THE HANDLING OF UNCERTAINTY

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ABSTRACT
We argue that evidential logics based on a variety of non-classical frameworks, implementable with such machinery as extensions of logic programming and neural networks, will play an increasing role over the coming decades. These logics will provide frameworks for further improving both the intelligence of AI-related computer-based systems, and the fit of human discourse systems to the mainly evidential knowledge, which we most often have. Further, by increasingly adopting such evidential knowledge representation and processing frameworks, computer-based domains and human domains will come to increasingly *share the same language and logic*, which in turn will lead to substantial improvements in the problematic computer-human interface.

Theories are nets cast to catch what we call "the world": to rationalize, to explain, and to master it. We endeavor to make the mesh ever finer and finer. - Karl Popper, *The Logic of Scientific Discovery*, p. 59

INTRODUCTION

Our knowledge is often less than certain. Indeed, it is regularly the case, both in scientific domains and in the myriad circumstances of daily human interaction, that what we have to deal with is *evidence*. This evidence is often only partial and tentative (Faust, 1999) and consists of both "evidence in favour" and "evidence against". It is these evidential predications with which we routinely deal.

Yet, for over two thousand years the logic, and its language, for dealing with this uncertainty, has been the logic of *absolute certainty*. This logic of absolute certainty, usually called Classical Logic (CL), allows us to assert a statement only in absolute terms. Let P be such a statement.

For example, in the realm of a computer-based robotic environment, P might be the assertion that "repair #47 is required on robotic arm #23". Sensors will have provided data on the condition of the robotic arm and the nature of its malfunctioning, and from these data evidence in favor (confirmatory evidence) and evidence against (refutatory evidence) the appropriateness of repair #47 on robotic arm #23 will have been derived. That is, we have in hand confirmatory evidence regarding P and refutatory evidence regarding P. This is in fact the knowledge we have. Yet CL requires us to know *with absolute certainty*, a level of certainty we do not often, if indeed ever, have: CL does NOT meet our needs.

Similarly, in the realm of daily human interaction, P might be the assertion that "social justice can be better advanced by implementing plan A than plan B". Careful analyses of the complex web of human conditions and potentialities, together with extensive public debate, will have provided data relevant to P. From these data, evidence in favor (confirmatory evidence) and evidence against (refutatory evidence) assertion P will be distilled. That is, we have both confirmatory and refutatory evidence regarding P: that is the knowledge with which we have to work. Yet CL requires unrealistically that we have knowledge of P at the level of *absolute certainty*. Again here as well, this is a level of certainty we just do not have: again CL does NOT meet our needs.

This misfit, between our knowledge, which is so often less-than-certain, and the Classical Logic of absolute certainty we have traditionally used to represent that knowledge, is a misfit we are finally making some progress in overcoming. In this paper we will try to gain a perspective on this progress which will help us to better see where, over the coming decades, we may be able to continually move forward, in both the computer-based and human domains, in building and utilizing improved knowledge representation frameworks which better fit the evidential knowledge with which we most often have to deal. First we will survey some of the history of this progress, helping us to be able to discern productive future directions. Then we will briefly describe a new logic, called Evidence Logic (EL), which allows for the representation and processing of evidential knowledge. Following this, we will use EL to help us look to the near-term future in computer-based domains and human domains respectively. Finally, we will synthesize the evidential perspective for computer-based systems and the broader human context, arguing the essential role this perspective will play in any future progress at the level of the computer-human interface.

IMPROVING ON A 2000 YEAR-OLD TRADITION

Although our historical survey will be brief, we must start with Aristotle who, over two thousand years ago, observed "to say of what is that it is or of what is not that it is not, is true; to say of what is that it is not or of what is not that it is, is false". Thus begins, roughly, the first steps in Man's analysis of the nature of truth and the development of logics for representing our knowledge (Faust, 1999). Classical Logic (CL) provides a framework for representing absolute knowledge: every statement is true or false.

Aristotle's "syllogistic logic" presented, and analyzed the nature of, the logic of 'all' and 'some' with respect to unary (one-place) predications. Regarding the latter, his logic considered only predications like Hx: x is a horse or Gx: x is green; it did not consider at all binary predications like Bxy: x is the brother of y, ternary predications like Txyz: x is a friend of a child of y and z, or indeed n-ary predications for any n > 1. Further, throughout the Middle Ages, this very limited analysis continued in excruciating detail. Excellent work was done regarding the complex nature of the problematic concept of negation, especially by the Indian logicians of the Nyaya tradition (Matilal, 1968), but the focus continued to be on just one-place predicates and on the Classical Logic of absolute certainty.

Initial attempts to broaden the scope and depth of logic can be seen throughout the Renaissance, and certainly Leibniz deserves mention for his valiant attempts to develop a "universal logical language". However, it was not until the nineteenth century did we begin to take giant steps forward. For example, George Boole, in The Laws of Thought first published in 1854, although primarily focused on the algebraic structure of Classical Logic, ruminates seminally over the relationship between evidence and knowledge, that "with the degree of information which we possess concerning the circumstances of an event, the reason that we have to think that it will occur ... will vary", that as the evidence for a proposition increases so will our confidence in the possibility of the occurrence of the event described by that proposition (Boole, 1958, p. 244).

This progress, during the second half of the 19th century, continued apace throughout the twentieth century. Let us first note the Polish logician Jan Lukasiewicz and two of his many seminal contributions. Early in the century, he published a paper (Lukasiewicz, 1910) wherein he carefully disputed Aristotle's venerated arguments (Aristotle, 1933) for the absolute certainty that P and NOT P could never both be true at the same time.

This was such an important step forward, for it helped to illuminate the 'brittle' character of Classical Logic and to raise important questions about the 'goodness of fit' of Classical Logic to the meager knowledge we so often have about reality. He also did ground-breaking work in *multi-valued* logics, helping to move forward the building of new logics transcending Classical Logic and providing knowledge representation and processing schemes better suited to the handling of uncertainty.

Indeed, the whole first half of the twentieth century was rich with seminal work raising deep and helpful questions about the nature of human knowledge and the logics we 'ought to be building' to improve upon Classical Logic and provide better machinery for representing and processing our uncertain knowledge. Workers like Bertrand Russell and Ludwig Wittgenstein, and centers of research like the *Vienna Circle* in Austria and the *Lvov-Warsaw School* in Poland, and similar centers in, among other places, Prague and Berlin, all helped to advance our understanding of the nature of both scientific and general human knowledge. The wonderfully incisive paper (Russell, 1923), arguing that in fact *all* knowledge is vague, is a fine example.

The second half of the century, however, was when much of the 'soul-searching' of the first half of the century began to give rise to very significant progress. Many non-classical logics were designed and studied carefully, "fuzzy" logics which allowed many different 'evidence levels' or 'truth levels' which were often any number between 0 and 1 or even an interval of such numbers, where usually 0 designated false and 1 designated true. To cite one further example, paraconsistent logics, where a contradiction can arise without trivializing the logic by making every sentence thereby derivable, were defined and studied.

All of this work of the last century continues to blossom in the new century, bringing forth further research on a helpful variety of non-classical logics to help us begin to deal more effectively with uncertainty. As we will see in Sections 4 and 5, we are indeed just at the beginning of this long trek of building logics better fitted to our actual knowledge of the world and therefore better able to represent and effectively process that knowledge.

AN EXAMPLE: EVIDENCE LOGIC (EL)

First, we need a space of evidence values which a predication could have associated with it. EL will use an Evidence Space $E_n = \{i/(n-1): i = 1,\ldots,n-1\}$, for fixed $n > 1$, with smallest evidence value and evidence increment $\epsilon = 1/(n-1)$. At the implementation level, more finely-grained evidence 'packets' in the application domain will require a larger choice for n, while the implementation hardware and software will impose an upper limit on the choice for n. Usually we will use a variable name e to stand for an arbitrary evidence value. For example, if $n = 11$, then we have an evidence space consisting of the ten evidence values .1, .2, ..., .9, 1 with evidence increment $\epsilon = .1$, and e would range over these ten values.

Now, for any predication, we can assert, at any evidence value e, that there is confirmatory evidence for the predication at level e and/or there is refutatory evidence for the predication at level e. Although arbitrary predications can be easily handled (Faust, 2000), in this brief survey let us explicate EL just in terms of sentences with no variables at all, what we call in logic "propositional sentences". So let P be a proposition. For example, P could be "machine #27 is currently operating at an unsafe speed" or "the economy will be improved if sector #8 is given more expansion incentives".

We are ready now to give some indication of the fundamental syntax innovations involved in EL which provide it with expressive power exceeding CL. First, in EL we can express the assertion that "there is confirmatory evidence at the evidence level e for P", as P_c:e.

And further, in EL we can also express the assertion that "there is refutatory evidence at the evidence level e regarding P", as P_r:e.

So, for example, if P asserts "machine #27 is currently operating at an unsafe speed", then P_c:.7 AND P_r:.5 asserts that there is confirmatory evidence at the .7 level that machine #27 is currently operating at an unsafe speed and that also there is refutatory evidence at the .5 level that machine #27 is operating at an unsafe speed. Note that this *evidential conflict* expressed by the above sentence of EL, the presence of considerable conflicting evidence in regard to P, is very common in both computer-based systems and the broader human arena. Indeed, the widely used common phrase, to "weigh the pros and cons", reflects the ubiquity of this sort of phenomenon. We encounter such evidential situations very often, and it is a major feature of the new logic EL that it contains machinery which can handle these situations.

Further, the lack of any axiomatized correlation in EL between confirmatory and refutatory evidence is intentional, providing a framework where the rich variety of such correlations can be represented and analyzed. This is in sharp contrast to, for example, the standard probability theory where the basic theorem that Probability (NOT E) = 1 – Probability (E) for any event E, although appropriate in many application areas, is too stipulative to provide a *foundational framework*, like EL, where one can express and study a multitude of potential relations between the confirmatory and the refutatory.

Penultimately, in this brief introduction to EL, let us note how EL provides also machinery for distinguishing "absence of evidence" and "evidence of absence". For example, NOT P_c:.6 asserts an *absence of evidence* confirming P at the .6 level, while P_r:.2 asserts *evidence of absence* in that it asserts evidence refuting P at the .2 level. Using EL, we can clearly see here that these two knowledge assertions are substantially different.

Finally, consider how we would express in EL "absolute knowledge that P holds", a level of knowledge rarely, if ever, attained when P is speaking about the real world. Although EL is specially equipped with machinery to express less-than-certain evidentials, it may be argued that "absolute knowledge that P holds" is captured adequately in EL by the sentence P_c:1 AND (NOT P_r:ϵ) which asserts that there is the highest possible level of confirmatory evidence for P and also the absence of even the smallest possible level of refutatory evidence for P (Faust, 1997).

The reader is referred to other papers (Faust, 2000 and 2001) which provide careful analyses of the structure of EL, proving theorems which elucidate the Boolean Sentence Algebras of the various families of EL which attain as the language is stipulated to contain various predicates and functions.

In each AI application domain, the evidence logic EL will involve some stipulated collection of predicates and functions, plus some axioms reflecting the nature of that particular domain, and the resulting *domain theory* will have associated with it a rather complex infinite Boolean Sentence Algebra. Careful analysis of these Boolean Algebras, as is presented in these two papers, sheds considerable light on the mathematical structure of the associated domain theories.

Hence, readers will find that these two papers provide a deeper formal analysis of EL and its applications in AI. In particular, in (Faust, 2001) various families of axiomatizable extensions of EL are studied, extensions which reach out in carefully stipulated ways to a rich variety of domains which commonly occur across a broad range of application areas.

HANDLING UNCERTAINTY IN COMPUTER-BASED SYSTEMS

When we contemplate the degree of 'intelligence' of computer-based systems, there is rather broad agreement that we have a long way to go yet. Of course, part of the problem is hardware-based, and we can look forward to the continuation of great strides in this regard over the coming decades. But part of the problem is also clearly software-based, and it is this side of the problem that is the focus of this paper. Certainly there has been, and continues to be, much progress in this regard. However, there is much room for further improvement in the coming decades.

Here I would like to focus briefly on the potential for greatly decreasing the 'brittleness' of intelligent systems, for greatly increasing the ability of the system's knowledge representation and knowledge processing schemes to more flexibly handle the evidential knowledge with which it so often is faced.

Of course, EL is an example of a knowledge representation and processing scheme of this type. However, in the coming decades we must give much effort to carefully designing and implementing the way the processing goes forward. In many domains we desire better intelligence, not just in the processing itself, but also in the control of the processing. For example, in a computer-based environment involving evidential knowledge, "[c]onclusions will sometimes have a degree of uncertainty to them. Such less than certain conclusions may thrust themselves upon us by necessity, because of unclear information or because a real-time processing environment precludes the luxury of complete argumentation to a crisp conclusion. Or such conclusions may in fact be preferred, for example, because crisp conclusions are not required for the triggering of appropriate action." (Faust, 2000, p. 479)

Here we see how important intelligent control of the processing itself will be in increasing the intelligence of the system. Indeed, this level of control exposes some of the factors involved in real human intelligence, namely the ability to know when 'enough' evidence has been collected and processed, when the evidence has reached a 'sufficiently high degree of affirmation' so that action may be 'intelligently' taken. Such subtleties of human intelligent behavior are clearly more likely to become implementable in future computer-based intelligent systems if those systems utilize, in their knowledge representation and processing engines, evidential frameworks which go substantially beyond Classical Logic in directions exemplified by EL.

To wit, with such systems we will be able to work toward embedding the intelligence of how to "fish or cut bait" evidence-wise as we humans do routinely all day long, how to realize when the level of certainty thus far ferreted out is sufficient to draw a reasonable conclusion and take appropriate action, how to be intelligently decisive the way humans so regularly are every day.

HANDLING UNCERTAINTY IN HUMAN DOMAINS

As in computer-based domains, in domains of human interaction there is also much room for improvement. Here we concentrate on one foundational aspect of this interaction: the knowledge representation and knowledge processing schemes through which the communication and interaction takes place. An example may help to clarify why schemes based on EL may well provide an improvement over present schemes based on Classical Logic.

Often when two people, or more broadly two groups or two societies, argue about some position or potential action, they do so in absolute terms. In other words, they use Classical Logic. Since our knowledge is, however, only evidential and hence not absolute, *both are wrong*. And, worse still, each party will argue that it is right since the other is wrong: so, *both are right*. Hence we get a mess indeed, and a quagmire that attains constantly in our real world of 'position staking' and fruitless argumentation using the far too meager framework of Classical Logic.

Our suggested evidential framework gets us out of this mind-boggling dilemma, or such absurd and unproductive polarization, and provides tools for an enhanced discourse able to uncover agreeable compromises upon which productive action can be based. With knowledge representation and processing schemes which are evidential like EL is, positions are no longer absolutist. Rather, positions are clearly stated as simply 'evidenced', with some confirmatory and some refutatory evidence regarding the position.

Hence the two sides can get beyond the unrealistic right or wrong dichotomy of Classical Logic which creates so much trouble and indeed erects unnecessary impasses to debate and understanding. Classical Logic just doesn't fit the data they have. But EL better fits this evidential knowledge they have, and utilizing it they will be able to communicate better and move toward the triggering of appropriate compromises, compromises acceptable to both sides since they 'adequately fit' the evidential data upon which both have constructed their positions.

THE MELDING OF THE COMPUTER-BASED AND HUMAN SPHERES

In Sections 4 and 5 we have seen advantages for progressively moving toward the increased use of evidential knowledge representation and processing schemes in both computer-based and human domains. But there is a further, and just as clear, advantage, having to do with the very complex and problematic *interface* between these two domains, the infamous computer-human interface. What exactly is that further advantage, which can help pave the way for continued improvement of the computer-human interface?

Roughly, it is as follows. Having improved the computer-based domain by replacing Classical Logic with an evidential logic such as EL, and having similarly improved the human domain by replacing its communication/argumentation foundation of Classical Logic likewise with an evidential logic such as EL, a further advantage accrues. Namely, the computer-based and human domains are now operating on the basis of a *shared* knowledge representation and processing framework. Hence many of the seemingly intractable, or at least very difficult, computer-human interface problems disappear or at least are substantially mitigated. At the interface, they are speaking a common language, a language of evidence, of confirmatory and refutatory evidence, of evidential data, evidential inferences, evidential conclusions, evidential decisions, and evidential action assertions.

Not only are the computer-based system and the human discourse in a language that better fits the knowledge to be had most often about the real world, the computer-based system and the human are talking the same language. This may help substantially as we move forward over the coming decades to make this interface more and more seamless, which is surely of crucial importance in the work of increasing computer-human interaction, understanding, and cooperation.

Diagrammatically, computer-based and human-based systems, both becoming increasingly founded upon evidential frameworks, move toward an increasingly evidential discourse at the computer-human interface (Figure 1).

There, at the computer-human interface, both domains will be using a language and a logic better fitted to the reality of less-than-certain knowledge with which they both work. Indeed, since it is the same language and logic, a *shared*

Computer Based Systems → THE COMPUTER-HUMAN INTERFACE: evidence-based languages and logics for knowledge representation and processing ← Human Based Systems

Figure 1. The Computer-Human Interface

language and logic, their discourse at this crucial computer-human interface will be progressively improved.

Beside the positive aspects of moving toward the improvements argued briefly here, we need also to ponder, and work to ameliorate, impediments on both sides. Let us mention one important impediment in regard to each side.

With regard to moving toward computer-based frameworks which are evidential like EL, some would be reluctant to do so, arguing that we should not introduce such "fuzziness" into the computer's linguistic framework. However, if one reflects on this criticism, it is quickly seen to be spurious: the computer-based system itself is still as crisp as it always was; it is just the information that it is dealing with which involves uncertainty so as to better fit our knowledge of the real world.

Further, with regard to moving toward human frameworks which are evidential like EL, some refuse to adjust their understanding of human knowledge from an absolutist view to an evidential view. Certainly at present, and probably for a long time to come (Faust, 1999, p. 4), evidential knowledge is the best we have and it behooves us to work to bring about a better understanding of this fact. For example, some of these 'refusers' cite (far too often, genuflectingly) scientific knowledge, and especially mathematical knowledge, as instances where our knowledge is certain: we need to point out to them the "modeling" nature of both science and mathematics (Faust, 1989 and 2002), that what is being done in science and mathematics is to build approximative systems which fit the reality only fairly well (Faust, 1999, p. 3) and hence usually, if not always, provide only less-than-certain evidential knowledge.

CONCLUSION

We have explored some of the advantages of using evidential knowledge representation and processing frameworks in both computer-based and human domains. Using Evidence Logic (EL) as an example of such a framework, we explained a bit about the linguistic and logical machinery involved in EL and how it might be used efficaciously in handling uncertainty in both domains. Finally we have argued that, in addition to the utility of EL in both domains separately, there may be also an added advantage of facilitating further improvements over the coming decades in the persistently problematic area of the computer-human interface.

Emphasizing these advantages of evidential frameworks, while carefully providing argumentation and experimental implementations which can serve to allay the skepticism of nay-sayers, research and development in this area over the coming decades should contribute to significant advances in computer-based systems, human systems, and the computer-human interface where we seek to knit them together.

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