Practical Reasoning Approaches for Web Ontologies and Multi-Agent Systems

Renate Schmidt (Manchester) and Ullrich Hustadt (Liverpool)

1 Previous Research Track Record

The proposed research project will be undertaken jointly by the School of Computer Science at the University of Manchester and the Department of Computer Science at the University of Liverpool.

Dr. Renate Schmidt (PI MANCHESTER) is an expert on automated reasoning methods, resolution decision procedures, agent-based systems, non-classical logics and relation algebras and has published widely in these areas. Since 1991 she has published nearly 50 major publications in respected journals, books, and refereed conference proceedings. In 2002 she held a visiting fellowship with the *Max-Planck-Institut für Informatik* in Saarbrücken funded by the EPSRC and the Max-Planck-Institut. She serves on the editorial board of the *Journal of Applied Non-Classical Logic*, an international journal which promotes the development of non-classical logics in Computer Science. She is guest editor of a special issue of this journal on the implementation of logics. She is and has been involved with the organisation of a number of international and national scientific initiatives, conferences or workshops: the AiML Initiative (steering committee), AiML 2004 (local organiser, program committee), RelMiCS & KA 2006 (conference chair), ESCoR 2006 (co-organiser), ARW (organising committee), WIL 2003 (PC co-chair), AAMAS 2005 (PC), M4M 2005 (PC), FTP 2005 (PC), CLIMA 2005 (PC), WIL 2004 (PC), JELIA 2004 (PC), and others. Dr. Schmidt has secured and worked on a series of research projects funded by the EPSRC, the British Council, the Deutsche Forschungsgemeinschaft and the Deutscher Akademischer Austauschdienst (both German funding councils).

Dr. Ullrich Hustadt (PI LIVERPOOL) is an expert on proof theoretical approaches to the decidability problem in classical and non-classical logics, in particular, resolution decision procedures, and their realisation, evaluation and application. Applications he is interested in vary from agent-based systems, formal verification of software and hardware, to reasoning about ontologies. Since 1991 he has published 47 major publications in learned journals, books (including a contribution to the *Handbook of Automated Reasoning*), and refereed international conferences. He has been and is involved in a number of conferences and workshops: ARW (organising committee); WIL 2001, 2003, 2005 (PC); TABLEAUX 2005 (PC); TIME 2002, 2003, TIME 2004 (PC); Workshop on the Combinations of Temporal and Modal Logics 1998 (co-organiser). Dr. Hustadt has helped to secure and worked on a number of research projects funded by the EPSRC as well as the Deutsche Forschungsgemeinschaft.

Selected recent projects.

2004: EPSRC GR/T08210/01, PI R. A. SCHMIDT, U. HUSTADT, W. VAN DER HOEK, F. WOLTER, "Visiting Fellowship in Computational Logic". Grant to support a visit by V. GORANKO and W. CONRADIE (Johannesburg) to Manchester and Liverpool.

2001–2004: EPSRC GR/M88761/01, PI R. A. SCHMIDT, U. HUSTADT, M. FISHER, C. DIXON, RA D. TISHKOVSKY. "Proof Methods for Multi-Agent Systems".

2002: EPSRC Visiting Fellowship GR/R92035. PI R. A. SCHMIDT. "Decision Procedures for Description and Modal Logics".

1999–2002: EPSRC GR/M36700, PI R. A. SCHMIDT, RS L. GEORGIEVA. "Path-Based Reasoning on Guarded Formulae".

Relevant recent work. Recent work of the PIs has led to several ground-breaking contributions on a variety of topics, including:

- Efficient automated reasoning and model generation for expressive description logics and modal logics [10, 15].
- Translating logics and simulating proof procedures in first-order logic [15].
- Resolution-based proof techniques, decision procedures and model generation for solvable first-order classes.
- Empirical investigations of implemented reasoning systems [11, 12].
- A series of powerful logics and deductive systems for applications in the area of multi-agent systems, and strong results in the area of modal logic.
- Clausal temporal resolution calculi for monodic first-order linear time temporal logic and their implementation [8, 9, 14].
- Fragments of monodic first-order linear time temporal logic decidable by clausal temporal resolution.
- The investigation of the technology underlying the SCAN tool for computing correspondence properties for modal axiom schemas, including those relevant to standard agent theories.

The PIs have authored a series of commissioned survey papers [3, 13, 15]. Invited overview papers for the *Handbook of Modal Logic* and the volume in memory of H. GANZINGER are in preparation.

The PIs have actively been involved in the development of a range of reasoning tools. These include:

- MSPASS, `http://www.cs.man.ac.uk/~schmidt/mspass/`: An extension of the award-winning first-order theorem prover SPASS, which can be used as a modal logic theorem prover, a theorem prover for description logics and a theorem prover for the relational calculus. MSPASS has won of the TANCS 2000 competition of modal and description logic reasoning systems for being the most scalable modal logic theorem prover. It is still the most powerful and flexible theorem prover currently available for description logics, modal logics and first-order logic and can handle expressive description and modal logics that the current state-of-the-art provers cannot handle.

- TABSPASS, `http://www.csc.liv.ac.uk/~ullrich/tabspass/`: A modified version of the first-order theorem prover SPASS which simulates derivations of tableau decision procedures for basic modal logic.
- TRP [12], TRP++ [8], and TeMP [9] `http://www.csc.liv.ac.uk/~ullrich/TRP/`, `http://www.csc.liv.ac.uk/~konev/trp++/`, `http://www.csc.liv.ac.uk/~konev/TeMP`: Implementations of theorem provers for propositional and a monodic fragment of first-order linear-time logic based on temporal resolution.
- PDL-TABLEAU, `http://www.cs.man.ac.uk/~schmidt/pdl-tableau`: An implementation of a tableau calculus for propositional dynamic logic and (to our knowledge) the only existing implementation of a prover for *PDL*.
- The Agent Dynamic Logic package, `http://www.cs.man.ac.uk/~schmidt/projects/PMfMAS/ADL`.
- SCAN, `http://www.mpi-sb.mpg.de/~scan/`: A tool for the elimination of second-order quantifiers which facilitates the automated computation of correspondence properties for in modal logics.
- Under the supervision of the PIs a number of other automated reasoning tools have been and are being developed by Masters and PhD students.

Competitiveness and quality of research. The investigators have excellent track records and international reputations in the aforementioned research areas. Much of the potential is still untapped and future work is likely to significantly contribute to automated theorem prover development. Their combined expertise across a broad range of relevant topics (automated reasoning, model generation, proof theory, algebra) and experience in the development of automated reasoning systems put them in a very strong position to successfully tackle the problems of this project. Past EPSRC research projects have all been assessed either as internationally leading or outstanding overall (best possible).

Expertise at host organisation and collaborating institutions. Manchester and Liverpool are excellent places to carry out the proposed research. Both have large and internationally leading groups in relevant areas, and they have among the best Computer Science Departments in the UK, having respectively achieved $5*$ and 5 gradings in the most recent research assessment exercise. Manchester has strong research groups working in the areas of automated reasoning, formal methods, description logics, semantic web and AI. Liverpool has strong research groups working in the areas of multi-agent systems, logic, and computation. In particular, complementary expertise will be available through the following persons, all top experts in their areas of research.

- PROF. ANDREI VORONKOV (Manchester) has considerable experience in developing fully-automated theorem proving tools for first-order logic. Being a regular award winner and current 'world champion' at the the CASC theorem prover competition organised annually at the CADE and IJCAR conferences, his prover VAMPIRE is one of the most sophisticated and fastest theorem provers for first-order logic. Together with J. A. ROBINSON, the inventor of resolution, he has published the influential *Handbook of Automated Reasoning*.
- PROF. IAN HORROCKS (Manchester) is internationally renowned for his involvement in the creation and realisation of the semantic web. As a member of the W3C WebOntology working group he was jointly responsible for the development of the new standard semantic web ontology language OWL. He has designed and implemented the state-of-the-art FACT system, a highly optimised description logic reasoning system.
- DR. ULRIKE SATTLER (Manchester) is a senior lecturer at Manchester. Her work has made substantial contributions to the theory and application of logics in knowledge representation and the semantic web, focussing in particular on decision procedures and complexity issues. Together with I. HORROCKS, she designed description logics such as $\mathcal{SHIQ}$ and $\mathcal{SHOQ}(\mathbf{D})$ and inference algorithms for these logics which form the basis of the OWL DL language.
- PROF. FRANK WOLTER (Liverpool) has been conducting advanced research in computational logic and its applications to knowledge representation and reasoning for more than ten years. He is one of the 'founding fathers' of the 'combining systems' movement in logic and computer science and is an author of numerous influential research papers in this area, as well as in modal, spatial, description, and temporal logic.
- PROF. WIEBE VAN DER HOEK (Liverpool) is internationally renowned for his research on knowledge representation formalisms, and has made substantial contributions to the theory of modal and epistemic logic in AI and computer science. He also works on theory/belief revision, agent programming languages, and the logical foundations of game theory. Recently, he has also published on dynamic epistemic logic, in which both the knowledge of the agents involved, and the dynamics of it, are dealt with in one and the same object language.

Further expertise will be available from I. PRATT-HARTMANN (Manchester), M. FISHER, C. DIXON, and D. TISHKOVSKY (Liverpool) who are working in related research areas.

2 The Proposal

A Background

Logical and automated reasoning methods are crucial for web technologies and agent technologies for the intelligent processing of large ontologies, decision making based on knowledge bases of structured data, and formal specification and verification of multi-agent systems.

1. Web ontology reasoning. The *semantic web* is an extension of the world-wide-web in which information is given a well-defined meaning better enabling computers and people to work together in cooperation. The semantic web involves a number of technologies forming a layered architecture. The top layers are *ontologies*, for the description of vocabularies, *rules*, to further enrich those descriptions, *logic*, for inferring unstated facts, and *trust*, for authentication and establishing the trustworthiness of statements. The OWL web ontology language is intended to formalise ontologies and has three sublanguages of increasing expressivity, *OWL Lite*, *OWL DL* and *OWL Full*. Entailment in OWL Full is undecidable, while entailment in OWL Lite and OWL DL is decidable and can be reduced to knowledge base unsatisfiability in certain *description logics* ($\mathcal{SHOIN}(\mathbf{D})$ and $\mathcal{SHIF}(\mathbf{D})$) in a straightforward way using a simple semantics-based translation. In general, description logics (DLs) provide formalisms for representing and reasoning about knowledge in a given domain of application. Since their invention in the mid-eighties, the advance in this area has been rapid. On the theoretical side the decidability and computational complexity of description logics has been extensively studied, and on the practical side fast sophisticated description logic reasoners are now available. Currently regarded as state-of-the-art are the systems FACT and RACER, both tableau provers. Based on the correspondence between sublanguages of OWL and description logics, these reasoners can be used to solve entailment problems for web ontologies.

For the purposes of ontology reasoning the current description logic reasoners have a number of significant shortcomings however.

- Lack of expressiveness: The languages OWL Lite and OWL DL are for the purposes of ontology reasoning much too limited in expressiveness. It is difficult or impossible to massage even very simple ontology definitions into these languages or the corresponding description logics. For example the definition of an 'expert in automated reasoning' as someone who has studied every proof method ($x \in$ expert-of-automated-reasoning iff $\forall y \,.\, y \in$ proof-method $\rightarrow (x, y) \in$ has-studied) cannot be expressed in OWL DL and cannot be handled by reasoners like FACT or RACER. Even though decidable description logics exist which can handle this kind of example (such DLs must allow the negation of roles) so far the DL community has failed to develop tableau decision procedures for such logics.
- Non-optimal complexity: Tableau decision procedures for EXPTIME-complete description logics have suboptimal computational complexity.
- Over specialised algorithms: FACT and RACER are much too specialised to provide a suitable basis for developing practical systems which go beyond OWL DL. These systems use very specific algorithms, data structures and optimisation techniques which have been highly tuned for OWL DL and certain DLs. Extending these to more expressive decidable DLs is proving difficult and progress is slow.
- Currently ontology engineers and users of DL systems are at the mercy of the developers of ontology reasoners. Often the sources of DL provers are not accessible and available descriptions of the implemented algorithms and data structures are not sufficiently detailed.
- Incomplete formal treatment: While formal soundness and completeness results are available for the tableau calculi upon which existing DL systems are based, the actual implementations employ different strategies, heuristics and optimisation techniques which have not been formally analysed. For example, no formal soundness and completeness proofs can be found for DL systems employing techniques such as caching and forms of clever backtracking such as backjumping.
- Practicality of a tiered architecture: It is not at all apparent why the architecture of the semantic web should adopt a layered model.

All these are serious issues which need to be tackled and overcome if DL reasoners are to form the backbone ontology reasoning for the semantic web.

2. Multi-agent systems. Logical methods are widely used for studying and formalising *multi-agent systems*. Modal logics, in particular, have been popular for this purpose and offer a number of advantages. Among the more well-known agent formalisms with a modal flavour are the BDI model, the *KARO* framework, and temporal logics of knowledge and belief. Examples of more recent work includes coalition game logics, alternating-time temporal logic ATL [1], alternating-time temporal epistemic logic ATEL [17]. Thus, there exists a multitude of modal agent formalisms.

Most of these agent logics are defined purely semantically, typically by a model-theoretical semantics. For some Hilbert axiomatisations exist also, especially, if the agent logic is a straightforward fusion of several standard modal logics like linear time *PLTL* or branching time temporal logic *CTL* with epistemic or doxastic logic together possibly with some interaction axioms. Given a model-theoretical semantics it is usually also straightforward to define model checking procedures for agent logics, although efficiency and scalability are issues.

The same is not true for the validity problem in agent logics. Inference calculi for agent logics are typically developed individually. Given the ever increasing number of agent logics *rather than developing calculi one by one for each agent logic in turn, it is therefore desirable to have systematic ways of developing calculi for classes of agent logics*. Of particular interest for applications is finding systematic ways of developing *decision* procedures. Even though impressive advances have been made with regards to certain topics in modal logic (completeness theory, correspondence theory, duality theory, transfer theory, interpolation – these are all topics requiring a sophisticated mathematical apparatus), it is difficult to find *general* decidability results in the literature on modal logic. Notable exceptions are decidability results by Gabbay, Wolter, Zakharyaschev, et al. [6]. However these decidability results are obtained either by reduction of the satisfiability problem of various modal logics to that of monadic second-order logic, or by showing the finite model property. A disadvantage of these decidability results is the complexity and inefficiency of decision procedures for monadic second-order logic, and the impracticality of decision procedures exploiting the finite model property. Also popular is the use of automata based decision procedures. But again, as a solution to the validity or satisfiability problem of expressive modal logics these procedures are not sufficiently efficient [12].

An alternative approach is translation to first-order logic. However, underlying most agent logics is a component logic which allows us to describe dynamic aspects of agents. Typically this is a dynamic logic or a temporal logic. Both contain operators which are not first-order definable, namely the explicit or implicit transitive-reflexive closure operators, for example, the ‘repetition’ operator of dynamic logic or the ‘always in the future’ operator of linear time temporal logic. So an encoding of the semantics of an agent logics into first-order logic is not possible.

B Programme and Methodology

Aim. *The aim of this three year project is to investigate the extent to which resolution methods can be used to develop practical reasoning approaches for web ontologies and multi-agent systems.* The project is part of a research programme to develop a powerful and versatile logic engineering platform which will comprise various tools aimed to support both users and developers of logic theories, formal specification frameworks, and automated reasoning formalisms to carry out logical reasoning.

Research objectives. The principal objectives for this project are:

1. To develop resolution-based methods for various inference tasks in expressive description logics and fragments of OWL Full.
2. To develop resolution methods for a range of agent formalisms and the modal logics which these formalisms are based on.
3. To develop an integrated formal framework of ontologies and agent logics, together with reasoning methods.
4. To solve the problem of automatically synthesising tableau inference calculi for description logics.
5. To solve the problem of automatically generating code of tableau provers for these calculi.
6. To implement a series of tools that exploit the developed calculi and procedures.
7. To measure, via empirical evaluation, the utility and performance improvements provided by the tools.

Methodology. In this project, our intention is to tackle the research objectives by a systematic study of ways of developing resolution-based inference systems for ontology reasoning and agent logics. The choice of methodology is motivated by the following considerations.

- The framework of resolution provides a generic and application-independent platform, not restricted to clausal logic or first-order logic [2]. For example, we have been able to develop resolution-based calculi for propositional linear time temporal logic [5] and for the monodic fragment of first-order linear time temporal logic over expanding domains [14] which have been implemented in the systems TRP++ [8] and TeMP [9], respectively.
- The available concepts of refinement and simplification within this framework are ideally suited for the development of proof techniques specialised for specific semantic theories or interactions. Very few proof systems offer this level of sophistication.
- The framework forms the theoretical basis for state-of-the-art automated reasoning systems (VAMPIRE, E, MSPASS).
- Currently resolution provides the most successful approach of developing *practical* decision procedures. The PIs have shown that very many modal logics and expressive description logics are decidable by resolution [15]. Moreover, the same refinements of resolution that decide these logics can be seen to decide very expressive fragments of first-order logic (guarded fragments, FO^2, fluted logic, Maslov’s class K).
- Other approaches, such as tableau proof methods, can be seen to be notational variants of particular instances of the framework [3, 15]. This has fundamental consequences, providing on the one hand valuable insight into the similarities and differences of various proof methods, and showing also that resolution-based methods are provably more powerful than methods which are currently more popular.
- In [3, 15] we show how the relationship between hyperresolution and tableau can be exploited for systematically developing sound, complete and terminating tableau procedures for expressive *PDL*-like modal logics. In [16] we give another example of how tableau calculi can be more or less read off from the combination of a new non-standard translation approach and resolution.
- On the practical side, a number of very fast first-order logic theorem provers exist (VAMPIRE, E, MSPASS) which can be immediately exploited for realising and testing the theoretical results obtained in the context of first-order resolution. In contrast to special-purpose approaches no major implementation effort is necessary, often all that is required is the implementation of translation routines; decision procedures and simulations of other styles of deduction are then obtained by simply selecting a correct set of parameters for the first-order prover (thus we get implemented tableau provers practically for free).

- In contrast to logical frameworks based on higher-order logic our overall approach will allow us to exploit the highly sophisticated and fast methodologies of first-order logic provers. Lack of efficiency is also a distinct disadvantage of programming environments for modal tableau systems developed in Toulouse and Canberra.

All this makes our approach particularly attractive for the kind of project proposed here.

Timeliness and novelty. If the ambitious goals of the semantic web are to be realised, then much better, more powerful and versatile inference systems are needed than are currently employed. Likewise, with the growing importance of multi-agent systems, support for their specification, verification, and realisation also grows in importance. Again, powerful inference systems will be a key component for such support. In the past a common misconception in the research community has been that first-order techniques cannot help in dealing efficiently with the development of inference systems relevant in these areas. However this is completely without foundations. *On the contrary, we strongly believe that significant advances are possible and resolution methods/provers will play a leading role in the future of reasoning in the context of the semantic web and the development of multi-agent systems.*

Programme of work. The research programme is broken down into seven workpackages, and each workpackage is further divided into tasks. For each workpackage, we present an overview of the tasks, the methodology to be utilised, and the milestones. Time is measured in person-month including the time committed by the principal investigators, totalling 78 person-months overall.

WP1. Web ontology reasoning for fragments of OWL Full. (MANCHESTER [RA]: Month 1–15)

In this WP we plan to investigate and develop resolution-based decision procedures for expressive description logics and solvable fragments of OWL Full.

TASKS:

1.1 Become familiar with semantic web technologies, OWL, description logics, first-order resolution, existing resolution decision procedures for non-classical logics and solvable first-order fragments.

1.2 Devise practical reasoning methods for expressive DLs extended with role constructors and role axioms.

1.3 Study the (un)decidability of fragments of OWL Full and devise practical decision procedures for decidable fragments.

1.4 Devise practical reasoning methods for the rules layer of the semantic web.

1.5 Investigate the use of first-order reasoning methods for other reasoning tasks such as classification, query answering, reasoning with respect to distributed knowledge bases.

METHODOLOGY: Description logics like $\mathcal{SHIF}(\mathbf{D})$, $\mathcal{SHOIN}(\mathbf{D})$, and their associated ontology web languages lack expressive power regarding roles, that is, binary relationships, which in turn also limits their expressive power regarding concepts whose definition would involve such roles. For example, often it is useful to endow roles with special properties, like transitivity, symmetry, confluence, or similar properties (e.g. *ancestor_of* is a transitive relation, *relative_of* is a symmetric and transitive relation). In description logic reasoners such properties are accommodated by special inference rules, which means that the reasoner can exactly deal with those properties for which the developer of the system has implemented such inference rules, but no others. Similarly, the set of supported role-forming constructors is usually rather limited (no role negation, no role conjunction, only trivial occurrences of role composition), and the forms that role axioms can take is rather restricted (typically, role inclusion and role equivalence). The majority of these enhancements are currently outside the scope of tableau methods. It is therefore not surprising that, despite the importance of this expressivity for applications, description logics at this end of the spectrum have not been extensively studied. However, initial positive results using resolution are available, cf. e.g. [15, 16] (e.g. role negation poses no problem to resolution methods).

In this WP our interest will be on satisfiability and subsumption problems (tasks 1.2 to 1.4) as well as other inferences services such as classification and query answering (task 1.5). Resolution methods are much better suited for the latter than tableau methods, because tableau methods need to reduce all inference problems to satisfiability tests and are therefore unnecessarily inefficient. In task 1.4 we will not limit our investigation to rule specifications in Datalog, Horn logic or Prolog. Our aim is to develop a flexible, fully integrated framework of the rules layer and the ontology layer and provide general conditions of compatibility for these two layers. This framework is likely to be based on a language of first-order logic combined with (fragments of) OWL Full. We also expect to explore computational complexity issues, search strategies, heuristics, optimisation techniques and model generation.

MILESTONES: M1: Papers on new decision procedures for extensions of expressive descriptions logics. M2: Papers with new solutions to classification, query-answering and other non-standard inference services. M3: Papers on useful fragments of OWL Full with practical inference procedures.

TOTAL: 15 PERSON-MONTHS

WP2. Synthesis of tableau provers. (MAN [RA]: Month 16–24)

TASKS:

2.1 Become familiar with tableau methods, resolution framework, techniques of implementing modal tableau provers and DL tableau provers.

2.2 Devise a generic encoding of existing tableau calculi into first-order logic and explore the logical and computational behaviour of resolution strategies on these encodings with the aim of transferring these to tableau procedures.

2.3 Devise methods for automatically synthesising tableau calculi from semantic specifications of a DL.

2.4 Develop a tool for automatically generating the code for tableau-based tableau procedures.

METHODOLOGY: In previous work we have shown that DL and modal logic tableau procedures can be studied and developed with techniques from first-order logic and resolution [3, 15]. We have shown to simulate tableau procedures of certain modal and description logics with resolution. In this WP we will first investigate the transfer of refinements and redundancy elimination techniques from resolution to DL tableau calculi. We then intend to take this study a step further and develop methods of automatically synthesising tableau calculi. For first-order definable logics the automatic synthesis of sound and complete tableau calculi is actually straightforward and can for example be done in a higher-order logical framework like ISABELLE, COQ, MAUDE, ATHENA, etc. However our aim is to also generate the code for a tableau prover. In addition, we want the tableau prover to be decision procedure if the logic is decidable, and we want the prover to be efficient. For this the use of logical frameworks is not sufficient. This means we need to develop new methods to accomplish this aim. We know that for modal logics the new axiomatic translation approach allows us to transform Hilbert-style axiomatisations for modal logics into a set of tableau rules [16]. Soundness and completeness of calculi generated in this way is automatic. In this WP we want to explore the workability of this idea for (expressive) DLs. However, DLs will not be specified by Hilbert-style axiomatisations but by semantic specifications, thus we won't be able to apply the axiomatic translation approach directly. It would also be interesting to explore the automatic synthesis of other styles of deduction calculi. The ultimate dream would be to have a tool that lets the user specify the logic, either as a Hilbert axiomatisation or a semantic definition, together with the style of inference, 'sequent calculus' say, and at the touch of a button the tool will output a sequent calculus for the logic, or better it could immediately generate the code of a sequent-style prover. Given that in automated reasoning there are standard principles for integrating simplification and optimisation techniques, we intend to apply these principles to help generate an implemented prover. In addition, we want to guarantee soundness, completeness and termination, if applicable, of the prover.

MILESTONES: M4. Paper(s) on the automatic synthesis of tableau calculi and implemented provers.

TOTAL: 9 PERSON-MONTHS

WP3. Modal agent logics. (LIVERPOOL [RS]: Month 1–24)

The aim of this WP is to systematically study resolution methods for a range of agent formalisms and the modal logics which these formalisms are based on.

TASKS:

3.1 Become familiar with fundamental properties of modal, temporal logics and agent logics, translation approaches, resolution calculi for classical and temporal logic.

3.2 Investigate how first-order theorem proving techniques can be used to realise the clausal temporal resolution calculus for the propositional branching time logic *CTL* [4], in analogy to the way in which we utilise those techniques to realise the temporal clausal resolution calculus for *PLTL* [14].

3.3 Study fragments of first-order *CTL*, in particular, identify decidable and undecidable fragments, and develop resolution decision procedures for decidable fragments.

3.4 Develop a clausal temporal resolution calculus for alternating-time temporal logic *ATL*.

3.5 Investigate how the clausal temporal resolution calculus for propositional linear time logic *PLTL* [5] can be extended to *DLTL* and $DLTL^{\oplus}$ [7].

3.6 Study translation embeddings into the logics studied in the previous tasks of various agent logics, for example, BDI logics combined with linear or branching time logics, coalition logics, alternating-time temporal epistemic logic *ATEL* and logics within the KARO framework.

METHODOLOGY: The point of departure for this WP is our previous work on decision procedures for various modal logics, including basic modal logic, deontic logic, and epistemic logic, based on translation and first-order resolution, as well as the work on clausal temporal resolution calculi for propositional linear time logic *PLTL*, monodic first-order linear time logic, propositional branching time temporal logic *CTL*, and the relationship of these methods to other approaches, for example, tableau methods for modal logics and automata methods for temporal logics. The use of first-order theorem proving techniques may seem curious, but we know that the inference rules of the clausal temporal resolution calculus for *PLTL* can be simulated by ordered first-order resolution. We expect the same to be true for the inference rules of the clausal temporal resolution for *CTL*. The theoretical work of task 3.2 would then form the basis of an implementation as part of WP5.

Previous work on *CTL* also considered its combination (fusion) with the epistemic logic *S5*. In analogy to our work on the combination of *PLTL* with a variety of modal logics, including *S5*, which makes use of an embedding of such combinations into monodic first-order linear time logic, we want to explore and identify fragments of first-order *CTL* into which such an embedding is possible and allows for effective decision procedures for the combined logics. This will be the approach taken in task 3.3.

Since *CTL* can be embedded into ATL, a deeper understanding of the clausal temporal resolution calculus for the former, developed in tasks 3.2 and 3.3, also provides a basis for developing a resolution calculus for ATL, which is the goal of task 3.4. Similarly, our previous work on *PLTL* provides the basis for developing a resolution calculus for *DLTL* and $DLTL^{\oplus}$, the goal of task 3.5. *DLTL* is an extension of *PLTL* in which the next state modality is labelled by actions and the until operator is indexed by programs in propositional dynamic logic *PDL*. These two tasks are more challenging than the previous tasks in this WP, as it is not clear whether the principles underlying resolution calculi for *PLTL* and *CTL* can be applied to *DLTL* and *ATL*, respectively. However, it might also be possible to utilise the work on the relationship between ω-automata and temporal logic normal forms, as automata decision procedures for both *DLTL* and *ATL* exist.

Finally, logics like *PLTL*, *CTL*, *DLTL*, *ATL*, combined with other modal logics, like doxastic or epistemic logic, form the basis of a variety of agent logics. The final task of this WP will consider how the methods developed in previous tasks of the WP can be used to provide reasoning methods for those agent logics.

MILESTONES: M5. Paper on the realisation of a *CTL* decision procedure taking advantage of first-order theorem proving techniques. M6. Paper on (un)decidable fragments of first-order *CTL* and decision procedures for decidable fragments. M7. Paper on a clausal temporal resolution calculus for *ATL*. M8. Paper on a clausal temporal resolution calculus for *DLTL* and $DLTL^{\oplus}$. M9. Paper on translation embeddings of various agent logics.

TOTAL: 24 PERSON-MONTHS

WP4. Integration of ontologies and agent logics. (MAN & LIV: Month 24–33)

Here the aim is to investigate the integration of the methods developed in WP1 and WP3.

TASKS:

4.1 Devise an the integrated formal framework of ontologies and agent logics.

4.2 Devise reasoning methods for this framework.

METHODOLOGY: So far, the theoretical aspects of an integration of ontologies and of agent logics or multi-agent systems has mainly been investigated in the context of temporalised description logics. These logics are more suited to the formalisation of concepts involving temporal aspects than to the formalisation of multi-agent systems incorporating the use of ontologies, e.g. to facilitate agent communication or to allow agent knowledge bases which are not simply propositional. On the other hand, the consideration of practical aspects has focused on the integration of ontological reasoning systems with multi-agent systems with the question of the formalisation and verification of such systems being left open.

MILESTONES: M10. Paper(s) on the integration of ontologies and agent logics.

TOTAL: 9 PERSON-MONTHS

WP5. Implementation. (MAN & LIV: Month 3–30)

This WP aims to build tools that exploit the developed technologies.

TASKS:

5.1 Implementation of reasoning systems for ontologies.

5.2 Implementation of reasoning systems for modal agent logics.

5.3 Implementation of a reasoning system for a framework integrating ontologies and modal agent logics.

METHODOLOGY: In the project we plan to start early with implementation work and continue it in parallel to the theoretical investigations. This 'rapid prototyping' approach has the advantage that practical experience can feed back quickly into the theoretical investigations and potentially vague ideas can be tested immediately with the developed tools. The tasks of this WP provide also opportunities for Masters students to contribute to the research.

The implementation work will take advantage of the fact that both the ontological reasoning appraoch and the appraoch of reasoning in agent logics aim to utilise first-order reasoning techniques. Thus, the implementation of reasoning systems for those two classes of logics as well as for the framework integrating them will not start from scratch, but will start from existing state-of-the-art first-order logic theorem provers (VAMPIRE, E) as well as from earlier systems developed along this line for modal and description logics (MSPASS) and temporal logics (TRP++ and TeMP).

MILESTONES: M11. Reasoning systems for ontologies. M12. Reasoning systems for modal agent logics. M13. Reasoning system for a framework integrating ontologies and modal agent logics.

TOTAL: 9 PERSON-MONTHS

WP6. Empirical evaluation. (MAN & LIV: Month 10–36)

The aim of this WP is to measure, via empirical evaluation, the utility and performance improvements provided by the newly implemented reasoning systems.

TASKS:

6.1 Study of benchmarking principles and design of the most appropriate experimental approach.

6.2 Gather problems suitable for the experiments and develop suitable random problem generators.

6.3 Performance tests of newly implemented tools and comparative analysis with existing provers.

METHODOLOGY: Measurements of performance are important to quantify the practical gain of any developed methodology. In order to allow meaningful conclusions to be drawn from experimental studies empirical tests need to be designed very carefully [11]. To determine the practical benefit of the new technology competitive benchmarking [11], which might be suitable to compare existing description logics reasoners to the ontological reasoning system developed in WP5 on existing knowledge base benchmarks, as well as hypothesis-driven benchmarking [12] will be used.

MILESTONES: M14. Repository of problems, sample case studies and evaluation of reasoning systems. M15. Paper(s) on the implementation and evaluation of the developed reasoning systems.

TOTAL: 6 PERSON-MONTHS

WP7. Dissertation. (LIV [RS]: Month 30–36)

Writing up the work of WP3 and the relevant parts of WP5 and WP6 (and possibly WP4) as a PhD thesis.

MILESTONES: M16. PhD dissertation.

TOTAL: 6 PERSON-MONTHS

Management. The project will be carried out within the Departments of Computer Science at the University of

Manchester and the University of Liverpool, and will be managed by the principal investigators. In order to ensure progress towards the goals of the project frequent meetings will be held; more frequent meetings (weekly or fortnightly) are anticipated by the local research teams, and meetings involving both hosts at longer intervals (quarterly). Given the geographical closeness of Manchester and Liverpool more frequent meetings can be arranged, as needed.

C Relevance to Beneficiaries

Our expectation is that the ideas and techniques developed and explored have the potential to dramatically enhance the facilities and technologies available for reasoning in the semantic web and multi-agent systems. This research will have direct benefit to the automated reasoning community, the modal logic and the description logic community; the agent community; the semantic web community; and more generally to Artificial Intelligence, Computer Science and any disciplines benefiting from routine tasks requiring logical reasoning. The work will further strengthen the position of UK research in all these areas.

D Dissemination and Exploitation

The results will be presented at recognised conferences and will be published in respected journals. Among the most important journals through which our results may reach a wider audience are the *ACM Trans. Computational Logic*, *Artificial Intelligence*, *Inform. and Computat.*, *J. Applied Logic*, and *J. Automated Reasoning*.

A practical outcome of the project will be prototype automated reasoning support tools and algorithms, and enhanced theorem provers, which will be made publicly available in order to enable the future exploitation of the developed methods.

E Justification of Resources

Staff. We require funds to support one research associate for three years. In order to fulfil the project's aims and to conduct the required technically challenging research, postdoctoral experience and an excellent track record is important. A research background in logic, proof theory, complexity theory, theory and implementation of systems for logics like modal logic, temporal logic, description logics, first-order logic is clearly essential for investigation into this area.

Exceptional items. One area has been identified to be carried out by a research student with strong programming skills and a strong background in logic and reasoning methods. One PhD studentship is therefore requested.

Equipment. High performance PCs for the RA and the RS together with printing facilities, and a laptop are requested. This will provide the required infrastructure for developing and testing prototype systems and for producing high-quality conference and journal papers.

Travel and subsistence. In addition to travel between the collaborating institutions, a number of visits are planned to various academic and industrial sites within the UK, Europe and worldwide. We seek funds for the RS to attend a summer school in a relevant area, e.g. ESSLLI. Also, we request funds to attend international conferences relevant to the project, e.g. IJCAR, CADE, IJCAI, KR, AAAI, LICS, etc. together with workshops on automated reasoning, description logics, non-classical logics and knowledge representation.

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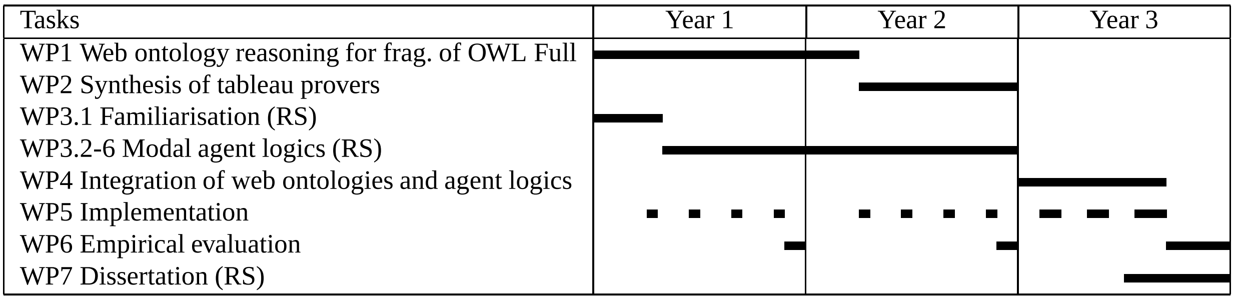
Diagrammatic Project Plan



WP1 Web ontology reasoning for fragments of OWL Full (MANCHESTER).
<u>MILESTONES:</u>
M1. Papers on new decision procedures for extensions of expressive descriptions logics.
M2. Papers with new solutions to classification, query-answering and other non-standard inference services.
M3. Papers on useful fragments of OWL Full with practical inference procedures.

WP2 Synthesis of tableau provers (MANCHESTER).
<u>MILESTONES:</u>
M4. Paper(s) on the automatic synthesis of tableau calculi and implemented provers.

WP3 Modal agent logics (LIVERPOOL).
<u>MILESTONES:</u>
M5. Paper on the realisation of a *CTL* decision procedure taking advantage of first-order theorem proving techniques.
M6. Paper on (un)decidable fragments of first-order *CTL* and decision procedures for decidable fragments.
M7. Paper on a clausal temporal resolution calculus for *ATL*.
M8. Paper on a clausal temporal resolution calculus for *DLTL* and $DLTL^{\oplus}$.
M9. Paper on translation embeddings of various agent logics.

WP4 Integration of web ontologies and agent logics (MANCHESTER & LIVERPOOL).
<u>MILESTONES:</u>
M10. Paper(s) on the integration of ontologies and agent logics.

WP5 Implementation (MANCHESTER & LIVERPOOL).
<u>MILESTONES:</u>
M11. Reasoning systems for ontologies.
M12. Reasoning systems for modal agent logics.
M13. Reasoning system for a framework integrating ontologies and modal agent logics.

WP6 Empirical evaluation (MANCHESTER & LIVERPOOL).
<u>MILESTONES:</u>
M14. Repository of problems, sample case studies and evaluation of reasoning systems.
M15. Paper(s) on the implementation and evaluation of the developed reasoning systems.

WP7 Dissertation (LIVERPOOL).
<u>MILESTONES:</u>
M16. PhD dissertation.

Concerning the project organisation, in years 1 and 2 the workpackages of the Manchester team are delineated from the workpackages of the Liverpool team, so that the teams can work largely autonomously, without significantly disrupting the other team due to synchronisation problems. In year 3, both teams will work together on WP4, the integration of the work of WP1 and WP3, as well as on WP5 and WP6.

The division of the project is in line with the relative strengths of the institutions: The Manchester group (one RA) will focus on the semantic web, ontologies, and description logics, while the Liverpool group (one research student) will focus on multi-agent systems and agent logics.