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Non-Classical Logics in Computer Science

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Dagstuhl Seminar 9338

Non-Classical Logics in Computer Science

September 20. - 24., 1993

Organized by:

Anil Nerode,
Wiktor Marek,
Peter H. Schmitt

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1 Preface

During the last ten, fifteen years we could witness a remarkable revival of interest in non-classical logics foremost in connection with topics from computer science. There seem to be two explanations for this phenomenon:

- The intention to use non-classical logics, like many-valued, modal or temporal logics for real world applications has made the usual reductions to classical first-order logic less attractive, since they obscure the intuitive meaning of formulas. Also the implementations of theorem provers for these logics seem to work more efficient without first translating them.

- Computer science also brought about a change in the focus of application areas of logic, from mathematics to the representation of and reasoning with more general and less structured domains of knowledge. This led to the invention of new types of logic. Non-monotonic logic is the prime example to be named here.

To provide the necessary focus for a fruitful interaction during the seminar we limited the contributions to the following subjects:

- non-monotonic logics to model common sense reasoning,

- Horn-clause logic and its extensions as a basis for declarative programming and as a source of non-monotonic inference,

- many-valued logics to extend the expressiveness of first-order logic and as a frame for explaining phenomena arising in two-valued logic and modal logics as a basis for treating temporal and epistemological aspects.

The bulk of the talks turned out to be on the subject of non-monotonic logic, which can rightly be jugded to have turned into a mature subject with a sound theoretical basis and moving towards serious implementations and applications. Despite the seemingly non-homogeneous audience but supported by the known interactions between modal and non-monotonic logic and also between many-valued logic and semantics of logic programs intensive and stimulating conversations evolved during the week of the seminar and will, it is to be hoped, further continue.

Peter H. Schmitt

2 Workshop Programme

Monday, September 20

7.30 - 8.30:	**Breakfast**
8.30 - 8.45:	**Opening**
8.45 - 9.30:	**A. Nerode** *Non-Monotonic Rule Systems and Predicate Logic by Linear Programming*
9.30 - 10.15:	**J. Remmel** *Various Aspects of Nonmonotonic Rule Systems: Normal NRS, Forward Chaining and NRS*
10.15 - 10.45:	**Coffee Break**
10.45 - 11.30:	**D. Lehmann** *A new Perspective on Default Logic*
11.30 - 12.15:	**M. Truszczyński** *Subnormal Modal logics*
12.15 - 14.00:	**Lunch**
14.30 - 15.15:	**A. S. Troelstra** *Natural Deduction for Intuitionistic Linear Logic*
15.15 - 16.00:	**B. Hösli** *Robust Logics*
16.00 - 16.30:	**Coffee Break**
16.30 - 17.15:	**A. Herzig** *Interference Logic and Change*
17.15 - 18.00:	**A. Gomolinska** *On Logic of Acceptance and Rejection*
18.15:	**Dinner**

Tuesday, September 21

7.30 - 8.30:	**Breakfast**
8.45 - 9.30:	**D. Mundici** *Deduction in Many-Valued Logic*
9.30 - 10.15:	**R. Hähnle** *Short Conjunctive Normal Forms for Finitely-Valued Logics*
10.15 - 10.45:	**Coffee Break**
10.45 - 11.30:	**T. Mellouli** *Three-Valued TMPR Theorem Prover and its Use for Handling Presuppositions and Vagueness*
11.30 - 12.15:	**L. Iturrioz** *A Many-Valued Logic for Reasoning about Knowledge*
12.15 - 14.00:	**Lunch**
14.30 - 15.15:	**R. Stärk** *A New Semantics for Negation-as-Failure: Classical Logic*
15.15 - 16.00:	**D. Cvetković** *The Logic of Preference and Non-Classical Logics*
16.00 - 16.30:	**Coffee Break**
16.30 - 17.15:	**T. Strassen** *The Basic Logic of Proofs*
17.15 - 18.00:	**E. Orlowska** *Applied Non-Classical Logics in a Relational Framework*
18.15:	**Dinner**

Wednesday, September 22

7.30 - 8.30:	**Breakfast**
8.45 - 9.30:	**W. Marek** *DeReS – Default Reasoning System: Theory and Paradigm*
9.30 - 10.15:	**H. Herre** *Contributions to Nonmonotonic Model Theory*
10.15 - 10.45:	**Coffee Break**
10.45 - 11.30:	**G. Antoniou, V. Sperschneider** *The Role of Process in Default Logic*
11.30 - 12.15:	**P. Marquis, E. Grégoire** *The Concept of "Novelty" in Non-Monotonic Logics*
12.15 - 14.00:	**Lunch**
14.30 - 18.15:	**EXCURSIONS**
18.15:	**Dinner**

Thursday, September 23

7.30 - 8.30: Breakfast
8.45 - 9.30: M. Gelfond
Formalizing Commonsense in Logic Programming: In Search of new Logical Connectives
9.30 - 10.15: T. Przymusinski
Semantics of Logic Programs and Non-Classical Logics
10.15 - 10.45: Coffee Break
10.45 - 11.30: J. Dix
An Axiomatic Approach to Semantics of Logic Programs
11.30 - 12.15: J. Schlipf
Kripke Models for Logic Programming with Incomplete Information
12.15 - 14.00: Lunch
14.30 - 15.15: D.S. Warren
On Implementing SLG-Resolution
15.15 - 16.00: St. Brass
Query Evaluation for Modular Specifications with Simple Defaults
16.00 - 16.30: Coffee Break
16.30 - 18.00: General Discussion
18.15: Dinner

Friday, September 24

7.30 - 8.30: Breakfast
8.30 - 8.45: Opening
8.45 - 9.30: G. Gottlob
Carnap's Modal Logic and NP Trees
9.30 - 10.15: R. Goré
Semi-Analytic Tableaux for Propositional Modal Logics of Nonmonotonicity
10.15 - 10.45: Coffee Break
10.45 - 11.30: E. Börger
Logic vs. Logic Programming: A Model for Control in the Language GÖDEL
11.30 - 12.15: H. Blair
Nonstandard Models of Unification
12.15 - 14.00: Lunch

3 Abstracts of presented talks

The Role of Processes in Default Logic

Grigoris Antoniou
(with Volker Sperschneider),
University of Osnabrück

We introduce an operational interpretation of the fixedpoint definition of default logic extensions. It consists essentially in applying defaults in some order while fulfilling a success condition; if the condition is violated, we have to backtrack. Furthermore, we must proceed in a fair way. Using this model it is easy to determine the extensions of a default theory even for the beginner in the field of nonmonotonic reasoning.

Then we demonstrate how this interpretation can be used as a theoretical tool which allows to derive simpler, more understandable proofs for known results. We demonstrate this point especially on Etherington's result on the existence of extensions for ordered, semi-normal default theories. We point out that this result is found in several, wrong variants in literature. We give the correct version of the theorem and a new proof that is clearer and makes the usually missing conditions immediately apparent.

Finally, we use processes as the starting point for some implementational work. First we give a prototypical Prolog implementation using an external theorem prover. The main work, though, aims at implementing (portions of) default logic in logic programming with its standard semantics by mapping default theories T to definite logic programs calculating the generating defaults of the extensions of T. We present the main idea of our approach and show soundness and completeness for a quite restricted class of default theories (truths in Horn logic, finite set of defaults, only literals occur in the defaults). We are working on weakening some of the conditions.

Nonstandard Models of Unification

Howard A. Blair,
Syracuse University

For a first-order language $\mathcal{L}$ we construct algebras satisfying K. Clark's equality theory CET_L which are quotients of the set of ground and nonground terms of $\mathcal{L}$. In contrast to the Herbrand universe of $\mathcal{L}$, each such algebra $\mathcal{C}$ has the property that every logic program P in the language $\mathcal{L}$ is canonical with respect to $\mathcal{C}$; that is, the one step deductive consequence operator $\mathbf{T}_P^{\mathcal{C}}$ corresponding to P satisfies $\mathbf{T}_P^{\mathcal{C}} \downarrow \omega(\mathbf{B}_{\mathcal{L}}) =$ greatest fixed point($\mathbf{T}_P^{\mathcal{C}}$), where $\mathbf{B}_{\mathcal{L}}$ is the Herbrand base of $\mathcal{L}$ relativized to $\mathcal{C}$. λ-terms built from the function and predicate symbols of $\mathcal{L}$ are representable as elements of $\mathcal{C}$. Subalgebras of $\mathcal{C}$ can be extended to applicative structures satisfying the simple theory of types. Moreover, $\mathcal{C}$ can be constructed to contain elements representing various arbitrary functions on $\mathcal{C}$, provided the cardinality of the collection of represented functions does not exceed the cardinality of $\mathcal{L}$. In particular, if $\mathcal{L}$ is countable, then $\mathcal{C}$ can be constructed to be countable.

Logic versus Programming: Modelling control of the language GOEDEL

Egon Börger
(with E. Riccobene),
University of Pisa

J. Lloyd and P. Hill have recently proposed the new logic programming language GOEDEL, which puts particular emphasis on improving the declarative semantics compared with PROLOG. Also the attempt is made to give implementors the option of using other theorem proving techniques than SLDNF resolution to implement the language.

We present a mathematically precise but simple interpreter which describes the full (control flow) behaviour of GOEDEL programs (pruning, negation, conditionals including their delay features) on the basis of abstract—machine and resolution independent— search trees. We exemplify the model for (an SLDNF like) resolution as basic computation mechanism, in a modular way and exhibiting an explicit interface.

Our definition uses Gurevich's notion of evolving algebras. It is mathematically precise and starts from scratch, thus establishing a rigorous basis for an equivalence proof between declarative and procedural semantics of Goedel programs. It provides a tool for mathematical—machine and proof system independent—description and analysis of design decisions in the development of the language; it also lays the ground for stepwise refinement and correctness proofs, through a hierarchy of specifications at lower levels, down to implementations.

Query Evaluation for Modular Specifications with Simple Defaults

Stefan Brass,
University of Hannover

We add a simple module system to supernormal default specifications in order to distinguish between "defining" and "calling" occurrences of predicates. This greatly improves the understandability of large default specifications and especially helps to solve the problem of unwanted contrapositions of rules.

Most logic programs can be naturally translated into modular default specifications, whereas the converse is not true. So our results can help to integrate both approaches — at least on the semantical side for specification purposes.

We also prove a strong connection to specifications with prioritized defaults. But there the dependencies between the defaults have to be specified, whereas here only the defined predicates of each module must be given.

Finally, we introduce a syntactic completion which characterizes the intended models of a specification. It can be used as a basis for query evaluation.

The Logic of Preference and Non-Classical Logics

Dragan Cvetković,
Max-Planck-Institute Saarbrücken

In this talk we are exploring some models for von Wright's preference logic. Given (initial) set of axioms and a set of formulas, some of them valid, some of them problematic (in the sense that it is not always intuitively clear should they be valid or not), we investigated some matrix semantics for those formulas including semantics in relevant logics (first degree entailment and RM3), various many-valued (Kleene, Łukasiewicz, ...) and/or paraconsistent logics, Sugihara matrix, and one interpretation for preference relation using modal operators $\Box$ and $\Diamond$. In each case, we also investigated dependence results between various formulas. Also, models are searched with given constraints with respect to a set of formulas which should or should not be valid.

An Axiomatic Approach to Semantics of Logic Programs

Jürgen Dix,
University of Koblenz-Landau

We present a method for classifying and characterizing the various different semantics of logic programs that have been considered in the last years. Instead of appealing to more or less questionable intuitions we take a more structural point of view: our starting point is the observation that all semantics induce in a natural way nonmonotonic entailment relations " $\mid\!\sim$ ". The novel idea of our approach is to ask for the properties of these $\mid\!\sim$ -relations and to use them for describing all possible semantics. We introduce two sorts of properties:

- Strong Properties, and
- Weak Properties.

The former are adaptations of notions well-known in general nonmonotonic reasoning: they were introduced and investigated by Gabbay, Makinson, Lehmann, Kraus and Magidor. The latter are inspired by serious shortcomings of some of the existing semantics and intended to avoid this strange behaviour. We argue that any reasonable semantics should satisfy our weak principles – we call these semantics *well-behaved.*

We show that any well-behaved semantics is an extension of M_P^{supp} and a $\leq_k$-extension of the wellfounded semantics. We also show that Schlipf's wellfounded-by-case semantics can be defined as the $\leq_k$-least supraclassical extension of WFS satisfying *Cut*. We also conjecture that some semantics can be uniquely determined by their strong and weak properties.

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[Dix92a] Jürgen Dix. A Framework for Representing and Characterizing Semantics of Logic Programs. In B. Nebel, C. Rich, and W. Swartout, editors, *Principles of Knowledge Representation and Reasoning: Proceedings of the Third International Conference (KR '92)*, pages 591–602. San Mateo, CA, Morgan Kaufmann, 1992.

[Dix93b] Jürgen Dix. A Classification-Theory of Semantics of Normal Logic Programs: I. Strong Principles. *Fundamenta Informaticae*, forthcoming, 1993.

[Dix93c] Jürgen Dix. A Classification-Theory of Semantics of Normal Logic Programs: II. Weak Principles. *Fundamenta Informaticae*, forthcoming, 1993.

Representing knowledge in logic programming languages

Michael Gelfond,
University of Texas at El Paso

In recent years the traditional language of declarative logic programming was significantly enhanced to allow for a better representation of incomplete information. New, more expressive languages, contain not only negation as failure but also stronger form(s) of negation, disjunction, and even modal operators. The attempt to understand the meaning of all these connectives led to the development of various semantics and to the investigation of the relationship between them.

I believe that, though this direction of research proved to be very successful, it should be complemented by a serious investigation of a methodology of using these languages for knowledge representation and even system design. This paper aims to illustrate a possible approach to such an investigation and to outline some problems relating to it. It starts with a simple story S, collection A of the closed world and other assumptions about the world, and a description U of possible updates of S. We start with a logic program Π_0 formalizing S and A together with a description of the way it should be expanded under the update. Then Π_0 is gradually modified to allow for more complicated forms of updates. We investigate properties of programs $\Pi_0, \ldots, \Pi_n$ obtained in this way. We are especially interested in monotonicity of updates, i.e. conditions under which $\Pi_i \models f$ implies $\Pi_i + 1 \models f$ and in changes which should be made in Π_i in order to remove (or to impose) an old (new) assumption(s) about the domain of discourse.

On Logic of Acceptance and Rejection

Anna Gomolińska,
University of Warsaw

In the paper we focus on a certain aspect of reasoning about knowledge with incomplete information closely related to the autoepistemic logic approach. The agents knowledge is understood as an ability to classify facts. The agent can believe a given fact, disbelieve it or cannot decide about this fact at all. The uncertainty of the agent is expressed using a formalism based on classical propositional logic. We propose a formal solution to the following problem:

> *Given a pair $\langle A, A'\rangle$ of sets of formulae where A (resp. A') is an initial set of formulae accepted (resp. rejected) by the agent, what are the sets of all formulae accepted and rejected by her in this situation?*

Such sets of formulae form so-called AE2 extensions being pair of theories, say $\langle T, T'\rangle$ that fulfill special conditions. AE2 extensions are characterized syntactically by means of so-called stable pairs of theories. A Kripke-style semantics for AE2 extensions is proposed as well.

Acceptance and rejection are not complementary notions in our approach. Facts neither accepted nor rejected are allowed. Additionally, we discuss two undesirable cases:

1. $T \cap T' \neq \emptyset$, i.e. there is a fact accepted and rejected simultaneously,
2. T, T' are *mirror-images* of each other, i.e. $\neg T \subseteq T'$ and $\neg T' \subseteq T$.

Semi-Analytic Tableaux for Propositional Modal Logics of Nonmonotonicity

Rajeev Goré,
University of Manchester

The propositional monotonic modal logics **K45**, **K45D**, **S4.2**, **S4R** and **S4F** elegantly capture the semantics of many current *nonmonotonic* formalisms as long as (strong) deducibility of A from a theory Γ, $\Gamma \vdash A$, allows the use of necessitation on the members of Γ. This is usually forbidden in modal logic where Γ is required to be empty, resulting in a weaker notion of deducibility.

Recently, Marek, Schwarz and Truszcziński have given algorithms to compute the stable expansions of a *finite* theory Γ in various such nonmonotonic formalisms. Their algorithms assume the existence of procedures for deciding (strong) deducibility in these monotonic modal logics and consequently such decision procedures are important for automating nonmonotonic deduction.

We first give a sound, (weakly) complete and cut-free, semi-analytic tableau calculus for monotonic **S4R**, thus extending the cut elimination results of Schwarz for monotonic **K45** and **K45D**. We then give sound and complete semi-analytic tableau calculi for monotonic **K45**, **K45D**, **S4.2** and **S4F** by adding an (analytic) cut rule. The proofs of tableau completeness yield a deterministic satisfiability test to determine theoremhood (weak deducibility), $\vdash_L A$, because all proofs are constructive. The techniques are due to Hintikka and Rautenberg. We then show that the tableau calculi extend trivially to handle (strong) deducibility, $\Gamma \vdash A$, for *finite* Γ.

Using a general theorem due to Rautenberg we also obtain the (weak) interpolation theorem for **K45**, **K45D**, **S4.2** and **S4R**.

Carnap's Modal Logic and NP Trees

Georg Gottlob,
Technische Universität Wien

We consider problems and complexity classes definable by interdependent queries to an oracle in **NP**. How the queries depend on each other is specified by a directed graph G. We first study the class of problems where G is a general dag and show that this class coincides with $\mathbf{\Delta}_2^P$. We then consider the class where G is a tree. Our main result states that this class is identical to $\mathbf{P}^{\mathbf{NP}}[O(\log n)]$, the class of problems solvable in polynomial time with a logarithmic number of queries to an oracle in **NP**. This result has interesting applications in the fields of modal logic and artificial intelligence. In particular, we show that the following problems are all $\mathbf{P}^{\mathbf{NP}}[O(\log n)]$ complete: validity-checking of formulas in Carnap's modal logic, checking whether a formula is almost surely valid over finite structures in modal logics **K**, **T**, and **S4** (a problem recently considered by Halpern and Kapron), and checking whether a formula belongs to the stable set of beliefs generated by a propositional theory.

We generalize the case of dags to the case where G is a general (possibly cyclic) directed graph of **NP**-oracle queries and show that this class corresponds to $\mathbf{\Pi}_2^P$. We show that such graphs are easily expressible in autoepistemic logic. Finally, we generalize our complexity results to higher classes of the polynomial-time hierarchy.

Short Conjunctive Normal Forms for Finitely-Valued Logics

Reiner Hähnle,
University of Karlsruhe

New applications for many-valued theorem proving in various subfields, for example in the theory of error-correcting codes, in non-monotonic reasoning, and in formal software and hardware verification, demand efficient automatic proof procedures for many-valued logics. Many successful theorem proving methods in twovalued logic, notably resolution, presume the existence of a conjunctive normal form (CNF). We present a general satisfiability preserving transformation of formulae from arbitrary finitely-valued logics into a CNF which is based on signed atomic formulae. The transformation is always linear with respect to the length of the input, and we define a generalized concept of polarity in order to avoid the generation of redundant clauses. The transformation rules are based on the concept of 'sets-as-signs' developed earlier by the author in the context of tableau-based deduction in many-valued logics. We discuss several possible resolution rules that operate on the signed CNF including a streamlined version for so-called regular logics, a class of finitely-valued logics defined earlier by the author. We compare our work to related approaches to many-valued resolution, and argue that our approach is computationally more efficient.

Contributions to Nonmonotonic Model Theory

Heinrich Herre,
University of Leipzig

I present a general framework for nonmonotonic reasoning inspired by the paradigm of model theory. It is refinement and continuation of [He 91] where the idea of a model operator was introduced to formalize nonmonotonic reasoning.

A deductive frame (L, C_0, C) is defined by a language L and inference operations $C_0, C : 2^L \rightarrow 2^L$ such that C_0 is monotonic, idempotent, satisfies inclusion and compactness, and C satisfies left absorption and congruence, i.e. $C_0(C(X)) = C(X)$ and $C_0(X) = C_0(Y)$ implies $C(X) = C(Y)$. (L, C_0) is a logical base and C is said to be logical over (L, C_0). A semantical frame $(L, M, \models, \Phi)$ is given by a language L, a set M of models, a satisfaction relation $\models \subseteq L \times M$ and a selection function $\Phi : 2^L \rightarrow 2^M$, satisfying $\Phi(X) \subseteq Mod^{\models}(X)$. Then we introduce the inference operation $C_\Phi(X) = Th(\Phi(X))$ where $Th(K) = \{\phi : K \models \phi\}$. In this framework several model theoretic questions are studied and solved, in particular representation theorems, the existence of deductive bases which are maximal below a cumulative inference operation C, and weak compactness properties of minimal reasoning in propositional calculus.

Independently and recently, several researchers used the notion of a selection function to formalize nonmonotonic inference operations; the selection function correspondes to the notion of a model operator. Among them are G. Amati, St. Brass, J. Bell, S. Lindstroem and H. Thiele.

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Independence and Change

A. Herzig
(with L. Farinas del Cerro),
Université Paul Sabatier

We study the notion of independence as a basis for change operations. Such a notion permits us to enrich conditional logics with the following frame axiom:

$$C \rightarrow (A > C) \text{ if } A \text{ and } C \text{ are independent.}$$

We show in particular how updates based on Winslett's Possible Models Approach can be axiomatized in this way.

Sequent Calculus with Restricted Weakening

Brigitte Hösli,
ETH Zürich

The weakening rules of Gentzen's sequent calculus admit adding new formulas to a derivable sequent. Thus, the weakening rule on the left (lW) corresponds to the monotony of the logic, whereas the rule on the right (rW) is related to the paraconsistency of the logic.

LC_R is defined as a sequent calculus, where the rule (rW) is only missing - in contrast to Gentzen's calculus - and where the other rules do not imply the weakening or transfer the weakening from the left to the right hand side. The derivable sequents are robust against loosing prime formulas. This means: if we discard some prime formulas from a derivable sequent we obtain a new derivable sequent.

LC_R is sound and complete w.r.t. a 3-valued semantics where the third truth-value has the intention "neutral". Hence, this value is a neutral element of the conjunction as well as the disjunction.

By a suitable restriction of Girard's phase-semantics (of the linear logic) we obtain this semantics from the multiplicative connectives and Kleene's (strong) semantics from the additive ones.

A Many-Valued Logic for Reasoning about Knowledge

Luisa Iturrioz,
University of Lyon

A generalized Łukasiewicz logic is proposed as a model for reasoning about knowledge of fully communicating agents which are completely symmetrical connected. In this approach, the abilities of different agents may be comparable or non comparable and knowledge of an agent about a predicate p can be reflected by her abilities to recognize objects which are positive or negative instances of predicate p . The notion of "agent t perceives p" is interpreted as a modal operator. The proposed system, which is related to a Rasiowa-Marek model (1989), has interesting provable properties as, for example, the possibility to manage incoherent observations made by agents. If only two comparable agents are involved, the formal system here proposed is equivalent to the three-valued Łukasiewicz logic.

A New Perspective on Default Logic

Daniel Lehmann,
Hebrew University

Nonmonotonic Logic is the study of deduction (of formulas from a set of formulas) in the presence of some fixed "default" or "background" information. This information may be of a statistical nature, about speech conventions, or express heuristics. Default information should define a rational consequence relation. As a first rough approximation one may consider that default information is given by a set of conditional assertions K and that the relation defined should be a rational extension of K. Two constructions satisfying these conditions have been found: the rational closure construction defined in my KR'89 paper and a lexicographic closure found independently by Benferhat, Cayrol, Dubois, Lang and Prade (IJCAI 93) and by myself. Both constructions are similarly described as the relations defined by ranking the models by the set of defaults (of K) they violate. They differ in the rankings used. Both rankings agree on how to compare singletons, but disagree on how to handle bigger sets. Rational closure enjoys pleasant meta-level properties, the lexicographic closure does not. The latter provides for inheritance of generic properties to exceptional classes whereas the former does not. Some ideas have been presented as to the kind of other basic items of default information one could like to have at his disposal. The idea of a triple (c,a,b) expressing the fact that, in the context c, the truth of a can never undermine b seems attractive. This meaning is easily formalized as a property of consequence relations. It seems that given any set I of such triples and any set K, there is a rational extension of K that satisfies the triples of I that is less than (in the sense of Lehmann-Magidor) any other such extension, at least for finite K's.

DeReS – Default Reasoning System Theory and Paradigm

Victor W. Marek,
University of Kentucky

We describe DeReS, a software system for nonmonotonic reasoning. This system is an extensible shell for conducting nonmonotonic reasoning such as finding stable models of a propositional program or finding extensions of a default theory.

This project represents the paradigm of "Second-order Logic Programming". "Second-order" here means that we are interested in finding the subsets rather than elements of the Herbrand Base.

We indicate how the nonmonotonic reasoning can be used to declaratively describe solutions to various combinatorial problems. As a consequence, DeReS will use a large number of combinatorial problems as benchmarks for its algorithms.

The Concept of Novelty in Nonmonotonic Logics

Pierre Marquis
(with E. Gregoire),
CRIN-CNRS/ INRIA-Lorraine

A concept of novelty of a formula for a topic w.r.t. a deductive batabase is investigated from a logical point of view. Intuitively, a formula is new for a topic when inserting the formula together with some additional information in the database allows us to infer an instance of the topic (or its negation) from the resulting database, while this proves impossible when only the additional information is inserted. First, this concept is analyzed in the framework of first-order (Herbrand) monotonic databases. A decision procedure is provided, based on a prime implicants characterization of novelty. Then, novelty is investigated in the context of non-monotonic - completed - databases. Actually, four types of novelty are put forward to capture various intuitions about the relations between novelty and forms of non-monotonicity. These types of novelty are proved incomparable in the general case and their decision problems are discussed.

Three-Valued TMPR Theorem Prover and its Use for Handling Presuppositions and Vagueness

Taieb Mellouli,
University of Paderborn

In this paper, two complementary topics are discussed. The first concerns automated deduction for the three–valued logic L3, which has been introduced e.g. in the study of natural language semantics. We present our three–valued deduction system TMPR, Tree–structured Modified Problem Reduction, which we have developed in an earlier work. TMPR expands only positive goals and utilizes a controlled case analysis mechanism for non-Horn reasoning in the classical as well as in the three–valued case. The second topic is to show how our three–valued TMPR proof procedure can be used for handling two natural language phenomena: presupposition failure and vagueness, also occurring in scientifical formulations. This non–trivial application using three–valued logical inferencing includes the following three aspects: Designing an adequate semantical modeling allowing for the occurrence of the mentioned phenomena by making some modifications to Blau's "three–valued logic of language" (De Gruyter, 1978), giving a logical framework in which information about presuppositions as well as about vagueness can be formulated, and finally developing an inference system extending the three–valued TMPR inferencing techniques and capable of a correct handling of the two phenomena. Owing to a differentiation between undefinedness caused by presupposition failure and that caused by vagueness at the inferencing level, this differentiation is reflected as special informations in the proofs generated by the inference system.

Deduction in many-valued logic (and desingularization of toric varieties)

Daniele Mundici,
University of Milan

Up to logical equivalence, a formula in the infinite-valued calculus of Lukasiewicz is a piecewise linear function f from $[0,1]^n$ to $[0,1]$, each piece being a linear polynomial with integer coefficients (McNaughton's theorem). The linear subdomains of f give a complex C of convex polyhedra with rational vertices. Passing to homogeneous coordinates in $\mathbf{Z}^{n+1}$, we obtain a complex K of cones with integral vertices–called a fan in algebraic geometry. K canonically corresponds to a toric variety $X(K)$, and desingularizing $X(K)$ amounts to finding a subdivision K' of K such that each cone in K' is generated by a part of a basis of $\mathbf{Z}^{n+1}$. Going back to nonhomogeneous coordinates, K' determines a unimodular subdivision C' of C, from which we obtain a disjunctive normal form representation of f as a sum of pyramids, known as the Schauder hats of C'. Before discovering in 1992 their relationship with toric varieties, the author had introduced Schauder normal forms as an interesting tool for deduction in all many-valued calculi. Algebraic geometry makes this tool even more interesting. For instance, toric desingularization and factorization techniques yield a purely geometric proof of the completeness of the Lukasiewicz axioms for the infinite-valued calculus. Conversely, computational familiarity with desingularizations of fans arising from normal form reductions yields tight upper and lower bounds for the Euler characteristic of desingularizations of 3-dimensional toric varieties.

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Hybrid Systems

Anil Nerode
(joint with W. Kohn),
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Hybrid Systems are interacting networks of continous plants and digital control programs. The fundamental problem of hybrid systems is to extract from simulation models and performance specifications of the plants, control programs which force the plants to obey performance specifications. The Kohn-Nerode model is a model mixing differential equations descriptions of plants with automata descriptions of digital control programs. The Kohn-Nerode Extraction-Procedure casts all problems as problems of finding an ϵ-optimal solution to a variational problem. For each plant state there is a lower semi-continuous functional from possible control functions to the nonnnegative reals to be minimized. The control functions are measure valued, the measures being on the space of controls. The problems are compact convex. in this context of so-called relaxed control. Then, with an ϵ error from optimality allowed, the optimal control function of state is approximated by a finite control automaton which realizes ϵ optimality. The subject is a mix of Lie algebras of controls, relaxed calculus of variations, and solving Schuetzenberger series equations by the Kleene-Eilenberg method to extract the required control automaton. The program that does this is a large constraint Meta-Prolog program with domains for the subjects above. Non-Monotonicity enters when deviations from the performance specification to the plants is detected and a new control automaton has to be computed. Current applications include control of firing of tank cannon, traffic control, control of industrial plants, etc.

Applied Nonclassical Logics in a Relational Framework

Ewa Orlowska,
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Relational formalization of nonclassical logics is realized on the following three methodological levels: Semantics and model theory: With a logic L there is associated a class of relational models for L. Proof theory: With logic L there is associated a relational logic for L such that its proof system provides a deduction method for L. Algebraization: With the class of standard semantic structures for L there is associated a class of nonclassical algebras of relations that provide an algebraic semantics for L. Relational formalization enables us to treat formulas of logical systems as relations and propositional connectives as relational operations in a suitable algebra of relations. Intensional connectives, like modal operations, intuitionist ic or relevant implication etc., become nonclassical relational operations, and accessibility relations from possible world models of these logics become constants in the respective algebras. Relational proof systems are Rasiowa-Sikorski style systems consisting of decomposition rules for all the underlying relational operations and specific rules that reflect properties of relational constants. In the paper relational formalization is outlined for a class of information logics for reasoning with incomplete information.

Semantics of Logic Programs and Non-Classical Logics

Teodor Przymusinski,
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During the last couple of years a significant body of knowledge has been accumulated providing us with a better understanding of *semantic issues* in logic programming and the theory of deductive databases. In particular, the class of *perfect models* was shown to provide a suitable semantics for stratified logic programs. Subsequently, two closely related extensions of the class of perfect models to all normal, *non-disjunctive* logic programs were introduced and extensively investigated. One of them is the class of *well-founded models* and the other is the class of *stable models*. Subsequently, another extension of the class of perfect models, namely the class of *partial stable models*, later renamed *stationary models*, was introduced (Partial stable models were also called *3-valued stable models*.), for arbitrary normal programs. Stationary models include both stable and well-founded models. Moreover, every normal program has the *least stationary model* which coincides with its well-founded model.

In my talk I discussed various characterizations of stationary models in the language of 2-valued and 3-valued logic, epistemic logic and default logic.

Rule systems, well-orderings, and forward chaining

Jeffrey Remmel,
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We survey some recent results on logic programming and nonmonotonic rule systems which is joint work with A. Nerode of Cornell University and W. Marek of the University of Kentucky. In particular, we describe a basic forward chaining type construction which can be applied to any general logic program. The input of the construction is any well ordering of the non-Horn clauses of the program. The construction will then output a subprogram of the original program and a stable model of the subprogram. We show that for any stable model M of the original program P, there is a suitable ordering of the non-Horn clauses of the program so that the subprogram produced by our construction is just P itself and the stable model of subprogram produced by our construction is M. Thus all stable models of the original program can be constucted by our foward chaining construction for suitable orderings. Moreover, we show that for finite propositional logic programs, our construction runs in polynomial time. More specifically, our fowarding chaining construction runs in order of the square of the length of the program.

In fact, we present a basic Forward Chaining (FC) construction which can be applied to any nonmonotonic rule system (NRS) as defined in [MNR90, MNR92c].

In [MNR90, MNR92c], it was shown that nonmonotonic rule systems capture all the essential features of many nonmonotonic reasoning formalisms, including logic programming with negation as failure , general logic programming with classical negation, Reiter's default logic, and truth maintenance systems. Thus in the setting of nonmonotonic rule systems, one can give general proofs for many of the basic theorems about such nonmonotonic reasoning formalisms. Our FC construction can thus be applied to any of these formalisms. Our FC construction will take any wellordering $\prec$ of the nonmonotonic rules of a NRS $\mathcal{S} = \langle U, N \rangle$ and produce a subset $C^{\prec}$ of N, the set of rules of $\mathcal{S}$, and a subset $E^{\prec}$ of U, the universe of $\mathcal{S}$, which is an extension of the rule system $\mathcal{S}' = \langle U, C^{\prec} \rangle$. Here an extension of a nonmonotonic rule system is the comman generalization of a stable model of logic program, an extension of a default theory, and an extension of truth maintenance system. We will call $E^{\prec}$ a *partial extension* of $\mathcal{S}$. We show that any extension E of S can be produced via our FC construction for some well ordering $\prec$, i.e. every extension of $\mathcal{S}$ is a partial extension of $\mathcal{S}$.

In the case where our original rule system $\mathcal{S} = \langle U, N \rangle$ is inconsistent in the sense that $\mathcal{S}$ has no extensions, our FC construction can be viewed as a way of extracting a maximal consistent subset of rules $C^{\prec} \subseteq N$ such that the system $\mathcal{S}' = \langle U, C^{\prec} \rangle$ has an extension. This feature of the FC construction has a number of potential applications. In particular, in the construction of expert systems, one often consults several experts and the rules of different experts may conflict. Thus the designer of the expert system is left with the task of extracting a consistent set of rules from the rules supplied by different experts. Our FC construction is ideally suited to this task for it allows us to favor the rules of one expert over another by the simple process of placing the rules of our favored expert earlier in the list. Because there are simple translations of general logic programs, default theories, and truth maintenance systems into nonmonotonic rule systems, our results apply equally well to the construction of stable models of general logic programs, answer sets of logic programs with classical negation, extensions of default theories, or extensions of truth maintenance systems and to the problem of extracting maximal consistent information from general logic programs, default theories, or truth maintenance systems when they are inconsistent.

We also have analyzed the complexity of our FC construction. For example, for general recursive nonmonotonic rule systems, we can always produce a partial extension which is r.e. in the jump of the empty set, $\emptyset'$. Note that in [MNR92b], the authors constructed a recursive rule sytem $\mathcal{S}$ such that $\mathcal{S}$ had extensions but no hyperarithmetic extensions. Thus we are always guaranteed that a recursive nonmonotonic rule system has a partial extension which occurs at a relatively low level in the arithmetic hierarchy where no such guarantee can be made for extensions of recursive nonmonotonic rule systems even when such systems have extensions. More importantly, for finite nonmonotonic rule systems, we can always find a partial extension and its corresponding subsystem in polynomial time. Thus our FC construction has potential applications for real time systems.

Finally we define a class of rule systems called *Forward Chaining Normal* rule systems for which our FC construction always produces an extension of the original rule system. It turns out that Forward Chaining Normal rule systems are a generalization of Rieter's normal default theories and such rule systems have all the desirable properties possessed by normal default theories.

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Kripke Models for Logic Programming with Incomplete Information

John S. Schlipf,
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The study of stable expansions of theories in modal logics has proved very fruitful in logic programming and nonmonotonic reasoning, both as an inspiration for semantics and as a way of understanding semantics. Notably, Gelfond used Moore's autoepistemic logic in developing the stable semantics for logic programming, and the modal viewpoint provides one very natural intuitive justification for that semantics.

Competing with the stable semantics, which is founded upon traditional two-valued logic, is the well-founded semantic, which turns out to be the three-valued analogue of the stable semantics. Przymusiński showed that the well-founded semantics can be defined using a three-valued autoepistemic logic. Other papers have shown how to define the well-founded semantics using extra relation symbols with assumed meanings. Schwarz has pointed out that these extra relation symbols are taken to be implied modalities, and it would clarify our understanding of the semantics if we could make these modalities explicit. Also, a development of the well-founded semantics in a two-valued modal logic should clarify our intuitions about the semantics.

In this paper we present such a definition of the well-founded semantics. We also present a similar definition of our well-founded-by-case semantics, which Dix showed coincides with his well-founded$^+$ semantics. Finally, we point out some other applications of the incomplete information approach, where we explicitly include a form of incomplete information into some of the rules of a logic program; this adds no significant extra complexity to computing the well-founded semantics.

A New Semantics for Negation-as-Failure: Classical Logic

Robert F. Stärk,
Universität München

We introduce the partial completion of a normal logic program as a new declarative semantics for Negation-as-Failure. The partial completion of a program P, denoted by *partcomp*(P), is a refined version of Clark's completion. We obtain it by extending the language by new predicate symbols $\overline{R}$ for every predicate R. The intended meaning of an atom $\overline{R}(\vec{t})$ is that $R(\vec{t})$ finitely fails. We show that the classical consequences of the partial completion are exactly the formulas which are true in all three-valued models of the completion. Thus, the partial completion is just a classical formulation of the three-valued Fitting/Kunen semantics of a logic program. The partial completion has several advantages compared with Clark's completion. It is always consistent and it can be viewed as a simultaneous positive elementary inductive definitions of the relations R and $\overline{R}$. The partial completion captures exactly the meaning of a large class of normal programs. We prove that SLDNF-resolution is sound and complete with respect to the partial completion for the class of so called well-moded programs. A program is well-moded if all clauses of the program are correct with respect to some mode specification. A mode specification assigns to every predicate a set of positive and a set of negative modes. Positive modes are used in positive calls and negative modes are used in negative calls. A mode declares the arguments of predicates as input arguments, output arguments or logical arguments. Definite programs together with definite goals and allowed programs together with allowed goals are correct with respect to some mode specification. Since we have always some modes in mind when we write logic programs, we believe that all programs of practical interest are well-moded and therefore covered by our theory.

The Basic Logic of Proofs

Tyko Strassen,
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The Propositional Provability Logic GL for Peano Arithmetic was axiomatized 1976 by R.M . Solovay. GL describes the behaviour of the arithmetical operator "A is provable" by means of modal logic. Since GL is decidable, one has an elegant and efficient tool for studying subjects centered around Gödel's incompleteness theorems, e.g. Löb's theorem, substitutions, fixed points and formalizations.

The Basic Logic of Proofs is defined exactly in the same environment as GL. But instead of having modal formulas of the form $\Box A$ and interpreting $\Box A$ as "A is provable", the language of the Basic Logic of Proofs contains labeled modalities $\Box_p A$ which can be interpreted in a wide range of applications, e.g. as "p is a proof of A", "p is a proof which contains A", "p is a program which computes A", or "A is computable by a program which size is bounded by p". The Basic Logic of Proofs is provided with syntactical models; as neither the necessitation rule $A \vdash \Box_p A$, nor the substitution rule $A \leftrightarrow B \vdash \Box_p A \leftrightarrow \Box_p B$ is valid, the usual technique of Kripke models cannot be applied. Some basic properties, mainly concerning fixed points, are investigated. Finally, a system of finite models is introduced, from which the decidability of the logic follows.

Natural deduction for intuitionistic linear logic

Anne S. Troelstra,
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The talk deals with two versions of the fragment with unit, tensor, linear implication and storage operator (the exponential !) of intuitionistic linear logic. The first version, **ILL**, appears in a paper by Benton, Bierman, Hyland and de Paiva; the second one, **ILL$^+$**, is described in this talk. **ILL** has a contraction rule and an introduction rule !I for the exponential; in **ILL$^+$**, instead of a contraction rule, multiple occurrences of labels for assumptions are permitted under certain conditions; moreover, there is a different introduction rule for the exponential, !I$^+$, which is closer in spirit to the necessitation rule for the normalizable version of **S4** discussed by Prawitz in his monograph "Natural Deduction".

It is relatively easy to adapt Prawitz's treatment of natural deduction for intuitionistic logic to **ILL$^+$**; in particular one can formulate a notion of strong validity (as in Prawitz's "Ideas and Results in Proof Theory") permitting a proof of strong normalization.

The conversion rules for **ILL** explicitly mentioned in the paper by Benton et. al. do not suffice for normal forms with subformula property, but we can show that this can be remedied by addition of a single conversion rule.

ILL$^+$ also suggests the study of a class of categorical models, more special than the class introduced by Benton et. al.

Subnormal modal logics

Miroslaw Truszczynski,
University of Kentucky

Attempts to provide modal account of default reasoning lead recently to an interesting class of modal logics. These logics contain all propositional tautologies in the modal language. They are closed under uniform substitution, necessitation and modus ponens and, finally, they do not contain the axiom schema K. We provide a semantic characterization of these logics — similar to Kripke semantics for normal modal logics. We then focus on two very special logics in this class: the logic N, which does not contain any axiom for manipulating modalities, and the logic NT, which is obtained from N by including the axiom schema T. We argue that both logics are intuitively well- motivated and have applications in default logic and logic programming. In particular, nonmonotonic logics N and NT provide characterizations of extensions of default theories, stable and supported models of logic programs, and stable expansions in autoepistemic logic. We present several properties of nonmonotonic logics N and NT including minimal model characterizations of these logics and the property of being robust under extensions by new definitions.

Implementing SLG-Resolution

David. S. Warren
(with Weidong Chen and Terrance Swift),
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SLG resolution is strategy for computing answers to queries to General logic programs (those with unrestricted closed-world negation) [PODS'93]. It is a partial evaluation strategy that reduces queries/programs with respect to the partial (or 3-valued) stable model semantics. It can be used directly to evaluate queries with respect to the well-founded semantics, and the residual program could be further processed to compute partial stable models. For Datalog programs, the procedure is terminating and has polynomial data complexity.

In this talk we briefly describe the transformations that define SLG resolution. We then discuss issues involved in implementing it efficiently. We desribe a full implementation of SLG, written as a meta-interpreter in Prolog. We present the results of simple benchmarks that indicate that it is competitive in performance with current implementations of other bottom-up algorithms. We then describe a partial implementation of SLG at the engine level of a WAM-based Prolog system. This XSB system implements a subset of the transformations of full SLG that handles stratified programs. Benchmarks show that the XSB system is approximately 30 times faster than the SLG meta-interpreter on stratified programs. Finally we present benchmark results that show that XSB is approximately an order of magnitude faster than some other deductive database systems on simple recursive Datalog queries.

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