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Guest Editorial

The scientific legacy of Marco Cadoli in Artificial Intelligence

Maurizio Lenzerini* and Marco Schaerf
Dipartimento di Ingegneria Informatica Automatica, e Gestionale Antonio Ruberti, Università di Roma La Sapienza, Roma, Italy

It was in 1988 when Marco Cadoli asked me (Maurizio Lenzerini) if I could propose a master thesis work to him. I had just finished my first course as a professor. The course was about Software Engineering and Programming Languages, and during the lectures I had noticed Marco's outstanding performance in the course, both in the part related to Software Design, and in the part devoted to object-oriented, functional and logic programming. I thought it was great that such a brilliant student was willing to work with me. So, we started discussing about possible topics, and I suggested Artificial Intelligence and in particular Knowledge Representation. More specifically, I talked to him about the research program I was pursuing, centered around the idea of understanding the exact computational complexity of various KR formalisms, in particular the formalisms for nonmonotonic reasoning. Although we now take it for granted that analyzing the computational complexity of a logical formalism is an essential tool for characterizing the properties of the formalism itself, at that time this kind of investigation was not so common. Only recently, people like Hector Levesque, Ron Brachman, Ray Reiter and others had started pointing out the importance of understanding the inherent complexity of reasoning tasks, and relating such complexity with the expressive power of the representation language. Marco had studied Theoretical Computer Science in several courses and had a deep understanding of computational complexity theory. He clearly loved the topic, and after a few meetings, I challenged him: "why don't you try to characterize the computational complexity of circumscription in a very simple language, namely the one with unary predicates (classes) only, and with just two kinds of axioms, one for class generalization, and one for class disjointness? You think about this problem, and we meet again in one week." The day after he got in my room, with 14 hand-written paper sheets (see Fig. 1 for the first two sheets, where the first page says: "These sheets contain the proof that the problem $T_z^c \models A(z)$ is co-NP-complete –Marco"), where he had proven not only that circumscription was intractable in the proposed formalism, but that intractability held for three interesting variants of the language.

We like to consider those 14 sheets to be the beginning of a wonderful research journey that Marco made until the 21st of November 2006, when he passed away after a long battle with a rare form of cancer. The goal of this special issue is to provide an (incomplete) account of such journey, based on 6 papers, each one addressing a specific area which Marco has contributed to.

- **Non-monotonic reasoning.** This is probably the first research area that Marco felt in love with. He liked in particular the idea of trying to formally capture various forms of common-sense reasoning, e.g., reasoning in minimal models, which cannot be formalized using classical logic. During his work on the master thesis, he became immediately interested in verifying the validity of the intuition that reasoning in minimal models could

*Corresponding author: Maurizio Lenzerini, Dipartimento di Ingegneria Informatica Automatica, e Gestionale Antonio Ruberti, Università di Roma La Sapienza, Roma, Italy. E-mails: lenzerini@dis.uniroma1.it (Maurizio Lenzerini); marco.schaerf@uniroma1.it (Marco Schaerf).

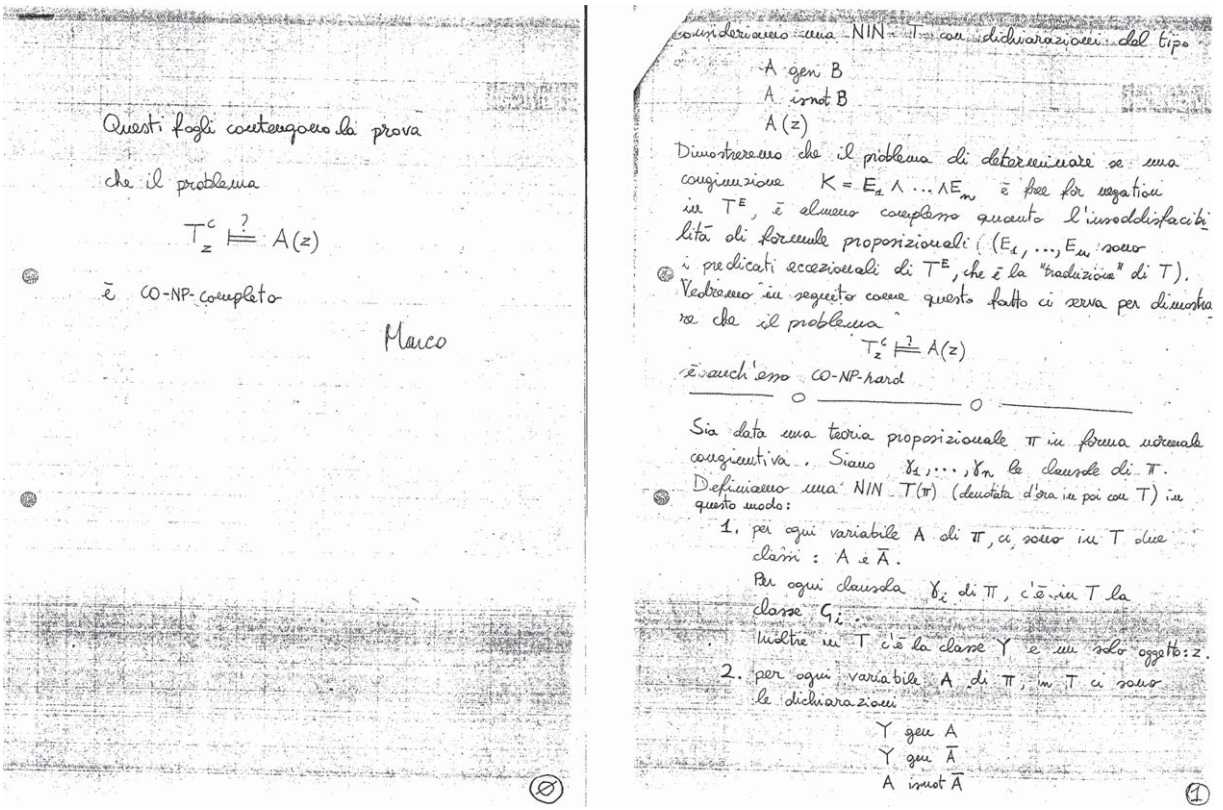

Fig. 1. Marco's hand-written proof.

help in pruning the search space of inference. We now know, also with help of Marco's results, that this intuition was not valid. Also, this is the area where he could apply the notion of finding an optimal trade-off between expressive power and feasibility/complexity of reasoning. This was a notion that Marco had learned during his studies in Theoretical Computer Science, and would constitute a recurring theme in his PhD thesis [2] and further expanded in many other papers, see, for example, [7, 10]. The first paper of this collection, titled *"Marco Cadoli's Work on Nonmonotonic Reasoning"*, by Thomas Eiter and Georg Gottlob, is a wonderful picture of the various contributions by Marco in this area. More broadly, the paper provides an enlightening view of Marco's scientific career, enriched by personal memories.

- **Description logics.** There are several families of Knowledge Representation Languages. Many textbooks typically distinguish among logic-based, object-based, and rule-based languages. Object-based languages express knowledge in terms of objects and classes, and have always attracted much attention, inspiring a huge number of formalisms in Computer Science, including Programming Languages, Database Models, and Software Specification Languages. Description Logics form a family of both Object-based and Logic-based Knowledge Representation Languages which allow for modeling an application domain in terms of objects, classes (also called concepts) and relationships (also called roles) between classes, and for reasoning about them. When Marco started his PhD, he became part of a research group that was very active in this area, and Marco gave many brilliant contributions for the advance of our knowledge on the subject. Notably, an important part of his thesis deals with reasoning in Description Logics and his most influential papers in this area are [4, 12]. This area is represented in this collection by the paper titled *"Compiling Subsumption to Relational Databases"*, by Eufemia Tinelli, Francesco M. Donini, and Eugenio Di Sciascio. Interestingly,

the paper somehow bridges the area of Description Logic with another area that Marco studied deeply at the beginning of his career, namely Relational Database Theory.

- **Knowledge compilation.** Knowledge compilation is a research approach aiming at addressing the computational intractability of reasoning suffered by many logical formalisms. According to this paradigm, a logical theory is compiled off-line into a chunk of knowledge, i.e., set of axioms, expressed in a target language, which is then used on-line to answer a large number of queries efficiently, or at least in polynomial time. The basic idea of knowledge compilation is therefore to accept paying a considerable computational price in the off-line phase, but then to amortize the cost over all on-line queries. Associated to this idea is the problem of trying to generate a very compact compiled representation, so as to help speeding up as much as possible the on-line phase. Marco and his colleagues have provided pioneering contributions in this area and his most important results are presented in [5, 6]. Two of these colleagues, namely Paolo Liberatore and Marco Schaerf, are the authors of the third paper in this collection, titled *"The Compilability Framework"*.
- **Executable specification languages.** Marco had a great interest in software engineering, and learned from that field a number of relevant principles that are valid in software design. One of these principles is the one of separating the descriptions of what software should do from the question of how it should do it. Such separation is the basis for pursuing an approach where the declarative specification of the problem becomes one of the central artifacts in software development. Obviously, the ideal goal is to have systems that are able to reason about the declarative specification, and to automatically generate the software stratum that correctly implements the functions required by the specification. Marco was simply excited by this idea, and worked hard on it, especially at the end of his career. His most interesting results have been presented in [9, 13]. The fourth paper in this collection, titled *"The NP-SPEC Project"*, authored by Luigi Polopoli and Andrea Schaerf, illustrates the basic characteristics of a research project enthusiastically carried out by Marco and colleagues in this area.
- **Agents.** Marco also worked on agent-based systems, and in particular, on negotiation. The goal of the work carried out by Marco in this area is to verify how automated formal reasoning could help in speeding up the search for an agreement during negotiation between two partially cooperative agents. The interest of Marco in this area is a good example of his attitude to research, based on the use of several techniques taken from different areas, and on a profound interest in a multi-disciplinary approach. Inspired by Marco's work on negotiation [3], that combined techniques from game theory and artificial intelligence, the fifth paper in this collection presents a recent work on an agent-based system related to a real-world problem on funding distribution in Italian University. The paper, titled *"Fair Division Rules for Funds Distribution: The Case of the Italian Research Assessment Program"*, is authored by Gianlugi Greco and Francesco Scarcello.
- **Constraint satisfaction.** This is a classical problem in Artificial Intelligence, deeply studied by Marco, see for example [1, 11]. Indeed, several of his research contributions have strong connections to many aspects related to constraints, such as constraint modeling, reasoning on constraints, checking constraint satisfaction, and constraint programming. The sixth paper in this collection is a good representative of this area. The goal of the paper is to show how to encode finite model reasoning in UML class diagrams as a constraint satisfaction problem. Notably, the result is the first implemented system that performs finite model reasoning on UML class diagrams. The paper, titled *"Finite Model Reasoning on UML Class Diagrams Via Constraint Programming"*, is authored by Marco himself, Diego Calvanese, Giuseppe De Giacomo and Toni Mancini, and is a reprint of a paper published in 2007. It is interesting to observe that the solution proposed in the paper combine techniques from Automated Reasoning, Description Logics, Constraint Programming, and Finite Model Reasoning, thus confirming the multidisciplinary nature of Marco's approach to research.

Each of the authors of the above papers has shared with Marco at least a portion of his journey. We are grateful to them for their contribution to this special issue. We know that they are deeply honored to be part of this modest tribute to Marco by the Artificial Intelligence community.

We point out that Marco contributed to many other areas of Artificial Intelligence, and here we want to briefly mention two of them.

- **Approximate reasoning.** This is one of the first research topic investigated by Marco and the topic that brought together me (Marco Schaerf) and Marco. At the beginning of 1990 Marco contacted me and proposed to work together on "Approximate Reasoning" by combining his knowledge of computational complexity and my knowledge of multivalued logics, that he already believed could be the semantical basis for the framework. We worked on this topic for several years producing many results, the most important one being [15].
- **Quantified boolean formulae.** In 1996, Marco realized that SAT solvers were rapidly becoming an important tool to solve many different computational problems that belong to NP. In order to solve problems that are in higher complexity classes, we needed to identify a reference computational problem and develop efficient algorithms for it. The reference problem was already well-defined and known, that is the evaluation of Quantified Boolean Formulae (QBF), but the algorithms developed so far were not efficient enough. In [8, 14] Marco, together with Marco Schaerf, Andrea Giovanardi e Massimo Giovanardi, developed the first efficient algorithm for QBFs that has since been the basis for all the QBF algorithms developed so far.

Marco's research has not only spanned many topics in Artificial Intelligence, and other areas in Computer Science. It has also had a profound and lasting impact in the research communities. If you look at Marco's pages either on DBLP http://www.informatik.uni-trier.de/~ley/pers/hd/c/Cadoli:Marco.htmlor in Google Scholar http://scholar.google.it/scholar?as_q=&as_epq=&as_oq=&as_eq=&as_occt=any&as_sauthors="M+Cadoli" you immediately notice:

- Beyond Artificial Intelligence, Marco's scientific production has covered many different areas, including Theoretical Computer Science, Database Theory and Software Engineering;
- There are almost 10 papers that appeared after his death in 2006, testifying both his amazing ability to obtain results that were of great impact on the research community, and his incredible attitude to do research even when his health was already deteriorating.

The scientific and academic community has honored Marco in many ways, including:

- The main classroom of the Department of Computer, Automation and Management Engineering Antonio Ruberti of Sapienza University in Rome is named after Marco, as a special recognition from his Department not only for his research career, but also for his ability and dedication in teaching;
- The annual award for the best PhD thesis of the Italian AI Association (AI*IA) is named after Marco http://www.aixia.it/premi;
- The GULP (Gruppo Ricercatori e Utenti Logic Programming, Italian Association for Logic Programming) Dissertation Award 2007–2009 http://lia.deis.unibo.it/gulp/Burocrazia/bando-premi-tesi-2009.html;
- The International Conference on Principles of Knowledge Representation and Reasoning (KR) dedicates his Distinguished Student Paper Award (starting from 2014) to Marco.
- Many web pages have been dedicated to Marco's memory, most notably the Sixth International Workshop on Constraint Modelling and Reformulation (ModRef'07) http://www.cse.cuhk.edu.hk/~jlee/cp07Model/.

All the above considerations show how rich and important is the scientific legacy of Marco. However, such legacy is not the main reason why we, and all the people who have been lucky enough to work with him, will always regret his loss. Indeed, Marco was a wonderful human being, and what we deeply miss is his presence, his smile, his mind, and, most of all, his friendship.

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