CONTRIBUTIONS to SCIENCE, **2** (1): 9-22 (2001)
Institut d'Estudis Catalans, Barcelona

Contributions to artificial intelligence: the IIIA perspective

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Abstract

Artificial intelligence is a relatively new scientific and technological field which studies the nature of intelligence by using computers to produce intelligent behaviour. Initially, the main goal was a purely scientific one, understanding human intelligence, and this remains the aim of cognitive scientists. Unfortunately, such an ambitious and fascinating goal is not only far from being achieved but has yet to be satisfactorily approached. Fortunately, however, artificial intelligence also has an engineering goal: building systems that are useful to people even if the intelligence of such systems has no relation whatsoever with human intelligence, and therefore being able to build them does not necessarily provide any insight into the nature of human intelligence. This engineering goal has become the predominant one among artificial intelligence researchers and has produced impressive results, ranging from knowledge-based systems to autonomous robots, that have been applied to many different domains. Furthermore, artificial intelligence products and services today represent an annual market of tens of billions of dollars worldwide.

This article summarizes the main contributions to the field of artificial intelligence made at the IIIA-CSIC (Artificial Intelligence Research Institute of the Spanish Scientific Research Council) over the last five years.

Resum

La intel·ligència artificial (IA) és un camp científic i tecnològic relativament nou dedicat a l'estudi de la intel·ligència mitjançant l'ús d'ordinadors com a eines per produir comportament intel·ligent. Inicialment, l'objectiu era essencialment científic: assolir una millor comprensió de la intel·ligència humana. Aquest objectiu ha estat, i encara és, el dels investigadors en ciència cognitiva. Dissortadament, aquest fascinant però ambiciós objectiu és encara molt lluny de ser assolit i ni tan sols podem dir que ens hi haguem acostat significativament. Afortunadament, però, la IA també persegueix un objectiu més aplicat: construir sistemes que ens resultin útils encara que la intel·ligència artificial de què estiguin dotats no tingui res a veure amb la intel·ligència humana i, per tant, aquests sistemes no ens proporcionarien necessàriament informació útil sobre la naturalesa de la intel·ligència humana. Aquest objectiu, que s'emmarca més aviat dins de l'àmbit de l'enginyeria, és actualment el que predomina entre els investigadors en IA i ja ha donat resultats impresionants, tan teòrics com aplicats, en moltíssims dominis d'aplicació. A més, avui dia, els productes i les aplicacions al voltant de la IA representen un mercat anual de desenes de milers de milions de dòlars.

Aquest article resumeix les principals contribucions a la IA fetes pels investigadors de l'Institut d'Investigació en Intel·ligència Artificial del Consell Superior d'Investigacions Científiques durant els darrers cinc anys.

Keywords: Artificial intelligence, fuzzy logic, similarity-based reasoning, automated deduction, constraint satisfaction, conceptual modelling, information fusion, case-based reasoning, machine learning, intelligent agents, autonomous robots

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Artificial intelligence began in the late fifties as a field concerned with studying the nature of intelligence by using computers as a new and revolutionary tool to produce intelligent behaviour. The main hypothesis was that the best way to study intelligent behaviour was to build it artificially in a computer. Initially, the main goal was a purely scientific one, understanding human intelligence, and this remains the aim of cognitive scientists. However such an ambitious and fascinating goal is not only far from being achieved but has yet to be satisfactorily approached. Fortunately, there was also a secondary, engineering goal: building systems that are useful to people even if the intelligence of such systems has no relation whatsoever with human intelligence, and therefore being able to build them provides no insight into the nature of human intelligence. This engineering goal has become the predominant one among artificial intelligence researchers and has produced impressive results, ranging from knowledge-based systems to autonomous robots, that have been applied to many different domains. Furthermore, artificial intelligence products and services today represent an annual market of tens of billions of dollars worldwide.

This article summarizes the contributions and main results of the IIIA (Artificial Intelligence Research Institute) in the field of artificial intelligence during the last five years: 1996 to 2000. For a description of the contributions from 1985 to 1995, the reader should refer to the following web site: http://www.iiia.csic.es/History/.

The IIIA is a leading artificial intelligence research laboratory in Spain and belongs to the Spanish Council for Scientific Research (CSIC). Since 1994, the IIIA has been located in the campus of the Autonomous University of Barcelona. It was created out of the AI research group that has existed at the CEAB in Blanes since 1985.

On average, the IIIA has had about twenty five members per year during the last five years and, in total, around sixty people (including visiting researchers and Masters and PhD students) have been members of the IIIA over the past fifteen years. Most of these researchers have a background in computer science, electrical engineering, physics or mathematics. Twenty-three students have completed their PhD work at our institute and more than thirty students have completed their Masters degree. The IIIA has also organized many workshops and conferences and has contributed to the setting up of new scientific journals, in particular the European AI journal: AI Communications.

On average, about 40% of the institute's total funding (approximately 200 million pesetas per year including salaries) comes from competitively obtained external research grants (a total of 49 since 1986), from the European Community (14 grants), the Spanish government (23 grants), the Catalan government (3 grants), private companies (8 grants), and a joint Spain-US project. We also receive additional funding as a «consolidated group» from the Catalan government.

A balance between fundamental research and applications has always been our concern. Various theoretical foundations, at the leading edge of the field, have been developed, including: mathematical foundations of fuzzy logic, approximate reasoning models based on fuzzy and multi-valued logic, automated deduction in multi-valued logic, possibilistic logic and higher order logic, conceptual modelling and languages, efficient constraint satisfaction algorithms, similarity logic and consensus theory. Also, in connection with this fundamental research, many working systems, languages, and tools have been built: knowledge-based systems, multi-agent systems, machine learning systems, case-based systems, intelligent agents and autonomous robots. This research has always been guided by concrete and challenging applications in fields such as medicine, biology, electronic commerce, personal information agents and music. Several of the above-mentioned systems, tools and applications have been distributed outside the institute and in some cases have been commercialised. In addition, ISOCO, a spin-off company of the IIIA, was set up in summer 1999 and is dedicated to the design of intelligent software components for Internet-related applications. Today, with more than 160 employees, it is already a leading company within its sector in Spain.

The articles published by IIIA members over the last five years (a total of 355 or 2.84 per person per year) account for almost half of the total Spanish publications in the main AI journals and conferences during this period.

IIIA researchers have been awarded, among other prizes, the DEC European Artificial Intelligence Research Award in 1987, the ECAI best paper award in 1992, and the ICMC (International Computer Music Conference) best paper award in 1997. In addition, some IIIA members are, or have been, present on the editorial board of more than twenty international journals, they are systematically requested to review papers submitted to the best international journals and conferences, they participate in the programme committees of the main AI conferences, and are invited to give talks at international conferences.

Intensive collaborations have taken place with both industry and academic institutions from many countries but particularly with France, Belgium, the Netherlands, Italy, Germany, the United Kingdom, Denmark, Slovenia, the United States, Mexico, and Argentina. The IIIA regularly receives visiting researchers from other universities and research institutions. Postdoctoral and senior researchers from the USA, the United Kingdom, France, Belgium, and the Netherlands have all chosen the IIIA for their research stays abroad.

This article is organized into eleven different sections that describe in some detail the major recent contributions of IIIA scientists to different aspects of artificial intelligence. I acknowledge the invaluable help of the following IIIA scientists in preparing this article: Jaume Agustí, Gonçal Escalada, Francesc Esteva, Lluís Godo, Jordi Levy, Pedro Meseguer, Enric Plaza, Carles Sierra, and Vicenç Torra.

Foundations of mathematical fuzzy logic

The term «fuzzy logic» has been used in the literature with two different meanings. In a wide sense, fuzzy logic applies to any technique involving some elements of fuzzy set theory. In a narrow sense, fuzzy logic refers to the mathematical logical systems, generally many-valued logical systems, which underlie the above-mentioned techniques, and which until very recently lacked a formal basis. A lot of research has been done on fuzzy logic «in the narrow sense» with remarkable results, due in part to fruitful collaborations with Prof. Petr Hájek (Prague, Czech Republic), since the mid nineties, and, more recently, with Prof. Montagna (Siena, Italy) and Prof. Cignoli (Buenos Aires, Argentina). The main results obtained concern the axiomatization of several t-norm based residuated logics: product logic [53], completeness of Hájek's basic fuzzy logic BL [22], residuated logics with involutive negation [41], Lukasiewicz product logic [42] and monoidal t-norm based logic [40]. Another important result has been the modelling of probability in the fuzzy logic setting [52] and the expression of fuzzy inference as deduction in some of these types of logic [47].

Similarity-based reasoning

The notion of similarity among knowledge states plays an important role in different inference patterns of approximate reasoning. Two relevant examples are the reasoning mechanisms used in fuzzy rule-based systems and in case-based reasoning. A fuzzy rule-based system interpolates rule consequents according to the degree of match between actual variable values and those in the rule premises. In doing so, the system extends the domain of application to system states which are similar to those described in the fuzzy rule base. On the other hand, case-based reasoning techniques follow an analogy principle which states that similar problems have similar solutions, leading – naturally – to a formalization using similarity-based reasoning. Research on similarity-based reasoning, in close collaboration with the group of Profs. D. Dubois and H. Prade from IRIT (Toulouse, France), has focused on two major issues:

Logical foundations of similarity-based reasoning

We have addressed several fundamental problems ranging from semantic to syntactic considerations, one being based on two graded similarity-based consequence relations [27, 28], which allow an interpolation mechanism to be defined, and another on graded logics, both classical [38] and many-valued [48], for which completeness results are provided. Their relationship to other kinds of graded logical formalism, like possibilistic logic, have also been considered [37, 39].

Similarity-based reasoning and case-based reasoning and decision

We have used fuzzy set techniques based on fuzzy similarity relations to formalize some common problems which appear in case-based reasoning, such as retrieving the most relevant cases, or getting a more flexible adaptation of past solutions by interpolating them [24, 25, 26]. A logical modelling of the inference patterns involved in case-based reasoning, using the similarity-based consequence relations formalism, has also been introduced in [92]. Regarding case-based decision theory, Gilboa and Schmeidler [46] have recently proposed a new approach to decision theory based on similarity, rather than probability, where the utility function is defined on partially described situations in terms of their similarity with previously experienced decision. Using fuzzy similarity relations and possibility theory, a new qualitative decision model has been proposed, closely related to Dubois-Prade's possibilistic decision theory, and with an axiomatic basis [29, 30]. Extensions to this latter model have been also investigated [50, 118].

Automated deduction

Automated deduction concerns the automatization of deduction in logic. In addition to proving mathematical theorems, it has important applications in the area of program analysis, synthesis and transformation, in computational linguistics, artificial intelligence, etc. However, from the computational point of view, this is not an easy problem. It is well known that the problem of deciding if a given formula is a tautology in propositional logic gave rise to the first NP-complete problem.

In automated deduction, problems are formulated as follows: given an explicit knowledge expressed in a formal language, deduce, applying inference rules, implicit knowledge which has some interest for the application at hand. The deduction of implicit knowledge usually requires many inferences which makes a huge time and space memory necessary. Thus, methodologies have been developed to optimise such resources in order to render them suitable for practical applications.

Following this idea, our latest work on automated deduction focuses on problems expressed in classical binary logic, many-valued logic, possibilistic logic, and in second-order logic

The different aspects of automated deduction to which we have contributed are described below.

Many-valued automated deduction

This is a large topic which we have addressed in a review that summarizes: the many-valued logic used in deduction, the main deduction problems with respect to the nature of many-valued languages, deduction principles such as tableaux methods, resolution and sequent calculi used to tackle deduction problems, the main theorems established, the complexity results found, etc. This work has been published as a survey in a special issue of the journal Mathware and Soft-Computing [32, 51].

Automated deduction in generalized possibilistic logic

Possibilistic logic is a logic of uncertainty that has been developed by Dubois, Lang and Prade and which has many applications to plausible reasoning under incomplete information. Automated proof techniques were also developed for a classical first order language. Things become much more complex (both semantically and syntactically) when one allows the language to deal with imprecise or fuzzy constants, a very natural extension. Therefore, a line of research has been developed in order to provide both semantic foundations and efficient and sound proof methods. First results are already available in [6, 7, 8, 107], where two different extended possibilistic logic programming systems PLFC and PGL are proposed and fully investigated.

Many-valued logic programming
We have designed an efficient interpreter of a many-valued logic programming language to process deductive databases, incorporating a truth degree in the rules and facts which model some uncertainty aspects inherent in some databases. We have developed both propositional and first-order many-valued logic programming interpreters based on a different strategy from that followed by the well-known SLD resolution strategy [33, 34, 35].

Many-valued non-clausal forms
In this topic, our contribution basically consists in defining some techniques to reduce huge non-clausal formulas obtained in several applications, for example in the verification and design of many-valued hardware. We apply a technique called anti-link that significantly reduces the size of the formulas but preserves their logical properties. Thus, the resulting formulas can be processed with a reasonable amount of resources [18].

Many-valued satisfiability
The problem dealt with in this work is satisfiability in many-valued logics. The principle used to solve the problem is an extension of the well-known Davis and Putnam scheme. Our method has been implemented and some interesting new results have been obtained, such as the existence of the transition phase phenomenon and the way it varies with respect to the number of truth values allowed for the propositional variables [78].

Many-valued temporal logic for real time control
We have proposed a hybrid logic formed by two components, a many-valued and a temporal one. The goal is twofold: to represent information of real settings, containing temporal and uncertain information, and to perform real time control [31].

Satisfiability
This is an old problem in automatic deduction that consists in finding out if there is a model for a given propositional formula in conjunctive normal form. The most efficient way of solving this problem, after many empirical studies, has proven to be the Davis and Putnam scheme. In this area we have studied some analytical properties of the above-mentioned scheme from the point of view of its algorithmic complexity [36].

Non-clausal satisfiability
Many applications need to represent and reason with non-normal formulas. Our contributions have enabled this line of research to take a step forward by identifying some formulas in non-clausal formulas, proposing correct logical calculi and the corresponding algorithms that prove that the satisfiability problem, associated with the aforementioned class of formulas, is strictly linear [9, 10].

Second-order logics
In predicate logic the problem is undecidable, and most effort has been put into avoiding redundant inferences. This is done by considering special theories, for instance, equational theories in rewriting systems. In some early work, we studied the problem of deduction in transitive theories, using bi-rewrite systems [59, 63, 64, 108]. This work has applications in the specification of non-deterministic programs [62] and the capture of program requirements [102]. When we come to second-order logics the problem gets worse. We are constrained by the limits of Godel's incompleteness theorem and some simple problems, like unification, become undecidable. The unification problem is crucial for applying resolution techniques. We proved [61, 65, 66] that the problem is undecidable even for unification problems with only one second-order variable, and where this variable occurs only four times. Restrictions on the number of second-order variables, their arity, or their number of occurrences do not simplify the problem. However, in 1994, a variant of second-order unification, called context unification, that could be decidable was proposed. The problem has important implications for automated deduction (it has been used to prove the decidability of distributive unification, to automate deduction in membership theories, etc), rewriting, computational linguistics (in order to deal with under-specification and parallelism), constraint programming (some kinds of constraints have been proven to be expressible as context unification problems), etc. Context unification is known to be decidable in some particular cases, for instance, when no second-order variable occurs more than twice [60], or when there are not more than two variables. Although some decisive advances have been made in order to prove decidability in the general case [67, 68], the question remains open.

Constraint satisfaction and search

Constraint satisfaction (CSP) involves finding values for variables under a set of constraints which discard some value combinations. The solution lies in the assignment of values that satisfy all constraints. Although computationally intractable, this problem has received a lot of attention because many real problems (scheduling, resource allocation, etc.) can be formulated using the CSP model. Most CSP solving algorithms consider binary constraints only, while many real problems are inherently non-binary. Although it is always theoretically possible to convert a non-binary problem into a binary one, the conversion has severe disadvantadges and, therefore, there is a great interest in developing non-binary algorithms. We have proposed several extensions of the popular *forward checking* algorithm in the non-binary case, each with a different degree of propagation and domain filtering [20].

Heuristic methods play a fundamental role in achieving efficient solutions in the average case. Along these lines, we have developed new generic heuristics for variable and value selection [54, 84] which have been shown to be very effective for random problems and for job-shop scheduling instances [55]. Similarly, we have developed generic variable selection heuristics to exploit symmetries in CSPs and these have been shown to be quite effective in symmetric puzzles and mathematical problems [85].

If all constraints cannot be satisfied simultaneously one solution is the assignment that best respects the constraints. In that case, those constraints which might potentially be unsatisfied are called soft. Extending the CSP model with soft constraints is a major advance because it allows many problems that deal with priorities or preferences among values or value combinations to be included. Thus, we have developed a sequence of algorithms [55, 56, 57, 58] for the Max-CSP problem, where all constraints are considered soft with equal weight. Among these algorithms is the one which the scientific community considers to be the most efficient for Max-CSP.

Most algorithms performing systematic search for constraint satisfaction follow a depth-first schema, because of its low space complexity. However, this schema has some disadvantadges if the algorithm makes early mistakes at the beginning of a search. To overcome this weakness, we have proposed an interleaved search approach which enables the search effort to be shared among the most promising sub-problems that contain a solution [82]. This strategy is closely related to discrepancy search techniques, which have shown excellent results in a number of problems [86].

Internet now provides opportunities for distributing constraint satisfaction applications. This requires the distribution of classical algorithms among different processors which communicate by message passing. Some limited proposals have been made to extend the simplest algorithms into the distributed case. We have presented a distributed version of the popular forward checking algorithm [83] which offers some advantages over previous approaches, increasing the privacy of decisions among the agents.

Conceptual modelling: pragmatics of design for computational logic

The research described in this section cuts across the boundaries of formal methods, software engineering and artificial intelligence. Its general aim is to allow formal methods to be used throughout systems engineering life cycles as a means of reducing ambiguity of description and of introducing automation into design processes. We would like formal methods based on logic, but unfortunately most people involved in systems engineering, particularly in the early stages, are not logicians. Therefore, putting formal methods into practice means that the pragmatics of engineering design using logic, especially computational logic, needs to be studied. It is in the early stages of software design where the breakdowns in engineering practice often occur.

Formal methods have been used with respect to this problem. Formal methods based on mathematical logic have been shown to be useful in sharpening descriptions at this stage of development. But formal expression does not guarantee good engineering. Formality is a means rather than an end. We need to understand how formal methods can be used appropriately and communicated to non-experts in logic. This is crucial for making formal specifications useful in practical applications. This research should be understood in the context of the efforts being made to relate formal methods and engineering.

Conceptual modelling

In the design and analysis of complex systems it is often necessary to build conceptual models of some aspects of the problem which we are attempting to solve. Sometimes these models are idealised descriptions of systems [4] which may never be understood with precision (as in environment simulation modelling [103]). Sometimes they are vehicles for discussing information processing within an organisation, independently of the physical media used to transfer that information (as in business process modelling). Sometimes they are not models of a physical system at all but, instead, describe the argument and rationale which influence design (as in some requirements models). A common feature of all these forms of modelling is that they require us to work with abstract concepts of knowledge representation and inference rather than with notation which relates closely to the physical world. This raises the problem of how to engineer such models when they are based on the intangible currency of knowledge and information. Traditionally, many of the ideas behind engineering in this form of early problem description come from informal, pragmatic notions of standard practice. These are conditioned by the experience of those working in particular domains of application. Automation and formal methods have played a minor role, normally being relegated to the representation of the models themselves but seldom being harnessed to support the reasoning which takes place during their construction. In other words, we are sometimes given a formal representation of a model, but are rarely provided with any precise account of the engineering method which was used to obtain it. Our research has taken a close look at such methods.

Our view and research contributions on conceptual modelling have been published in a book [101] in an attempt to consolidate this area of research. Conceptual modelling rests on three pillars: communication of our arguments, pragmatics in model design, an appropriately targeted automation of design and analysis. In the following, we summarise our research on these issues.

Communication
We know that our models will be both subjective and abstract. This means that other people may legitimately question not only the inferences we make within the model, but also the choices we made in representing the problem. For this reason our models are not closed and need to be open to inspection by others. We contributed to this by introducing a new diagrammatic computational logic language. Our logic diagrams are completely formal and can be executed by a mechanism of diagrammatic reasoning. They allow the structure of the modelled problem to be visualized and help with the pragmatics of model design. Our results have been published in [3, 96, 97, 98].

Pragmatics
By pragmatics we mean the study of those aspects of formal languages which are determined by their use in practice, rather than by their syntax and semantics alone. The effects of pragmatics can be seen both in our styles of description and our design procedures. We often want to allow ourselves the flexibility of a full logical system, but to guide designers in its appropriate use for certain types of model. One way of doing this is to supply predefined components, targeted at a particular class of problems, but with enough flexibility to be adaptable to a wide range of specific problems within that class. An overview of our contribution to pragmatics can be seen in [100].

Automation
Conceptual modelling languages are supported by computer-based tools to assist in their authoring or analysis. Different types of tools are needed to support a component-based design paradigm, depending on the degree of initiative expected from the human designer, it often being very useful to be able to use original definitions of the model in more than one way. This can be done through meta-interpretation and we have explored the use of two-layer meta-interpreters [23, 101]. All these tools rely on the encoding of forms of design expertise, specific to particular domains of application. LSS [99] is a set of tools for distributed design in whose development we collaborated. The aim of LSS is to allow diverse styles of description to be used when representing different parts of a problem. This is done by constructing editing tools that are targeted at particular styles of description and have interfaces that reinforce that style. The tools do not interact with each other but rather, they communicate through a shared formal language. This has the practical advantage that new tools can be added to LSS without the cost of building interfaces between them and the existing tools. However, the empirical evaluation of this system reveals some difficulties in its use stemming from the loose integration of the different tools. Another system, Hansel [99], has been developed to address some of these problems through a refinement applicable to problems that can be viewed as transformations on sets of axioms. In this system, all Horn clauses express relations over sets of axioms (themselves Horn clauses). Hansel is an innovative system of design by refinement. Initial specifications are refined by a system of rewrite rules. Subsequently, specifications are given detail by introducing task-specific skeletal definitions and by adding argument slices to carry additional information through the specification. Hansel is the first system of its kind to combine set-based refinement, for high level design, with editing techniques for low level design. It opens up many opportunities for further research, especially the search for a methodology that would enable the empirical testing of already existing models.

Information fusion and consensus theory

Information fusion becomes an essential process in intelligent systems as soon as data is easily available through several information sources (e.g. sensors, experts). Due to the fact that data is often incomplete, contradictory and subject to errors, there is a need for integration methods to deal especially with these problems.

Consensus theory (data fusion) concerns aspects related to the combination of information, in particular combination functions, their properties and how to build a function from a set of imperative properties. A number of techniques have been developed in several fields (e.g., mathematics, economics, biology) and applied to different environments. Although the set of artificial intelligence applications is large, aggregation techniques have been basically used for two main purposes: (i) to have good representations of the application domains and (ii) decision making. In both cases, techniques are applied: (i) to combine information from different sources; (ii) to combine information from a single source but obtained in different time instants; or (iii) to combine evaluations that correspond to different criteria.

Due to the fact that information can be provided under several representation formalisms, aggregation operators and techniques have been developed in order to deal with the existing knowledge representation formalisms. We have contributed some theoretical work in this direction. In particular, we have studied numerical aggregation operators and also those for values in ordinal scales.

For numerical values, we have introduced a family of fuzzy measures [114] able to represent not only the importance of the different information sources but also to deal with interacting (and complementary) criteria. The main advantage of these measures is that they avoid the disadvantages of non-restricted fuzzy measures, that is to say, the need to define 2N consistent values, if N is the number of sources.

For ordinal scales we have defined [49] a new aggregation function that operates in the qualitative setting without any transformation (either explicit or implicit) into the numerical setting. This is achieved by means of t-norms and t-conorms directly defined in the ordinal scale.

We have also considered some other open problems in this area: we have proved some relationships between different operators (when one generalizes another), we have analyzed the modelling capability of a hierarchy of quasi-arithmetic means [116] and we have developed and tested algorithms to learn the parameters of some operators [115] (e.g. weighted mean and OWA).

In the area of decision under uncertainty, aggregation is needed to combine preference (utility) and uncertainty evaluations of outcomes, for a given decision, in order to come up with an overall evaluation of the decision's correctness. In this area, we have been working [29, 117] on the axiomatic description of pessimistic and optimistic aggregation criteria in the framework of qualitative decision theory, where only ordinal scales for both preference and uncertainty are available.

Case-based reasoning

Case-based reasoning (CBR) is an approach to problem solving and learning that has grown from being a rather specific and isolated research area to a field of widespread interest. A feature of CBR is that it does not rely solely on general knowledge of a problem domain, but uses the specific knowledge of previously experienced, concrete problem situations (cases). A new problem is solved by finding a similar past case, and re-using it in the new problem situation. Case-based reasoning can be considered as a form of analogical reasoning restricted to intra-domain analogy while the main body of AI research on analogy has a different focus, namely, analogies across domains. A second feature of CBR is the integration of problem solving and learning. Learning in CBR occurs as a natural by-product of problem solving. When a problem is successfully solved, the experience is retained in order to solve similar problems in the future. When an attempt to solve a problem fails, the reason for the failure is identified and remembered in order to avoid the same mistake in the future. The process model of CBR proposed in [1] has become the standard way to refer to the CBR cycle within the CBR research community and, for this reason, this paper is one of the most cited papers in case-based reasoning.

Research on CBR started at the IIIA around 1990-91, soon after its origins in the US, we developed a case-based learning apprentice system for medical diagnosis [93]. This paper was among the pioneers in the field in Europe and the first to explicitly relate CBR and fuzzy logic techniques. This combination of techniques has since become very important and there are now numerous papers on fuzzy-CBR. Later, we investigated the use of case-based methods for strategy-level reasoning [69]. This led to the development of the NOOS language and integration framework [14], and to sustained work on the integration of knowledge-intensive problem solving with learning.

Assessing the similarity between past cases and the current problem is a central issue in CBR. When cases are simply represented as feature vectors similitude can be assessed using weighted mean of feature-wise distance measures. We have developed several techniques for CBR systems that assess similitude when cases have a complex and structure-rich representation. Our approach has been to construct a symbolic description of similarity instead of a numerical one and to use available domain knowledge in assessing the similarity importance. The notion of anti-unification can be used to construct an abstract description of what is common between a problem and a case [89]. This abstraction can be understood as a symbolic similitude description among the two. Moreover, the importance of the similitude can be assessed by an entropy-based measure on the cases that share that abstraction, as shown in [94]. Domain knowledge is here used in the anti-unification process that exploits an ontology of that domain.

A more knowledge-intensive approach to assess similarity in retrieval is the use of perspectives. A perspective is a pattern that specifies which sub-parts of a case are important. Extracting from a case the sub-structure that conforms to that pattern provides different views of cases, and those cases which share particular views with the current problem can be retrieved [11].

One of the most successful and widely cited CBR systems developed at our institute is an application to the generation of expressive music performances [12, 13]. The problem-solving task of the system is to infer, via imitation, and using case-based reasoning, a set of expressive transformations to be applied to every note of an inexpressive musical phrase given as input. To achieve this, it uses a case memory containing human performances and background musical knowledge. The score, containing both melodic and harmonic information, is also given. The expressive transformations to be decided and applied by the system affect the following expressive parameters: dynamics, rubato, vibrato, articulation, and attack. The similarity reasoning capabilities provided by CBR allow the system to retrieve those notes in the case base of expressive examples (human performances) that are, musically speaking, similar to each current inexpressive note of the input. The system is connected to software for sound analysis and synthesis based on spectral modelling as pre– and post-processor. This allows the obtained results to be listened to. These results clearly show that a computer system can play expressively. In our experiments, we have used Real Book jazz ballads. The web page http://www.iiia.csic.es/~arcos/noos/Demos/Example.html contains a sound file showing a result of the system. This work has been awarded the «Swets & Zeitlinger» prize of the International Computer Music Association. This is the most prestigious award in the field of computer music.

Other CBR systems developed at IIIA have been applied to medical domains. The Bolero system [69] investigated the use of CBR for strategy-level reasoning in a pneumonia diagnosis system. This allowed the diagnostic system to learn from experience instead of starting the diagnostic process from scratch for each new patient. Another medical application, the DIST system [17], also uses case-base reasoning to assess an individualized prognosis of long-term risks for diabetes patients.

CBR has also been applied to marine sponges identification. The main goal here has been to investigate learning methods in a domain where instance descriptions (sponges) have incomplete data, non-applicable predicates. The structured representation supported by the NOOS language [14] has been shown to be adequate for capturing the non-applicability of predicates. A new inductive method that generalizes structured instances into structured descriptions, based on the notion of the anti-unification of feature terms, has also been developed. Moreover, the structured representation of instances in the domain of sponges yields generalizations that - being structured - are very intuitive to the domain experts.

Machine learning

Inductive Learning

Case-based reasoning can be seen as a form of *lazy learning* from the viewpoint of machine learning (ML). On the other hand, induction is a form of *eager learning* where examples are used to acquire general knowledge about a domain [71]. In general, induction can be seen as a search process in a space of hypotheses. Heuristics may guide this process until a hypothesis that is correct (or almost correct) is found. In our institute we have contributed to the improvement of the most important inductive learning system, the ID3. In [70], we introduced a new attribute selection heuristic for ID3-like inductive learning algorithms that we called «distance heuristic». This heuristic, based on a distance between partitions, generates trees that are smaller than those generated using the original alternative heuristics without losing predictive accuracy. The paper describing this heuristic has become one of the most cited papers in the field of inductive learning of decision tress, ranking among the top ten most cited papers according to the web search engine «ResearchIndex», and the thirtieth most cited paper published in the journal Machine Learning from a total of around one thousand papers published since the first issue in 1986. Several experimental studies performed inside and outside our institute have confirmed the advantages of this new measure [72].

Another contribution to inductive learning is a new discretization method for continuously valued attributes. Many machine learning algorithms work only for attributes whose values are discrete rather than continuous. In our work we introduced a new discretization method that had the advantage of being easily parallelizable [21].

Relational learning

Involves ML methods capable of learning hypotheses that describe not only one object, but relations among objects. Relational learning explores a bigger hypothesis space, a space generated by a relational language, usually a subset of first order logic. When the hypothesis language is one of Horn clauses, relational learning is called ILP (inductive logic programming). The inductive method INDIE uses a different subset of first order logic, namely, feature terms [16]. INDIE is a bottom-up heuristic method for induction. Objects are represented by sorts and features represent relations between objects. INDIE uses anti-unification to find the most specific generalization from positive examples. If there is no negative example covered by the hypothesis the process finishes, otherwise the hypothesis is specialized by a disjunct of new hypotheses. INDIE uses the distance heuristic [70] to select a relevant feature and build a specialized hypothesis for each possible value of that feature. When the process is finished, the distance heuristic is used to simplify the hypotheses by eliminating as many less relevant features as possible, i.e. without covering any negative examples. Feature terms are the representation formalism used in the language NOOS, so INDIE can easily integrate CBR into an application system [15]. INDIE has also been used for marine sponge identification and for assessing individual risks of diabetes patients.

Unsupervised learning algorithms

In this type of learning, we proposed a methodology to classify objects within a specific context and then obtain generic information by induction based on the common properties between the objects of each class. The work places special emphasis on the design and analysis of the algorithms involved in order to enable the proposed methodology to work with a large number of objects in bounded time [80].

Multiagent learning

A new and very promising line of research is the application of learning techniques to agents and multiagent systems (MAS). Our approach focuses on collaboration among agents in a MAS; the agents are capable of learning by themselves and also of learning how to improve their goals by collaborating with other agents [79]. We have developed the framework of cooperative CBR [90], where agents in a MAS are capable of solving problems using their own cases, but have collaboration policies that allow them to ask for help from other agents. Specifically, each agent has a *competence model* of the other agents and a *self-competence* model. The agents are thus able to assess their own competence in solving a particular problem and, if necessary, propose a collaboration with other agents in order to improve their performance. Moreover, learning techniques are also used to learn those competence models and as a result the MAS is capable of adapting the individual performance of agents to the environment provided by the other agents' capabilities.

Information agents

Intelligent information agents are programs that, using AI techniques, have a computational software entity that has access to one, or multiple, heterogeneous and distributed information sources, and pro-actively searches for and maintains relevant information on behalf of users or other agents. Our research has been focused along two main lines: context-aware agents and I^3 agents [91]. Context-aware agents are personal information agents that work for a community of users and that are aware of the physical and social context of their users. The use of context information allows the agents to focus their information search and, as a result of this, increase the quantity and quality of information delivered to the user. The COMRIS (Co-Habited Mixed-Reality Information Spaces: ESPRIT LTR 25500) project developed context-aware agents for assisting people attending large conferences and fairs.

Intelligent Information Integration (I^3) agents access multiple, heterogeneous and distributed information sources and integrate their relevant information using AI techniques to achieve the specific goals of a user. The Web Information Mediator (WIM) is an open multiagent architecture that supports knowledge components and domain ontologies [19]. Developed in the IBROW (An Intelligent Brokering Service for Knowledge-Component Reuse on the World Wide Web) european project, agents in WIM can register their capabilities as knowledge components in the WIM library using the UPML language. For each specific task, WIM analyzes it and forms a coalition of agents with the competence needed to carry out that task. WIM provides an Intelligent Information Integration service for a professional user, e.g. a doctor. A WIM application for a domain (e.g. medical information) is built by connecting (via *bridges*) the knowledge components with the ontologies of the domain (e.g. MeSH) and the information sources (via *wrappers*) that support those ontologies (e.g. PubMed).

Intelligent agents

Internet continues to grow at a very swift pace. This growth is providing plenty of opportunities to apply artificial intelligence techniques for solving the many new, and old, problems in the understanding and management of the 'global computer' – consisting of millions of small distributed computers – associated to the network. One of the basic needs of human users when approaching this vast computing machinery is that of mediation. Information changes - and grows – constantly, business opportunities appear and disappear over the network at light speed, the network itself is, of course, dynamic. Therefore, human beings are incapable of benefitting from the network without the help of 'intelligent' tools as intermediaries. At the IIIA we have been working to provide solutions in this area by means of intelligent agents and infrastructures for multiagent systems. Agents are understood as computer programs that have several characteristics: they are autonomous, they choose their course of action without human intervention, they are proactive, they pursue their own goals, and they are reactive, they perceive their environment and react to sudden changes in it. These characteristics make agents the perfect candidates for helping humans in the interaction with huge information networks.

Another very important characteristic that is usually required for a program to be labelled as an agent is that of social awareness, that is, it is capable of recognising its peers – other agents – and establishing mutually beneficial dialogues with them. This means that infrastructures which enable agents to dialogue are needed. At the IIIA we have developed infrastructures for agent-mediated auction houses, that is, virtual places on the network where agents meet to sell and buy goods according to particular auction protocols. In particular, a tool called FM enables auction houses to be created [88, 104, 105]. This tool comes with a series of agents that are programmed with different bidding strategies based on fuzzy logic [45]. It is a free tool for academic purposes and has become one of the most cited works in the literature on agent-mediated auctions. We have also developed techniques for agent mediation when the dialogue between agents corresponds to a multi-issue negotiation, protocol [81, 111]. Different tactics for negotiation, that is customizable by users, have been developed and experimental results have been obtained regarding which parameter values are most adequate for certain types of environments [44]. One of the main problems in agent-mediated negotiation is that of the credibility of the agents and therefore, we are carrying out research on reputation measures as a means of evaluating the credibility of agents when negotiating. We are also working on the area of specification of agent societies, that is to say, how to formally establish the norms of interaction between agents and how to enforce these norms on actual agent behaviours [43, 87]. Finally, new mediation protocols based on complex dialogical exchanges have been studied, mainly on argumentation as a means of negotiation, i.e. to complement offers and counteroffers on negotiation promises, threats or enticements of different sorts, in order to persuade the others about a particular course of action [106, 112].

Autonomous robots

A very interesting application of fuzzy logic undertaken at our institute (in collaboration with the ESAII Dept. of the UPC) is that concerning the problem of mapping unknown environments by means of a troup of autonomous mini-robots [74]. The goal of map generation is to obtain the most plausible position of walls and obstacles based on the IR perception of several mini-robots. The mini-robots detect portions of walls or obstacles with different degrees of precision depending on the length of the run and the number of turns they have done. The main problem is to decide whether several detected portions, represented by imprecise segments, are from the same wall or obstacle or not. If two segments are from the same wall or obstacle a segment fusion procedure is applied to produce a single segment. This process of segment fusion is followed by a completion process in which hypotheses are made with respect to non-observed regions. The completion process is achieved by means of hypothetical reasoning based on declarative heuristic knowledge about the orthogonal environments in which the mini-robots evolve. Finally, an alignment process also takes place so that, for example, two walls separated by a doorway are properly aligned. All these operations are based on modelling the imprecise segments by means of fuzzy sets [75, 76, 77]. In concrete terms, the position of the wall segment is a fuzzy number and the length a fuzzy interval. The main advantage of using fuzzy techniques is that the position and imprecision of the resulting fused segments can be very easily computed. Furthermore, it is very natural to use fuzzy sets to model the imprecision about the position of obstacles. The results obtained are very good and have been widely cited.

We are also working on the problem of providing autonomous robots with some «sense of orientation» based only on visual feedback, with the aim of navigating unknown outdoor environments. To achieve this, a landmark-based qualitative navigation algorithm is being developed [113]. The architecture of this algorithm is a multiagent system in which the coordination among the different agents, each one an expert on a different navigation subtask, is based on a bidding mechanism. The results obtained in a simulated setting are very good. The short term goal is to migrate the algorithm into a real robot that is being built by our partners in the project at the Robotics Institute (IRII) of the CSIC-UPC.

References

[1] Aamodt A., Plaza E. (1994); Case-Based Reasoning: Foundational Issues, Methodological Variations, and System Approaches. Artificial Intelligence Communications, Vol. 7: 1, pp. 39-59.

[2] Agusti J., Puigsegur J., Robertson D. (1998); A Visual Syntax for Logic and Logic Programming. Journal of Visual Languages and Computing.Vol. 9, pp. 399-427.

[3] Agusti J., Puigsegur J., Robertson D., Schorlermmer W.M. (1996); Visual Logic Programming through Set Inclusion and Chaining. CADE-13. WP-2: Workshop on Visual Reasoning. New Brunswick, USA.

[4] Agusti J., Puigsegur J., Schorlemmer W.M. (1997); Towards specifying with inclusions. Mathware & Soft Computing 4 (3), pp. 281-297

[5] Agusti J., Puigsegur J., Schorlemmer W.M. (1998); Query answering by means of diagram transformation. Lecture Notes in Artificial Intelligence series, Springer, Verlag, Vol. 1495, Proceedings of the Third International Conference of Flexible Query Answering Systems (FQAS'98), pp.13-28.

[6] Alsinet T., Godo L., Sandri S. (1999); On the Semantics and Automated Deduction for PLFC. Uncertainty in Artificial Intelligence Conference (UAI'99), Stockholm, Morgan Kaufmann Pub., pp. 1-12.

[7] Alsinet T., Godo L. (2000); A Complete Calculus for Possibilistic Logic Programming with Fuzzy Propositional Variables. Uncertainty in Artificial Intelligence Conference (UAI'2000), Stanford (USA), Morgan Kaufmann,, pp. 1-10.

[8] Alsinet T., Godo L. (2001); Towards an Automated Deduction System for Logic Programming with Fuzzy Constants. International Journal of Intelligent Systems. (in press)

[9] Altamirano E., Escalada-Imaz G. (2000a); Finding tractable formulas in NNF. First International Conference on Computational Logic. Lecture Notes in Artificial Intelligence, Springer-Verlag. Vol. 1861, pp. 493-507.

[10] Altamirano E., Escalada-Imaz G. (2000b); An efficient proof method for non-clausal reasoning. XII International Symposium on Foundations of Intelligent Systems. Lecture Notes in Artificial Intelligence, Springer-Verlag, Vol. 1932, pp. 534-543.

[11] Arcos J.L., Lopez de Mantaras R., (1997); Perspectives: A declarative bias mechanism for case retrieval. Second International Conference on Case-Based Reasoning. Lecture Notes in Artificial Intelligence. Springer, Vol. 1266, pp. 279-290.

[12] Arcos J.L., Lopez de Mantaras R. (2001); An Interactive CBR approach for generating expressive music. Journal of Applied Intelligence 27(1), pp. 115-129.

[13] Arcos J.L., Lopez de Mantaras R., Serra X. (1998); Sax-Ex: A Case-Based Reasoning system for generating expressive musical performances (Swets & Zeitlinger Award from the International Computer Music Association). Journal of New Music Research 27(3), pp. 194-210.

[14] Arcos J.L., Plaza E. (1996); Inference and reflection in the object-centered representation language Noos. Future Generation Computer Systems Journal. Elsevier. Special issue on Reflection and Meta-level AI Architectures . Vol. 12 (2 & 3), pp. 173-188.

[15] Armengol E., Plaza E. (1995); Integrating induction in a case-based reasoner. Lecture Notes in Artificial Intelligence, Springer. Vol. 984, pp. 3-17.

[16] Armengol E., Plaza E (2000); Bottom-up Induction of Feature Terms, Machine Learning Journal 41(3), pp. 259-294.

[17] Armengol E., Palaudaries A., Plaza E (2001); Individual Prognosis of Diabetes Long-Term Risks: A CBR Approach. Methods of Information in Medicine Journal, 40, pp. 46-52.

[18] Beckert B., Hähnle R., Escalada-Imaz G (1998); Simplification of Many-Valued Logic Formulas Using Anti-links. Journal of Logic and Computation.. Vol. 8, N 97-18, pp. 569-587.

[19] Benjamins V.R., Plaza E., Motta E., Fensel D., Studer R., Wielinga B., Schreiber G., Zdrahal Z., Decker S. (1998); An Intelligent Brokering Service for Knowledge-Component Reuse on the WorldWideWeb. In Proceedings of the 11th Banff Knowledge Acquisition for Knowledge-Based System Workshop (KAW98), Banff, Canada.

[20] Bessiere C., Meseguer P., Freuder E.C., Larrosa J. (1999); On Forward Checking for Non-binary Constraint Satisfaction. (J. Jaffar, Ed.) Proceedings of the 5th International Conference on Principles and Practice of Constraint Programming (CP-99), Alexandra, USA, pp. 88-102.

[21] Cerquides J., Lopez de Mantaras R. (1997); Proposal

and empirical comparison of a parallelizable distance-based discretization method. 3d Int. Conference on Knowledge Discovery and Data Mining (KDD'97) Newport Beach, California, pp. 139-142.

[22] Cignoli R., Esteva F., Godo L., Torrens A. (2000); Basic fuzzy logic is the logic of continuous t-norms and their residua. Soft Computing. 4, pp. 106-112

[23] Correa da Silva F., Wascocelos W., Agusti J., Robertson D. (1999); Why ontologies are not enough for knowledge sharing. In Engineering and Industrial Applications of Artificial Intelligence . Lecture Notes in Artificial Intelligence, 1611.

[24] Dubois D., Esteva F., Garcia P., Godo L., Lopez de Mantaras R., Prade H. (1997); Fuzzy modelling of case-based reasoning and decision. Second International Conference on Case-Based Reasoning. Lecture Notes in Artificial Intelligence, vol. 1266, pp. 599-610.

[25] Dubois D., Esteva F., Garcia P., Godo L., Lopez de Mantaras R., Prade H. (1998); Fuzzy Set Modelling in Case-Based Reasoning. International Journal of Intelligent Systems. Vol. 13, no. 4, 345-373.

[26] Dubois D., Esteva F., Garcia P., Godo L., Lopez de Mantaras R., Prade H. (1998); In: A. Ralescu and J.G. Shanahan (eds.), Case-based reasoning: a fuzzy approach. Fuzzy Logic and Artificial Intelligenc, Lecture Notes in Artificial Intelligence, 1566, pp.79-90.

[27] Dubois D., Esteva F., García P., Godo L., Prade H. (1995), Similarity-Based Consequence Relations. Lecture Notes in Artificial Intelligence, 946, pp. 171-179.

[28] Dubois D., Esteva F., García P., Godo L., Prade H. (1997); A Logical Approach to Interpolation Based on Similarity Relations. International Journal of Approximate Reasoning, 17 (1), pp. 1-36.

[29] Dubois D., Godo L., Prade H., Zapico A. (1998); Making decisions in a qualitative setting: from decision under uncertainty to case-based decision. In: Cohn, Schubert and Shapiro (eds.) Sixth International Conference on Principles of Knowledge Representation and Reasoning (KR'98) (Trento, Italy, June 2-5 1998), Morgan Kaufmann, pp. 594-605.

[30] Dubois D., Godo L., Prade H., Zapico A. (1999); On the Possibilistic Decision Model: from Decision under Uncertainty to Case-Based Decision. International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems 7(6), pp. 631-670.

[31] Escalada-Imaz G (2000); A Temporal Many-Valued Logic for Real Time Control. IX International Conference on Artificial Intelligence: Methodology, Systems, Applications, Varna, Bulgaria. Lecture Notes in Artificial Intelligence, 1904, pp 91-100.

[32] Escalada-Imaz G., Hähnle R. (1997); Editorial. Mathware & Soft Computing. Vol 4(2).

[33] Escalada-Imaz G., Manya F. (1995); Efficient Interpretation of Propositional Multiple-Valued Logic Programs, Advances in Intelligent Computing. Lecture Notes in Computer Science, 945, pp. 428-439.

[34] Escalada-Imaz G., Manya F. (1996); On Multiple-Valued Logic Programming In (V. Dhal and A. Sobrino, eds.) Logic Programming and its Applications. Chapter XII. Editorial: Univ. de Santiago de Compostela. pp 387-419.

[35] Escalada-Imaz G., Manya F., Sobrino A. (1996); Principios de la Programación Lógica con Información Incierta. Descripción de algunos de los Sistemas más Relevantes. Theoria 11(27), pp 123-148.

[36] Escalada-Imaz G., Torres R. (2000); Complexities Issues in the Davis and Putnam Scheme, IX International Conference on Artificial Intelligence: Methodology, Systems, Applications, Varna, Bulgaria. Lecture Notes in Artificial Intelligence, 1904, pp. 261-271.

[37] Esteva F., Garcia P., Godo L. (1994); Relating and Extending Semantical Approaches to Possibilistic Reasoning. International Journal of Approximate Reasoning, 10(4), pp. 311-344.

[38] Esteva F., Garcia P., Godo L., Rodriguez R. (1997); A Modal Account of Similarity –Based Reasoning. International Journal of Approximate Reasoning, 16, pp. 235-260.

[39] Esteva F., Garcia P., Godo L. (2000); Similarity-Based Reasoning. In Discovering World with Fuzzy Logic (V. Novak and I. Perfilieva eds.). Series: Studies in Fuzziness and Soft Computing, Springer (Physica-Verlag, Heidelberg), pp. 367-396.

[40] Esteva F., Godo L. (2001); Monoidal t-norm based logic: towards a logic for left-continuous t-norms. Fuzzy Sets and Systems, 124(3), pp. 271-288.

[41] Esteva F., GodoL., Hajek P., Navara M. (2000); Residuated fuzzy logics with an involutive negation. Archive for Mathematical Logic, 39, pp.103-124.

[42] Esteva F., Godo L., Montagna F. (2001); The LΠ and LΠ Logics: two complete fuzzy systems joining Lukasiewicz and product logics. Archive for Mathematical Logic, 40(1), pp. 39-67.

[43] Esteva M., Rodriguez J.A., Arcos J.L., Sierra C., Garcia P. (2000); Formalising Agent Mediated Electronic Institutions, Catalan Congres on AI (CCIA 00), pp. 29-38.

[44] Faratin P., Sierra C., Jennings N.R. (1998); Negotiation decision functions for autonomous agents, Robotics and Autonomous Systems, 24(3-4), pp. 159-182.

[45] Garcia P., Gimenez E., Godo L., Rodríguez J.A. (1999); Bidding Strategies for Trading Agents in Auction-Based Tournaments. Agent Mediated Electronic Commerce. Lecture Notes in Artificial Intelligence, 1571, pp. 151-165.

[46] Gilboa I., Schmeidler D. (1995); Case-Based Decision Theory, The Quarterly Journal of Economics, pp. 607-639.

[47] Godo L., Hajek P. (1997); Fuzzy Inference as Deduction. Journal of Applied Non-Classical Logics, 9(1), pp. 37-60.

[48] Godo L., Rodriguez R. (1999); A Fuzzy Modal Logic for Similarity Reasoning. In Fuzzy Logic and Soft Computing (Guoqing Chen, Mingsheng Ying and Kai-Yuan Cai eds.), Kluwer, pp. 33-48.

[49] Godo L., Torra V. (2000); On aggregation operators for

ordinal qualitative information, IEEE Trans. on Fuzzy Systems, 8(2), pp. 143-154.
[50] Godo L., Zapico A. (2001); On the Possibilistic-Based Decision Model: Characterization of Preference Relations Under Partial Inconsistency. Journal of Applied Intelligence, 14, pp. 319-333.
[51] Hähnle R., Escalada-Imaz G. (1997); Deduction in Multivalued Logics: a survey. Mathware & Soft Computing, 4(2), pp. 69-97.
[52] Hajek P., Godo L., Esteva F. (1995); Fuzzy logic and probability. In (P. Besnard & S. Hanks, Eds.) Uncertainty in Artificial Intelligence Conference. Morgan Kaufmann Pub., San Francisco, California, pp. 237-244.
[53] Hajek P., Godo L., Esteva F. (1996); A complete many-valued logic with product conjunction. Archive for Mathematical Logic, 35(3), pp. 191-208.
[54] Larrosa J., Meseguer P. (1995); Optimization-Based Heuristics for Maximal Constraint Satisfaction. Proceedings of the First International Conference on Principles and Practice of Constraint Programming (CP-95). Lecture Notes in Computer Music (Ed. U. Montanari, F. Rossi), 103-120.
[55] Larrosa J., Meseguer P. (1998); Generic CSP Techniques for the Job-Shop Problem. Proceedings of the 11th International Conference on Industrial & Engineering Applications of Artificial Intelligence & Expert Systems (IEA-AIE-98), pp. 46-55.
[56] Larrosa J., Meseguer P. (1999); Partition-Based Lower Bound for Max-CSP, In: (J. Jaffar ed.) Proceedings of the 5th International Conference on Principles and Practice of Constraint Programming (CP-99), Alexandra, USA, pp. 303-315.
[57] Larrosa J., Meseguer P., T. Schiex (1999). Maintaining reversible DAC for Max-CSP. *Artificial Intelligence Journal*, vol. 107, (1), 149-163.
[58] Larrosa J., Meseguer P, Schiex T., Verfaille G. (1998); Reversible DAC and other improvements for solving MAX-CSP. Proceedings of the 15th National Conference on Artificial Intelligence (AAAI-98), Madison, USA, pp. 347-352.
[59] Levy J. (1994); The Calculus of Refinements: A Formal Specification Model Based on Inclusions. PhD thesis, Departament de Llenguatges i Sistemes Informàtics, Universitat Politècnica de Catalunya.
[60] Levy J. (1996); Linear Second Order Unification. In (H. Ganzinger, Ed.) Rewriting Techniques and Applications (RTA'96), Lecture Notes in Computer Science, 1103, pp. 332-346.
[61] Levy J. (1998); Decidable and Undecidable Second-Order Unification Problems. Rewriting Techniques and Applications (RTA'98), Lecture Notes in Computer Science, 1379, pp. 47-60.
[62] Levy J., Agusti J. (1992); Implementing Inequality and Nondeterministic Specifications with Bi-Rewriting Systems. In (H. Ehrig and F. Orejas, Ed.) Recent Trends in Data Type Specification, Lecture Notes in Computer Science, 785, pp. 252-267.
[63] Levy J., Agusti J. (1993); Bi-Rewriting: A Term Rewriting Technique for Monotonic Order Relations. In (C. Kirchner, Ed.) Rewriting Techniques and Applications (RTA'93), Lecture Notes in Computer Science 690, pp. 17-31.
[64] Levy J., Agusti J. (1996); Bi-Rewriting Systems. Journal of Symbolic Computation, 22, pp. 279-314.
[65] Levy J., Veanes M. (1998); On Unification Problems in Restricted Second-Order Languages. Annual Conference of the European Association for Computer Science Logic (CSL'98), Brno, Czech Republic.
[66] Levy J., Veanes M. (2000); On the Undecidability of Second-Order Unification. Information and Computation, 159, pp. 125-150.
[67] Levy J., Villaret M. (2000); Linear Second-Order Unification and Context Unification with Tree-Regular Constraints. Rewriting Techniques and Applications (RTA'00), Lecture Notes in Computer Science, 1833, pp. 156-171.
[68] Levy J., Villaret M. (2001); Context Unification and Traversal Equations. Rewriting Techniques and Applications (RTA'01), Lecture Notes in Computer Science.
[69] Lopez B., Plaza E. (1997); Case-based learning of plans and goal states in medical diagnosis. Artificial Intelligence in Medicine, 9, pp. 29-60.
[70] Lopez de Mantaras R. (1991); A Distance-Based Attribute Selection Measure for Decision Tree Induction. Machine Learning Journal, 6(1), pp. 81-92.
[71] Lopez de Mantaras R., Armengol E. (1998); Machine Learning from Examples: Inductive and Lazy Methods. Invited paper for the 25th anniversary issue of the Data and Knowledge Engineering Journal, 25(1-2), pp. 99-123.
[72] Lopez de Mantaras R., Cerquides J., Garcia P. (1998); Comparing Information-Theoretic Attribute Selection Measures: A Statistical Approach. Artificial Intelligence Communications 11(2), pp. 91-100.
[73] Lopez de Mantaras R., Plaza E. (1997); Case-Based Reasoning : An Overview. Artificial Intelligence Communications 10(1), pp. 21-29.
[74] Lopez-Sanchez M., Esteva F., Lopez de Mantaras R., Sierra C., Amat J. (1998); Map Generation by Cooperative Low-Cost Robots in Structured Unknown Environments. Autonomous Robots Journal 5, pp. 53-61.
[75] Lopez M., Lopez de Mantaras R., Sierra C. (1997); Incremental map generation by low cost robots based on possibility/necessity grids. 13th Int. Conference on Uncertainty in Artificial Intelligence, Providence, Rhode Island, pp. 351-357.
[76] Lopez-Sanchez M., Lopez de Mantaras R., Sierra C. (1998); Possibility theory-based environment modelling by means of behaviour-based autonomous robots. European Conference on Artificial Intelligence (ECAI'98), Brighton, United Kingdom, pp. 590-594.
[77] Lopez-Sanchez M., Lopez de Mantaras R., Sierra C. (2001); Map Generation by Cooperative Autonomous Robots using Possibility Theory. In: Fuzzy Logic Tech-

niques for Autonomous Vehicle Navigation (D. Driankov and A. Saffiotti), Studies in Fuzziness and Soft Computing, Vol. 61. Physica-Verlag, pp. 281-312.
[78] Manya F., Bejar R., Escalada-Imaz G. (1998); The Satisfiability Problem for Regular CNF Formulas. Soft Computing 2(3), pp. 116-123.
[79] Martín F., Plaza E., Arcos J.L. (1999); Knowledge and Experience Reuse through Communication among Competent (Peer) Agents. International Journal of Software Engineering and Knowledge Engineering, 9(3), pp. 319-341
[80] Martinez-Enriquez A.M., Escalada-Imaz G. (1998); The Revision of Inductive Learning Theory within Incomplete and Imprecise Observations. International Journal of Expert Systems with Applications 15, pp. 357-366.
[81] Matos N., Sierra C., Jennings N.R. (1998); Negotiation Strategies: An Evolutionary Approach, Proceedings of the Int. Conf. On Multi-Agents (ICMAS98), pp. 182-189.
[82] Meseguer P. (1997); Interleaved depth-first search. Proceedings of the 15th International Joint Conference on Artificial Intelligence (IJCAI-97), Nagoya, Japan, pp. 1382-1387.
[83] Meseguer P., Jimenez M.A. (2000); Distributed Forward Checking. Workshop on Distributed Constraint Satisfaction (CP-00), Singapore.
[84] Meseguer P., Larrosa J. (1995); Constraint Satisfaction as Global Optimization. Proceedings of the 14th International Joint Conference on Artificial Intelligence (IJCAI-95), Montreal, Canada, pp. 579-584.
[85] Meseguer P., Torras C. (1999); Solving Strategies for Highly Symmetric CSPs, Proceedings of the 16h International Joint Conference on Artificial Intelligence (IJCAI-99), Stockholm, Sweden, pp. 400-405.
[86] Meseguer P., Walsh T. (1998); Interleaved and Discrepancy-Based Search. Proceedings of the 13th European Conference on Artificial Intelligence (ECAI-98), Brighton, UK, pp. 239-243.
[87] Noriega P., Sierra C. (1996); Towards Layered Dialogical Agents. Proceedings of the Workshop Agents Theories, Architectures and Languages (ATAL'96). Budapest, pp. 69-81.
[88] Noriega P., Sierra C. (1999); Auctions and multiagent systems, In (Klusch M. ed) Intelligent Information Agents, Springer, pp. 153-175.
[89] Plaza E. (1995); Cases as terms: A feature term approach to the structured representation of cases. Lecture Notes in Artificial Intelligence, 1010, pp. 265-276.
[90] Plaza E., Arcos J.L., Martin F. (1997); Cooperative Case-Based Reasoning. Lecture Notes in Artificial Intelligence, 1221, pp.180-201.
[91] Plaza E., Arcos J.L., Noriega P., Sierra C. (1998). Competing Agents in Agent-Mediated Institutions. Journal of Personal Technologies, 2, pp. 212-220.
[92] Plaza E., Esteva F., Garcia P., Godo L., Lopez de Mantaras R. (1998); A Logical Approach to Case-Based Reasoning Using Fuzzy Similarity Relations. Journal of Information Sciences, 106, pp. 105-122.
[93] Plaza E., Lopez de Mantaras R. (1990); A case-based apprentice that learns from fuzzy examples. In (Z. Ras et al., Eds.) Methodologies for Intelligent Systems 5, North-Holland, pp. 420-427.
[94] Plaza E., Lopez de Mantaras R., Armengol E. (1996); On the Importance of Similitude: An Entropy-Based Assessment. 3d European Workshop on Case-Based Reasoning. Advances in Case-Based Reasoning, Lecture Notes in Artificial Intelligence, 1168, pp. 324-338.
[95] Puigsegur J., Agusti J. (1998); Visual Logic Programming By Means of Diagram Transformations. Proceedings of the Joint Conference on Declarative Programming (APPIA-GULP-PRODE'98), A Coruña, Spain, pp. 311-328.
[96] Puigsegur J., Agusti J., Pastor J.A. (1998); Towards Visual Schemas in Deductive Databases. Proceedings of the 9th International Conference and Workshop on Database and Expert Systems Applications (DEXA'98), Lecture Notes in Computer Science, 1460, pp.881-891.
[97] Puigsegur J., Agusti J., Robertson D. (1996); A Visual Logic Programming Language. Proceedings IEEE Symposium on Visual Languages. IEEE Computer Society Press, Colorado, pp. 214-221.
[98] Puigsegur J., Schorlemmer W.M., Agusti J. (1997); From Queries to Answers in Visual Logic Programming. Proceedings of the 13th IEEE Symposium on Visual Languages, Capri, Italy, pp. 102-109.
[99] Robertson D. (2000); Pragmatics in the Synthesis of Logic Programs. Monografies del IIIA, 12.
[100] Robertson D., Agusti J. (1998); Pragmatics in the Synthesis of Logic Programs. In Logic-Based Program Synthesis and Transformation. Lecture Notes in Computer Science, 1559.
[101] Robertson D., Agusti J. (1999); Software Blueprints: Lightweight Rigorous Design, Addison-Wesley.
[102] Robertson D., Agustí J., Hesketh J., Levy J. (1994); Expressing Program Requirements using Refinement Lattices. Fundamenta Informaticae, 21(3), pp. 163-182.
[103] Robertson D., Haggith M., Kendon G., Agusti J., Goldsborough D. (1995); The application of logic programming to decision support systems in ecology. Artificial Intelligence Applications in Resource Management, 9(3), pp. 23-29.
[104] Rodriguez-Aguilar J.A., Martin F., Noriega P., Garcia P., Sierra C. (1998a); Competitive Scenarios for Heterogeneus Trading Agents, Proceedings of the Second International Conference on Autonomous Agents (Agents'98), Minneapolis/St Paul, pp. 293-300.
[105] Rodriguez-Aguilar J.A., Martin F., Noriega P., Garcia P., Sierra C. (1998b): Towards a test-bed for trading agents in electronic auction markets, Artificial Intelligence Communications, 11, pp. 5-19.
[106] Sabater J., Sierra C., Parsons S., Jennings N. (2001);

Engineering executable agents using multi-context systems, Journal of Logic and Computation, (in press).
[107] Sandri S., Godo L. (1999); Treatment of Temporal Information in Possibilistic Logic with Fuzzy Constants. Proc. of IFSA'99, August 1999, Taiwan.
[108] Schorlemmer W. M. (1999); On Specifying and Reasoning with Special Relations. PhD thesis, Departament de Llenguatges i Sistemes Informàtics, Universitat Politècnica de Catalunya.
[109] Schorlemmer W.M., Agusti J., Puigsegur J. (1998); On Reasoning in Category Theory by Diagram Chasing. Workshop on Logicand Diagrammatic Information (LICS'98), Indianapolis, Indiana, USA, June 1998, pp. 1-15
[110] Schorlemmer W.M., Agusti J., Puigsegur J. (1998); On Diagrammatic Reasoning in Category Theory. Proceedings of the «Primer Congrés Català d'Intel.ligència Artificial (CCIA'98)», Tarragona, Spain, October 21-23, pp. 46-57.
[111] Sierra C., Faratin P., Jennings N. (1997); A Service-Oriented Negotiation Model between Autonomous Agents, MAAMAW'97, Ronneby, Sweden. Lecture Notes in Artificial Intelligence, 1237, pp. 17-35.
[112] Sierra C., Jennings N., Noriega P., Parsons S. (2000); A framework for argumentation-based negotiation.Intelligent Agents IV, Lecture Notes in Artificial Intelligence, 1365, pp 177-192.
[113] Sierra C., Lopez de Mantaras R., Busquets D. (2000); Multiagent Bidding Mechanisms for Robot Qualitative Navigation, in Agent Theories, Architectures, and Languages (ATAL), Boston, Massachusets, July 2000, pp. 187-201. (extended version to be published in Lecture Notes in Artificial Intelligence, Springer Verlag).
[114] Torra V. (1999); On hierarchically S-decomposable fuzzy measures, International Journal of Intelligent Systems, 14(9), pp. 923-934.
[115] Torra, V. (1999); On the learning of weights in some aggregation operators: The weighted mean and the OWA operators. Mathware and Soft Computing, 6(2/3), pp. 249-265.
[116] Torra V. (1999); On some relationships between hierarchies of quasi-arithmetic means and neural networks, International Journal of Intelligent Systems, 14(11), pp. 1089-1098.
[117] Zapico A. (1999); Axiomatic Foundations for Qualitative/Ordinal Decisions with Partial Preferences, 16th Int. Joint Conf. on Artificial Intelligence (IJCAI'99), Stockholm (Sweden), pp. 132-136.
[118] Zapico A., Godo L. (2000); Representation of preference relations induced by lattice-valued, generalised possibilistic utility functions. International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems, 6(8), pp. 719-734.

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