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Logic Programming as an Inference Engine for Non-Monotonic Reasoning

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Ten (10) papers were published and two (2) additional papers were accepted for publication. Moreover, four (4) papers are currently under preparation, including joint papers with W. Drabent, H. Przymusinska, L. Pereira and D.S. Warren. Significant progress has been made towards both theoretical and algorithmic foundations of a non-monotonic reasoning system based on logic programming. An implementation of such a system, limited to circumscriptive theories, has been also completed.

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1 Articles Sponsored by ARO which Appeared in Print or were Accepted for Publication

1. "Extended Stable Semantics for Normal and Disjunctive Logic Programs", Proceedings of the International Logic Programming Conference, Jerusalem, Israel, June 1990, MIT Press, pp. 459-477.

2. "The Well-Founded Semantics Coincides With The Three-Valued Stable Semantics" invited paper, Fundamenta Informaticae 13(4)(1990), pp. 445-464 (special issue on Non-Monotonic Reasoning; W. Marek, editor).

3. "Stationary Semantics for Disjunctive Logic Programs", North American Conference on Logic Programming, Austin, Texas, 1990, MIT Press, pp. 40-59.

4. "On the Relationship Between the Minimal Model Semantics and CWA", invited paper, special issue of the International Journal of Intelligent Systems 5(5) (1990) (M. Leash, editor), (coauthors: M. Gelfond and H. Przymusinska), pp. 549-564.

5. Weakly Stratified Logic Programs, invited paper, Fundamenta Informaticae 13(1990), 51-65 (special issue devoted to Logical Foundations of AI; K. Apt, editor; coauthor: H. Przymusinska).

6. Non-monotonic Reasoning vs. Logic Programming: A New Perspective, invited paper, The Foundations of Artificial Intelligence. A Sourcebook (eds. Y.Wilks and D.Partridge), Cambridge University Press, 1990, 49-71.

7. "Semantic Issues in Deductive Databases and Logic Programs", invited paper, in: 'Formal Techniques in Artificial Intelligence. A Sourcebook' (Editor R. Banerji), North Holland, 1990, 321-367. (coauthor: H. Przymusinska).

8. "Autoepistemic Logics of Closed Beliefs and Logic Programming", Proceedings of the First International Workshop on Logic Programming and Non-monotonic Reasoning, Washington, D.C., July 1991, MIT Press, 3-20.

9. "Well-Founded Completions of Logic Programs", Proceedings of the Eight International Logic Programming Conference, Paris, France, MIT Press, 1991, 726-744.

10. "Three-Valued Non-Monotonic Formalisms and Semantics of Logic Programs", special issue of the Journal of Artificial Intelligence 49, 1991, 309-343.

11. "Extended Stable Semantics", invited paper, special issue of the New Generation Computing Journal 9(3), 1991, K. Ueda and T. Chikayama, editors, Springer Verlag, in print.

12. "Semantics of Disjunctive Logic Programs", Proceedings of the Conference on Deductive Object-Oriented Databases (DOOD'91), Munich, Germany, 1991, to appear.

2 Summary of Conducted Research

During the period of two years of funding provided by the ARO, ten (10) papers were published and two (2) additional papers were accepted for publication. Moreover, four (4) papers are currently under preparation, including joint papers with W. Drabent, H. Przymusinska, L. Pereira and D.S. Warren. Significant progress has been made towards both theoretical and algorithmic foundations of a non-monotonic reasoning system based on logic programming. An implementation of such a system, limited to circumscriptive theories, has been also completed.

Below we briefly describe the major findings:

- In [10] we introduced *3-valued extensions* of all four major non-monotonic formalisms and we proved that the *well-founded semantics* of logic programs is equivalent, for *arbitrary* logic programs, to 3-valued forms of McCarthy's circumscription, Reiter's closed world assumption, Moore's autoepistemic logic and Reiter's default theory.

  This result not only provided a further justification of the well-founded semantics, as a natural extension of the perfect model semantics from the class of stratified programs to the class of all logic programs, but it also established the class of *all logic programs* as a large class of theories, for which *natural forms of all four non-monotonic formalisms coincide.* It also paved the way for using relatively efficient computation methods, developed for logic programming, as inference mechanisms for non-monotonic reasoning. Coupled with other results discussed below, it also led to a significant expansion of the class of non-monotonic theories translatable into logic programs.

  In recent papers, equivalent non-monotonic formalisms were introduced, this time based on standard, *2-valued* logic, and thus demonstrating that 3-valued logic is *not* required to obtain a suitable semantics for logic programs with coincides with natural forms of all four major non-monotonic formalisms.

- In [1], [2] and [11] we introduced *partial stable model semantics* of *normal* and *disjunctive* logic programs, which naturally extends the concept of the standard (total) stable model semantics, defined only for some normal (i.e., non-disjunctive) programs. As a result we obtained the following results:

- Every normal logic program P has at least one partial stable model. In fact, the *well-founded model* of any normal program P is the smallest (in the sense of inclusion) partial stable model of P.
- Consequently, the well-founded semantics of an *arbitrary* normal logic program *coincides* with the partial stable model semantics.
- For (locally) stratified *disjunctive* programs the partial stable model semantics coincides with the *perfect model semantics.* In particular, for positive disjunctive programs, it coincides with the *minimal model semantics.*
- After translation of the program P into a suitable autoepistemic (resp. default) theory $\hat{P}$ the partial stable semantics of P coincides with the 3-valued autoepistemic (resp. default) semantics of $\hat{P}$.

- In [3] and [12] we extended the *well-founded semantics*, defined originally for normal (non-disjunctive) logic programs, and the *partial stable semantics*, discussed above, to the class of *all disjunctive* logic programs and deductive databases and proved that the new semantics, which we call the *stationary semantics*, has the following properties:
  - The stationary semantics is constructively defined for *all disjunctive logic programs* and deductive databases.
  - For normal (non-disjunctive) logic programs it *coincides* with the well-founded semantics.
  - For (locally) stratified disjunctive programs it coincides with the *perfect model semantics.*
  - The stationary semantics is the *only* currently known semantics which is defined for all disjunctive programs and extends both the well-founded semantics of normal programs and the perfect model semantics of stratified disjunctive programs.
  - The stationary semantics can be naturally extended to programs using *"classical"* negation, in addition to negation as failure.

- Using the above results the author was able to significantly broaden the class of non-monotonic theories which can be translated (compiled) into logic programs. In particular, non-monotonic theories can now be translated not only into stratified logic programs but into arbitrary normal (or even disjunctive) programs. This fact is crucial for the development of a non-monotonic reasoning system which will combine a relatively efficient *logic programming* engine and a *translation unit*, allowing translation of non-monotonic theories into logic programs. The paper describing these results is currently under preparation.

- In [8] we proposed a new and more general approach to autoepistemic reasoning by introducing *Autoepistemic Logics of Closed Beliefs* AEL_{NMF}, where NMF denotes a specific *non-monotonic formalism* on which the logic is based. Moore's autoepistemic logic AEL is a *special case* of AEL_{NMF} obtained when Reiter's Closed World Assumption CWA is used as NMF. The proposed logics provide a natural and mathematically elegant framework where by choosing different non-monotonic formalisms NMF we obtain different autoepistemic logics AEL_{NMF} reflecting the properties of NMF. We documented this claim by investigating the Autoepistemic Logic of Closed Beliefs AEL_{CIRC}, based on McCarthy's *Circumscription* $CIRC$, in the class of *logic programs* and showing that AEL_{CIRC} represents an attractive non-monotonic formalism which eliminates well-known drawbacks of Moore's AEL. In particular, for logic programs, the autoepistemic logic based on circumscription coincides with the well-founded semantics thus proving that both the stable and well-founded semantics are based on autoepistemic logic and that the only difference between the two semantics stems from the fact that the former is based on Reiter's CWA while the latter is based on Minker's GCWA or McCarthy's Circumscription.

- Based on the above results, in [9], we defined, for *every* logic program P, the *Well-Founded Completion* $comp_{wf}(P)$ of P which, like Clark's Predicate Completion $comp(P)$ of P, is an extension of P providing a suitable meaning or *semantics* for the program. We showed that the set of sentences logically implied by $comp_{wf}(P)$ precisely coincides with the set of sentences satisfied in the well-founded model M_P of P, thus showing that the new completion $comp_{wf}(P)$ of P, which is described entirely in terms of classical *2-valued logic*, in fact describes the *well-founded semantics* of P.

  This result not only provided a simpler and more intuitive formalization of the "negation as failure" operator, but it also put the well-founded semantics on *equal footing* with other semantics, in terms of being defined entirely within classical, 2-valued logic, while at the same time preserving its various advantages over the other semantics. In particular, for propositional programs, the well-founded completion can be computed in *quadratic* time. This result is also important because it allows a natural translation of autoepistemic theories into logic programs.

Subsequently, we extended those results to the class of *all* disjunctive logic programs and deductive databases by defining *stationary completions* of disjunctive programs and thus introducing a natural iterated minimal model semantics for all such programs. These results significantly extend the class of logic programs which can be used in the process of translation of non-monotonic theories into logic programs and thus are of significant importance for our project.

- In the paper [4], written jointly with M. Gelfond and H. Przymusinska, we compared three types of non-monotonic semantics:

  - Proof-theoretic semantics based on the closed world assumption,
  - Model-theoretic semantics based on the notion of a minimal model,
  - Model-theoretic semantics based on the notion of a minimal *Herbrand* model,

  in the class of *positive logic programs.* We showed that, although the three semantics usually differ for universal sentences, they always coincide for *existential* queries. This result is particularly significant in view of the fact that in many applications existential queries are of main interest.

- In the paper [5], written jointly with Halina Przymusinska, we have introduced the weakly stratified semantics which places somewhere in between perfect and well-founded semantics.

- Papers [6] and [7] are invited survey articles discussing the relationship between non-monotonic reasoning and logic programming and the semantics of deductive databases.

- In parallel, we have been intensively working on procedural and implementation aspects of a non-monotonic reasoning system based on logic programming. Our work has been conducted in cooperation with a group of researchers at the University of Linkoping in Sweden and also in cooperation with David S. Warren from SUNY at Stony Brook.

We have used David Warren's algorithm to implement an interpreter for the well-founded semantics of logic programs and tested it on a number of benchmark examples. The interpreter is written in Prolog and therefore is relatively slow. Nevertheless it is very well-suited for testing and clearly demonstrates the feasibility of computing the well-founded semantics.

We have also completed work on the implementation of a circumscriptive theorem prover based on translation of a circumscriptive theory C into a logic program $P(C)$, which then uses the above interpreter for well-founded semantics to provide answers to queries about C. As opposed to the original approach, proposed by Gelfond and Lifschitz, which was restricted to stratified programs, our circumscriptive theorem prover allows translation into *arbitrary* logic programs with the well-founded semantics.

Its extended version, which is currently under development, uses the theoretical results mentioned above to test whether a given circumscriptive theory C and a given query Q can be translated into a logic program $P(C)$ and a query Q' and, subsequently, provides answers to the query Q by suitably interpreting the answers to Q' given by the logic programming interpreter.

3 Scientific Cooperation

- We have closely collaborated with M. Gelfond and H. Przymusinska, who were working in the Computer Science Department at UT El Paso. This collaboration led to two joint papers [4] and [5]. We have also organized a joint seminar which gathers several other faculty members and 5-7 graduate students.
- We have established a very close cooperation with a group of researchers at the University of Linkoping in Sweden, particularly with Jan Maluszynski and Wlodek Drabent and with a group of students of Jan Maluszynski and Erik Sandewall. We are jointly working on the problems of constructive negation and translation of non-monotonic theories into logic programs.

- We have also established a close cooperation with David S. Warren from SUNY at Stony Brook, with whom we are preparing a joint paper on the theory and implementation of the well-founded semantics for logic programs. We hope that this extensive work will lay out a groundwork for further research on well-founded semantics and provide a basis for its implementation.

- Recently, we have established cooperation with Luis Pereira and his students at the University of Lisbon in Portugal. Their research work includes some of the same goals as ours and we have been recently coordinating our approaches. We are also working on a joint publication.

4 Goals vs. Accomplishments

As a result of these developments, most of the theoretical and implementation work scheduled for the first two years of the grant has now been completed or is close to completion. This involved (among other issues):

- Investigation of suitable procedural mechanisms to compute the well-founded semantics of normal programs, namely, SLS-resolution and its variants such at OLDTNF-resolution;

- Extension of the well-founded semantics to the class of all disjunctive logic programs;

- Investigation and suitable broadening of the compilation methods allowing translation of circumscriptive theories into logic programs with well-founded semantics;

- Development of methods of syntactic identification of classes of circumscriptive theories which can be compiled into logic programs;

- Implementation of an interpreter for the well-founded semantics of logic programs based on SLS-resolution;

- Implementation of a circumscriptive theorem prover based on translation of circumscriptive theories into arbitrary logic programs with well-founded semantics.

We expect to complete the implementation and testing of the translation unit for circumscriptive theories by the end of the Fall semester.

While we made some limited progress on the problem of extendability of the circumscriptive query answering algorithm, due to Przymusinski, to first order theories, more theoretical work on this problem will be needed in the future.

5 Future Research Plans

Due to the fact that the principal investigator moved from the University of Texas at El Paso to the Univerity of California at Riverside and due to the impossibility of transfering the funding to the new institution, the project had to be terminated one year ahead of schedule, namely in September of 1991 instead of September of 1992.

However, most of the goals scheduled for the first *two years* of the grant have been completed. Moreover, as far as research goals are concerned, some of the goals originally scheduled for the third year are already highly advanced. On the other hand, several research and, primarily, implementation goals scheduled for the *third year* have not yet been completed.

As a result, a significant amount of both research and implementation work remains to be done. This includes both some of the work originally planned for the third year of the grant as well as new research ideas and directions that arose in the process.

Following is a brief listing of some of the tasks that are planned in the future:

Theory:

- Develop methods allowing partitioning of a circumscriptive theory into subtheories (subunits) which individually allow translation into logic programs;
- Using methods developed in concurrent programming develop methods allowing to produce global answers to queries from answers provided by individual subunits.
- In order to handle cases of "stubborn" theories which cannot be easily translated into logic programs and in order to permit combination of answers returned by subunits, extend the circumscriptive query answering algorithm, due to Przymusinski, to first order theories.

- Develop similar compilation methods for non-monotonic formalisms other than circumscription, primarily for autoepistemic logic and default theory. Recent papers proposing new approaches to these non-monotonic formalisms based on well-founded semantics (Przymusinski and Lee & You) as well as extensive work on the relationship between these formalisms (e.g., Marek & Truszczynski) appear to suggest promising ways of approaching this problem.
- Investigate problems involving constructive negation in well-founded semantics. Significant work has already been done on this problem but a number of issues remain. Without constructive negation, a query answering system is severely limited as to the type of negative queries it can handle.
- Extend compilation methods onto the much broader class of disjunctive logic programs, thus significantly enlarging the class of non-monotonic theories translatable into logic programs. Recent work of the author as well as of J. Minker and his students provides us with a solid starting foundation.
- Investigate the development of an abductive reasoning system based on well-founded semantics. Recent developments in this area, particularly recent work by Kekes and Mancarella, seem to make it a very promising goal.

Implementation:

- Implement a reasonably complete experimental circumscriptive query answering system with the added capabilities to (1) identify compilable parts of a circumscriptive theory, (2) pass them for processing to the compiling and logic programming modules and (3) combine the obtained output to produce the final answer. In particular, implement the query answering module, as described in the proposal.
- Extend the system to handle other than circumscriptive non-monotonic theories, such as autoepistemic logic and default theory.
- Implement an interpreter for well-founded semantics with constructive negation.
- Implement an abductive reasoning system based on well-founded semantics.

- Investigate the possibility of extending the implementation of the non-monotonic query answering system so that it can handle disjunctive logic programs.

The above extensive research program will likely require two to three years of additional research and implementation work.