blogs where questions and issues may be raised and discussed a community—some participants also exemplify Sextus Empiricus' [52] critical skepticism that provides counter-examples to any established position.
- Aristotle's codification of the abstract schemata for knowledge representation and inference underlies the description logic foundations of the semantic web.

EVOLUTION OF INFORMATION TECHNOLOGY

Where to start?—*infrastructure of information technology*—a major activity of the Knowledge Science Institute (KSI) distinct from those reported at KAW was the modeling and forecasting of information technology [53-55]. The underlying electronics technology has undergone a continuing exponential growth since 1959 with a doubling period of some 1.5 years [56, 57], and this rapid sustained quantitative growth over five decades, unique to information technology, has triggered qualitative structural changes in the nature of the information sciences and their applications.

The KSI tracked these changes, modeling them as a tiered structure of learning curves of sub-disciplines built upon the layers below, and applied this to model the past impact of information technology on many economic sectors and industries and to project its likely future impact.

Figure 1 shows the overall structure of the model extended to 2012 [55]. The underlying learning curve for each tier may be characterized by six phases:

1 The era before the learning curve takes off, when too little is known for planned progress, is that of the *inventor* having very little chance of success but continuing a search based on intuition and faith.

2 Sooner or later some inventor makes a *breakthrough* and very rapidly his or her work is *replicated* at research institutions worldwide.

3 The experience gained in this way leads to *empirical* design rules with very little foundation except previous successes and failures.

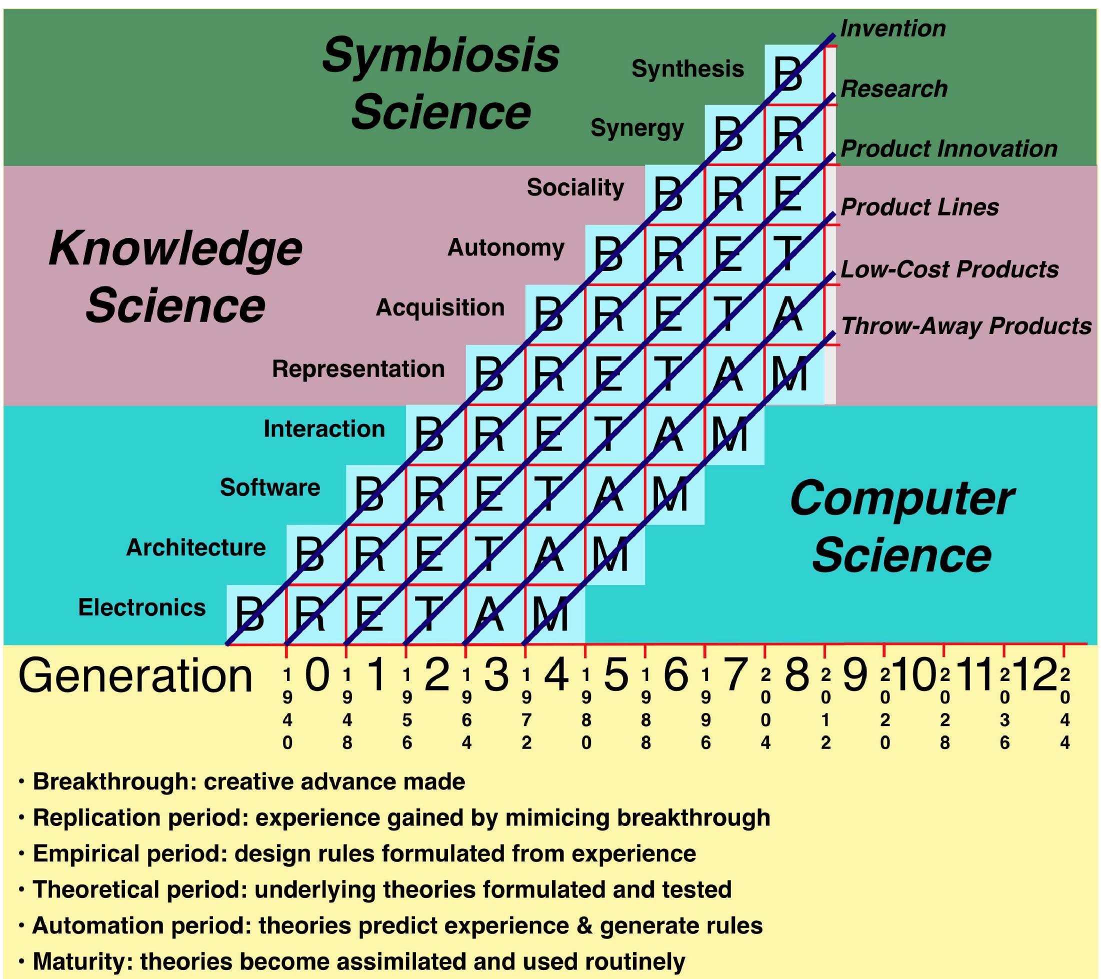

Figure 1 Infrastructure of information technology

4 As enough empirical experience is gained it becomes possible to inductively model the basis of success and failure and develop *theories*. This transition from empiricism to theory corresponds to the maximum slope of the underlying logistic learning curve [55].
5 The theoretical models make it possible to *automate* the scientific data gathering and analysis and associated manufacturing processes.
6 Once automaton has been put in place effort can focus on cost reduction and quality improvements in what has become a *mature* technology.

Empirically, from an analysis of several thousand events in the history of the computing and the information sciences, we identified the time-scale of each phase, and hence each computer generation, as 8 years.

We identified the different tiers as being:

- the underlying digital *electronics*;
- its application in computer *architectures*;
- the programming of general-purpose computers through *software*;
- the development of computer-people and computer-computer *interactivity*;
- the *representation* of human knowledge;
- the *acquisition* of additional knowledge from interaction with the world, people and stored knowledge;
- the development of goal-directed *autonomous* knowledge creating processes;
- the increasing coupling of knowledge processing entities in *social* networks;
- the development of techniques to facilitate the *synergy* between human and computer knowledge processes;
- the *synthesis* of both into a unified system.

We characterized the theory of the lowest four tiers as constituting *computer science*; of the next four as *knowledge science*—the focus of the KSI; and project those above to form a currently developing *symbiosis science*.

When the KSI was formed in 1985 [58] we saw the knowledge acquisition tier as having achieved major breakthroughs and to be in a research phase on the verge of the transition to the empirical phase where product innovation occurs. The development of knowledge acquisition techniques and tools was established as a second major project area, and contacts were made internationally with others having related interests, in particular John Boose at Boeing Computer Services, the co-founder of the KAW community.

Twenty-five years later the knowledge acquisition learning curve is on the verge of the transition from automation to maturity. What characterizes that stage is the weight of knowledge required to make a meaningful contribution, and a small number of major products which are well-established and difficult to displace, for example, the Protégé [59] tool for logical knowledge modeling, the WebGrid [60] tool for conceptual modeling, and the Google [14] search engine for textual knowledge indexing.

Note that the maturity of the learning curve does not indicate that research and innovation ceases, only that it becomes increasingly difficult. Innovative research continues on syllogistics that matured two millennia ago and on matrix algebra that matured over a century ago, but it is very rare and requires an immense depth of knowledge of the existing literature.

From this perspective, one would expect the knowledge acquisition research community to become increasingly specialized, managing a repository of expertise that is significant to research and development in the tiers that build upon it, and responsible for incorporating advances in the fields upon which it builds in order to provide state-of-the-art techniques and tools.

CONCLUSIONS

This article presents a number of perspectives on knowledge capture that enable us to construct histories for our community that empower and constrain our futures in interesting ways. Considering the choices available seems an appropriate agenda for our twenty-fifth anniversary. They are neither mutually exclusive nor exhaustive—just food for thought—what will be our themes, targets and agendas for the next twenty-five years?

In general there is a continuing need to consolidate and extend all that we know of knowledge capture processes and techniques, drawing upon all literatures and disciplines to support our stewardship of the state-of-the-art in knowledge acquisition. That includes the need to continue to enhance the tools we make available to take advantages of developments in knowledge representation and computer technologies.

We also need to track user requirements for knowledge capture technologies to support both the needs of those applying them and the innovations in knowledge capture that may be outside of, or substantially extend, our current frameworks. In particular, the original logicist framework that has dominated artificial intelligence and expert systems research, may need substantial extension to support knowledge capture systems that incorporate the information indexing techniques of the web.

Modeling 'Muddling Through'

One of the continuing major issues for our community is that all knowledge capture and transmission assumes some degree of *cognitive commonality.* This is a difficult notion, with connotations of *collective cognition* [61, 62], *collective rationality* [63, 64], *organizational knowledge* [65, 66] and the extent to which we do actually use what we regard as *shared concepts* in the same way [67].

Sextus Empiricus criticized Greek philosophers' focus on exact definitions, noting that "we must allow ordinary speech to use inexact terms" [52, Anim.Math.129]. Hattiangadi [68, p.15] notes that "our understanding of language is approximate—I do not believe that we ever do understand the *same* language, but only *largely similar* ones."

A miracle of human social existence is that we manage to 'muddle through' despite major lack of cognitive commonality [69]. Computer tools have the same issues as those of a human learner coming to calibrate their cognition against the norms of their communities, and can only develop approximate models with which we can, hopefully, muddle through in an improved fashion. We need to develop a science of such *muddling through* that models human use of open concepts to capture and transmit knowledge, and to come to comprehend the value of what might appear to be a logical defect as a necessary capability for coping with a complex and incompletely knowable world.

Much of what is needed for such a science already exists in older literatures that have become neglected since the advent of mathematical logic. In writing a recent paper [70] on the foundations of semantic networks as visual languages for description logics for a journal targeted on philosophy and linguistics, I developed the logical constructs of description logics through examples drawn from the philosophical literature. I was surprised to find that I had encompassed most of the classical knowledge structures, such as determinables, contrast sets, genus/differentiae, taxonomies, faceted taxonomies, cluster concepts, family resemblances, graded concepts and frames, using only the two connectives of Aristotelian syllogistics. I added the truth-functional connectives necessary to definitions and rules as simple extensions of these connectives through Koslow's [71] constructions for substructural logics.

In a follow-up paper on human rationality within a universal logic framework [63], I suggested that the reasoning processes of people, outside the realm of mathematics, could best be modeled as based on open concepts having only necessary conditions used abductively through inference to the best schema. Under conditions of complete knowledge this is equivalent to the use of definitions and rules, but it also models the non-monotonic process of muddling through with incomplete knowledge.

I predict that we will need to extend the logical frameworks for knowledge capture using the major advances being made in theories of substructural and universal logics in order to incorporate natural language indexing and 'understanding' within our knowledge capture frameworks, but that much of the theory we need is already available.

Knowledge capture is intrinsically a major component of all the developing tiers above it in the infrastructure of information technology shown in Figure 1. It is clear from the papers at recent KCAP's that we have moved well beyond the original objectives of supporting the development of 'expert systems.' I hope this presentation provides an interesting and provocative framework for what our research community is doing now and what it will do in the future. May you all live in interesting times.

To end on a personal note, I would like to express my thanks to those present, and to absent friends and colleagues, who have constituted the knowledge acquisition community, and made our world-wide meetings both a brief haven from the pressures of our working careers and a source of ideas, challenges and understanding that have stimulated us to new achievements each year. We have been part of one another's extended intellectual family, and it has been a pleasure both to participate and to see the community continue to thrive.

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