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Aλonzo: Higher-order Reasoning Agents for Mathematics

Christoph Benzmüller

January 26, 2004

Abstract

The long-term goal of my research is the development of a mathematical assistance environment and its integration into the emerging Mathematical Semantic Net[a]. Interactive proof systems are today routinely employed in industrial applications for safety and security verification and more recently they find applications in e-learning systems for mathematics.
The vision of a powerful mathematical assistance environment which provides computer-based support for most tasks of a mathematician has stimulated new projects and international research networks across the disciplinary and systems boundaries. Examples are the European CALCULEMUS[b] (Integration of Symbolic Reasoning and Symbolic Computation) and MKM[c] (Mathematical Knowledge Management, [BGH03]) initiatives, the EU projects MONET[d], OPENMATH and MOWGLI[e], and the American QPQ[f] repository of deductive software tools. Furthermore there are now numerous national projects in the US and Europe, which cover partial aspects of this vision, such as knowledge representation, deductive system support, user interfaces, mathematical publishing tools, etc.
The immediate goal of the Aλonzo project is (I) to provide basic research results on the semantics and mechanisation of higher-order logic, (II) to exploit these results for the development of powerful, application-oriented higher-order proof tools, (III) to exemplarily employ these proof tools as proof agents (or Web services) for the mathematical assistance environments OMEGA and λ *Clam* and to support their interoperability and coordination with other reasoning agents, (IV) to apply these agents as semantic mediators between mathematical assistance environments (or humans) and the currently emerging huge repositories of formalised mathematical knowledge in the Internet, and finally (V) to produce introductory literature on this subject.
The applicant is the coordinator of the EU Research Training Network CALCULEMUS, of the successor proposal CALCULEMUS-II, and of the Saarland University node in MKM.

[a] `www.win.tue.nl/dw/monet/`
[b] `www.calculemus.org`
[c] `monet.nag.co.uk/mkm/index.html`
[d] `monet.nag.co.uk/cocoon/monet/index.html`
[e] `www.mowgli.cs.unibo.it/`
[f] `www.qpq.org`

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Part A

Application Forms

The Part A Application Forms are attached to this document.

Part B

Background of the Applicant

B.1 Own Research in the Area

(A) Mathematical Knowledge Management The mathematical knowledge management (MKM) research initiative has the goal of revolutionising computer-based mathematics in the new millennium by a top-down approach starting from existing, mainly pen and paper based mathematical practice down to system support. At the core of MKM research is the transition from current forms of managing, maintaining, and accessing mathematical knowledge (MK) through its digitalisation and formalisation to fully computer-supported solutions.

My MKM relevant contributions include (i) an agent-based approach enabling distributed search for applicable assertions in repositories of formalised mathematical knowledge [C14-03, C13-03, W19-03, W16-02, W14-01, R20-03][1], (ii) a representation language for human-constructed mathematical proofs with under-specification [J08-03]; see also (F) below, (iii) a proposal for a human-oriented user interface (UI) based on so called *proof tasks* [W24-03, W16-02], and (iv) the active involvement in the EU MKM network[2] as head of Saarland University node.

(B) Mathematical Assistance Environments The CALCULEMUS research community[3] is pursuing a bottom-up approach starting from existing tools and systems up to building a new generation of mathematical assistance environments (MAS) that provide integrated computer-based support for most tasks of a mathematician.

My contributions in this direction include (i) the development of the MAS OMEGA (head of OMEGA group) [B01-03, C12-02, C11-02, C01-97], (ii) the coordination of the CALCULEMUS-II proposal [R24-03] in the EU 6th framework on *Systems for Computer-Supported Mathematical Knowledge Evolution* with 13 European project partners and further 18 academic and industrial collaborators — including SRI, NASA, and Intel, (iii) the agent-based suggestion mechanism OANTS for interactive theorem provers (TPs) [C06-99, C04-98, W03-99, R12-99, R09-99], (iv) an approach for learning proof methods in proof-planning [J07-03, C09-00, W08-01, W06-01, R16-02, R14-01], (v) the analysis of shortcomings of proof-planning such as its dependency on the underlying logic layer [W12-01], (vi) an approach to agent-based expansion of proof tactics [W19-03], and (vii) the multi-modal UI LOUI for MASs [J03-99, J02-99, W01-98].

(C) Integration of Reasoning Systems The integration of reasoning tools and the improvement of their interoperability is central to foster progress for (A) and (B).

My contributions include (i) the coordination of the CALCULEMUS-I research training network on *Systems for Integrated Symbolic Reasoning and Symbolic Computation* [W22-03, W21-03, E05-03, R22-03], (ii) my role as co-organiser and co-chair of the 2002 CALCULEMUS Autumn School in Pisa [E04-02, E03-02, E02-02, E01-02], (iii) a tactic-based approach for white-box integration of the higher-order proof assistants OMEGA and TPS [J01-99, W02-98], (iv) the extension of the OANTS suggestion mechanism into a heuristic, resource adaptive, automated, agent-based reasoning system supporting the integration of specialist reasoners [C10-01, C08-00, C07-00, C06-99, W15-02, W11-01, W10-01, W07-00, W04-99, R10-99], and (iv) the supervision of the PhD project of Jürgen Zimmer, the main developer and expert of the mathematical software bus MathWeb, on the automated coordination of reasoning tools within the MathWeb [Zim04].

(D) Higher-Order Logic — Semantics and Mechanisation As a consequence of Gödels incompleteness theorems the scientific community interested in the automation of logical and mathematical reasoning has mainly concentrated on first-order logic while on the other hand the community developing interactive proof assistants has preferred higher-order logic (HOL) as an elegant and expressive representation formalism. This discrepancy in the historic development, especially the lack of interest in the direct (appropriately limited!) automation of HOL reasoning is very unfortunate for the development of MASs. Amongst the frequently used arguments against research on the automation of HOL are: (a) the lack of an appropriate semantics and respective proof methods that can guide the development of complete

[1] The bibliography uses a special bibliographystyle for the applicants own papers. These entries are labeled '[Xnn-mm]' where 'X' describes the type/category of publication ('B' stands for Books and Chapters in Books, 'J' for International Journals, 'E' for Edited Proceedings and Books, 'C' for International Conferences, 'W' for International Workshops, 'T' for Theses, and 'R' for Technical Reports and Others), 'nn' is a consecutive numbering in each category, and 'mm' describes the year of publication.

[2] `monet.nag.co.uk/mkm/index.html`

[3] `www.calculemus.org`

HOL calculi[4], (b) the mechanisation of equality and extensionality reasoning is not sufficiently developed, and (c) the mechanisation of set variables is an open problem.

Problems (a) and (b) have been the main interest of my PhD project [T2-99] and I have contributed to (i) the development of a landscape of HOL model classes motivated by different roles extensionality and equality plays in them [J06-04, R18-03, R05-97], (ii) the extension of Smullyan's abstract consistency principle to this landscape of semantical notions [J06-04, R18-03, R05-97], (iii) investigation of the connection between cut-elimination and saturation in HOL [R19-03], (vi) the development of calculi for HOL reasoning with equality and extensionality: extensional resolution [J05-02, T2-99, C02-98, R06-97, R04-97], extensional paramodulation and RUE-resolution [T2-99, C05-99], natural deduction calculus [J06-04, R18-03], and sequent calculus [R19-03], and (v) the development of the HOL resolution TP LEO [T2-99, C03-98].

(E) Semantical Mediators Mediation of mathematical knowledge based on syntactical and semantical filtering is required in order to make the fast emerging distributed repositories of formalised mathematical knowledge better accessible for MASs and humans.

My own work in this direction concentrated on (i) the proposal of a two layered architecture for semantic mathematical knowledge retrieval that combines syntactical pre-filtering with full semantic analyses supported by TPs [C13-03, W14-01] and (ii) the automation of full assertion level reasoning as a means for semantic filtering [C14-03].

(F) Tutorial Natural Language Dialog in Mathematics The DIALOG project [R25-01] in the collaborative research centre SFB 378 *Resource-adaptive Cognitive Processes* aims at a mathematical tutoring system that employs an elaborate natural language dialogue component. To tutor mathematical proofs it supports a formally encoded mathematical theory including definitions and theorems along with their proofs, means of classifying the student's input in terms of the knowledge of the domain, and a theory of tutoring that should make use of hints. A main challenge is to couple natural language analysis with dynamic domain reasoning (supported by MASs and TPs) since the set of all valid mathematical proofs to be tutored cannot be statically modelled in general.

My contributions include (i) an architecture for the DIALOG system [W20-03], (ii) a corpus of data gained in a Wizard of Oz case study [W23-03], and (iii) an analysis of this corpus and consequences for dynamic domain reasoning with MASs in the DIALOG system context [W20-03]; this in particular includes the phenomenon of under-specification [J08-03, W25-03] in the representation of human constructed proofs and the challenge to analyse information completeness, accuracy, level of granularity, and relevance of uttered proof steps within the DIALOG system [J08-03].

[4]Standard semantics does according to Gödel not allow for complete calculi. Weaker notions of semantics such as Henkin semantics [Hen50] are thus required.

B.2 Current and Past Positions

Position (1): Assistant Professor (C1/C2)
Date: since January 2001
Institution: Department of CS, Saarland University, 66041 Saarbrücken, Germany. Contact: Prof. Jörg Siekmann, +49(0)681-3025275, siekmann@ags.uni-sb.de
Description: Project leader of the OMEGA group at Saarland University under the professorship of Jörg Siekmann (approx. 10 researchers), development of the MAS OMEGA.

Position (2): Postdoctoral Research Fellow, EPSRC Grant GR/M99644: Agent-oriented TP
Date: 01/00–12/00
Institution(s):
(3 months) Department of AI, The University of Edinburgh, Edinburgh EH8 9LE, Scotland. Contact: Prof. Alan Bundy, +44-131-650-2716, a.bundy@ed.ac.uk
(9 months) School of CS, The University of Birmingham, Birmingham B15 2TT, England. Contact: Dr. Manfred Kerber, +44-121-414-4787, M.Kerber@cs.bham.ac.uk
Description: Integration of heterogeneous reasoning systems in the agent-based OANTS reasoning system, learning of proof methods.

Position (3): Visiting Researcher
Date: 01/99–03/99
Institution: School of CS, The University of Birmingham, see Position (2)
Description: Preparation of position (2).

Position (4): Postdoctoral Research Fellow
Date: 01/99–12/99
Institution: Graduate College for Cognitive Science, Dep. of Psychology, Saarland University, 66041 Saarbrücken, Germany. Contact: Prof. Werner Tack, +49 (0)681-302-3588, w.tack@mx.uni-saarland.de
Description: Development of the resource-adaptive agent-based suggestion mechanism

OANTS.

Position (5): Research Fellow, DFG Grant HOTEL
Date: 08/97–12/98
Institution: See position (1)
Description: HOL semantics & mechanisation.

Position (6): Visiting Research Student
Date: 01/97–7/97
Institution: Department of Mathematical Sciences, CMU, Pittsburgh, PA 15213, USA. Contact: Prof. Peter Andrews, +1-412-268-2554, andrews@cmu.edu
Description: HOL semantics & mechanisation.

Position (7): Research Fellow, DFG SFB-378 Grant OMEGA
Date: 04/95–12/96
Institution: see position (1)
Description: Interactive TP, UI, MathWeb.

Position (8) + (9): Student Researcher in project VSE (Verification Support Environment) and KORSO (Correct Software)
Date: 01/91–03/95
Institutions:
(VSE) DFKI GmbH, Stuhlsatzenhausweg 3, 66123 Saarbrücken, Germany. Contact: Dr. Dieter Hutter, +49-681-302-5317, hutter@dfki.de
(KORSO) Department of CS, Saarland University, 66041 Saarbrücken, Germany. Contact: Prof. Jacques Loeckx, loeckx@cs.uni-sb.de
Description: Case studies in formal methods.

B.3 Experience of Team Leadership and Project Management

Coordinator of the CALCULEMUS-II research training network proposal on *Computer-supported Mathematical Knowledge Evolution* in the EU 6th framework (under evaluation).

Coordinator of the CALCULEMUS-I[5] research training network on *Systems for integrated Computation and Deduction* funded in the EU 5th framework.

Co-organiser and Co-chair of the CALCULEMUS Autumn School 2002 in Pisa[6].

Project leader of the OMEGA group[7] with approximately 10 full-time researchers at Saarland University.

Principal Investigator of the project DIALOG [R25-01] *Tutorial Dialog with a MAS* in the Collaborative Research Centre *Resource-adaptive Cognitive Processes* (SFB 378)[8] at Saarland University.

Principal Investigator of the project OMEGA [R26-01] *Resource-adaptive Proof-Planning* in the SFB 378 at Saarland University.

Head of the Saarland University node of the evolving EU MKM research network[9].

Assistant (to Prof. Siekmann) for the coordination of the collaborative research centre *Resource-adaptive Cognitive Processes* (SFB 378)[10] at Saarland University with approx. 30 researchers.

B.4 Most Relevant Publications

[B01-03, J06-04, J05-02, J01-99, C14-03, C13-03, C08-00, C05-99, C03-98, C02-98]; see the list of of publications starting from page 8 in the applicants CV.

B.5 EURYI Timeliness in Career

Career Development Perspective After my PhD study — which included a research visit at Carnegie Mellon University, USA — I have gained experience as postdoctoral fellow in research projects in Germany and the UK (Birmingham and Edinburgh). Since 2001 I am heading the OMEGA group and I am responsible for the joint development of the OMEGA system (partner nodes thereby include the University of Birmingham, International University of Bremen, and the DFKI, Saarbrücken). Further project responsibilities have been sketched in Section B3.

A consequent next step in my career is to create my *own and independent* research environment with which I want to place myself amongst the scientific and organisational driving forces in the CALCULEMUS and MKM communities.

I am currently Assistant Professor (Hochschulassistent, C1/C2) at Saarland University. I am furthermore involved in the supervision of several PhD and master students — e.g. the PhD students Martin Pollet and Jürgen Zimmer, which are amongst the most active students currently trained in CALCULEMUS-I. Jürgen Zimmer is since 01/2003 visiting Alan Bundy at Edinburgh University.

Moving from my current position at Saarland University to an individual researcher position (e.g. Lecturer in the UK or Junior Professorship in Germany) without sufficient resources to even create a small research group will have a negative impact on the spectrum of my research and thus also on the students I am supervising.

[5] `www.eurice.de/calculemus/`
[6] `www.eurice.de/calculemus/autumn-school/`
[7] `www.ags.uni-sb.de/~omega/`
[8] `www.coli.uni-sb.de/sfb378/`
[9] `monet.nag.co.uk/mkm/index.html`
[10] `www.coli.uni-sb.de/sfb/`

Scientific Perspective Aλonzo wants to reverse the unfortunate fragmentation of today's deduction system area by showing ways to employ HOL deduction tools as part and in cooperation with other reasoning tools within MASs.

Mathematical textbooks naturally employ HOL constructs and thus the currently fast evolving repositories of formalised mathematics also provide a high amount of mathematical knowledge (MK) encoded in HOL (either classical HOL or constructive type theory). Examples are the libraries of the MASs NuPrl[11], COQ[12], HOL[13], PVS[14], MIZAR[15], ISABELLE[16], and THEOREMA[17]. The knowledge of some of these libraries is currently translated into unified representations and merged in European projects such as MBASE[18] and HELM[19] or the very recent American LOGOSPHERE project[20]. Prof. Robert Constable (Cornell University, USA) in his invited lecture at the MKM workshop[21] in November 2003 at Heriot Watt University estimated that the LOGOSPHERE MKB contains approx. 70% HOL entries.

My own contributions as sketched in B1(D) and the recent work of Chad Brown [Bro02] w.r.t. the set variable problem are important milestones for the automation of HOL.[22]

Within the research initiatives of CALCULEMUS and MKM there is *now* an increasing need for the direct (appropriately limited!) mechanisation of HOL reasoning and thus the proposed EURYI project Aλonzo is just in time to strengthen the sparse existing research in this direction and to combine it with the other research strains mentioned in Section B1.

It is also *now* that I will be able to create a highly competitive research group together with Chad Brown and Jürgen Zimmer, which will contribute to the strengthening of the leading role Europe still has in the MKM initiative.

While the research in the long run will have impact on maths research practice it is expected to have immediate impact on the fast developing e-learning and formal methods areas.

[11] `www.cs.cornell.edu/Info/Projects/NuPrl`
[12] `coq.inria.fr`
[13] `hol.sourceforge.net`
[14] `pvs.csl.sri.com`
[15] `www.mizar.org`
[16] `www.cl.cam.ac.uk/Research/HVG/Isabelle`
[17] `www.theorema.org`
[18] `www.mathweb.org/mbase`
[19] `helm.cs.unibo.it`
[20] `www.logosphere.org`
[21] `www.macs.hw.ac.uk/~fairouz/mkm-symposium03`
[22] The anonymous JSL-referee of [J06-04] says: "This is a very significant paper which provides much needed foundations for further work in this area, ..."

B.6 Research Collaboration

The following list mentions my current research collaborations in the OMEGA project for the areas given in Section B1:

(A) MKM consortium, M. Kohlhase (International University of Bremen, Germany), J. von der Hoeven (Université Paris-Sud, France), D. Hutter (DFKI GmbH, Saarbrücken, Germany), B. Buchberger (RISC Linz, Austria)

(B) CALCULEMUS-II consortium, M. Kerber and V. Sorge (University of Birmingham, UK), W. Sieg (CMU, Pittsburgh, USA)

(C) CALCULEMUS-I consortium, A. Bundy (University of Edinburgh, UK), V. Sorge (University of Birmingham, UK), C. Brown (CMU, Pittsburgh, USA)

(D) C. Brown and F. Pfenning (CMU, Pittsburgh, USA) and M. Kohlhase (International University of Bremen, Germany)

(F) M. Pinkal (Computational Linguistics Department, Saarland University, Germany)

B.7 Prizes and Awards

Grantholder (2001-2004) in the Collaborative Research Centre (SFB 378) *Resource-adaptive Cognitive Processes*, Project MI 4 OMEGA: *Resource-Adaptive Proof-Planning.*

Grantholder (2001-2004) in the Collaborative Research Centre (SFB 378)*Resource-adaptive Cognitive Processes*, Project MI 3 DIALOG: *Tutorial Dialogue with a Mathematics Assistance System.*

Postdoctoral Fellowship (1999-2000) in the Graduate College for Cognitive Science at the Saarland University, Saarbrücken, Germany.

Ph.D. Scholarship (1996-1998) holder of the Studienstiftung des Deutschen Volkes[23], the most elitist support organisation in Germany.

B.8 Other

The TPS system has been developed by Peter Andrews at Carnegie Mellon University, Pittsburgh, USA, since the early 80s. With respect to automation of HOL reasoning it is probably the most powerful system currently available. Chad Brown is currently the leading developer of this system. I worked personally with TPS during my research visit in 1997 and later integrated it via a collaboration with Peter Andrews' group into the OMEGA system [J01-99]. Peter Andrews will retire/emeritate in a few years and he agreed that we will continue the development of the TPS system and its maintenance.

[23] `www.studienstiftung.de/`

Part C

Project Description

C.1 Overall Aims and Objectives

C1.1 Overall Aims

The long-term goal of my research is the development of a mathematical assistance environment and its integration into the emerging Mathematical Semantic Net[24]. Interactive proof systems are today routinely employed in industrial applications for safety and security verification and more recently they find applications in e-learning systems for mathematics.

The vision of a powerful mathematical assistance environment which provides computer-based support for most tasks of a mathematician has stimulated new projects and international research networks across the disciplinary and systems boundaries. Examples are the European CALCULEMUS[25] (Integration of Symbolic Reasoning and Symbolic Computation) and MKM[26] (Mathematical Knowledge Management) initiatives, the EU projects MONET[27], OPENMATH and MOWGLI[28], and the American QPQ[29] repository of deductive software tools. Furthermore there are now numerous national projects in the US and Europe, which cover partial aspects of this vision, such as knowledge representation, deductive system support, user interfaces, mathematical publishing tools, etc.

The immediate goal of the Aλonzo project is (I) to provide basic research results on the semantics and mechanisation of higher-order logic, (II) to exploit these results for the development of powerful, application-oriented higher-order proof tools, (III) to exemplarily employ these proof tools as proof agents (or Web services) for the mathematical assistance environments OMEGA and λ *Clam* and to support their interoperability and coordination with other reasoning agents, (IV) to apply these agents as semantic mediators between mathematical assistance environments (or humans) and the currently emerging huge repositories of formalised mathematical knowledge in the Internet, and finally (IV) to produce introductory literature on this subject.

The applicant is the coordinator of the EU Research Training Network CALCULEMUS, of the successor proposal CALCULEMUS-II [R24-03], and of the Saarland University node in MKM.

[24] www.win.tue.nl/dw/monet/
[25] www.calculemus.org
[26] monet.nag.co.uk/mkm/index.html
[27] monet.nag.co.uk/cocoon/monet/index.html
[28] www.mowgli.cs.unibo.it/
[29] www.qpq.org

The situation in the unfortunately fragmented deduction systems area is similar to that of the AI field as a whole and as it was criticised by Nils Nilsson (Kumagai Professor at Stanford, USA) in his speech at IJCAI 2003 where he received the IJCAI Research Excellence Award. Today many of the deduction system subareas even have separate conferences. As a consequence the ambitious goal of an integrated mathematical assistance environments (MASs) was very weakly represented at these conferences and in the deduction systems community until the end of the 90s. It is only very recently that this trend is reversed, with the CALCULEMUS and MKM communities as driving forces of this movement.

Project Aλonzo addresses some core research issues of CALCULEMUS and MKM and has five work packages:

WP I (Foundations) Semantics and Mechanisation of HOL On the one hand there is an increasing interest in HOL — e.g., in Computer Science, Mathematics, and Computational Linguistics — as a powerful, elegant, and expressive representational formalism. On the other hand there are many insufficiently investigated issues w.r.t. the semantics and mechanisation of HOL. The goal of WP I is to tackle this discrepancy by providing appropriate HOL semantics and to develop or refine respective calculi for interactive and automated HOL reasoning. This work will be built upon my own research results (see Section B1(D)) and carried out together with Chad Brown. In addition to calculi development the emphasis will be on specialised heuristics that serve the needs of the particular application directions proposed in WP III and WP IV.

WP II (System Development 1) Theorem Provers for HOL The improved and appropriately specialised approaches to mechanising HOL developed in WP I will be implemented and tested within the existing HOL theorem provers (TP) LEO (Resolution) and TPS (Matrix). Special efficiency increasing techniques and tricks as developed and employed in first-order theorem proving shall, if possible, be adapted to HOL TP. To foster interoperability with MASs and other reasoning tools, a proof representation translation module shall be developed that transforms machine-oriented proofs generated by LEO and TPS into the semi-formal proof representation formats currently developed and investigated in MKM.

WP III (System Development 2) Agent or Web Service based Integration and Coordination The goal is to exemplarily employ the proof tools of WP II as proof agents (or Web services) for the MASs OMEGA and/or λ *Clam*. Thereby a close collaboration with the recent initiative to create a Mathematical Semantic Web as proposed in the EU MONET project is planned in order to support interoperability with other reasoning agents or services. Within MASs the new HOL proof agents shall pro-actively and autonomously tackle subproblems in varying system- and problem-contexts. Further research addresses cooperation and coordination of these proof agents with other reasoning agents in the scenario, such as first-order TPs, computer algebra systems or a mathematician. Three candidate approaches for automated coordination of reasoning agents are: (a) centralised guidance by the MASs the agents are working for (e.g. by employing proof-planning [CMPS03, MPS02] or the ΩANTS-approach [C10-01]), (b) decentralised guidance within a network of cooperating reasoning agents such as MathWeb [Zim04], and (c) a direct cooperation with other reasoning agents guided internally within the HOL proof agents. Ideally the HOL proof agents will be made available to other MASs as well; candidates are Isabelle/HOL or PVS, i.e., systems with particular strengths in formal methods applications (complementary to the strengths of OMEGA and λ *Clam*).

WP IV (Application) Semantic Mediators for MKBs Knowledge acquisition and retrieval in the currently emerging huge repositories of formalised mathematical knowledge shall be supported by semantic mediators. These mediators should, for instance, be capable of suggesting applicable theorems and lemmata in a given proof context within a MAS. Informal mathematical practice and mathematical textbooks implicitly more often than not exploit higher-order arguments and constructs. Thus, most mathematical assistance environments as well as most of the emerging MKBs also provide HOL as their basic representation language. Therefore we propose to directly exploit HOL proof tools — in the range from HOL matching to fully extensional higher-order theorem proving — as core algorithms underlying the semantic mediators to be developed in this work package. Generally, mediation in this context may be supported also by state-of-the-art first-order TPs when employing higher-order to first-order transformation tools such as the OMEGA group's TRAMP system [Mei00]. Such an approach is currently pursued in a project of Larry Paulson at Cambridge University. We propose to consider this approach as a cooperating solution (parallel to or as a pre-filter for the Aλonzo-agents) in our project. This is easily possible since OMEGA, TRAMP, and several state-of-the-art first-order TPs have been interoperating within the MathWeb system for several years (see a recent application in [B01-03]), i.e., the required infrastructure is already completely developed.

Why do we additionally propose to apply HOL proof agents for the mediation task? We will illustrate in Section C.8 that, for instance, answer substitutions (instantiations of free/universal variables in the mediation context) are very interesting as a form of justification for the applicability of each retrieved lemma in a MKB. HOL answer substitutions can, of course, not easily be realised within a transformational first-order approach as sketched above and it would require several highly non-trivial modifications to the transformation module TRAMP and in particular to the employed first-order TPs (which are usually only capable of producing *proof-found* or *no-proof-found* answers). And additionally extensionality reasoning is beyond the scope of such a transformational approach.

In addition to their application as semantic mediators within MASs the HOL proof agents to be developed shall also be employed as semantic search engines for mathematicians and they shall be integrated with e-learning systems, such as the Saarbrücken ActiveMath system. An application for the semantic mediation of mathematical knowledge for the DIALOG project (tutorial natural language dialog with a MAS) is sketched in [C14-03].

WP V (Dissemination) Introductory Literature and Sociological Goals There is currently only very little and highly restricted introductory literature on HOL TP. We want to address this problem by the preparation of ideally two introductory textbooks: one on semantics and calculi (extending and didactically improving [J06-04, J05-02, R18-03]) and subsequently a second book on the Aλonzo framework, i.e., the modelling of HOL proof agents and their application within MASs and as semantic mediators.

The Aλonzo group shall furthermore support the built-up of an HOL theorem prover competition similar to the CASC competition for first-order systems at CADE conference.

C1.2 Detailed Project Objectives

$\boxed{\textbf{WP I}}$ **Semantics and Mechanis. of HOL**

1. Semantics for HOL

(a) Refinement of Model Classes for HOL The results in [J06-04, T2-99] shall be refined and extended. In addition to extensionality, the parameters that are relevant are the axiom of choice, the description operator, and the axiom of infinity. They are particularly relevant for mathematics and the representation of partial functions but they are not sufficiently investigated yet in our context.

(b) Abstract Consistency for Model Classes For all of the model classes introduced in (Ia) a corresponding abstract consistency principles (i.e., a set of respective abstract consistency conditions) shall be provided. These proof principles are crucial, e.g., for the analysis of calculi for higher order logic as illustrated in [J06-04] for HOL natural deduction calculi. However, the abstract consistency conditions used there include a saturation condition which requires proof methods as strong as those needed for cut-elimination; see [R19-03]. In order to support the analysis of machine-oriented calculi the saturation condition therefore needs to be replaced by respective less strong conditions. This research task will exploit and extend first ideas as already discussed in [R19-03].

(c) Annotations and Partiality This task proposes the development of HOL semantics supporting annotated functional and Boolean terms. Instead of globally requiring (or prohibiting) Boolean or functional extensionality the idea is to allow for respective annotation of individual terms. In the envisioned semantics extensional and non-extensional functions may coexist, which is not possible yet (i.e., one may talk at the same time about proper mathematical functions and computer programs realizing these functions)

A further research aspect adresses partial functions.

2. Calculi, Extensionality, and Equality

(a) Calculi for Model Classes For the model classes introduced in WP I(a) machine-oriented calculi (resolution and matrix) and interaction-oriented calculi (natural deduction and sequent) shall be developed. Completeness shall be analysed with the help of the techniques developed in WP I(b).

(b) Refinement, Extensionality These calculi (especially the machine-oriented) shall be refined and coupled with application-oriented strategies and heuristics. Some work hypotheses for completeness maintaining strategies already exist (see also [T2-99]): the infinitely branching *FlexFlex*-rule is admissible and recursive calls from unification to proof search can be restricted to base types.

(c) Mechanisation of Equality An important issue is the automation of equality and extensionality reasoning in HOL. For this, the paramodulation and difference reduction approaches from [T2-99] and [Bro03] shall be improved and the development of strategies for intelligent definition expansion and contraction shall be fostered. For instance, the dual instantiation approach of Matt Bishop [BA98] has not yet been adapted to the extensional reasoning case.

(d) Non-normal Form Calculi The current trend in machine-oriented TP towards non-normal form calculi[30] is especially interesting for the automation of HOL reasoning. In fact, in my extensional resolution approach [T2-99, J05-02] unification and proof-search are integrated at one conceptual layer and they allow for mutual recursive calls. Thus, extensional HOL unification may employ proof search for comparing formulas which is an important ingredient for non-normal form reasoning and which is not supported in first-order unification. Note that unification of formulas, subsuming the question whether two formulas are equivalent, is particularly important for semantic mediation of knowledge as proposed in WP IV.

(e) Parameterised Calculi (Extensionality Annotations) Provided that appropriate model classes for annotated logics in WP I(c) can be developed, calculi for respective annotated HOL reasoning shall be developed. The idea is that the denotations of two functional terms, which are not $\alpha\beta$-equal, can only be identified if they are pointwise equal *and* if the functional terms are marked as functionally extensional. In such a framework it will be possible to talk simultaneously about *mathematical functions* (where only the input-output characteristics matters) and *functional programmes* (where efficiency of the programmes additionally matters).

[30] An example for this trend is the approach *Superposition with Equivalence Reasoning and Delayed Clause Normal Form Transformation* [GS03]. I have illustrated in a recent presentation at the annual German meeting of the deduction systems community (see slides at `www.ags.uni-sb.de/~chris/papers/2003-deduktionstreffen-talk.pdf`) that the new rules and ideas applied in this approach are actually closely related to rules already provided my thesis work [T2-99] and as presented at CADE 1999 [C05-99].

A further challenge is to support reasoning with partial functions.

3. Set Variables

(a) Set Variables and Induction Recent work of Chad Brown [Bro02, Bro03] introduces and analyses a goal-oriented approach for the instantiation of set variables in HOL. So far the problem which is also known as the *primitive substitution problem* is unsolved and is considered as a main challenge for automating HOL reasoning. Until now only blind guessing strategies (*choose-and-check*) have been applied in HOL TPs; see, e.g., [ABI$^+$96]. This a priori guessing strategies are related to what is known as *explicit induction* in induction theorem proving: the a priori determination or guessing of an appropriate induction scheme can in fact be seen as a special case of the *primitive substitution problem* in HOL, where higher-order set variables in the induction axiom have to be appropriately instantiated.

A posteriori methods employing the idea of delaying the instantiation of set variables and accumulating first respective constraints during proof search, as they are now proposed by Brown, similarly generalise the principle of *implicit induction* [Wir03].

We propose to further investigate this connection and to ideally stimulate a mutual fertilisation of strategies between induction theorem proving and the set variable instantiation problem in HOL. Thereby, we particularly want to benefit from the expertise of Alan Bundy's group on induction theorem proving.

(b) Domain Specific Heuristics Analogous to the progress achieved in induction theorem proving we propose to develop application-, domain-, and context-dependent strategies and heuristics for the set variable instantiation challenge. Thereby a special focus will be on the applications proposed in WP III and WP IV.

(c) Example: Gröbner Bases Theory The working hypotheses of Bruno Buchberger at RISC Linz is that only a few creative mathematical principles exists that have to be fruitfully combined depending on the nature of the mathematical problem under consideration. As developer of the theory of Gröbner bases [Buc85, Buc92], which is the underlying theory of today's computer algebra systems, Bruno Buchberger has gained broad experience in the modelling of mathematical theories. It is not difficult to see that the creative and challenging aspects of such theory modelling tasks correspond to the set variable instantiation problem in HOL. The challenging question thus is whether the assumed few creative mathematical principles can be identified (in cooperation with Buchberger) at least for the particular domain of Gröbner base theory and whether they can then be appropriately formalised and mechanised as special set variable instantiation strategies in our HOL TPs.

$\boxed{\text{WP II}}$ TPs for HOL

1. TPs for HOL The machine-oriented calculi, strategies, and heuristics developed in WP I shall be implemented and applied within the systems LEO (resolution TP) and TPS (matrix TP). Within case studies the strengths and weaknesses of both approaches shall be first analysed and then compared with the situation in first-order TP. There resolution- resp. superposition-based approaches are currently dominating.

2. Adaption of Techniques from FOL ATP Successful, efficiency increasing techniques developed for first-order TPs — term-indexing [RSV98], strong literal selection functions as employed in the superposition approach, etc. — shall, if possible, be adapted for the higher-order approaches and systems developed in Aλonzo.

However, this will cause non-trivial challenges: for instance, higher-order term-indexing modulo extensional equality generally requires full higher-order TP within indexing and is therefore hardly feasible. Similarly, the adaptation of literal selection functions for higher-order logic causes a challenge since well-ordering criterions such as $\forall x.F > \{x \leftarrow T\}F$ for all terms T of the considered logic (instances of quantified formulas F are always smaller w.r.t. the considered order relation than F itself) are problematic in HOL: e.g., the HOL formula $\forall x_o. x_o$ has as instance the formula $\{x_o \leftarrow \forall x_o. x_o\}x_o$ which reduces to $\forall x_o. x_o$ again.

Approaches to higher-order term-indexing for the non-extensional case have recently been investigated in the PhD project of Brigitte Pientka at Carnegie Mellon University [Pie03]. We propose to investigate if these results can be adapted to the extensional case.

3. Proof Transformation In order to enable white-box integrations of the HOL TPs developed in Aλonzo in MASs it is important to support proof transformations between the machine-oriented, resolution- and matrix-based proof representation formats and the user-oriented proof representation formats usually employed within MASs (e.g. natural deduction and sequent calculi or, as available in OMEGA, the less granular layer of assertion level proofs [Hua94] and natural language proofs [Fie01a]).

The motivation thereby is: (a) a base system such as the MAS OMEGA may require the translation of proofs constructed in external reasoners into its own proof representation format in order to be able to verify them, and (b) proof explanation systems such as P.rex [Fie01b], which are capable of natural language proof presentations and restricted dialogs, usually prerequire the transformation of machine-oriented proof formats into human-oriented proof representations.

Aλonzo shall therefore investigate whether proof transformation mechanisms as already employed in TPS (non-extensional matrix proofs into natural deduction) and the first-order proof translator TRAMP [Mei00] can be fruitfully adapted to the calculi developed in Aλonzo. Alternatively an adaption of the tactic-based proof transformation approach as described in [J01-99, W02-98] may be chosen.

WP III Agent or Web Service based Integration and Coordination

1. Agent or Web Service based Modelling The systems LEO and TPS shall be modelled as pro-active agents and exemplarily employed as proof agents working for the MASs OMEGA and λ *Clam*. Within these systems they shall be able to autonomously detect subgoals which potentially lie in their scope in order to attack them in the background. As integration infrastructure the systems ΩANTS and/or MathWeb shall be appropriately adapted and employed.

2. Coordination Cooperation between Aλonzo's HOL TPs and first-order TPs or computer algebra systems shall be investigated (e.g. in cooperation with the CALCULEMUS project). For the automated coordination of such cooperation three different guidance approaches are possible: (a) centralised guidance within a MAS, (b) decentralised guidance within a network of cooperating agents, and (c) direct guidance of cooperations within the the HOL TPs itself.

Experience for option (a) exists in the OMEGA project in terms of the ΩANTS approach [C10-01] and proof planning [B01-03, MPS02, CMPS03] which both have been employed to coordinate cooperation of external specialist reasoning systems.

For option (b) the MathWeb system may be employed which is currently extended in the PhD project of Jürgen Zimmer in order to support intelligent brokering and coordination of reasoning systems; see [Zim03] and [Zim04].

Distributed architectures for (c) have been proposed in first-order TP and they have been employed, for instance, in resolution-based systems. A respective taxonomy and an overview on the literature is given in [Bon00]. For HOL a stronger impact of such approaches seems plausible because HOL reasoning has many characteristics, such as alternative solutions in higher-order unification or alternatives for set variable instantiation, which naturally call for the application of distributed reasoning techniques.

3. White-Box Integration A proof transformation mechanism as investigated in WP II(3) shall be implemented and tested within case studies. λ *Clam* is recently extended such that it will support proof objects, which is crucial for a white-box integration of the HOL proof agents. With respect to white-box integration we will therefore first concentrate on OMEGA, which provides already good support for white-box integrations. Since the transformation of a found proof into another format may eventually require more computation time than proof search itself, it is an important issue to decouple both processes in our framework. Proof transformation shall thus be offered only upon request and subsequent to actual proof search.

4. User Interaction The users of MASs shall be fruitfully supported by the HOL proof agents within interactive proof construction. For this the HOL proof agents shall "silently" exploit available computation resources in the background in order to select and tackle subproblems in the interactive proof development. Successful proof attempts shall be signalled and communicated to the user in a human-oriented way. For this the proof transformation tool developed in (3) shall be coupled with the P.rex system in order to support natural language based proof representation and explanation.

WP IV Semantic Mediators for MKBs

1. Problem Analysis We propose the application of appropriately limited HOL reasoning for domain- and context-specific retrieval of mathematical knowledge from MKBs. For this we propose an adaption of the two stage approach as discussed in [C13-03], which combines syntactically oriented pre-filters with semantic analysis. The pre-filters may employ efficiently analysable criterions based on meta-data and ontologies in order to identify, e.g., sets of candidate theorems in the MKBs that are eventually applicable to a focused proof context within a MAS. Then the HOL agents may be employed as post-filters (eventually concurrently to other systems such as first-order TPs) to exactly determine the applicable theorems of this set. Thereby additional information justifying the applicability of each determined theorem might be generated and provided. Exact semantic retrieval generally includes the following aspects: (i) Eventually logical transformations are required in order to see the connection between a theorem in a MKB and a focused subgoal in a MAS; consider, e.g., a theorem of form $A \Leftrightarrow B$ and a subgoal of form $A \Rightarrow B \wedge (\neg A \Rightarrow \neg B)$. (ii) The variables of a theorem in a MKB may have to be instantiated with terms occurring in a focused subgoal; consider, e.g., a theorem $\forall X . is{-}square(X \times X)$ and a subgoal $is{-}square(2 \times 2)$. (iii) Free variables (meta-variables) may occur in a focused subgoal of a MAS and they may have to be instantiated with terms occurring in a theorem in a MKB; consider, e.g., a subgoal $irrational(X)$ with metavariable X and a theorem $irrational(\sqrt{2})$. A particular challenge is that these three aspects may generally occur in combination and have to be addressed in combination.

Furthermore, focused subproblems within MASs usually have theory contexts. Thus, if the compatibility of a subproblem's context with a theorem's context cannot be established by simple and efficient means, additional theorem proving tasks may arise. This problem shall be further analysed and respective ways to combine it with the above challenges shall be explored.

2. Distributed, Resource-adaptive Architecture Based on the above problem analysis and the ideas in [C13-03] an architecture for semantic mediators employing HOL reasoning agents shall be developed. This architecture shall ideally exploit the syntactical and restricted semantical filter mechanism already provided by the emerging MKBs.

The emerging MKBs today already contain thousands of theorems and an enourmous increase can be predicted for the future. Even very strong syntactical pre-filters will therefore eventually still generate large sets of candidate theorems to be semantically processed by the proof agents. Thereby for each candidate theorem a generally non-decidable proof problem has to be analysed. This motivates mechanisms supporting resource-adaptive, distributed search with anytime character as proposed and partly realised in ΩANTS [C10-01, C08-00].

3. Search Engine for Mathematics In (2) we have discussed semantic mediation solely from the perspective of its exploitation within MASs. However, semantic mediation of mathematical knowledge may similarly directly support the mathematician as an improved search engine for mathematical theorems.

The project shall therefore investigate whether the approach can be succesfully coupled with state-of-the-art search engines such as Google (eventually such an integrated approach is also adequate and applicable for (2)).

In this application the issue of analysing the compatibility between the theorem's theory contexts and the usually not explicitly given context assumed by the requesting mathematician raises a particular challenge.

$\boxed{\text{WP V}}$ Introductory Literatur and Sociological Goals

1. Introductory Textbook Ideally two introductory textbooks shall be produced in Aλonzo. The first book shall discuss semantic notions for HOL and machine-oriented calculi; this topic is not sufficiently covered in the literature so far. A second book is planned on the Aλonzo system.

2. Tutorials and Workshops Tutorials and courses on the subject shall be offered at summer schools (e.g. in CALCULEMUS), conferences, and locally at The University of Edinburgh.

3. Prover competition The presence of approaches for limited HOL automation at international conferences shall be fostered by the Aλonzo group's cooperation in the built-up of a HOL theorem proving competition similar to the CASC competition for first-order systems at CADE conference. This pre-requires the set-up of respective repositories of HOL proof tasks; a first meeting to foster this has taken place between Geoff Sutcliff, Peter Andrews, Michael Kohlhase, and myself during CADE 2003. It will be particularly important to connect the current first-order problem formalisations employed in CASC with respective higher-order formalisations in this new library to enable comparisons of the strengths and weaknesses of first-order and higher-order TPs in different mathematical domains.

C.2 Proposed Methodology

Aλonzo combines different research strains of the applicant in a single, coherent research project and integrates further expertise provided by Chad Brown and Jürgen Zimmer. The project will exploit the expertise provided by the School of Informatics at the University of Edinburgh and very closely cooperate with MKM and CALCULEMUS-I/II (as coordinator) research networks. Some members of MKM and CALCULEMUS will be direct collaborators:[31]

The University of Edinburgh (UK): Alan Bundy's Mathematical Reasoning group, WP I: Set Variables and Induction, WP III: Proof agents for λ *Clam*; Dave Robertson's Software Systems and Processes group, WPs III and IV: Software development and agent-based or web-service-based architectures

Int. University of Bremen (D): Michael Kohlhase, MBASE MKB, WP I: HOL semantics and mechanisation, WP IV: Semantic search in MKBs

Saarland University (D): OMEGA group of Jörg Siekmann, WP III: Integration and coordination of proof agents in MASs

RISC Linz (A): Bruno Buchberger, WP I: HOL reasoning in theory of Gröbner-bases

The University of Birmingham (UK): Manfred Kerber and Volker Sorge, WP III: Agent-based reasoning systems

In WPs I and II the research will built upon existing appraoches and systems and systematically adapt them for the applications proposed in WPs III and IV. In WP III coordination techniques, such as proof-planning [CMPS03, MPS02], agent-oriented reasoning [C10-01], and Jürgen Zimmer's MathWeb approach [Zim04] will be extended, and the MASs OMEGA and λ *Clam* will be considered as base environments these HOL proof agents are working for. Ideally, the HOL proof agents will subsequently be made available to other MASs as well. Candidates are Isabelle/HOL or PVS, i.e., systems with particular strengths in formal methods applications.

In WP IV a close collaboration with the MBASE project at International University of Bremen is planned. The syntactical filters developed in this project will be first coupled with the semantic filtering mechanism provided in the Aλonzo project. Experiments are planned to investigate the strengths and weaknesses of the approach for both, searching for applicable mathematical knowledge for subproblems occurring in MAs and for mathematical knowledge requested by humans in mathematical search engines. The approach shall be adaptable to further MKBs.

Feasibility of the project requires 2 full time researchers (myself and Chad Brown), 2 studentships (one of which is Jürgen Zimmer), a part-time working software engineer (20%) for the implementational work in WP IV and support by clerical staff for the preparation of the textbooks in WP V.

C.3 Timeliness and Novelty

The 2503rd Council Meeting *Education, Youth and Culture* in Brussels, 5 and 6 May 2003, 8430/03 (Presse 114) states that: "In the area of mathematics, science and technology the European Union needs an adequate output of scientific specialists in order to become the most dynamic and competitive knowledge-based economy in the world. The need for more scientific specialists is underlined by the conclusion of the Barcelona European Council (2002) that overall spending on R&D and innovation in the union should be increased with the aim of approaching 3% of GDP by 2010".

In addition to the scientific arguments already provided in Section B.5, the Aλonzo project directly addresses this recent objective of the European Union: Aλonzo proposes to develop interoperable knowledge-based reasoning techniques with applications in mathematics, engineering and e-learning, and it will contribute to the emerging Mathematical Semantic Web.

Aλonzo furthermore contributes directly and indirectly (via its involvement in the European research networks CALCULEMUS and MKM) to the education of students in exactly the connection between mathematics, computer science and knowledge-based technologies as envisioned by the European Commission.

Not only due to MKM and CALCULEMUS the development and merge of today's MKBs has recently strongly gained on pace. However, it is still a long way to go until major parts of today's mathematical knowledge inheritage (still maintained in ancient paper form in worldwide distributed libraries) become fully

[31] Letters of support have been sent by all collaborators directly to EPSRC.

accessible in the new computer-based MKBs. With more and more mathematical knowledge being formalised and distributed over the Internet, mediation of MK will become a central issue[32]. Aλonzo proposes to join the historic transition from pen and paper mathematics to modern, computer-supported mathematical knowledge management from its very beginning. Ideally the Aλonzo mediators fruitfully cooperate with state-of-the-art search engines such as Google and other emerging mediation approaches exploiting meta-data and taxonomies.

Unfortunately, the direct automation of HOL reasoning has widely been neglected in the last decades due to its assumed complexity and the confusion resulting from Gödels incompleteness results. Therefore, the deduction systems community today mainly concentrates on automation of first-order reasoning and thereby neglects the fact that first-order reasoning within, e.g., Zermelo-Fränkel set theory (as an alternative representation language for mathematics) can be considered as equally challenging and unsolved. Due to the current renaissance of HOL in many research areas it is *now* the time to further strengthen research on limited, application-oriented HOL reasoning and to adapt, if possible, successful techniques from first-order TP to higher-order TP. First-order TP has highly benefitted from its comparably high research funding in the last decades and it has developed very efficient techniques that are not yet available in HOL TP.

Research on interoperability and coordination of reasoning tools as proposed in Aλonzo is a core issue for the recent built-up of a new generation of MASs that provide integrated computer-support for most work tasks of mathematicians and engineers: rather than competing against first-order TPs our HOL proof agents shall cooperate with them within MASs.

C.4 Management of the Project

My broad project management experience has been sketched in Section B.3. For instance, I am currently heading the OMEGA group and its satellite project with approx. 10 researchers and further 15 students. The proposed Aλonzo project has smaller size and, compared with the OMEGA project, has also a more narrow research scope. It will allow me to create my own and independent research environment and to better focus on my main expertise and interest.

The work plan of Aλonzo is ambitious. This holds in particular for the basic research results aimed at in WP I. Here scientific progress is hard to precisely predict.

The progress in WPs II, III, IV, and V is more predictable and easier to monitor. WPs III and IV will employ the systems LEO and/or TPS. Independent from these systems stepwise improvement in WP II they are already in their current form applicable within WPs III and IV. Improvement in WPs I and II will thus lead to regular replacements of the system instances employed in WPs III and IV.

WPs I, II and IV will be carried out by myself and Chad Brown, WP III by myself and Jürgen Zimmer. In WP IV the whole group will be involved supported by the proposed (20% part-time) software engineer. A further student will be hired, presumably for WP IV, after one or two years.

The Aλonzo project will cooperate with project partners as mentioned in Section C.2, e.g. to join resources and to support interoperability of tools.

Collaborations are planned as already outlined in Section C.2. All collaborations will be supported by frequent research visits at partner sites. Letters of support have been sent by all collaborators directly to EPSRC.

The Aλonzo research programme will be coordinated with and adapted to the progress made in CALCULEMUS and MKM. It is furthermore planned to employ the CALCULEMUS infrastructure to train the Aλonzo students for some months at CALCULEMUS partner sides. The students are expected to actively participate once a year at a major conference in the field or to attend a summer school.

The management of the project (travel, conferences, workshop organisation) will be supported by clerical staff (10 % of working time).

Joint system developement and information exchange will be based on an information infrastructure similar to the one I have built-up for coordinating the CALCULEMUS network; see [R22-03]. A major means will be a CVS repository maintaining all project data and supporting joint system developement and publication.

C.5 International Context

On the international level the project is directly collaborating with Saarland University and the German Research Centre for AI (Saarbrücken, Germany), RISC Linz (Austria),

[32] See `www.ima.umn.edu/complex/spring/searching.html`: This workshop proposal particularly illustrates the interest in improving search in MKBs by using meta-data, taxonomies, etc.

and the International University of Bremen (Bremen, Germany). The project will furthermore benefit from my (e.g., as coordinator of CALCULEMUS-I and -II with 9 resp. 13 European project partners) and the OMEGA group's already existing international scientific links.

On the national level it will directly collaborate with the University of Birmingham and, of course, with researchers at The University of Edinburgh such as Alan Bundy's group and Dave Robertson's group. A potential further collaborator at Heriot Watt University is Fairouz Kamareddine (as a driving force of MKM).

Project Aλonzo will closely collaborate with CALCULEMUS and MKM. It will furthermore maintain close contacts to North American partners such as MKM North America[33] and the LOGOSPHERE project[34].

C.6 Expected Results

HOL is employed in the following areas:

- Functional Programming (e.g. ML[35], Haskell[36], OCAML[37]; see also [Pre98])
- Computational Linguistics (see e.g. [Koh98])
- Automated and Interactive Theorem Proving (see references in this proposal)
- Formal methods, verification (see references in this proposal)
- Database theory
- Component-based software development[38]

The theoretical contributions envisioned in WP I are relevant for all of these areas; see also the introduction of [J06-04].

In contrast to first-order TP, current research on the automation of HOL is very sparse. Therefore, and because of increasing requests for HOL automation, the work in WP II aims at an adaption of successful first-order TP techniques developed in the last decade and at their combination with the theoretical results in WP I in order to strongly improve direct automation of HOL with respect to special application directions as proposed in WPs III and IV

WP III will make the TPs LEO and TPS available as HOL reasoning tools in the emerging Mathematical Semantic Web and develop means for the coordination of cooperations of specialist reasoning systems within MASs. While many first-order and propositional reasoning tools are accessible in this sense, not least due to CALCULEMUS research, this does not hold yet for HOL TPs.

WP IV applies HOL reasoning for full semantic filtering of mathematical knowledge in the emerging distributed, huge MKBs. This application is at the heart of the research directions proposed in MKM and CALCULEMUS-II. Full semantic mediation of mathematical knowledge will play an important role in the future MASs envisioned by CALCULEMUS-II.

Dissemination of results on HOL semantics and automation is very important to foster the visibility and acceptance of the field. Very few good textbooks are currently available, especially for HOL calculi. Unfortunately, the deduction systems area has had a strong focus on automation of first-order logic and its decidable sub-fragments.

C.7 Scientific Impact and Potential for Promoting Innovation

Aλonzo research is at the core of the research tasks proposed in the CALCULEMUS and MKM initiatives. The research and computer systems developed in CALCULEMUS and MKM will have an impact on society, anticipatedly first on the computer-based mathematics education sector and subsequently (with a new generation of mathematicians trained on these systems) also on mathematical research practice and on practical application of formal methods in computer science. This last area, in particular, is an area of severe shortage of trained personal and there are several “head hunting”-companies, which cannot fulfil the current demand in industry. Computer supported mathematical reasoning tools and integrated assistance systems will have an impact in other fields such as bio-informatics, theoretical physics and chemistry. They are particularly relevant for the fast growing e-learning sector. The new generation of interoperable mathematical assistance environments and mathematical software tools particularly contrasts the current situation characterised by partial and often non-interoperable solutions. Except for computer algebra systems these partial solutions have not yet reached sufficient acceptance and usage in mathematical practice.

[33] `imps.mcmaster.ca/na-mkm-2004/`
[34] `www.logosphere.org`
[35] `www.smlnj.org`
[36] `www.haskell.org`
[37] `caml.inria.fr`
[38] `clip.dia.fi.upm.es/COLOGNET-WS/`; area: Component-based Software Engineering.

Publications (Others)

Due to space restriction we do not list the applicants own publications here. They can be found starting from page 8 in the applicants CV.

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C.8 Work Plan and Milestones

The work packages are listed below and the five year work plan is given in Figure 1.

WP I: Semantics and Mechanis. of HOL

1. Semantics for HOL
   (a) Refinement of Model Classes for HOL
   (b) Abstract Consistency for Model Classes
   (c) Annotations and Partiality
2. Calculi, Extensionality, and Equality
   (a) Calculi for Model Classes
   (b) Refinement, Extensionality
   (c) Mechanisation of Equality
   (d) Non-normal Form Calculi
   (e) Parameterised Calculi
3. Set Variables
   (a) Set Variables and Induction
   (b) Domain Specific Heuristics
   (c) Example: Gröbner Bases Theory

WP II: TPs for HOL

1. TPs for HOL
2. Adaption of Techniques from FOL ATP
3. Proof Transformation

WP III: Agent or Web Service based Integration and Coordination

1. Agent or Web Service based Modelling
2. Coordination
3. White-Box Integration
4. User Interaction

WP IV: Semantic Mediators for MKBs

1. Problem Analysis
2. Distributed, Resource-adaptive Architecture
3. Search Engine for Mathematics

WP V: Introductory Literatur and Sociological Goals

1. Introductory Textbook
2. Tutorials and Workshops
3. Prover competition

Milestones

(12 months)
All WP's: short progress overview, **WP V:** tutorial on semantics and mechanisation held at conference or summer school, course notes

(24 months)
WP I: report on refined model classes, adaptations of the abstract consistency principle, improved calculi and strategies, connection between set variables instantiation and induction, **WP II:** experiments withs improved calculi and strategies, **WP III:** report on agent-based or web-service based modelling of HOL TPs, **WP IV:** report on problem analysis, requirement specification

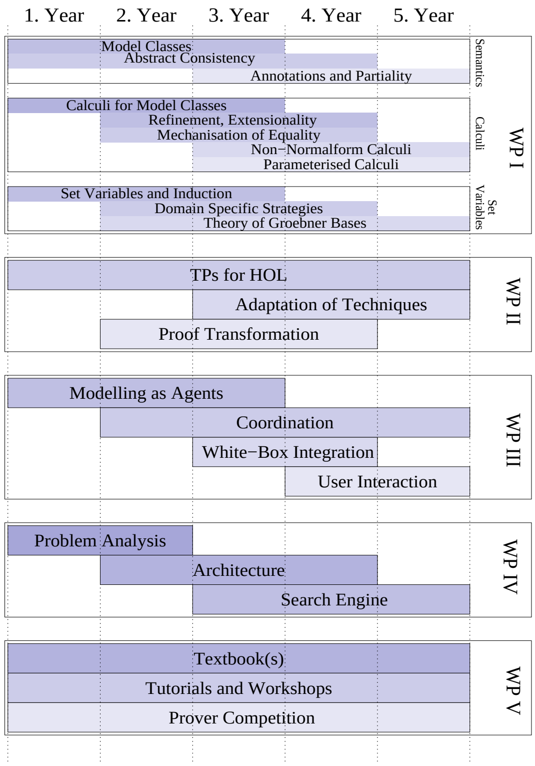

Figure 1: Work Plan.

(36 months)
WP I and WP V: first draft of textbook including main results of WP I, **WP II:** improved calculi and strategies implemented in Aλonzo TPs, **WP III:** demo of experiments with proof agents, **WP IV:** report/demo on experiments with first mediator prototype, **WP V:** HOL theorem prover competition entered, workshop on automation of HOL organised

(48 months)
WP I and V: improved draft for textbook on semantics and calculi, **WP II:** report on HOL proof transformation and adaptation of first-order techniques, **WP III:** white-box integration to OMEGA solved for both Aλonzo TPs, **WP IV:** report/demo on further experiments, **WP V:** further tutorial or workshop organised

(60 months)
WP I and V: textbook on semantics and calculi, draft for second textbook on Aλonzo framework including main results in WPs II, III and WP IV, **WP II:** comparison of Aλonzo HOL TPs and comparison with first-order TPs in selected domains, **WP III:** white-box integration in OMEGA fully realised, usability report, **WP IV:** report/demo on HOL mediator, comparison with other approaches

Part D

Financial Plan and Justification of Resources Requested

Staff

A Grantholder (C. Benzm., AR3, 60m-100%)	237,036[39]
B Postdoc (C. Brown, AR2, 60m-100%)	173,102
C Studentship I (J. Zimmer, 36m-100%)	31,500
D Studentship II (TBA 36m-100%)	31,500
E Clerical (TBA, 60m-10%)	9,060
F Clerical (TBA, 24m-20%)	6,049
G Software Engineer (TBA, 60-20%)	46,142

A and B will be employed full time for 5 years. C and D will contribute full time in years 1-3 and 3-5. E will organise a considerable amount of travel in view of the collaborative nature of the project and furthermore support the overall project management. F will assist in the preparation of the two books planned in WP V by typing the main parts of them. G will assist the implementation and testing of the semantical mediators in all hardware related questions. In WP IV we want to experiment with distributed search and resource guideance which requires a considerable amount of expert knowldege on distributed hardware architectures. G will furthermore locally install and maintain the mathematical knowledge bases as required for WP V.

The salary requests for A and B are justified as follows: A is currently working at Assistant Professor level in Germany at C1 level (promotion to C2 level is ongoing). His current yearly income (at C1 level) correspods to a total of approx. 68.000 Euro. An offer at DFKI, Germany exists for appox. 75.000 Euro yearly.

B has an offer from Jörg Siekmann to join the Saarbrücken OMEGA group after completeing his PhD at the Bat IIa level; this is approx. a yearly income of 57.000 Euro.

Travel and Subsistence

Relocation Relocation costs appear not to be eligible?

Research Visits The project collaborations foresee regular research visits at project partners.[40] We propose that each partner is visited three times by one member of the Aλonzo team. This includes training measures at these partner sites for the young students. We calculate with an average of two weeks for each research visit. In addtion to the University of Edinburgh the project partners are: (i) Saarland University/DFKI, (ii) International University of Bremen, (iii) RISC Linz, (iv) University of Birmingham. Each partner is visited for 3 times during the project. The proposed duration of these stays is 2 weeks. For Birmingham we calulate with 300 for the flight and 1,000 for hotel and subsistence. For the other partners the respective figures are 300 and 1,200.

Saarland University	4,500
International University of Bremen	4,500
RISC Linz	4,500
University of Birmingham	3,900

Conferences One project goal is to improve the dissemination of results in the field. Relevant international conferences and workshops are: CADE, TPHOLS, IJCAR, IJCAI, ECCAI, CALCULEMUS, MKM, etc. Experience shows that two conference or workshop contributions by the persons A and B per year are realistic. Persons C and D are expected to visit either one conference or one summer school (e.g. Types or Calculemus School per year). For simplicity the rates have been calculated assuming European destinations; each with 300 for the flight, 500 for the conference fee, and 500 for living expenses.

A (5 x 2 Conf.)	13,000
B (5 x 2 Conf.)	13,000
C (5 Conf.)	6,500
D (5 Conf.)	6,500

Visiting Researchers We plan to invite each year two researchers or project partners to visit our group in Edinburgh. The assumed duration of each visit is 1 week and we calculate with 300 for the flight and 500 for the hotel.

Material Costs

As material costs for the planned book productions we allocate 2,000

Minor Equipment

For persons A,B,C,D we propose as computing working environment: notebook + docking station + monitor (Dell Latitude Laptop). Not only for the experiments in WP4 the group needs a file server (Dell Power Edge) with two processors (distributed search).

4 x Dell Latitude Laptop	15,216
2 x Dell Power Edge	3,762

Exceptional Items

Studentships The project will cover the tuition fees for persons C and D 2 x 8,610

[39] All prices are given in Pounds if not stated otherwise.

[40] Letters of support have been sent by all collaborators directly to EPSRC.

Part E

Host Institution

The University of Edinburgh and the School of Informatics

The University of Edinburgh (UEDIN) is a leading international centre of academic excellence, and one of the largest and most successful research universities in the UK. The research covers a wide range of subjects in both traditional basic and applied research areas and in novel interdisciplinary topics. UEDIN has research groups of international standing in the physical sciences, biological and biotechnological sciences, engineering, informatics, earth and environmental sciences and mathematics, and an increasing focus on interdisciplinary research strengths. On top of the excellent academic research credentials, UEDIN has a strong record of technology transfer and commercialisation of research. UEDIN is an internationally leading centre for Informatics and it has been rated excellent in both teaching (Excellent SHEFC Teaching Quality Assessment for Computer Studies) and research (5*A 2001 RAE).

The Aλonzo project will contribute to and benefit from UEDIN's expertise represented by the following research centres:

Centre for Intelligent Systems and their Applications (CISA) Basic and applied research and development in knowledge representation and reasoning. Through its applications institute (AIAI) it works with others to deploy the technologies associated with this research.

Laboratory for Foundations of Computer Science Developing and applying foundational understanding of computation and communication: formal models, mathematical theories, and software tools.

Institute for Communicating and Collaborative Systems Basic and applied study of communication among humans and between humans and machines using text, speech, and graphics for interactive dialog.

A close cooperation is planned with Alan Bundy's **Mathematical Reasoning** group and with Dave Robertson **Software Systems and Processes** group within CISA.

Mathematical Reasoning Group Alan Bundy's Mathematical Reasoning Group forms part of CISA. The main research contribution of the group has been in the field of automated reasoning, contributing to understanding of the structure of proof in applicable domains such as software and hardware verification.

The group is a member of the Calculemus network and has been involved in a number of projects, lending its expertise particularly in the areas of proof-planning and automated theory formation. Young visiting researchers, such as Jürgen Zimmer, from other nodes in the Calculemus network have collaborated with the Mathematical Reasoning Group by combining the systems developed at Edinburgh with those from their node.

The λ *Clam* higher-order proof-planner, developed at Edinburgh, is a tool for automating mathematical proof by abstracting the proof-steps at the object level and working at a meta-level. In particular, annotated reasoning is used to help reason about the progress of a proof. This annotated reasoning is referred to commonly as *rippling*. The mathematical reasoning group has applied rippling and proof-planning to a number of different domains, including induction, ordinal arithmetic and non-standard analysis. λ *Clam* has both enhanced and been enhanced by other systems such as the MathWeb software bus.

HOL reasoning is represented in the group by Jacques Fleuriot and Paul Jackson.

Jacques Fleuriot research interests include geometry theorem proving, formalised mathematics, logical frameworks, and proof planning. His recent work has been on the mechanisation of non-standard analysis and in developing new techniques for geometry theorem proving. He is supervising a PhD project that is adapting proof planning to the Isabelle system.

Paul Jackson is an expert of the NuPrl MAS and his extensive enhancements to Nuprl now support all ongoing work with it. More recently, he has explored verifying garbage collection algorithms in the PVS theorem prover using temporal logic and refinement frameworks.

The Edinburgh node of the Calculemus network has worked with the University of Saarland in connecting both HR (an Automated Theory Formation tool) and λ *Clam* to the MathWeb Software Bus.

Software Systems and Processes Group Dave Robertson is director of CISA and his group is studying how people build software and using this understanding to improve software development in future. The groups research is not limited to a particular stage of development. On the contrary, they are most interested in how the various stages (from requirements specification to executable software) fit together, because it is in the transitions between them that breakdowns in engineering practice often occur. While there are no complete answers, progress is possible.

Appendix 1

CV of Applicant

Curriculum Vitae

Dr. Christoph Ewald Benzmüller

Born at September 8th, 1968 in Saarburg, Rhineland-Palatine, Germany

Male

German

Address

Landwehrplatz 6-7
66111 Saarbrücken
Germany

Homepage: `www.ags.uni-sb.de/~chris`

Email: `chris@ags.uni-sb.de`

Education

• 1999: Ph.D. (Promotion) in Computer Science, Saarland University, Saarbrücken, Germany
• 1995: M.Sc. (Diplom) in Computer Science, Saarland University, Saarbrücken, Germany
• 1992: Bachelor (Vordiplom) in Computer Science, Saarland University, Saarbrücken, Germany
• 1988: A-Level (Abitur) at Auguste Victoria Gymnasium, Trier, Germany

Career and Employment

• currently: Hochschulassistent (Assistant Professor) at Department of Computer Science, Saarland University, Saarbrücken, Germany; research visits during this period include:
- 2002: Carnegie Mellon University, Pittsburgh, USA (1 month)
- 2002: University of Pisa, Italy (2 months)
- 2001: Carnegie Mellon University, Pittsburgh, USA (1 month)
- 2001: Cornell University, Ithaca, USA (1 month)
- 2001: University of Birmingham, England (2 months)
• 2000: Research Fellow, Department of Artificial Intelligence, University of Edinburgh, Scotland (3 months)
• 2000: Research Fellow, Department of Computer Science, University of Birmingham, England (9 months)
• 1999: Visiting Researcher, Department of Computer Science, University of Birmingham, England (3 months)
• 1999: Postdoctoral Research Fellow, Graduate College for Cognitive Science, Saarland University, Saarbrücken, Germany
• 1997/1998: Researcher, Department of Computer Science, Saarland University, Saarbrücken, Germany
• 1997: Research stay at Carnegie Mellon University, Pittsburgh, USA (8 months)
• 1995/1996: Researcher, Department of Computer Science, Saarland University, Saarbrücken, Germany
• 1992-1995: Student researcher (Hiwi), Department of Computer Science, Saarland University, Saarbrücken, Germany

Specialization

Artificial Intelligence, Logic (especially Higher-Order Logic), Deduction Systems, Agent-oriented Theorem Proving, Integration of Reasoning Systems, Software Engineering, Mathematical Knowledge Management, Applications in Mathematics and Formal Methods

Awards

• Grantholder in the Collaborative Research Centre (SFB 378) *Resource-adaptive Cognitive Processes*, Project MI 4 OMEGA: *Resource-Adaptive Proof Planning.* (2001-2004)
• Grantholder in the Collaborative Research Centre (SFB 378) *Resource-adaptive Cognitive Processes*, Project MI 3 DIALOG: *Tutorial Dialogue with a Mathematics Assistance System.* (2001-2004)
• Postdoctoral Fellowship in the Graduate College for Cognitive Science at the Saarland University, Saarbrücken, Germany. (1999/2000)
• Ph.D. on *Equality and Extensionality in Automated Higher-Order Theorem Proving*, Grade: Excellent
• Ph.D. Scholarship holder of the Studienstiftung des Deutschen Volkes. (1996-1998)

Languages

German (native speaker)
English (fluent); with experience in talks and lectures in English
Latin (GroSSes Latinum)

Hobbies and Other Activities

• 1985 – 1992 Athlete in Middle- and long-distance Running:
- German Champion (Cross Country Team, 1990), 3rd at German Championships (Juniors 5000m, 1989)
- Attendance at Eurocup (Cross Country Team, 1991), best German starter at Military World

Championships (Cross Country, 1989), multiple Champion (> 15x) of the Rhineland or Rhineland-Palatinate in Middle- and Long-distance Running
- Personal Records: 2:25min (1000m), 3:49min (1500m), 14:13min (5000m), 30:04 (10000m)
- Athlete of the Olympic Centre Saarland in Saarbrücken, Germany; preparation for the Olympic Games
• 1989 Freelancer of the daily newspaper Trierischer Volksfreund, Trier

Selected Publications

[B01-03, J07-03, J06-04, J05-02, J01-99, C14-03, C13-03, C08-00, C05-99, C04-98, C03-98, C02-98]; see page 8 ff. of this CV.

Education

Postdoctoral Studies

• 2000: Postdoctoral Fellow of the EPSRC Research Project (Grant GR / M99644 on Agent-oriented Theorem Proving at the University of Edinburgh, Scotland.
• 2000: Postdoctoral Fellow of the EPSRC Research Project (Grant GR / M99644) on Agent-oriented Theorem Proving at the University of Birmingham, England.
• 1999: Postdoctoral Fellow of the Graduate College for Cognitive Science at Saarland University.

PhD Studies

• 1999: Ph.D., Department of Computer Science, Saarland University, Saarbrücken. Thesis: *Equality and Extensionality in Automated Higher-Order Theorem Proving.* Supervisor: Prof. Dr.-Ing. J. Siekmann, Prof. Dr. F. Pfenning (Carnegie Mellon University, USA), and PD Dr. M. Kohlhase. Grade: Sehr Gut (excellent).
• 1995 - 1998: PhD studies at the Department of Computer Science, Saarland University, Saarbrücken.
• 1997: Invited research stay for 8 months at the Department of Mathematical Sciences and the Computer Science Department, Carnegie Mellon University, Pittsburgh, USA.
• PhD Grantholder of the *Studienstiftung des Deutschen Volkes*; participation in several workshops and training camps organized by the Studienstiftung.

Graduate Studies

• April 1995: M.Sc. (Diplom), Department of Computer Science, Saarland University, Saarbrücken; in cooperation with the Fraunhofer Institute for Biomedical Engineering IBMT, St. Ingbert, Germany. Thesis: *Eine Fallstudie zur Spezifikation von Systemanforderungen in der Spezifikationssprache OBSCURE.* Supervisor: Prof. Dr.-Ing. J. Loeckx and Prof. Dr. med. K. Gersonde. Grade: Sehr Gut (excellent).
• 1991 - 1995: Graduate student at the Department of Computer Science, Saarland University Saarbrücken.Major subjects: AI, Logic, Formal Methods, Deduction Systems, Functional and Logic Programming. Minor subjects: Economics, Operations Research.

Undergraduate Studies

• 1989 - 1991: Undergraduate Studies at the Department of Computer Science (Department of Technology), Saarland University, Saarbrücken. Major subject: Computer Science. Minor subject: Economics.

High School Education

• 1988: Abitur at Auguste Victoria Gymnasium, Trier, Germany (second best of the one-year age group).

Areas of Interests

1. Theoretical Computer Science & Foundations

1.1 Formal Logic

• lambda-calculus and simple type theory
• classical and non-classical logics
• maschine-oriented and human-oriented calculi for classical first-order and higher-order logic and their integration
• development of calculi for higher-order logic; in particular resolution, natural deduction, sequent calculi
• equational reasoning and extensionality in higher-order logic
• cut-elimination and proof theory

Publications: J6, J5, C5, C2, W13, T2, R19, R18, R17, R11, R7, R6, R5, R4, R3

1.2 Semantics

• development of a landscape of semantical notions for higher-order logic that are differentiated with respect to the role of extensionality and equality
• definition of abstract consistency properties for the different semantical notions from above (extending Smullyan, Fitting, Andrews)
Publications: J6, R19, R18

1.3 Modeling of Reasoning Agents and Mathematical Service Systems

• agent-based approaches to interactive and automated theorem proving
• frameworks for integration of computation and deduction (Calculemus network)
Publications: J4, C8, C7, C6, C4, W15, W11, W10, W7, W4, R12, R10, R9

2. Practical Computer Science

2.1 Traditional Theorem Proving & Proof Planning

• design and implementation of the higher-order theorem prover LEO
• implementation and automation of human-oriented calculi
• knowledge based proof planning
Publications: B1, C12, C11, C3, C1, W24, W12, W9, R21, R15, R12

2.2 Mathematical Assistant Systems & Mathematical Service Tools

• development of the mathematical assistant system OMEGA
• development of various support tools for OMEGA
Publications: B1, J3, J2, C12, C11, C1, W24, W16, W9, W1, R15

2.3 Learning

• learning proof methods from proof patterns
Publications: J7, C9, W8, W6, R16, R14, R13

2.4 System Integration

• embedding of traditional automated theorem provers in human-oriented interactive mathematical assistant systems
• integration of systems for higher-order logic and first-order logic
• integration of systems for computation and deduction (Calculemus)
• use of agent-based frameworks for integration or embedding of reasoning systems
Publications: J4, J1, C8, C7, W20, W15, W11, W10, W7, W4, W2, R21, R10

2.5 Web-Services & Semantic Web

• modeling and realization of mathematical service tools as services on the web
• semantic web and mathematics; intelligent brokering of mathematical service requests
Publications: W18, W17

2.6 Mathematical Knowledge Management & Information Retrieval

• retrieval (i.e. mediation) of mathematical knowledge available in autonomous knowledge bases for application within mathematical assistant systems
• formalization and encoding of large pieces of mathematics in order to make them available for mathematical service systems
Publications: C14, C13, W19, W14, R20

2.7 Formal Methods

• support of formal methods by mathematical service tools
Publications: W18, W17

2.8 Applications

• case studies in mathematics
• case studies in formal methods
Publications: B1, C12, C10, T1, W18, W17, R15, R2, R1

3. Computational Linguistics

3.1 NL Dialog in Mathematics

• development of a tutorial natural language dialog system for teaching proofs in naive set theory
• empirical studies to find out about the phenomena of natural language dialog in mathematics
Publications: W23, W20, R20

4. Programming Languages

4.1 Functional Programming & Object-oriented Programming

• functional programming in LISP, ML, HASKELL, ALICE
• experience in large system development in CLOS/LISP

4.2 Logic Programming

• logic programming in PROLOG, MOZART and ALICE

4.3 Others

• constraint based programming (e.g. Oz), imperative programming
• html- and xml-based languages

Academic Experience

Project Management

• Coordination of funding proposal for the European Union Research Training Network CALCULEMUS-II Computer-supported Mathematical Knowledge Evolution in the EU 6th Framework.
• Coordination of the European Union Research Training Network CALCULEMUS Systems for integrated Computation and Deduction funded in the EU 5th Framework.
• Project leader of Prof. Siekmann's OMEGA group with approximately 10 researchers at Saarland University.
• Principal Investigator of the project DIALOG: Tutorial Dialog with a Mathematical Assistant System in the Collaborative Research Center Resource-adaptive Cognitive Processes (SFB 378) at Saarland University.
• Principal Investigator of the project OMEGA: Resource-adaptive Proof Planning in the SFB 378 at Saarland University.
• Head of the Saarland node of the evolving European Union research network Mathematical Knowledge Management (MKM).
• Researcher the projects HOTEL: Higher-Order Theorem Proving with Equality and FABEON: Flexible Adaptive Proof Presentation funded by the DFG.
• Assistant (substitute of Prof. Siekmann) for the coordination of the collaborative research center Resource-adaptive Cognitive Processes (SFB 378) at Saarland University.

Editorials

• Editor for Higher-Order Systems in the newly founded QPQ project aiming at a large repository of deductive software components (see www.qpq.org); this repository of refereed software components is currently being set up at SRI International Computer Science Laboratory, USA.
• Editor of several documents related to the EU Calculemus Research Training Network; it is planned to publish an overview of the networks scientific contributions in a book.
• Editor of the proceedings of the Calculemus Autumn School 2002 (3 reports with Course Notes, 1 report with student contributions)

Member in Steering Committees

• IJCAR 2004 (representing the CALCULEMUS community).

Conference and Workshop Chair

• Annual Meeting of the German Interest Group on Deduction Systems in 2004 in Saarbrücken, Germany.
• CALCULEMUS Autumn School 2002 in Pisa, Italy.
• Annual Meeting of the German Interest Group on Deduction Systems in 2000 in Saarbrücken, Germany.

Member in Program Committees

• International Joint Conference on Automated Reasoning (IJCAR) 2004, Cork, Ireland, 2004.
• IJCAI 2003 Workshop on Agents and Automated Reasoning, Acapulco, Mexico, 2003.
• 11th Symposium on the Integration of Symbolic Computation and Mechanized Reasoning (CALCULEMUS), Rome, Italy, 2003.
• Calculemus Autumn School in Pisa, Italy, 2002.
• 2002 Conference on Automated Deduction (CADE) in Copenhagen, Denmark, 2002.
• 10th Symposium on the Integration of Symbolic Computation and Mechanized Reasoning (CALCULEMUS), Marseilles, France, 2002.
• IJCAR 2001 Workshop: Future Directions in Automated Reasoning – Problems and Ideas for a new Millennium in Siena, Italy, 2001.

Organization of other Events

• Calculemus Session at the Workshop: Mathematics on the Semantic Web, Eindhoven, Netherlands, 2003.
• European Union Midterm Review Meeting of the Calculemus Research Training Network, Saarbrücken, Germany, 2003.

External Reviewing

• Journal of Automated Reasoning (JAR)
• Journal of Symbolic Computation (JSC)

• Conference on Automated Deduction (CADE),
• IEEE Symposium on Logic in Computer Science (LICS)
• European Conference on Artificial Intelligence (ECAI)
• German Conference on Artificial Intelligence (KI)
• European Conference on Logics in Artificial Intelligence (JELIA)
• Symposium on the Integration of Symbolic Computation and Mechanized Reasoning (CALCULEMUS)
• International Conference on Logic for Programming Artificial Intelligence and Reasoning (LPAR)
• Various International Workshops

Fund Raising

• 2002: EU IST-Grant for Calculemus Autumn School.
• 2002: 25 European Union Comenius grants for high school teachers to attend the CALCULEMUS Autumn School in Pisa.
• 2002: Research server and NFS server for the OMEGA group at Saarland University.
• Grantholder in the Collaborative Research Centre 378 Resource-adaptive Cognitive Processes, Project MI 4 OMEGA: Resource-Adaptive Proof Planning
• Grantholder in the Collaborative Research Centre 378 Resource-adaptive Cognitive Processes, Project MI 3 DIALOG: Tutorial Dialogue with a Mathematics Assistance System
• Involved in the successful preparation and implementation of various individually funded research projects funded by the DFG (Germany), EU, and the EPSRC (UK).

Industry Contacts

• In my role as coordinator of the Calculemus research training network I am involved in the initiation and implementation of several industry internships of young researchers of the network at leading European companies.

Invited Talks

• OMEGA: From Proof Planning towards Mathematical Knowledge Management, MKM Symposium 2003, Edinburgh, Scotland, November 2003.
• From Natural Deduction to Sequent Calculus and back, Calculemus Autumn School 2002, Pisa, Italy, September 2002.
• Tutorial Dialog with a Mathematical Assistant System, Computer Science Department, The University of Birmingham, England, July 2002.
• Agent-oriented Reasoning with O-ANTS, Pure and Applied Logic Seminar, Carnegie Mellon University, Pittsburgh, PA, USA, November 2001.
• Agent-oriented Reasoning with O-ANTS, Department of Computer Science, Cornell University, Ithaca, NY, USA, November 2001.
• Panel member of the IJCAR 2001 Workshop Future Directions in Automated Reasoning – Problems and Ideas for a New Millennium, Siena, Italy, June 2001.
• An Agent-based Approach to Reasoning, Invited talk at the AISB'01 Convention Agents & Cognition in conjunction with 8th Workshop on Automated Reasoning: Bridging the Gap between Theory and Practice, University of York, England, March 2001.
• Concurrent Resource Guided Deduction, Theoretical Computer Science Seminar, School of Computer Science, The University of Birmingham, Birmingham, England, January 2001.
• Resource Guided Concurrent Deduction with O-ANTS, Department of Artificial Intelligence, The University of Edinburgh, Edinburgh, Scotland, September 2000.
• OMEGA, MATHWEB & Friends, Department of Artificial Intelligence, The University of Edinburgh, Edinburgh, Scotland, August 2000.
• Towards Agent based Theorem Proving and Proof Planning in OMEGA, Department of Computer Science, The University of York, York, England, April 2000.
• OANTS – An Open Approach at Combining Interactive and Automated Theorem Proving, Centre for Agent Research and Development CARD, Department of Computer Science, Manchester Metropolitan University, Manchester, England, March 2000.
• A two layered Agent Approach for Guiding Interactive Proofs, Theoretical Computer Science Seminar, School of Computer Science, The University of Birmingham, England, January 1999.
• Extensional Higher Order Resolution, Paramodulation and RUE-Resolution, Theoretical Computer Science Seminar, School of Computer Science, The University of Birmingham, England, January 1999.

Complete List of Talks since 1999

See `www.ags.uni-sb.de/~chris/cv-texmacs/cv-academic-experience.html` for the complete list of talks including those before 1999.

2003

- OMEGA: From Proof Planning towards Mathematical Knowledge Management, MKM Symposium 2003, Edinburgh, Scotland, November 2003.
- Bemerkungen zur Semantik und Mechanisierung von Logik hoeherer Stufe, German 'Deduktionstreffen 2003, Augsburg, October 8th, 2003.
- The CALCULEMUS Research Training Network – A short Overview, Calculemus Symposium 2003, Rome, Italy, September 10th.
- Assertion Application in Theorem Proving and Proof Planning, IJCAI-03 Poster Presentation, Acapulco, Mexico, August 11th.
- A New Framework for Reasoning Agents, IJCAI-03 Workshop on Agents and Automated Reasoning, Acapulco, Mexico, August 11th.
- Tutorial Dialogs on Mathematical Proofs, IJCAI-03 Workshop on Knowledge Representation and Automated Reasoning for E-Learning Systems, Acapulco, Mexico, August 10th.

- The CALCULEMUS Research Training Network – A short Overview, First QPQ Workshop on Deductive Software (QPQ'03), CADE-19, Miami, Florida, USA, July 27th.
- OMEGA - Ein Assistenzsystem fr die Mathematik, Open day, Saarland University, Saarbrcken, Germany, July 5.
- OMEGA, meeting in camera of the Special Research Centre SFB 378, Dagstuhl, June 26.
- Proof Development with OMEGA – Square root of 2 is Irrational, Theorema-Omega '03 Workshop, Schloss Hagenberg, Austria, May 15th.
- CALCULEMUS - Systems for Integrated Deduction and Computation, Mathematics on the Semantic Web, Eindhoven, The Netherlands, May 13.
- Saarland University Node Report at the Midterm Review of the European Union Research Training Network CALCULEMUS, Saarbrcken, Germany, March 31st.
- CALCULEMUS Midterm Review Report, at the Midterm Review of the European Union Research Training Network CALCULEMUS, Saarbrcken, Germany, March 31st.

2002

- Proof Development with OMEGA: Sqrt(2) is irrational, LPAR 2002, Tbilisi, Georgia, Oct 14.
- From Natural Deduction to Sequent Calculus and back, Calculemus Autumn School 2002, Pisa, Italy, Sep 27.
- Proof Development with OMEGA, CADE-19, Copenhagen, Denmark, July 27.
- Reasoning Services in the MathWeb-SB for Symbolic Verification of Hybrid Systems, VERIFY'02 Workshop at FLOC 2002, Copenhagen, Denmark, July 25.
- Tutorial Dialog with a Mathematical Assistant System, Computer Science Department, The University of Birmingham, England, July 9th.
- Agent based proof search with Indexed Formulas, Calculemus 2002, Marseille, France, July 3rd.
- Tutorial Dialog with a Mathematical Assistant System, meeting in camera of the Special Research Centre SFB 378, Wallerfangen, June 26.
- Ressource-Adaptive Proof Planning with OMEGA, meeting in camera of the Special Research Centre SFB 378, Wallerfangen, June 26.

2001

- Agent-oriented Reasoning with O-Ants. Pure and Applied Logic Seminar, Carnegie Mellon University, Pittsburgh, PA, USA, 15th November.
- Agent-oriented Reasoning with O-Ants. Cornell University, Ithaca, NY, USA, 31th October.
- Distributed Assertion Retrieval. First International Workshop on Mathematical Knowledge Management RISC-Linz, Schloss Hagenberg, Austria, 24th September.
- Experiments with an Agent-oriented Reasoning System. KI' 2001, Wien, Austria, 21th September.
- A lost proof, TPHOLS 2001, Edinburgh, Scotland, 20th August.
- An Agent-oriented approach to reasoning, Calculemus Workshop 2001, Siena, Italy, June.
- Agent-oriented theorem proving and proof planning in OMEGA, C++ days of SFB 378 Resource adaptive cognitive processes, Mertesdorf, July.
- An Agent based Approach to Reasoning, Invited talk at AISB'01 Convention Agents & Cognition and Eighth Workshop on Automated Reasoning: Bridging the Gap between Theory and Practice, University of York, England, 23th March.
- Agents in OMEGA, meeting in camera of the OMEGA group, 26th February.
- Concurrent Resource Guided Deduction, Theoretical Computer Science Seminar, School of Computer Science, The University of Birmingham, January 12th.

2000

- OMEGA – Ressourcenadaptives Beweisplanen, meeting in camera of the Special Research Division SFB378, Schloss Dagstuhl, November 17th.
- Tutorielle Kommunikation fr ein mathematisches Assistenzsystem, meeting in camera of the Special Research Division SFB378, Schloss Dagstuhl, November 17th.
- Agent based proof planning with O-ANTS, Systemdemonstration at the German Deduktionstreffen 2000, Saarland University, Saarbrcken, October 7th.
- Eine bersicht zur AG Siekmann, joint talk with Joerg Siekmann at the German Deduktionstreffen 2000, Saarland University, Saarbrcken, October 6th.
- Towards agent based proof planning, talk at the German Deduktionstreffen 2000, Saarland University, Saarbrcken, Oktober 6th.
- Resource guided concurrent deduction with OANTS, talk at the Department of Artificial Intelligence (DREAM-Group), The University of Edinburgh, Edinburgh, September 13th.
- OMEGA, MATHWEB, and Friends, talk at the Department of Artificial Intelligence (DREAM-Group), The University of Edinburgh, Edinburgh, August 28th.
- Resource Guided Concurrent Deduction, short talk and poster presentation at the Calculemus Symposium 2000, St. Andrews, August 7th.
- OANTS – An open approach at combining Interactive and Automated Theorem Proving, Calculemus Symposium 2000, St. Andrews, August 6th.
- Resource Guided Concurrent Deduction, short talk and poster presentation at Automated Reasoning Workshop 2000, King's College, London, England, July 21th.
- Resource Guided Concurrent Deduction, poster presentation at AISB'2000 Convention, Symposium on 'How to design a functioning mind', The University of Birmingham, Birmingham, England, 17-20th April.
- Towards Agent based Theorem Proving and Proof Planning in OMEGA, Department of Computer Science, The University of York, York, England, April 3th.
- System demonstration: OMEGA, O-ANTS, and LEO, Department of Computer Science, The University of York, York, England, April 3th.

- Proof Planning based on a Multi Agent Architecture? 9th CLAM - INKA - OMRS Workshop (CIAO), Schloss Dagstuhl, Germany, March 20th.
- O-Ants - An Open Approach at Combining Interactive and Automated Theorem Proving, informal talk and system presentation at the Centre for Agent Research and Development (CARD), Department of Computer Science, Manchester Metropolitan University, Manchester, England, March 3th.

1999

- Ist KI eine empirische Wissenschaft? SAG-WAS der AG Siekmann, Schloss Dagstuhl, Germany, December.
- Ressourcenadaptive Vorschlagsagenten im Interaktiven Beweisen, Kollegiatentag im Rahmen der Herbstschule Kognitionswissenschaft, Saarbrcken, October.
- Critical Agents Supporting Interactive Theorem Proving, 9th Portuguese Conference on Artificial Intelligence, Evora, Portugal, September.
- Gleichheit und Extensionalitt im automatischen Beweisen in Logik hherer Stufe, Promotionskolloquium, Saarbrcken, Germany, July.
- Agent Based Mathematical Reasoning, Calculemus Workshop, Trento, Italia, July.
- Extensional Higher-Order Paramodulation and RUE-Resolution, 16th Conference on Automated Deduction, Trento, Italia, July.
- On Automated Higher-Theorem Proving and Henkin Completeness, Forschungskolloquium der Studienstiftung des Deutschen Volkes, Berlin, Germany, May.
- Poster Presentation (with V. Sorge): Agent based Proof Planning, Sixth Workshop on Automated Reasoning: Bridging the Gap between Theory and Practice; in conjunction with AISB'99 Convention, Edinburgh, Scotland, April.
- A two layered Agent Approach for Guiding Interactive Proofs, Theoretical Computer Science Seminar, School of Computer Science, University of Birmingham, England, January 21th.
- Extensional Higher-Order Resolution, Paramodulation and RUE-Resolution, Theoretical Computer Science Seminar, School of Computer Science, University of Birmingham, England, January 29th.

Teaching

Courses

• 2003: Lecture course in Winter 2003 at Saarland University: *Human-oriented Theorem Proving* (jointly with Prof. Claus-Peter Wirth and Armin Fiedler)
• 2003: Lecture course in Summer 2003 at Saarland University: *Introduction to Artificial Intelligence* (jointly with Prof. J"org Siekmann)
• 2002: Lecture course at CALCULEMUS Autumn School 2002 in Pisa: *Deduction Systems*(jointly with Prof. Jörg Siekmann).
• 2002: Lecture course at Saarland University: *Automated Theorem Proving in First Order and Higher Order Logic.*
• 2001: Lecture course at Saarland University: *Introduction to Artificial Intelligence*(jointly with Prof. Jörg Siekmann).
• 1999: Lecture course at Saarland University: *Introduction to Artificial Intelligence*(jointly with Prof. Jörg Siekmann).

Seminars

• Winter 2000/2001: *Tutorial Systems*; supervision of students.
• Summer 2000: *Deduction and Computation*; full organisation.
• Since 2000: weekly or two-weekly OMEGA seminar of the AG Siekmann.
• Winter 1999/2000: *AI Planning*, supervision of students.
• Winter 1999/2000: *Deductionsystems*; supervision of students.
• Summer 1998: *Deductionsystems*; supervision of students.

Supervision

PhD students

• Martin Pollet: *Representation of Mathematics in Proof Planning* (ongoing).
• Jürgen Zimmer: *Coordination of Mathematical Agents* (ongoing).
• Volker Sorge:*A Blackboard Architecture for the Integration of Reasoning Techniques into Proof Planning* (finished).

MSc/Diploma students

• Thomas Neumann: TeXmacs as interface for OMEGA (ongoing).
• Masood Obaid: A topic in*Higher-Order Theorem Proving* (ongoing).
• Frank Theiss: *Verification of Computations in Proof Planning and Interactive Theorem Proving* (ongoing).
• Stephan Hess: *LOUI – A Graphical User Interface for the OMEGA System* (finished).
• Malte Hübner : *Interactive Theorem Proving with Indexed Formulas* (finished).
• Lars Klein: *Indexing f ür Terme höherer Stufe* (finished).
• Ahmet Bozkurt: *Strategien f ür Resolutionsbeweiser in Logik höherer Stufe* (finished).

Software Projects / Student Traineeships

• 2000: *Resource-adaptive Agent-based Theorem Proving,* joint traineeship of The University of Birmingham, England and the OMEGA group at Saarland University.
• 1997: *Graphical User Interfaces for Deduction Systems.*
• 1996: *Extension of the Proof Planning Mechanism in the OMEGA-System.*
• 1995: *Deduction Systems.*

Own Publications

Note: The following bibliography uses a special bibliography style for my papers. These entries are labeled '[Xnn-mm]' where 'X' describes the type/category of publication ('B' stands for Books and Chapters in Books, 'J' for International Journals, 'E' for Edited Proceedings and Books, 'C' for International Conferences, 'W' for International Workshops, 'T' for Theses, and 'R' for Technical Reports and Others), 'nn' is a consecutive numbering in each category, and 'mm' describes the year of publication.

A complete list of publications can also be found at: `www.ags.uni-sb.de/~chris/cv-texmacs/cv-publications.html`.

[B01-03] J. Siekmann, C. Benzmüller, A. Fiedler, A. Meier, I. Normann, and M. Pollet. Proof development in OMEGA: The irrationality of square root of 2. In F. Kamareddine, ed., *Thirty Five Years of Automating Mathematics*, Kluwer Applied Logic series. Kluwer Academic Publishers, 2003.

[C01-97] C. Benzmüller, L. Cheikhrouhou, D. Fehrer, A. Fiedler, X. Huang, M. Kerber, M. Kohlhase, K. Konrad, E. Melis, A. Meier, W. Schaarschmidt, J. Siekmann, and V. Sorge. OMEGA: Towards a mathematical assistant. In W. McCune, ed., *Proceedings of 14th International Conference on Automated Deduction (CADE-14)*, no.1249 in LNAI, pp.252–255, Townsville, Australia, 1997. Springer.

[C02-98] C. Benzmüller and M. Kohlhase. Extensional higher-order resolution. In C. Kirchner and H. Kirchner, eds., *Proceedings of the 15th International Conference on Automated Deduction (CADE-15)*, no.1421 in LNAI, pp.56–71, Lindau, Germany, 1998. Springer.

[C03-98] C. Benzmüller and M. Kohlhase. LEO – a higher-order theorem prover. In C. Kirchner and H. Kirchner, eds., *Proceedings of the 15th International Conference on Automated Deduction (CADE-15)*, no.1421 in LNAI, pp.139–143, Lindau, Germany, 1998. Springer.

[C04-98] C. Benzmüller and V. Sorge. A blackboard architecture for guiding interactive proofs. In F. Giunchiglia, ed., *Proceedings of 8th International Conference on Artificial Intelligence: Methodology, Systems, Applications (AIMSA'98)*, no.1480 in LNAI, pp.102–114, Sozopol, Bulgaria, 1998. Springer.

[C05-99] C. Benzmüller. Extensional higher-order paramodulation and RUE-resolution. In H. Ganzinger, ed., *Proceedings of the 16th International Conference on Automated Deduction (CADE-16)*, no.1632 in LNAI, pp.399–413, Trento, Italy, 1999. Springer.

[C06-99] C. Benzmüller and V. Sorge. Critical agents supporting interactive theorem proving. In P. Borahona and J. Alferes, eds., *Proceedings of the 9th Portuguese Conference on Artificial Intelligence (EPIA'99)*, no.1695 in LNAI, pp.208–221, Evora, Portugal, 1999. Springer.

[C07-00] C. Benzmüller, M. Jamnik, M. Kerber, and V. Sorge. Resource guided concurrent deduction. In M. Kerber and M. Kohlhase, eds., *Symbolic Computation and Automated Reasoning*, pp.245–246. A.K.Peters, 2000.

[C08-00] C. Benzmüller and V. Sorge. OANTS – an open approach at combining interactive and automated theorem proving. In M. Kerber and M. Kohlhase, eds., *Symbolic Computation and Automated Reasoning*, pp.81–97. A.K.Peters, 2000.

[C09-00] M. Jamnik, M. Kerber, and C. Benzmüller. Towards learning new methods in proof planning. In M. Kerber and M. Kohlhase, eds., *Symbolic Computation and Automated Reasoning*, pp.142–159. A.K.Peters, 2000.

[C10-01] C. Benzmüller, M. Jamnik, M. Kerber, and V. Sorge. Experiments with an agent-oriented reasoning system. In F. Baader, G. Brewka, and Th. Eiter, eds., *KI 2001: Advances in Artificial Intelligence, Joint German/Austrian Conference on AI, Vienna, Austria, September 19-21, 2001, Proceedings*, no.2174 in LNAI, pp.409–424. Springer, 2001.

[C11-02] J. Siekmann, C. Benzmüller, V. Brezhnev, L. Cheikhrouhou, A. Fiedler, A. Franke, H. Horacek, M. Kohlhase, A. Meier, E. Melis, M. Moschner, I. Normann, M. Pollet, V. Sorge, C. Ullrich, C. P. Wirth, and J. Zimmer. Proof development with OMEGA. In A. Voronkov, ed., *Proceedings of the 18th International Conference on Automated Deduction (CADE-19)*, no.2392 in LNAI, pp.144–149, Copenhagen, Denmark, 2002. Springer.

[C12-02] J. Siekmann, C. Benzmüller, A. Fiedler, A. Meier, and M. Pollet. Proof development with OMEGA: Sqrt(2) is irrational. In M. Baaz and A. Voronkov, eds., *Logic for Programming, Artificial Intelligence, and Reasoning, 9th International Conference, LPAR 2002*, no.2514 in LNAI, pp.367–387. Springer, 2002.

[C13-03] C. Benzmüller, A. Meier, and V. Sorge. Bridging theorem proving and mathematical knowledge retrieval. In *Festschrift in Honour of J. Siekmann*, LNAI, 2003. Springer. To appear.

[C14-03] Q. B. Vo, C. Benzmüller, and S. Autexier. Assertion application in theorem proving and proof planning. In *Proceedings of the International Joint Conference on Artificial Intelligence (IJCAI)*, pp. 1343-1344, Acapulco, Mexico, 2003. IJCAI/Morgan Kaufmann.

[E01-02] J. Zimmer and C. Benzmüller (eds.). CALCULEMUS Autumn School 2002: Student Poster Abstracts. SEKI Technical Report SR-02-06, Fachbereich Informatik, Universität des Saarlandes, Saarbrücken, Germany, 2002.

[E02-02] C. Benzmüller and R. Endsuleit (eds.). CALCULEMUS Autumn School 2002: Course Notes (Part I). SEKI Technical Report SR-02-07, Fachbereich Informatik, Universität des Saarlandes, Saarbrücken, Germany, 2002.

[E03-02] C. Benzmüller and R. Endsuleit (eds.). CALCULEMUS Autumn School 2002: Course Notes (Part II). SEKI Technical Report SR-02-08, Fachbereich Informatik, Universität des Saarlandes, Saarbrücken, Germany, 2002.

[E04-02] C. Benzmüller and R. Endsuleit (eds.). CALCULEMUS Autumn School 2002: Course Notes (Part III). SEKI Technical Report SR-02-09, Fachbereich Informatik, Universität des Saarlandes, Saarbrücken, Germany, 2002.

[E05-03] C. Benzmüller. Systems for integrated computation and deduction – interim report of the CALCULEMUS ihp network. SEKI Technical Report SR-03-05, Fachbereich Informatik, Universität des Saarlandes, Saarbrücken, 2003.

[J01-99] C. Benzmüller, M. Bishop, and V. Sorge. Integrating TPS and OMEGA. *Journal of Universal Computer Science*, 5:188–207, 1999.

[J02-99] J. Siekmann, S. Hess, C. Benzmüller, L. Cheikhrouhou, A. Fiedler, H. Horacek, M. Kohlhase, K. Konrad, A. Meier, E. Melis, M. Pollet, and V. Sorge. LOUI: Lovely OMEGA user interface. *Formal Aspects of Computing*, 11:326–342, 1999.

[J03-99] J. Siekmann, H. Horacek, M. Kohlhase, C. Benzmüller, L. Cheikhrouhou, D. Fehrer, A. Fiedler, S. Hess, K. Konrad, A. Meier, E. Melis, and V. Sorge. An interactive proof development environment + anticipation = a mathematical assistant? *International Journal of Computing Anticipatory Systems (CASYS)*, 3:101–110, 1999.

[J04-02] C. Benzmüller, M. Jamnik, M. Kerber, and V. Sorge: Agent-based Mathematical Reasoning. In A. Armando and T. Jebelean (eds.), Electronic Notes in Theoretical Computer Science, (1999) 23(3). (12 pages). Elsevier.

[J05-02] C. Benzmüller. Comparing approaches to resolution based higher-order theorem proving. *Synthese*, 133(1-2):203–235, 2002.

[J06-04] C. Benzmüller, C. Brown, and M. Kohlhase. Higher order semantics and extensionality. *Journal of Symbolic Logic*, 2004. To appear. (74 pages)

[J07-03] M. Jamnik, M. Kerber, M. Pollet, and C. Benzmüller. Automatic learning of proof methods in proof planning. *Accepted for The Logic Journal of the IGPL*, 2003. (28 pages)

[J08-03] S. Autexier, C. Benzmüller, A. Fiedler, H. Horacek, and B. Q. Vo. Assertion-level proof representation with under-specification. *Electronic in Theoretical Computer Science*, 2003. To appear. (10 pages)

[R04-97] C. Benzmüller. A calculus and a system architecture for extensional higher-order resolution. Research Report 97-198, Department of Mathematical Sciences, Carnegie Mellon University, Pittsburgh, USA, 1997.

[R05-97] C. Benzmüller and M. Kohlhase. Model existence for higher-order logic. Seki-Report SR-97-09, Department of Computer Science, Saarland University, 1997.

[R06-97] C. Benzmüller and M. Kohlhase. Henkin completeness of higher-order resolution. Seki-Report SR-97-10, Department of Computer Science, Saarland University, 1997.

[R09-99] C. Benzmüller and V. Sorge. Resource adaptive agents in interactive theorem proving. Seki-Report SR-99-02, Department of Computer Science, Saarland University, 1999.

[R10-99] C. Benzmüller, M. Jamnik, M. Kerber, and V. Sorge. Towards concurrent resource guided deduction. Seki-Report SR-99-07, Department of Computer Science, Saarland University, 1999.

[R12-99] C. Benzmüller, V. Sorge, and J. Byrnes. OANTS for interactive ATP. Draft, AG Siekmann, Saarland University, 1999.

[R14-01] M. Jamnik, M. Kerber, and C. Benzmüller. Automatic learning of proof methods in proof planning. Tech. rep.CSRP-01-08, University of Birmingham, School of Computer Science, 2001.

[R16-02] M. Jamnik, M. Kerber, M. Pollet, and C. Benzmüller. Automatic learning of proof methods in proof planning. Tech. rep.CSRP-02-05, University of Birmingham, School of Computer Science, 2002.

[R18-03] C. Benzmüller, C. Brown, and M. Kohlhase. Higher order semantics and extensionality. Technical Report CMU-01-03, Carnegie Mellon University, Pittsburgh, PA, 2003.

[R19-03] C. Benzmüller, C. Brown, and M. Kohlhase. Semantic techniques for cut-elimination in higher order logic. Technical Report Draft Version, Carnegie Mellon University, Pittsburgh, PA, 2003.

[R20-03] Q. B. Vo, C. Benzmüller, and S. Autexier. An approach to assertion application via generalized resolution. SEKI Report SR-03-01, Fachrichtung Informatik, Universität des Saarlandes, Saarbrücken, Germany, 2003.

[R22-03] C. Benzmüller and C. Hahn (editors). The CALCULEMUS Midterm Report. Unpublished EU Report, Saarland University, Saarbrücken, Germany, March 2003.

[R24-03] C. Benzmüller and D. Hutter. Calculemus-ii: Computer-supported mathematical knowledge evolution. Project proposal for a Marie Curie Research Training Network within the EU 6th framework, 2003.

[R25-01] M. Pinkal, J. Siekmann, and C. Benzmüller. Dialog: Tutorieller dialog mit einem mathematik assistenzsystem. Project proposal in the Collaborative Research Centre SFB 378 on Resource-adaptive Cognitive Processes, 2001.

[R26-01] J. Siekmann, C. Benzmüller, and E. Melis. Omega: Ressourcenadaptive beweisplanung. Project proposal in the Collaborative Research Centre SFB 378 on Resource-adaptive Cognitive Processes, 2001.

[T2-99] C. Benzmüller. *Equality and Extensionality in Higher-Order Theorem Proving.* Ph.D. thesis, Naturwissenschaftlich-Technische Fakultät I, Universit"at des Saarlandes, 1999.

[W01-98] J. Siekmann, S. Hess, C. Benzmüller, L. Cheikhrouhou, D. Fehrer, A. Fiedler, H. Horacek, M. Kohlhase, K. Konrad, A. Meier, E. Melis, and V. Sorge. A distributed graphical user interface for the interactive proof system. In *Proceedings of the International Workshop "User Interfaces for Theorem Provers 1998 (UITP'98)*, pp.130–138, Eindhoven, Netherlands, 1998.

[W02-98] C. Benzmüller and V. Sorge. Integrating TPS with ΩMEGA. In J. Grundy and M. Newey, eds., *Theorem Proving in Higher Order Logics: Emerging Trends*, Technical Report 98-08, Department of Computer Science and Computer Science Lab, The Australian National University, pp.1–18, Canberra, Australia, October 1998.

[W03-99] C. Benzmüller and V. Sorge. Towards fine-grained proof planning with critical agents. In *Proceedings of the 6th Workshop on Automated Reasoning*, pp.19–20. Edinburgh College of Art & Divison of Informatics, University of Edinburgh, 1999.

[W04-99] C. Benzmüller, M. Jamnik, M. Kerber, and V. Sorge. Agent based mathematical reasoning. In *Proceedings of the Calculemus Workshop: Systems for Integrated Computation and Deduction*, pp.1–12, July 1999.

[W06-01] M. Jamnik, M. Kerber, and C. Benzmüller. Towards learning new methods in proof planning. In *In Proceedings of the CADE-17 Workshop: Automated Deduction in the Context of Mathematics*, pp.1–12, 2001.

[W07-00] C. Benzmüller, M. Jamnik, M. Kerber, and V. Sorge. Resource guided concurrent deduction. In *Proceedings of the AISB'2000 Symposium 'How to design a functioning mind'*, pp.137–138, Birmingham, England, 2000. Also in: Proceedings of the 7th Workshop on Automated Reasoning 'Bridging the Gap between Theory and Practice'.

[W08-01] M. Jamnik, M. Kerber, and C. Benzmüller. Learning proof methods in proof planning. In *Proceedings of the Eighth Workshop on Automated Reasoning, Bridging the Gap between Theory and Practice*, pp.5–6. University of York, 2001.

[W10-01] C. Benzmüller. An agent based approach to reasoning. In *Extended abstract for invited plenary talk at AISB'01 Convention 'Agents and Cognition*, pp.57–58. University of York, 2001.

[W11-01] C. Benzmüller, M. Jamnik, M. Kerber, and V. Sorge. An agent-oriented approach to reasoning. In *Proceedings of the Calculemus Workshop 2001*, pp.48–63, Siena, Italy, 2001.

[W12-01] C. Benzmüller, A. Meier, E. Melis, M. Pollet, and V. Sorge. Proof planning: A fresh start? In *Proceedings of the IJCAR 2001 Workshop: Future Directions in Automated Reasoning*, pp.25–37, Siena, Italy, 2001.

[W14-01] C. Benzmüller, A. Meier, and V. Sorge. Distributed assertion retrieval. In *First International Workshop on Mathematical Knowledge Management RISC-Linz*, pp.1–7, Schloss Hagenberg, 2001.

[W15-02] C. Benzmüller and V. Sorge. Agent-based theorem proving. In *Proceedings of the 9th Workshop on Automated Reasoning: Bridging the Gap between Theory and Practice*, pp.1–3, London, England, 2002.

[W16-02] M. Hübner, S. Autexier, and C. Benzmüller. Agent-based proof search with indexed formulas. In *Additonal Proceedings of 10th Symposium on the Integration of Symbolic Computation and Mechanized Reasoning (CALCULEMUS 2002)*, pp.11–20, Marseilles, France, 2002.

[W19-03] B. Q. Vo, C. Benzmüller, and S. Autexier. Assertion application in theorem provinf and proof planning. In *Proceedings of the 10th Workshop on Automated Reasoning: Bridging the Gap between Theory and Practice*, Liverpool, England, 2003.

[W20-03] C. Benzmüller, A. Fiedler, M. Gabsdil, H. Horacek, I. Kruijff-Korbayova, M. Pinkal, J. Siekmann, D. Tsovaltzi, B. Q. Vo, and M. Wolska. Tutorial dialogs on mathematical proofs. In *Proceedings of IJCAI-03 Workshop on Knowledge Representation and Automated Reasoning for E-Learning Systems*, pp.12–22, Acapulco, Mexico, 2003.

[W21-03] C. Benzmüller. The CALCULEMUS research training network: A short overview. In *Proceedings of the 11th Symposium on the Integration of Symbolic Computation and Mechanized Reasoning (CALCULEMUS 2003)*, pp.1–16, Rome, Italy, 2003. MMIII ARACNE EDITRICE S.R.L. (ISBN 88-7999-545-6).

[W22-03] C. Benzmüller. The CALCULEMUS research training network: A short overview. In *Proceedings of the First QPQ Workshop on Deductive Software Components at CADE-19*, pp.13–27, Miami, USA, 2003.

[W23-03] C. Benzmüller, A. Fiedler, M. Gabsdil, H. Horacek, I. Kruijff-Korbayova, M. Pinkal, J. Siekmann, D. Tsovaltzi, B. Q. Vo, and M. Wolska. A wizard of oz experiment for tutorial dialogues in mathematics. In *Proceedings of AI in Education (AIED 2003) Workshop on Advanced Technologies for Mathematics Education*, Sydney, Australia, 2003.

[W24-03] M. Hübner, C. Benzmüller, S. Autexier, and A. Meier. Interactive proof construction at the task level. In *Proceedings of the Workshop User Interfaces for Theorem Provers (UITP 2003)*, pp.81–100, Rome, Italy, 2003. ARACNE EDITRICE S.R.L. (ISBN 88-7999-545-6). Also available as: Technical Report No. 189, Institut für Informatik, Albert-Ludwig-Universität, Freiburg.

[W25-03] C. Benzmüller, A. Fiedler, M. Gabsdil, H. Horacek, I. Kruijff-Korbayova, M. Pinkal, J. Siekmann, D. Tsovaltzi, B. Q. Vo, and M. Wolska. Discourse phenomena in tutorial dialogs on mathematical proofs. In *In Proceedings of AI in Education (AIED 2003) Workshop on Tutorial Dialogue Systems: With a View Towards the Classroom*, Sydney, Australia, 2003.

Appendix 2

Formal Letter of Acceptance from the Host Institution

The Formal Letter of Acceptance from the Host Institution is attached to this document.