Knowledge Representation and Reasoning

Grigoris Antoniou
Dept of Computer Science
University of Crete
Heraklion 711 10, Greece
antoniou@ics.forth.gr

Pavlos Peppas
Dept of Business Adminstration
University of Patras
Patras 265 00, Greece
pavlos@upatras.gr

1 Introduction

In this chapter we shall review some of the recent work by Greek academics in Knowledge Representation and Reasoning (KRR).

In writing this survey it came as a pleasant surprise to us to see how much our fellow Greeks have accomplished in the past few years. Ranging from core KRR topics like *Non-Monotonic Reasoning*, *Epistemic Logics*, *Belief Revision*, and *Reasoning about Action*, to *Logic Programming*, the *Semantic Web*, and *KRR Applications*, the research output of Greek academics is impressive both in quantity and quality.

In Nonmonotonic Reasoning we find the work of *Grigoris Antoniou* and his colleagues[1] in defeasible reasoning and its applications. Antoniou has also been active in Reasoning about Action, along with *Antonis Kakas*, *Nikos Papadakis*, *Pavlos Peppas*, and *Dimitris Plexousakis*, all of which have made important contributions to the frame, ramification, and qualification problems, and have producing interesting meta-level results. Work in Belief Revision focuses on the classical AGM paradigm and its migration to Description Logics. Once again, Antoniou, Plexousakis, and Peppas are among the key players, with the recent addition of *George Flouris* – a young and promising researcher – bringing in fresh ideas to the field.

Costas Koutras and his colleagues dominate the area of Epistemic Logics with important results in many-valued modal logics. Cognitive Agents is yet another area where Kakas has produced interesting results in collaboration with *Yiannis Dimopoulos* and *Pavlos Moraitis*. Kakas has also been active in Logic Programming (LP) (more specifically Abductive and Inductive Logic Programming). Yet he is not alone in this area. *Foto Afrati*, *Manolis Gergatsoulis*, *Christos Nomikos*, and *Panos Rondogiannis*, have worked extensively in LP producing important results

[1] Much of the work of Greek academics is in collaboration with colleagues overseas. Since however this is a survey on the Greek KRR community, in the text we shall only name the Greek researchers – of course our citations include all contributors.

in temporal logic programming, semantics of general logic programs with negation, and Datalog programs.

Applications of KRR in the Semantic Web has also attracted a lot of interest from Greek researchers. People like *Anastasia Analyti*, *Nikos Bassiliades*, *Antonis Bikakis*, *Vassilis Christophides*, *Panos Constantopoulos*, *Yiannis Tzitzikas*, *Ioannis Vlahavas*, and researchers already mentioned earlier like Antoniou, Gergatsoulis, Kakas, and Plexousakis, have made significant contributions on rules systems and Semantic Web languages, faceted taxonomies, modeling semi-structured data, and ontology evolution.

In the applications front, a declarative modeling approach to computational biology developed by Kakas, *Papatheodorou* and their colleagues has already delivered promising results. Finally *Ioannis Hatzilygeroudis*, *Jim Prentzas*, *Basilis Boutsinas*, *Mihalis Vrahatis* and their colleagues have integrated symbolic rules and non-symbolic methods to produce powerful hybrid systems.

A survey of this size couldn't possibly be complete. It simply offers a glimpse at the work of our fellow Greeks in KRR, and it reveals a fairly young and yet thriving research community.

2 Non-Monotonic Reasoning

Defeasible reasoning is an approach that seeks to combine advanced representational capabilities to capture reasoning with incomplete and inconsistent information with low computational complexity. Main characteristics include, (i) the approach are rule-based, without disjunction, (ii) classical negation is used in the heads and bodies of rules, (iii) rules may support conflicting conclusions, (iv) the logics are skeptical in the sense that conflicting rules do not fire – thus consistency is preserved, and (v) priorities on rules may be used to resolve some conflicts among rules.

Working on defeasible reasoning, Antoniou et al have developed an argumentation semantics for defeasible logics [51], the extension of defeasible logic with dynamic priorities [4], and have established relationships between defeasible logics and logic programming [5].

Antoniou et al have also have also considered applications of defeasible reasoning to the Semantic Web. In recent years, attention within the Semantic Web community has turned towards the use of rule languages, either as additions or alternatives to description based languages. In addition, the need for some forms of inconsistency-tolerant reasoning has become apparent. Members of the FORTH laboratory in Crete have applied defeasible reasoning to the Semantic Web domain, arguing that some of its properties (rule-based, low computational complexity) make it particularly appropriate for this domain.

This work has produced two prototype systems: DR-Prolog [6], which is written in Prolog, and DR-DEVICE [15], written on top of a deductive rule system (see more details in section 8). Both systems combine the functionalities of defeasible reasoning, RDF and RDF Schema, and are compatible with the rule standardization initiative RuleML (which they extend to represent defeasible rules and priorities).

These systems were used to develop advanced applications in the areas of semantic matching [7],automated negotiation [108], and mobile services [9]. In addition, DR-Prolog was extended to represent modalities [8], in particular for reasoning about permission. Finally, a proof layer, including proof extraction, representation and exchange, was implemented on top of DR-Prolog [10].

3 Reasoning about Action

In the area of Reasoning about Action (RAA) Dimitris Plexousakis and his colleagues have focused on investigating the interaction between knowledge and action both at a theoretical level but also at a more applied level in the context of Ambient Intelligence computing. The field of Ambient Intelligence provides an appropriate context as it is characterized by a shift in computing towards a multiplicity of stationary and mobile communicating devices disappearing into the background, providing an intelligent, augmented environment. Devices operate autonomously in proactive and reactive manner, acquiring information from sensors and communicating with others, in order to distribute resources and collaborate during planning. Action theories can provide the tools to produce formal models to verify the specifications of an ambient system and to prove their correctness properties. The advent of Ambient Intelligence poses pragmatic challenges for planning, for which the handling of knowledge-producing and sensing actions will prove to be an important leverage.

Responding to these challenges, Plexousakis et al work have followed two main lines of research [20, 87, 18, 89, 85, 83, 79]: (a) addressing the ramification problem in a temporal context where actions and time affect present, past or future states of affairs, and (b) devising a unifying theory of knowledge, action and time for dynamic systems. The former is based on extensions of the Situation Calculus and aims at supporting applications in temporal databases and cognitive robotics. The latter is based on formalism inspired by the Event Calculus and aims at supporting ambient intelligence applications.

Kakas' recent work in Reasoning about Actions has focused primarily on the qualification problem and how it relates to the properties of the modularity and elaboration tolerance of action theories [58]. Together with his colleagues, Kakas has extended the Language E to a new language, called Modular E, where an integrated solution to all three major problems in RAA (frame,ramification and qualification problems) is given. This new language exhibits a high degree of modularity and elaboration tolerance. Kakas et al are also studying how a family of languages E can be translated into Answer Set Programming (ASP) so that they can take advantage of the effective ASP systems available.

Work on Reasoning about Action has also been undertaken by Pavlos Peppas and his colleagues [101, 78, 91, 37, 66, 67, 38, 39, 40, 41]. There are mainly three lines of research pursued by Peppas et al. The first relates to the study of *causality-based* approaches in RAA, and their relation to *minimal-change* approaches. More precisely, Peppas et al have devised unifying possible-world semantics for some of the predominate causal approaches to RAA [101]. The preferential flavor of this semantics facilitates an in-depth comparison between causal-based and minimal-change approaches. Indeed, in [78] a precise characterization of the range of applicability of minimal change approaches was provided and comparisons were made with the most popular causal-based approaches.

The second line of research pursued by Peppas at al relates to the notion of *conciseness* in RAA. Questions like how concise does a representation have to be to qualifies as a solution to the frame problem, or how do we even measure conciseness in Reasoning about Action, have not been properly addressed, despite the fact that conciseness of representations has been the main aspiration driving most of the research in RAA. Peppas and his colleagues have taken preliminary steps towards developing a framework within which the notion of conciseness in RAA can be formally assessed [91, 66, 67].

Peppas' final line of work in RAA has been undertaken primarily in collaboration with Norman Foo. In [37, 38, 39], Peppas and Foo studied the connections between Systems Theory and Reasoning about Action, borrowing ideas from the former to address problems in the later. Related to this, but not quite in the same line of work, is the duo's work with Yan Zhang on extracting state constraints from STRIPS descriptions [40, 41].

4 Belief Revision

Much of the work by Greek academics in Belief Revision focuses on the classical AGM paradigm and application of its ideas and results in other areas.

Starting from the University of Crete, we find Plexousakis', Flouris', and Antoniou's, important results in the area [27, 28, 29, 30, 31, 32, 34, 35, 36]. Focusing on the problem of retracting knowledge from a knowledge base, as well as the problem of updating Propositional and Description Logic-based knowledge bases, Plexousakis et al have contributed a number of theoretical results that are of primary importance for accommodating change in evolving knowledge-based systems. More precisely, they have proposed a generalization of the most salient theory of belief revision and updating, namely the AGM theory of change. This generalization focuses on the formalization of an appropriate knowledge contraction operator and the axiomatization of a theory of knowledge change supporting the operation of contraction. The applicability of the proposed axiomatization in the case of Description Logic updates has also been examined. Plexousakis et al have explored the limits of this generalization, showed a different facet of the AGM postulates and provided a new representation theorem for contraction operators satisfying the AGM postulates. Other results include a study on the connection of the AGM theory with the foundational model, the role of the various assumptions of the AGM theory on its applicability and some preliminary thoughts on revision. As a case study, Plexousakis et al have explored the applicability of their generalized theory in the context of languages used for ontological representation in the Semantic Web (Description Logics and OWL). Plexousakis et al argue that this application may solve some of the thorny problems currently faced by ontology evolution researchers (see section 8 for more details).

In Patras University, Peppas' recent work in Belief Revision, [90, 115, 116, 75, 92, 93, 111, 42, 94, 95], has focused primarily on possible-world semantics for revision functions. Together with his colleagues, Peppas studied a number of constraints in the context of *systems of spheres*, and the implications that these constrains have on AGM revision functions as well as on multiple revision. Among these constraints, of particular interest is Winslett's measure of similarity between worlds. As it was proved recently by Peppas et al, [92], this constraint characterizes precisely Parikh's postulate for *relevance-sensitive belief revision*. Peppas and his colleagues have also produced interesting results on *iterated belief revision*, the most recent one of which is proof of incompatibility between Darwiche and Pearl's prominent postulates for iterated revision and Parikh's postulate for relevance-sensitive belief revision [95]. A final direction of Peppas' work has been the application of ideas and techniques from Belief Revision in other areas like *Knowledge Management* and *Software Engineering* [115, 116, 111].

5 Epistemic Logics

The advent of multi-agent systems revived the interest of the KRR community in modal epistemic logics. Greece is no exception.

In a series of papers, Costas Koutras and his colleagues have studied properties of an important family of many-valued modal logics introduced by Fitting in the early '90. More precisely, in [64] generalized "weak" versions of the classical modal axiom schemata **D**, **T**, **B**, **4**, and **5** were introduced and the elegant canonical model argument of Fitting is extended to obtain frame completeness results. The axioms are shown to be canonical for properties of labeled frames which look like natural many-valued versions of the familiar classical conditions of *seriality*, *reflexivity*, *symmetry*, *transitivity* and *euclideanness*. In [65, 26] this family of logics is investigated from the perspective of Correspondence Theory and Algebraic Modal Model Theory.

In [68] a concrete example of this family of logics is given, along with its axiomatic content, completeness and complexity results. It is a 3-valued logic whose truth space makes it very attractive for uncertainty-handling applications.

Koutras et al also produced important results on non-monotonic counterparts of Fitting's multi-valued logics. More precisely, building on earlier work by Fitting who lifted the many-valued setting Schwarz's earlier theorem on the equivalence of nonmonotonic **KD45** with Moore's autoepistemic logic, Koutras and Zachos, [62], proved that this is also true also nonmonotonic **Sw5** and Schwarz's reflexive autoepistemic logic.

Finally, in [69], Koutras and Peppas investigated ranges of many-valued modal nonmonotonic logics. The notion of *range* has been introduced by W. Marek, G. Schwarz and M. Truszczyński and is one of the most important findings in modal non-monotonic reasoning. A range is a collection of modal logics that generate the same concept of a consistent expansion and thus, the same non-monotonic consequence operator. Typically, a range contains a closed interval of the lattice of modal logics: for instance, it is known that every modal logic Λ such that $\mathbf{5} \subseteq \Lambda \subseteq \mathbf{KD45}$ gives rise to the same McDermott-Doyle non-monotonic logic. Of particular interest is also the range $\mathbf{w5} - \mathbf{D4w5}$ which provides the (consistent) *strict expansions* and the range $\mathbf{Tw5} - \mathbf{Sw5}$ which captures Schwarz's reflexive autoepistemic logic (rAEL). For many-valued modal languages built on finite chains, Koutras and Peppas have extended previous results by proving two quite general range theorems, similar to the classical ones mentioned above.

6 Cognitive Agents

Work on *Cognitive Agents* has been carried out primarily by Antonis Kakas and his colleagues [56, 25, 57, 11, 22, 23].

More precisely, Kakas et al have examined how one can allow context sensitive forms of *argumentation* and how, with the help of abduction, argumentation and decision making can be carried out in cases where there is missing background information.

These enhancements are integrated in the *Gorgias* system providing general support for various applications of argumentation. These applications include the declarative control of agents, medical decision systems for advising on treatments and the formalization of network security policies, such as firewall policies.

Kakas et al are also studying the development a cognitive agent's architecture based on the high-level integration of argumentation policies linked to the different faculties of the agent.

7 Logic Programming

Although *Logic Programming* is not traditionally considered part of KRR, the two research areas are not totally disjoint. Much of the work carried out by Greek researchers in Logic Programming falls in this overlap with KRR.

Starting with the joint work of Gergatsoulis and Rondogiannis we find their research focusing on the following issues: (i) the definition of new and expressive temporal logic programming languages; (ii) the extension of existing temporal logic programming languages with new powerful features (such as for example, the extension of Chronolog with disjunctive characteristics [47]); (iii) the use of branching-time temporal logic programming as the target language for transforming and simplifying logic programs (such as for example, the generalization of the *counting* transformation technique given in [105] and [96]); and (iv) the development of new semantical approaches for temporal logic programming languages equipped with negation-as-failure [76].

This last line of research – i.e. semantics for negation in Logic Programming – has also been pursued independently by Rondogiannins in [104], as well as in collaboration with other colleagues [106, 107, 24, 77].

More precisely, Rondogiannis et al. have introduced the so-called *infinite-valued approach* to the semantics of general logic programs with negation (see [106] and [107]). This approach is a purely logical reconstruction of the well-founded semantics of negation through the use of a new infinite-valued logic; under this new logic, it is demonstrated that every logic program with negation has a unique *minimum* model, which when collapsed to three-valued logic, coincides with the well-founded model of the program. This new approach to negation has recently resulted to a novel technique for assigning semantics to disjunctive logic programs with negation [24]. Additionally, this new approach has offered a (partial) solution to the problem of characterizing the notion of *strong equivalence* of logic programs with negation under the well-founded semantics [77].

Rondogiannis has also worked on various extensions of logic programming that can make this paradigm even more expressive. One such example is the extension of logic programming with higher-order characteristics [61]. Finally, a very recent and promising activity is the study of the interplay between logic programs and infinite games of perfect information [43].

Turning next to Gergatsoulis' research – other than that mentioned above – we find important contributions in a variety of topics.

Firstly, in continuation of his joint work with Rondogiannis, Gergatsoulis has contributed to the development of the branching-time logic programming language Cactus [44], whereas in collaboration with his colleagues he investigated proof procedures for expressive temporal logic programming languages like Cactus [49]. He also worked on the investigation of linearizable classes of database logic programs (Datalog programs), that is classes which turn out to express no more than the queries expressed by linear Datalog programs [1].

Important work in Logic Programming, more specifically Abductive and Inductive Logic Programming (ALP and ILP) has also been produced by Kakas and his colleagues [102, 103, 121, 112, 113, 114, 81]. Building on their previous work, they have recently further developed their tools *A-system* and *ProLogICA* for computing abduction. They have used these tools in several problems, such as the development of the KGP agent architecture and the development of declarative models for various biological phenomena.

8 Semantic Web

As already mentioned in the Introduction, where is important work by Greek academics in the intersection of KRR and the Semantic Web. We shall briefly look at these contributions.

8.1 Rule Systems

Nikos Bassiliades together with Grigoris Antoniou and Ioannis Vlahavas have worked on (monotonic and non-monotonic) rule systems for the Semantic Web.

A major line of their work focuses on the combination of rule systems with Semantic Web representation languages in order to facilitate the development of knowledge-based Semantic Web applications (e.g. Semantic Web Service discovery and composition). X-DEVICE, R-DEVICE, and O-DEVICE are the outcome of their efforts. X-DEVICE, [13], is a deductive object-oriented database for managing XML data and it is an extension of the active object-oriented knowledge base system DEVICE [12]. R-DEVICE, [14], is a deductive object-oriented knowledge base system for reasoning over RDF metadata. R-DEVICE imports RDF documents into the CLIPS production rule system by transforming RDF triples into COOL objects and uses a deductive rule language for reasoning about them. Finally, the knowledge base O-DEVICE [74] is a memory-based system for reasoning and querying OWL ontologies by implementing RDF/OWL entailments in the form of production rules in order to apply the formal semantics of the language. O-DEVICE is built over the CLIPS production rule system, using the object-oriented language COOL to model and handle ontology concepts and RDF resources.

Bassiliadies et al have also worked on the integration of rule systems with the aim of providing Semantic Web agents with efficient and flexible rule reasoning engines, capable of reasoning with multiple rule types. DR-DEVICE, [15], is rule-based system capable of reasoning about RDF metadata over multiple Web sources using defeasible logic rules. The system is implemented on top of CLIPS production rule system and builds upon R-DEVICE. Rules can be expressed either in a native CLIPS-like language, or in an extension of the OO-RuleML syntax. The operational semantics of defeasible logic are implemented through compilation into the generic rule language of R-DEVICE. Among other things, DR-DEVICE supports multiple rule types of defeasible logic, both strong negation and negation-as-failure, and conflicting literals (i.e. derived objects that exclude each other).

Complementary to this work is VDR-DEVICE, [60], a visual integrated environment for developing (creating, editing, running, testing, deploying and visualizing) defeasible rule bases for the Semantic Web, on top of RDF Schema ontologies.

Other work of Bassiliadues et al include (i) extending rule engines with the ability to explain their results by exporting and exchanging proofs with Semantic Web applications [16], and (ii) combining rule-based OWL reasoning with OWL-S Semantic Web Service descriptions, in order to build rule-based methodologies for Semantic Web Service discovery, composition and, finally, deployment [72, 73].

8.2 Extended RDFS and Faceted Taxonomies

Anastasia Analyti and her colleagues have focused on two different topics. The first is the extension of the Semantic Web language *Resource Description Framework Schema (RDFS)*. In [3, 2], Analyti et al extend RDFS to accommodate the two negations of Partial Logic, namely, weak negation (expressing negation-as-failure or non-truth) and strong negation (expressing explicit negative information or falsity), as well as derivation rules. The new language is called Extended RDF (ERDF) and the proposed stable model semantics of ERDF ontologies is based on Partial Logic and it extends the model-theoretic semantics of RDFS. ERDF enables the combination of closed-world (non-monotonic) and open world (monotonic) reasoning, in the same framework, through the presence of weak negation (in the body of the rules) and the new metaclasses erdf:TotalProperty and erdf:TotalClass, respectively.

The second line of Analyti's work relates to faceted taxonomies and compound terms. Faceted taxonomies carry a number of well known advantages over single taxonomies (clarity, compactness, scalability), but they also have a severe drawback: the high cost of avoiding invalid compound terms, i.e. compound terms that do not apply to any object in the domain. Analyti et al have proposed an algebra, [119, 117], called Compound Term Composition Algebra (CTCA), based on which one can built an algebraic expression to specify the valid compound terms of a faceted taxonomy, in a flexible and easy manner. The availability of algebraic expressions describing the valid compound terms of a faceted taxonomy enables the dynamic generation of navigation trees, whose nodes correspond to valid compound terms, only. These navigational trees can be used for indexing (for avoiding errors) and do not present the problem of missing terms or missing relationships that characterize single-taxonomies. Additionally, given a materialized faceted taxonomy M (i.e., a corpus of objects indexed through a faceted taxonomy), specific mining algorithms (such as, these in [118]) can be used for expressing the extensionally valid compound terms of M in the form of an algebraic expression. Such mined algebraic expressions enable the user to take advantage of the aforementioned interaction scheme, without having to resort to the (possibly, numerous) instances of M. Furthermore, algebraic expressions describing the valid compound terms of a faceted taxonomy can be exploited in other tasks, such as retrieval optimization, configuration management, consistency control, and compression.

The revision of a CTCA expression e after a taxonomy update is examined in [120]. The aim is to produce a new well-formed expression e' whose semantics (defined valid compound terms) is as close as possible to the semantics of the original expression e before the update.

8.3 Ontology Evolution

One of the crucial tasks to be performed towards the realization of the vision of the Semantic Web is the encoding of human knowledge in ontologies using formal representation languages. Simply creating an ontology is not enough though; ontologies, just like any structure holding knowledge, need to be updated for several reasons, including a change in the world being modeled, a change in users' needs, the acquisition of knowledge previously unknown, classified or otherwise unavailable or a design flaw in the original conceptualization.

Grigoris Antoniou, Vassilis Christophides, George Flouris, and Dimitris Plexousakis, all members of the FORTH laboratory in Crete, together with colleagues, seek to apply ideas and techniques from belief revision to ontology evolution. On a purely theoretical level, a study was conducted on how the AGM postulates can be modified to be relevant to description logics, and under what conditions description logics allow for AGM-like revision. Key publications reporting on these results include [27, 30, 35, 31].

A more practical approach seeks to apply belief revision ideas (rational change operator, minimal change) to RDF ontology evolution. The process defined consists of the determination of the allowed update operations, the identification of the invalidities that could be caused by each such operation, the determination of the various alternatives to deal with each such invalidity, and, finally, some selection mechanism for singling out the "best" of these alternatives. Preliminary results are reported in [59].

8.4 Extensions of XML, Semi-structured Data and RDF

A final topic on the Semantic Web pursued by Greek researchers is the development of formalisms suitable for representing context depended data and knowledge in the Web. Gergatsoulis and his colleagues have proposed multidimensional extensions for XML, [45], semi-structured data RDF, [109], and RDF, [50]. The new formalisms have been applied in representing and querying the history of conventional semi-structured data, [110], and XML, [48], as well as in defining techniques for handling multidimensional information in the web [46] and in designing a metadata model for representing information about cultural collections [71].

9 Hybrid Systems and Applications

Ioannis Hatzilygeroudis and his colleagues have produced integrating results on integrating symbolic rules with non-symbolic methods.

More precisely, one of the research directions pursued by Hatzilygeroudis et al is to combining rules and neural networks. Most of the existing approaches to this end incorporate or implement rule-based aspects in a neural net framework loosing in the process much of the benefits of explicit representation. Hatzilygeroudis et al attempt to combine rules and neural nets the other way round: by incorporating neurocomputing aspects within the symbolic framework of (propositional) rules. The result of this effort has been the so-called neurules (neural rules), based on which a hybrid system has been built that has been proved to be more efficient than both plain symbolic rules and neural nets alone in preliminary experiments. Moreover, neurules can be produced from either symbolic rules (via the traditional knowledge acquisition approach) or empirical data [52, 53, 98].

In continuation of the above effort, certain methods were proposed for maintaining a neurule base, i.e. updating it, when the source knowledge it came from is changed, without reconstructing the whole base. This was done for both cases of source knowledge, be it a symbolic rule base or empirical data [97, 99].

An extra step in this research direction has been the combination of a third representation/reasoning scheme with neurules, to enhance their representational and reasoning/inference capabilities. This has led us to two further developments. The first has been a successful combination of neurules with case-based reasoning. [54]. The second development incorporates fuzziness into neurules resulting in the *fuzzy neurules*. Fuzzy neurules are a kind of integrated rules that combine symbolic rules and a neuro-fuzzy unit, the fuzzy adaline unit. Although the majority of existing efforts in neuro-fuzzy community give pre-eminence to the neural side, in fuzzy neurules we do it again the other way round. Again, fuzzy neurules retain modularity of classical fuzzy rules, since a fuzzy neurule base consists of autonomous units [70].

A final research direction is the formulation of general principles for approaches that combine two or more schemes (i.e. hybrid systems). To this end, a new categorization of such approaches has been devised, focusing especially on approaches combining rules and neural nets. The new categorization remedies the deficiencies of existing categorization schemes, which are proved inadequate in accommodating all existing approaches [55, 100].

Before leaving the domain of hybrid systems, it is worth mentioning the important work of Basilis Boutsinas and Mihalis Vrahatis, [21], on enhancing neural networks with nonmonotonic reasoning capabilities.

Turning next to applications of KRR, we find the work of Antonis Kakas and his colleagues who have proposed a declarative modeling approach to computational biology in order to study a number of related problems [81, 112, 113, 114]. For example, they have been analyzing DNA microarray experiments (on M. tuberculosis and S. cerevisiae) through a simple but general model of how gene interactions can cause changes in observable expression levels of genes. This generates hypotheses about the possible gene interactions that explain the observed data. Another such application in the area of predictive toxicology concerns the study of the inhibitory effect of toxins in metabolic networks. Using these methods, an *in-Silico Sequencing System (iS3)* has been developed for reasoning about Human Immunodeficiency Virus (HIV) drug resistance in order to assist medical practitioners in the selection of anti-retroviral drugs for patients infected with HIV.

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