The Calculemus Final Report

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Project Data

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Research Training Networks

The Network Partners

USAAR	Saarland University, DFKI, and EURICE GmbH, Saarbrücken, Germany
UED	The University of Edinburgh, Scotland
UKA	Karlsruhe University, Germany
RISC	Research Institute for Symbolic Computation, Hagenberg Castle/Linz, Austria
TUE	Eindhoven University of Technology and University of Nijmegen, Netherlands
ITC-IRST/DIT	Instituto per la Ricerca Scientifica e Tecnologica, Trento, Italy
UWB	University of Bialystok, Poland
UGE	Unversità degli Studi di Genova, Italy
UBIR	The University of Birmingham, England

Prove:	$\forall x. Fx$
Solve:	$\exists x. Fx$
Compute:	$\lambda x. Fx$

Contents

Chapter A

Contract Amendments

The following contract amendments have been suggested in the midterm report. They have been accepted by our EU officer in course of the midterm review.

1. We propose to slightly adapt/broaden the research tasks 3.2, 3.3, and 3.5:

   3.2 (Industrial-strength Applications) There are two main application areas for the systems and approaches developed in the Network: (i) Formal Methods and (ii) Mathematics Education. While the original work plan mainly focused on (i) the proposal is to additionally investigate (ii). At RISC the THEOREMA system is, for instance, already employed in practice to teach students in courses and similarly the ΩMEGA system is used within the mathematical tutor system ACTIVEMATH.

   3.3 (Exams in Calculus and Economics – Harvard) We propose to allow more flexibility with respect to the concrete mathematical domain to be chosen for the comparative analysis of the experimental results on using the prototype systems. Related work has already been completed on comparing solutions of different systems for the problem of proving the irrationality of $\sqrt{2}$.

   3.5 (Challenge Mathematical Problems) The formalization and (semi-) automation of some challenging mathematical problems with our approaches and systems is possible but typically requires special techniques and very experienced users. Therefore, we propose to additionally investigate to what extent our systems also support non-expert and novice users in doing normal and every day mathematics with a computer.

2. As discussed in Section B.8 [of the midterm report] it is not reasonable and realistic that *all* young researchers go for an industry internship; we therefore propose to modify the industrial internship clause in the training program as follows: *The young researchers should accomplish an industry internship if this internship (a) is reconcilable with the duration of their employment as young researcher in the* CALCULEMUS *Network and (b) does at least loosely fit their own research interests or the work program of the host node.*

   If an internship is however directly beneficial to the young researcher we propose that the stay in industry may be extended in time.

3. We propose that the Network should be allowed to more flexibly redistribute young researchers person months from underspending nodes to nodes with additional young researcher capacity. A requirement, however, is that this redistribution of young researcher person months is also reflected in a respective redistribution of the work load of the involved parties.

4. Because of the slight delay at the beginning of the Network we propose to adjust the duration of the contract respectively.

5. For further research training networks we suggest that a small central budget is maintained for the organization of joint training measures such as the CALCULEMUS Autumn School. The reason for this suggestion is the avoidable hassle and work load the solution in our Network causes for the coordinator and event organizers (in the CALCULEMUS Network this budget was distributed over the partner nodes).

Part A

A.1 Scientific Highlights (4th year)

A significant scientific highlight of the fourth year of the CALCULEMUS Network was the joint preparation of a proposal for a follow-up research training network in the 6th framework. For this project proposal an extended research program has been worked out which builts on the achievements and results of the current network and which integrates further research aspects that are relevant for our vision of an all-embracing assistance system for mathematics. For CALCULEMUS II we have proposed, for example, to contribute to a better mutual fertilization between the formal methods area and the mathematical assistance systems area, to better integrate our systems within typical work tasks of mathematicians and engineers, to address the specific requirements when applying these systems to different scenarios such as formal theory development or maths teaching and to develop larger pieces of non-trivial mathematics fully within our systems. The proposal was prepared at the very beginning of our fourth year and submitted in November 2003 (FP6-2002-Mobility-1, deadline 19th November 2003) and while it was positively evaluated it unfortunately nevertheless failed to be selected for funding. The call we entered was very competitive (only 27 out 627 submitted proposals finally got funded) but there was one main line of criticism which we have to take into account: "the long-term goals on mathematical research practice seem difficult to achieve and probably they are not even desirable". Obviously, we have not very successfully explained that our research and research applications are scalable and there are many relevant contributions stimulated by our research to the mathematics e-learning and the formal methods areas which are practically highly relevant without reaching the mathematics research frontier.

The Network has also achieved significant results w.r.t. the individual work tasks as will be reported below. Furthermore, CALCULEMUS has been very active (and still is) in the preparation and publication of documents with overview or summary character; see also Section A.1.

We now sketch the latest scientific result with respect to the individual work tasks. Scientific meetings and networking activities will be addressed in Section B.6.

1.1: Mathematical Frameworks

(**Task Leader: EUT)** An environment, called MathDox, has been constructed for producing and reading interactive mathematical documents (Hans Cuypers, Arjeh Cohen, Manfred Riem). It operates with XML documents compatible with a MathDox DTD that is a combination of OpenMath, DocBook and ideas from OMDoc. Several tools to make the sources interactive have been constructed. Interaction with remote software packages is easy. Several computer algebra engines have been connected to the system. Several experiments were conducted regarding the notion of context (Ernesto Reinaldo Barreiro). This is a set-up for both static data, fixing the mathematical notions being used throughout a document, and dynamic data, registering the variables and their values at use at any particular point in time during a user session visiting a MathDox document. The revelance of this work is that it creates possibilities for interactive mathematical activity integrating computer algebra and proof assistants. The rigor obtainable by the use of context is sufficient for the integration of software systems like Coq into the MathDox set-up. A few experiments using Coq have been conducted after the successful attempt at proving primality, see `http://www.cs.ru.nl/~martijno/pocklington` (Martijn Oostdijk and Olga Caprotti), such as the Nijmegen work with IDA described below, see `http://helm.cs.kun.nl`.

To increase the usability within the CALCULEMUS project, EUT also worked on the construction of OpenMath Content Dictionaries (CDs). The result can be found at `http://www.openmath.org/cocoon/openmath/cdfiles2/cdgroups/riaca_algebra.html` (Arjeh Cohen). One of the CDs defines queries and is input to the EU funded MONET project that finished April 2004 and produced a prototype of Web-based Mathematical Services.

Work has continued on investigating the mathematical-logical primitives for interaction with a proof assistant. This has led to a development of an M-mode for Coq, which combines ideas from the Mizar system with the type checking features of Coq. This was joint work of Freek Wiedijk (Nijmegen) and Mariusz Giero (young researcher from the Mizar group, Bialystok). Also this has led to the notion of 'Formal Proof Sketches', which aim at providing a mechanism for the top-down incremental development of proofs. Other work has been conducted in the area of combining proofs and programs: extracting computational content from proofs and developing correct programs within a theorem prover. The key idea here was to start from an abstract mathematical proof (in real analysis) and to obtain a program by instantiating the abstract proof with concrete mathematical structures (i.e. actual constructions of the reals). Experiments have been conducted by Luis Cruz-Filipe and Bas Spitters, leading to some positive results but also many new research questions. Finally, we have worked on the presentation (rendering) of formal proofs and worked out a case study where formal proofs from our repository have been rendered in an interactive document using IDA (from Eindhoven) and Helm (from Bologna).

A representation for concepts was developed jointly at UBIR and USAAR that allows to identify certain objects for which computational algorithms are available. The relevant information about these objects is directly accessible and usable for computations. With the application to matrices it was even possible to reduce some of the deductive steps to computation on this representation [Pollet *et al.*, 2004].

Mathematical reasoning in proof planning systems is at the comparatively high level of abstraction of the proof planning methods. However, as these methods have to be expanded (e.g., in ΩMEGA) eventually to the concrete syntax of a logic layer higher order ND-calculus, systems still suffers from the effect and influence this logical representation has. In contrast, the proofs developed by a mathematician, say for a mathematical publication, and the proofs developed by a student in a mathematical tutoring system are typically developed at an argumentative level. This level has been formally categorized as *proofs at the assertion level* with different types of *underspecification* [Autexier *et al.*, 2003a; Benzmüller *et al.*, 2003d]. The CORE system [Autexier, December 2003] and the task level [Hübner *et al.*, 2004] have been designed to achieve this and to support also a better, abstract-level integration of external reasoners. Ongoing work in the ΩMEGA project is now to completely exchange the current natural deduction calculus by the CORE calculus; the new system is called OMEGA-CORE in the remainder.

1.2: Definition of Mathematical Service

(**Task Leader: IRST**) A reasonable amount of work has been devoted to the improvement of the infrastructure (i.e., languages, protocols, semantic specifications and architectural schemata) for service integration. In particular, following the discussion held during the workshop on *Mathematical Web Services* organized by RISC in Linz in November 2002 (joint workshop between partners of the CALCULEMUS project and partners of the MONET (http://monet.nag.co.uk) project), the following goals have been addressed [Caprotti and Schreiner, 2002a]: describing a mathematical Web service by XML-based meta information which can be published in the Web and discovered by clients; basing the architecture of a mathematical Web service on Web technologies such as XML, SOAP WSDL, OpenMath, RDF, etc; describing a service as consisting of interrelated parts, such as problem, algorithm, implementation, machine; organizing descriptions according to multiple classification schemes in order to help the process of discovery.

At USAAR the Mathematical Service Description Language (MSDL), which was partially developed at RISC, has been used to describe deduction systems as Mathematical Web Services [Zimmer, 2003]. Several theorem proving and proof transformation systems have been described using MSDL. A brokering mechanism based on AI planning techniques is used to automatically combine services to answer a given query [Zimmer, 2004].

An additional line of research has been devoted to the investigation of how complex mathematical services can be built out of simpler ones, with a particular emphasis on decision procedures, and in particular on the integration of procedures specific for solving mathematical problems with deductive procedures. Examples are CCR (Constraint Contextual Rewriting) developed by UGE and MathSat [Giunchiglia *et al.*, 2001; Audemard *et al.*, 2002b; 2002a; 2002c], developed by ITC-IRST/DIT. In particular, the work on MathSat has focused on further tuning [Bozzano *et al.*, 2004] and applications to hybrid systems [Audemard *et al.*, 2003].

2.1: Integration of CASs and DSs via protocols

(**Task Leader: UKA**) The first part work at UKA was to start the extension of OMSCS to numerical computation. In [Bertoli *et al.*, 1999a] IRST and UKA introduced a general framework for integrating computer algebra systems and automated theorem provers, named OMSCS (Open Mechanized Symbolic Computation System) and showed how this integrated system can be used to solve problems which could not be tackled by each single system alone. Contrary to systems that operate on exact data, numerical systems need to perform approximations; exact mathematical results are not even representable in general. This is a real problem for the integration with other systems, as this investigation did show. We did focus on what can be done concerning the results and their interpretation. We did not provide details on how this can be done, nor deal with the complexity (except when this is a real problem). Two young researchers, Vincent Lefevre and Nathalie Revol made research on this topic. In [**?**] the rationales for the problems have been investigated.

The second part of the contribution of UKA is based upon the fact that to design various protocols for integrating various pieces of software is both time consuming and requires too much resources. An alternative approach is to set the integration into the multiagent system methodology. We propose to introduce a new paradigm, the Agent-Oriented Abstraction (AOA) [Calmet *et al.*, 2004]. This is a very abstract methodology allowing to see the required communication protocols as components of this new paradigm. In this approach a protocol is part of the knowledge component that is part of any agent. This enables to consider many different protocols through the concept of annotations of the knowledge possessed by agents. The model we have proposed extends the abstraction capabilities of the existing Agent-Oriented Programming paradigm. We have started to investigate the applicability of this approach in the domain of E-transactions under the concepts of virtual knowledge communities or corporate knowledge in a company, just to quote some of them [Maret *et al.*, 2004; Maret and Calmet, 2004].

2.2: CAS with enhanced proving power

(**Task Leader: RISC**) At RISC, the integration of the "lazy thinking paradigm" into the existing THEOREMA-system has been continued. The lazy thinking paradigm for lemma-invention was introduced by Bruno Buchberger in the context of *systematic theory exploration*, see [Buchberger, 2000e], and then extended to the invention (synthesis) of correct *algorithms*, see [Buchberger, 2003a], [Buchberger, 2003c], and [Buchberger and Craciun, 2004]. In the context of algorithm synthesis, the main prerequisite for "lazy thinking" is the concept of *algorithm schemes*, which can be seen as predicate logic formulae, that describe an algorithm (recursively) in terms of unspecified subalgorithms. The implementation of the lazy thinking mechanism in THEOREMA consists of *the proof analyzer*, which takes as input a (failed) proof object and returns the failing proof situation, *the conjecture generator*, which constructs a conjecture from the failing proof situations, and *the lazy thinking cascade*, which integrates lazy thinking into the proving mechanism of THEOREMA. Further case studies have been done, most importantly on the automated synthesis of the Buchberger Algorithm for constructing Gröbner bases, see [Buchberger, 2004]. In the course of the case studies, some of the special provers in the THEOREMA-system have been improved, notably the prover for tuple induction, see [Windsteiger, 2003] for a case study using the tuple prover.

Tools for user interaction during automated proof generation have been implemented in the frame of the THEOREMA-system, see [Piroi and Jebelean, 2002; Piroi, 2004]. For further developments we refer to Section 3.1.

2.3: DS with enhanced computational power

(Task Leader: UED) The work on learning of proof steps [Jamnik *et al.*, 2003b] started at UBIR, was continued at UED and USAAR. Statistical methods are used to extract significant proof subsequences, which are then generalized to a pattern describing these sequences. The output of these computational algorithms is a tactic, which can be applied in the construction of other proofs [Duncan *et al.*, 2004]. These learnt tactics may also embody computations and calls to CASs.

UBIR, UED and USAAR developed techniques for automatically discovering and proving classifying properties for certain finite algebraic structures, with respect to isomorphism classes. This was done by integrating and improving several automated reasoning techniques, and by using the theorem prover SPASS to dispatch the proof obligations. One significant aspect of this work was the use of the CAS GAP to help reduce the complexity of the problems given to SPASS [Colton *et al.*, 2004b; Sorge *et al.*, 2004b].

UED continued its work in discovering attacks on security protocols, developing and making use of the CORAL system, which is built on the theorem prover SPASS. The CORAL tool finds counterexamples to incorrect inductive conjectures [Steel *et al.*, 2004; Steel and Bundy, 2004], by implementing the 'proof by consistency' technique.

3.1: Automated support to writing mathematical publications

(Task Leader: RISC) USAAR has defined the basics for interfacing the mathematics WYSIWYG editor TeXmacs to theorem provers such as the new OMEGA-CORE. Issues that have been addressed in this context are the *datastructures* required for representing mathematical fragments (including proof trees) and the *user interface* between TeXmacs and OMEGA-CORE. See [Lesourd, 2004] for details including also an example describing the interactive processing of an open goal shared between TeXmacs and the theorem prover.

In the MIZAR-group, the developments were focused on the enhancement of the MIZAR system and the development of the MIZAR Mathematical Library (MML). During the last year, 197 new MIZAR articles authored by 70 persons were submitted to the MML. At the same time the organization of the MML has been improved. The MIZAR system underwent significant changes, both on the syntactic- and the semantic level. The strength of the MIZAR inference checker was also improved by the implementation of new "properties" and "requirements" directives (see [Naumowicz and Byliński, 2004]).

The THEOREMA-system has been enriched by "mathematical knowledge management facilities". A tool supporting the organization of formal mathematical text (definitions, theorems, theories, etc.) extracted from the hierarchical structure of the document has been developed and implemented in [Piroi, 2004]. For the purpose of instantiating variables representing the unknown subalgorithms in the lazy thinking method for algorithm synthesis (see Section 2.2), a `FormulaFinder` has been implemented within THEOREMA. `FormulaFinder` checks, whether a proof goal "occurs in" Φ (a possibly huge, hopefully structured knowledge base) by first matching variables representing unknown subalgorithms against constants available in Φ and then trying to prove the resulting formula "by easy means", see [Buchberger, 2003b].

3.2: Support for the development of an industrial-strength application of formal methods to program verification (see also the contract amendment)

(Task Leader: USAAR) USAAR has continued to work on the integration of the ΩMEGA system as proof tutor for the mathematical education system ACTIVEMATH. With use cases USAAR furthermore analyses the demands on a proof tutor from the user's viewpoint and proposed an architecture to satisfy these demands [Meier *et al.*, 2004; Pollet *et al.*, 2003]. The architecture is based on a combination of proof planning and the agent based suggestion mechanism ΩANTS developed for ΩMEGA.

RISC continued the use of the THEOREMA-system in maths teaching. New approaches to interactive teaching and learning of mathematics by using computer-support for theorem proving are explored in a newly started joint project "CreaComp" at the University of Linz. Furthermore, we started to support program verification within the THEOREMA-system. For imperative programs, the model of Hoare logic and the method of weakest precondition, together with combinatorial methods for automatic generation of loop invariants is used, see [Kovács, 2003; Kovács and Jebelean, 2003], whereas for recursive programs a method based on Scott's induction has been investigated, see [Popov and Jebelean, 2003].

On the one hand, the young researchers Julien Musset and Graham Steel were working on issues dealing with security protocols. Luca Compagna visited Siemens, Munich, working on security and proofs issues. On the other hand, the UKA group is working on the security of mobile agents. Arno Wagner from ETH Zurich visited UKA to work on security issues [Endsuleit and Wagner, 2004] as a continuation of [Endsuleit and Mie, 2003]. More technical details ought to be found in the young researchers reports. It is worth to outline that both Musset and Steel got their PhD upon finishing their stay in Karlsruhe and that Wagner and Compagna are close to get it. Also important is that the future activities of the group are going to be developed in the direction of probabilistic proofs for the correctness of computations.

3.3: Support to the solution of undergraduate exam in calculus and economics (see also the contract amendment)

(Task Leader: USAAR) The *Irrationality of* $\sqrt{2}$ case study that has been pursued at Nijmegen (TUE) in 2002/2003 will be published as a book in the Springer LNAI series; Freek Wiedijk is currently preparing the final version.

At USAAR ongoing work in the DIALOG project on *Natural-language based interaction with a mathematical assisstance environment* investigates how our mathematical assistance systems can support the analysis and evaluation of proof steps uttered by students in a mixture of natural language (typed input) and mathematical formulas as they are typical within maths exercises and exams at university beginners level [Benzmüller *et al.*, 2003d; 2003e; Wolska *et al.*, 2004; Pinkal *et al.*, 2004b; 2004a].

The Networks' young researchers Henri Lesourd (USAAR) and Armin Fiedler (USAAR/UED) have started to develop an interface between the mathematical typesetting system TeXmacs and the new mathematical assistance environment OMEGA-CORE; see [Lesourd, 2004]. The interface is intended to provide a realistic environment in which theorem provers can be directly applied to check and verify (simple) mathematical texts such as student exams at beginners level.

3.4: Modelling of existing systems as Mathematical Services

(Task Leader: IRST) At USAAR several theorem proving and proof transformation systems have been described as Mathematical Web Services [Zimmer *et al.*, 2004] in the MathWeb/MathServ framework. Among others, the first-order automated theorem provers Otter, SPASS, Ep have been integrated in MathServ and described as Semantic Web Services. Furthermore, the Tramp system [Meier, 2000], which generates natural deduction proofs out of resolution proofs, has been integrated and described in MSDL.

Within the MathBroker project (`http://www.risc.uni-linz.ac.at/projects/basic/mathbroker/`), an infrastructure for describing, implementing, publishing, and discovering mathematical services has been developed. The development includes: sample mathematical services based on the SOAP protocol using the OpenMath standard for exchanging mathematical objects; the mathematical service description language MSDL with mutual influence from that of MONET; a Web registry for holding MSDL descriptions based on the ebXML (Electronic Business Using XML) registry.

Finally, the extensions and enhancements of the reasoning capabilities of some existing tools has been addressed. As an example, further tuning of the tool MathSat, developed by ITC-IRST/DIT, has been studied [Bozzano *et al.*, 2004]. In particular, the role of a new-generation SAT-solver, of incremental reasoning and learning have been discussed. Notable applications of the tool are in the field of verification of hybrid systems [Audemard *et al.*, 2003].

3.5: Challenge mathematical problems (see also the contract ammendment)

(Task Leader: UKA, UBIR) The combination of mathematical reasoning techniques developed in the Calculemus Network has been successfully applied to automatically produce and verify classification theorems in finite algebra. The work combined first-order theorem proving, computer algebra, model generation and machine learning and led to new mathematical results, namely to classification theorems for non-associative algebras (loops and quasigroups), that were not yet known and that could not have been derived with a single reasoning system alone. The research was done in collaboration of UBIR, UED, and USAAR, as well as by Simon Colton from Imperial College London, UK, who was a young researcher at UKA and USAAR [Colton *et al.*, 2004b].

We have now started looking into incorporating new technologies in order to enhance the power of our approach and to exploit its results in other contexts. In particular, we have started employing Grid technology in order to tackle mathematical existence problems with distributed model generation techniques [Sorge *et al.*, 2004b].

The work developed at UKA by Eduardo Saenz de Cabezon has been focused on the study of homological invariants that are present in both commutative algebra and the formal theory of partial differential equations. In particular, Spencer Cohomology and Koszul Homology have been studied and related to Pommaret Bases in the framework of Involution theory. A combinatorial algorithm to compute Spencer Cohomolgy of homogeneous monomial ideals (and their correspondent differential systems) was presented in communication at EACA 2004 [de Cabezón, 2004], the Spanish Computer Algebra conference, and as a poster session at ISSAC 2004. Work in progress inludes the completion of this algorithm, the study and algorithmization of the isomorphism between Koszul Homology and Minimal Resolution of Monomial Ideals, and the relation between both Spencer and Koszul (co)homology and Pommaret bases. Several tools for this study are being developed from different points of view that include Simplicial (cubical) homology, (co)homological algebra and commutative algebra, always in relation with differential systems. The rationale of such a work within Calculemus is twofold. On one side it extends symbolic computation to new domains of mathematics. On the other side, it allows to make statements on the integrability of systems. For instance, to prove theorems in geometry, one relies on the Buchberger algorithm to solve systems of polynomial equations. In fact, it ought to be sufficient to prove their integrability. Such a work goes in the latter direction.

4.1, 4.2, 4.3: Training

See Sections B.7 and B.8.

5.1, 5.2, 5.3, 5.4: Dissemination of Results

The high dissemination effort of the Network in terms of publications during this last year is documented in Section A.3. We particularly want to point to our ongoing dissemination efforts such as the forthcoming Special Issue on Calculemus'03 in the LMS Journal of Computation and Mathematics, forthcoming book on the *Irrationality of* $\sqrt{2}$ case study in the Springer LNAI series, the forthcoming Special Issue on *Mathematical Assistance Systems* in the Journal of Applied Logics.

See also Section B.6.3.

A.2 Scientific Highlights (all four years)

In the following paragraphs we sketch the overall highlights of our research in the different work tasks; we also point to publications and prototypes as required by the Networks' milestones.

1.1: Mathematical Frameworks

(Task Leader: EUT) In order to produce more examples of computer algebra support for deduction, existing permutation group algorithms were extended with information that, when given a permutation group by a list of permutations, returns enough information (witnesses) to allow a proof assistant program to construct a formal proof of correctness of the original computation. EUT, UBIR, and USAAR are currently working on an extension of this application towards the graph isomorphism problem (people involved are Jan Willem Knopper, Volker Sorge, Scott Murray, Arjeh Cohen, Martin Pollet). Graph isomorphism is fundamental to much of computer science including the theory of networks.

Another highlight is a working prototype of the idea of context of a mathematical document (Ernesto Reinaldo Barreiro), enabling a dynamic

MKMNet EU FP5 Network
(http://monet.nag.co.uk/mkm/index.html)
Involved: UBIR, USAAR, RISC, UWB

International Joint Workshop of MONET, Calculemus, MKM, Types, OpenMath, MoWGLI: "Mathematics on the Semantic Web", Eindhoven The Netherlands, May 12-14, 2003. See (http://www.openmath.org/meetings/eindhoven2003/).

MKM Symposia Mathematical Knowledge Management Symposia
RISC: MKM-2001 Hagenberg Castle, Austria (http://www.risc.uni-linz.ac.at/about/conferences/MKM2001/)
NA-MKM-2002 Hamilton, Ontario, Canada, 2002 (http://imps.mcmaster.ca/na-mkm-2002/)
MKM-2003 Bertinoro, Italy, 2003 (http://www.cs.unibo.it/MKM03/)
MKM-2004 Bialiwieza, Poland, 2004
Involved: UED, USAAR, UGE, UBIR, ITC-IRST/DIT, RISC

CIAO Workshops The yearly Clam-INKA-OMRS Workshops (CIAO)
UED 1999 (http://www.dai.ed.ac.uk/group/tw/ciao99)
USAAR 2000 (http://www.dfki.de/CIAO-2000)
UGE 2001 (http://www.mrg.dist.unige.it/events/CIAO2001)
UED 2002 (http://dream.dai.ed.ac.uk/ciao/ciao-2002.html)
USAAR 2003 (http://www.dfki.de/CIAO-2003/)
UGE 2004 (http://www.ai.dist.unige.it/CIAO2004/)
Involved: UGE, UED, USAAR, UBIR, ITC-IRST/DIT

AISC Conferences Artificial Intelligence and Symbolic Computation
AISC-2002: Joint conference AISC-2002 and Calculemus'02.
AISC-2004: Organized by RISC (chair: B. Buchberger) in Hagenberg, Austria (http://www.risc.uni-linz.ac.at/about/conferences/aisc2004/).
Involved: UKA, RISC.

Accredited joint PhD program
Involved: UGE, UED

2K* Symposium Annual event since 1995, (http://peano.mrg.dist.unige.it/2Kstar/2003/)
Involved: ITC-IRST/DIT, UGE

Working group Graph isomorphism
Involved: TUE, UBIR, USAAR

Table A.1: Examples of project involvements of Network partners beyond Calculemus.

interaction with a structured document delivered over the Web (via MathDox). Relevant work in this direction is the OMDoc standard for open mathematical documents, originally developed by M. Kohlhase at USAAR and now used by several project partners.

A representation for concepts was developed jointly at UBIR and USAAR that allows to identify certain objects for which computational algorithms are available.

USAAR has developed the CORE calculus and the task level as new basic layer in the Ωmega-CORE system; this framework is designed to better support *proofs at the assertion level* with different types of *under-specification* and to better support abstract-level integration of external reasoners, including DSs and CASs.

1.2: Definition of Mathematical Service

(Task Leader: IRST) The effort in this Task was mainly directed towards the enhancement of existing computer algebra systems and deductive systems, by turning them into *open* systems capable of using and/or providing mathematical services. This goal has been achieved by working in two different directions, namely with a top-down and a bottom-up approach.

In the top-down approach, new infrastructures (both at the conceptual, specification, and architectural level) for the seamless integration of mathematical services have been investigated, with an eye not only at current systems, but also at future implementations. Particular emphasis has been put on the definition of frameworks (languages, protocols, semantic specifications, architectural schemata) suitable for making mathematical services accessible over the web. The relevant top-down approaches are: OMRS (Open Mechanized Reasoning Systems) developed by UGE and ITC-IRST/DIT [Armando *et al.*, 2001a], LBA (Logic Broker Architecture) developed by UGE [Armando and Zini, 2000; 2001], MathWeb-SB (MathWeb Software Bus) and MathServ developed by USAAR and UED [Zimmer and Kohlhase, 2002; Zimmer, 2004], MathBroker developed by RISC [Mathbroker:URL,]. These networks can themselves be coupled again as, for instance, exemplarily investigated in [Zimmer *et al.*, 2001].

In the bottom-up approach, we have investigated how complex mathematical services can be built out of simpler ones. A particular emphasis has been devoted to decision procedures, and in particular to the integration of procedures specific for solving mathematical problems with deductive procedures. Examples for bottom up approaches are CCR (Constraint Contextual Rewriting) [Armando and Ranise, 2003] developed by UGE and MathSat [Giunchiglia *et al.*, 2001; Audemard *et al.*, 2002b; 2002a; 2002c; 2003; Bozzano *et al.*, 2004], developed by ITC-IRST/DIT.

In Task 1.2 the Calculemus Network has also closely cooperated with the EU project MONET (project number IST-2001-34145) and a joint workshop[1] has been organized by O. Caprotti in November 2002 at RISC. In MONET special ontologies comprising mathematical problems, queries and services have been defined and investigated.

2.1: Integration of CASs and DSs via protocols

(Task Leader: UKA) A first line of work has been in the spirit of the OMRS (Open Mechanized Reasoning System) methodology that was extended to symbolic computation under the name of OMSCS. It has consisted in extending this approach to numerical routines and to assess the feasibility to prove with numerical algorithms. The integration through protocols has a direct link to the third level of the OMRS methodology. The concept of multiagent systems has been used by several partners to provide integration through the communication mechanisms provided by such systems. An abstraction of the concept of agents has been proposed that will hopefully transform this abstraction into a paradigm to integrate distributed systems. Although not fully belonging to this Task, the analysis of and proofs for security protocols has been a highlight of the project.

2.2: CAS with enhanced proving power

(Task Leader: RISC) Different approaches to "enhancing CASs with proving power" have been investigated by UED, UGE, UKA, and RISC during the first phase of the Calculemus project, which has been described in the midterm report [Benzmüller, 2003c]. The Theorema-system developed at RISC has been chosen to be developed further into a prototype "CAS with enhanced proving power" in the frame of Task 2.2. A detailed description of Theorema can already be found in [Benzmüller, 2003c]. Theorema enriches the computational engine and the user front-end of the well-known computer-algebra system *Mathematica* with facilities for automated theorem proving. The system is envisaged to develop into *one system*, in which a mathematician gets computer-support during *all phases* of her/his work, from developing first sketches of a new concept, over implementation of algorithms, testing algorithms in examples, conjecturing properties of the algorithms, proving the conjectured properties, etc. until finally publishing the results in a journal and/or presenting the results at a conference.

The Theorema-system, see e.g. [Buchberger, 2001e; 2001f; Jebelean and Buchberger, 2001; Jebelean, 2002a], provides a *mathematical language*, which on the one hand appears syntactically very close to standard mathematical notation allowing all sorts of two-dimensional syntax common to mathematics but on the other hand is translated into an exact internal representation avoiding all ambiguities hidden in hand-written mathematical language. As a second language-layer, the system provides language constructs for describing *formal mathematical entities*, such as definitions, axioms, theorems, propositions, etc. The third language layer contains language constructs for describing *mathematical activities*, such as proving, computing, and solving.

For computations, we provide an implementation of the semantics of the Theorema mathematical language in the programming language of *Mathematica* based on the evaluation mechanism available in *Mathematica* using substitution and replacement. For proving, we implemented several general and domain-specific provers, which generate human-readable proofs in natural (english) language. The system architecture is *modular* in the sense that individual prover-modules (so-called "special provers") can be combined into bigger units (so-called "user provers"), which are available for the Theorema-user. We provide special provers for basic predicate logic reasoning, equational reasoning, induction on natural numbers, induction on tuples, set theory, quantified rewriting, solving over the reals, simplification, and several more, see e.g. [Buchberger, 2001d; Jebelean, 2001a; 2001b; Windsteiger, 2001b; Kutsia, 2002b; Windsteiger, 2002a]. In addition to those proving methods, the Theorema-systems provides links to external proving systems, such as Otter, Vampire, Bliksem, etc., see [Kutsia and Nakagawa, 2001].

As a distinguishing feature of the Theorema-system we want to mention the possibility implemented in several special provers to "prove by simplification (i.e. computation) using built-in knowledge". By this mechanism, the user can allow the prover to access built-in semantics of the Theorema language and perform certain simplifications based on the *Mathematica*-evaluation engine, which results in very efficient handling of arithmetic in basic number domains, tuples, and finite sets.

A prototype of the Theorema-system is avail-

[1] See `poseidon.risc.uni-linz.ac.at:8080/results/seminars/mathbrokerWS.html`.

able for free download at http://www.risc.uni-linz.ac.at/research/theorema/.

2.3: DS with enhanced computational power

(Task Leader: UED) The proof-planner *λClam* [Richardson *et al.*, 1998] has been combined with other systems, primarily in order to carry out computationally costly tasks. This includes (a) an implementation of the GS flexible decision procedure system framework within the *λClam* proof planning system [Bundy and Janičić, 2002] and (b) the integration of the *λClam* proof-planner into the MathWeb-SB system [Dennis and Zimmer, 2002]. Moreover, work has been done in the *λClam* proof-planner to construct very large and modular proof-plans for complicated real analysis theorems [Heneveld *et al.*, 2001; Maclean, 2001; Maclean *et al.*, 2002].

UED recently decided to concentrate efforts into developing ISAPlanner, a proof-planner built upon the Isabelle theorem-prover, taking into account the lessons learned from working with *λClam*. This new system will allow us to make use not only of the added computational abilities of Isabelle, but also of the many systems already coupled with Isabelle.

The ΩMEGA proof planner at USAAR has been coupled with different CASs via Math-Web-SB, see [Sorge, 2000; Meier *et al.*, 2002b; Benzmüller *et al.*, 2003f]. The ΩANTS approach to integrate CASs into mathematical assistant systems is sketched in [Benzmüller *et al.*, 2001b; 2001a; Benzmüller and Sorge, 2001; 2002]. This work proposes an agent-based modeling of inference rules and external systems at a very basic level within theorem provers. The improved mechanisms and facilities of ΩMEGA to cooperate with CASs are, e.g., illustrated in [Siekmann *et al.*, 2003]. Three different styles of proof development in ΩMEGA, which all include cooperation with an external CAS, are presented using the example of the irrationality of $\sqrt{2}$. The first style follows the traditional tactical theorem proving approach without any mathematical knowledge, the second employs the idea of interactive island proof planning, and the third is a fully automated proof based on planning with ΩMEGA's proof planner MULTI. More challenging case studies with ΩMEGA cooperating with a CAS did focus on permutation group problems [Cohen *et al.*, 2003b] and the classification of residue classes [Meier and Sorge, 2001; Meier *et al.*, 2001a; 2002b; 2002d]. A prototype of ΩMEGA is available for free at `www.ags.uni-sb.de/~omega`.

In addition, the theorem prover SPASS was employed in two quite different projects:

- to automatically discover and prove some classifying properties for certain finite algebraic structures. In particular, the CAS GAP was used to help reduce the complexity of the problems given to SPASS [Colton *et al.*, 2004b; Sorge *et al.*, 2004b].
- as a part of the CORAL system, to discover attacks on security protocols, by finding counterexamples to incorrect inductive conjectures [Steel *et al.*, 2004; Steel and Bundy, 2004].

Finally, work was done at UBIR and UGE which rendered certain techniques from automated reasoning highly efficient, by using enhanced computational power. This work is presented in [Jamnik *et al.*, 2002d; 2002c; 2002e] and [Audemard *et al.*, 2002a; 2002c; Armando *et al.*, 2001b]. Further relevant work is given in [Ranise, 2002].

3.1: Automated support to writing mathematical publications

(Task Leader: RISC) The case studies in using available systems for supporting the publication of mathematical material have been done based on different approaches.

UWB uses their MIZAR system and concentrated on two main goals:

- enhancement of the MIZAR system,
- development of the MIZAR Mathematical Library (MML).

The MIZAR system has been changed in various aspects, both on the syntactic- and the semantic level (e.g. new syntax for schemes, the separation of "notation" and "registration" blocks from "definition" block, the static reconstruction of the types of adjectives). The strength of the MIZAR inference checker was also improved by the implementation of new "properties" and "requirements" directives (see [Naumowicz and Byliński, 2004]). The MML showed substantial growth and at the same time we started the work aimed at better organization of MML:

- 5 MIZAR articles were created to initialize the Encyclopedia of Mathematics in MIZAR
- about 50% of all articles were revised (with moving pieces of information from one article to another if necessary) to separate the concrete part of MML from the abstract part.

At USAAR the mathematical database MBASE is used to support the distributed development of mathematical content, which is of particular importance in the context of distributed mathematical services such as MathWeb-SB/MathServ, see also Task 1.2. Furthermore, an interface between the mathematical WYSIWYG editor TeXmacs and the theorem prover OMEGA-CORE is under development, see [Lesourd, 2004].

At RISC, the THEOREMA-system has been used for supporting mathematical publications. In a first line of development, interactive lecture notes have been developed for elementary mathematics courses at the University of Linz. Apart from text processing features of the THEOREMA user front end available through the underlying *Mathematica*-system, these interactive lecture notes are based on the THEOREMA mathematical language, which gives a frame for the definition and execution of mathematical algorithms and at the same time for proving properties of these algorithms. Secondly, some developments towards mathematical knowledge management have been studied within the THEOREMA-system:

- Support for organizing formal mathematical text (definitions, theorems, theories, etc.) by using the hierarchical structure of the document, see [Piroi, 2004].
- `FormulaFinder` for supporting the lazy thinking paradigm for both theory development and algorithm synthesis. This tool checks, whether a formula occurs in a knowledge base of mathematical formulae. Textual search is enhanced by basic reasoning facilities that check whether the formula can be proven from the knowledge base by "elementary proving", see [Buchberger, 2003b].

3.2: Support to the development of an industrial-strength application of formal methods to program verification (see also the contract amendment)

(Task Leader: USAAR) The two main application areas for the integrated asssistance systems as proposed in CALCULEMUS are formal methods / engineering and mathematics education. While the original CALCULEMUS proposal has put an emphasis on the former the contract amendment agreed at the midterm review meeting supports also the investigation of the latter. Maths (and logic) education is actually the area where the Network has made most progress and several of our systems are actually employed to support teaching in practice.

Originating from the USAAR's ΩMEGA-team a new research group (the ActiveMath group) under the leadership of the CALCULEMUS senior researcher Erica Melis has been built-up during CALCULEMUS at the semi-industrial DFKI (German Research Centre for Artificial Intelligence in Saarbrücken). ActiveMath is a user-adaptive, interactive and web-based learning environment for mathematics which employs intelligent technologies and which integrates and applies the ΩMEGA system to support dynamic domain reasoning in exercises. One of the Networks' young researchers, Andreas Meier, has recently become the main developer of the ΩMEGA prover in the ActiveMath context. The ActiveMath e-learning environment is applied and evaluated in teaching practice. The ActiveMath homepage is available under `http://www.activemath.org/`.

The CALCULEMUS Network has also collaborated (e.g. via the young researchers Dimitra Tsovaltzi and Armin Fiedler) with the DIALOG project [Benzmüller *et al.*, 2003d; 2003c] in the Collaborative Research Centre 378 at Saarland University; see `http://www.ags.uni-sb.de/~chris/dialog/`. The goal of this basic research project is to investigate what requirements the flexible dialog paradigm poses for natural language based interaction with a mathematics assistance system and for mathematics tutoring. In a Wizard of Oz experiment [Benzmüller *et al.*, 2003e] with a simulated tutorial dialog system for teaching proofs in naive set theory a corpus [Wolska *et al.*, 2004] has been collected that reveales challenging phenomena at all levels of system design [Benzmüller *et al.*, 2003b; Tsovaltzi *et al.*, 2004; Tsovaltzi and Fiedler, 2003]: from input analysis, through mathematical domain reasoning, to tutorial dialog strategies. A CALCULEMUS relevant result of this collaboration is the finding that the resolution and disambiguation of underspecified (natural language) user-input as well as the analysis of the soundness, the appropriate granularity, and the relevance of user proof step utterances in maths tutoring contexts imposes novel challenges to mathematical domain reasoning. To address these challenges our mathematical assistance environments as well as their representation languages and interaction interfaces have to be appropriately adapted; see also [Autexier *et al.*, 2003a; Hübner *et al.*, 2004; Pinkal *et al.*, 2004b].

MIZAR (see `www.mizar.org`) has been extensively applied for teaching purposes and several MIZAR courses were conducted via the Internet: some students (mostly distant learning) at UWB are taught by using the MIZAR system by e-mail. It started with a student who is deaf and meanwhile there are six such students. Equalization of opportunities for persons with disabilities is thus a strong motivation for the improvement of e-learning technology in mathematics.

The THEOREMA-system is used to supplement teaching in undergraduate courses in the mathematics curriculum at the University of Linz. Not only that the lecture notes of the courses "Algorithmic Methods 1", see [Windsteiger, 2004], and "Predicate Logic as a Working Language", see [Windsteiger and Buchberger, 2004], are written in THEOREMA and based on the THEOREMA-syntax for mathematical formulae, also the presentation of the contents makes use of features available in the THEOREMA-system. Well-known mathematical algorithms (e.g. algorithms for polynomial interpolation, see also [Windsteiger, 2003]) are introduced by actually showing their implementation in the THEOREMA user language and their behavior is studied by executing the algorithms in the frame of THEOREMA. Teaching the techniques for mathematical proofs to undergraduate students is supported by presenting both successful and failing proofs produced by the THEOREMA-system.

New approaches to computer-supported teaching and learning of mathematics are studied within the joint project "CreaComp" between different mathematics institutes at the University of Linz. The THEOREMA-system is applied in experiments for students to interactively explore the truth or falsity of mathematical conjectures.

To foster applications of our systems in the formal methods area we have cooperated, e.g., with the VSE group at the DFKI in Saarbrücken (e.g. via young researcher Corrado Giromini). The selected industry internships of young researchers did foster a better awareness of our systems in the hosting companies. In order to stimulate bigger application projects the relative short internships of young researchers did however not prove a very successful instrument. For the CALCULEMUS-II Network [Benzmüller and Hutter, 2003] we therefore proposed to more directly involve the industry partners in the research and we have contacted and attracted respective partners (including INTEL, NASA, and SRI International) with a stronger a priori awareness and background knockledge regarding our goals and our systems to participate in CALCULEMUS-II; see the expressions of interest attached to the CALCULEMUS-II proposal [Benzmüller and Hutter, 2003].

3.3: Support to the solution of undergraduate exam in calculus and economics (see also the contract amendment)

(Task Leader: USAAR) In this Task we focus on simple, mathematics education oriented problems with a strong emphasis on the particular way the problems are solved, how interaction with the user is supported and how the solution is presented. We have analyzed whether our systems can be employed in a user friendly and adequate way and whether the interaction and maths presentation capabilities of the systems are appropriate.

The effortful *Irrationality of* $\sqrt{2}$ case study that has been pursued by Freek Wiedijk at Nijmegen (TUE) compares the solution of 16 mathematical assistance systems and theorem provers, including many systems from outside the CALCULEMUS community. This case study very well documents the strengths and weaknesses of the leading systems in the field, including those of the Network, in solving problems at a difficulty level as envisioned in this work package.

In the ΩMEGA-project at USAAR this case study has motivated several extensions and adaptations of the system such that more adequate interaction between the system and the student at argumentative level becomes feasible (see also WP 1.1). The extensions of the ΩMEGA system, such as the *interactive island proof sketches*, are best demonstrated in [Siekmann *et al.*, 2003]. The insights gained from the case study also provided additional motivation for work on *proofs at the assertion level* with different types of *underspecification* [Autexier *et al.*, 2003a; Benzmüller *et al.*, 2003d], the CORE system [Autexier, December 2003], and the task level [Hübner *et al.*, 2004]; see also Sections A.1(1.1) and A.2(1.2).

3.4: Modeling of existing systems as Mathematical Services

(Task Leader: IRST) The work in this Task has mainly concentrated on two aspects. First, the required infrastructure (languages, protocols, semantic specifications, architectural schemata) for making existing systems inter-operate, has been developed. Second, the extensions and enhancements of the reasoning capabilities of some existing tools has been addressed. The relevant contributions are: (i) MathSat framework developed at ITC-IRST/DIT [Audemard *et al.*, 2002b; 2002a; 2002c; 2003; Bozzano *et al.*, 2004], (ii) the RDL (Rewrite and Decision procedure Laboratory), (iii) the LBA [Armando and Zini, 2000; 2001; Zimmer *et al.*, 2001] developed by UGE, (iv) the modeling of existing systems, for instance, $\lambda Clam$ developed at UED [Richardson *et al.*, 1998], as mathematical services in MathWeb-SB developed at USAAR [Dennis and Zimmer, 2002].

Theorem proving and proof transformation systems have also been described as Mathematical Web Services [Zimmer *et al.*, 2004] in the new MathServ framework originating from MathWeb-SB. MathServ is currently developed by the young researcher Jürgen Zimmer at USAAR and UED in his PhD thesis.

MSDL [Caprotti and Schreiner, 2002d] is an XML instance that allows to represent the following concepts: mathematical problems , algorithms solving problems, software implementations of algorithms, machines as execution platforms for implementations, WSDL-described services located on these machines, and realizations that link implementations to services. The description of a mathematical service is thus highly structured which allows to build libraries of reusable concept descriptions that may be shared by different services.

Further work at USAAR has concentrated on the mediation of mathematical knowledge between the mathematical knowledge base MBASE, which has been integrated to the MathWeb-SB, and mathematical assistant systems such as ΩMEGA [Franke *et al.*, 2002; Benzmüller *et al.*, 2003f; 2001e].

3.5: Challenge mathematical problems (see also the contract amendment)

(Task Leader: UKA, UBIR) In accordance with the amendments mentioned in section A the work in this Task can roughly be categorised as follows:

1. Formalize and mechanize challenging and so far unformalized areas of mathematics in an intuitive and human-oriented way.
2. Certify interesting, non-trivial computer algebra computations in order to provide more reliability and possibly additional insights into their solution.
3. Provide automated support for mathematical tasks that are infeasible for human mathematicians and that could therefore lead to new mathematical results.

Under point 1 particularly interesting work was carried out by EUT and UWB. The former fully formalized a constructive proof of the fundamental theorems of algebra and calculus, which involved the development of a large library of constructive algebra and analysis that is now available for use by others [Geuvers *et al.*, 2001; Cruz-Filipe, 2003]. The latter formalized in the MIZAR library major parts of the book *A Compendium of Continuous Lattices* [Gierz *et al.*, 1980] (see [Bancerek and Endou, 2001] ff.) the proof of the Jordan Curve Theorem (see [Korniłowicz *et al.*, 2001] ff.), the theory of random access Turing machines (see [Korniłowicz, 2001b] ff.), and some functional analysis (see [Kotowicz, 2003c] ff.) (here most of the work was done in cooperation with Japanese partners from Nagano).

For point 2 UKA together with partners from La Rioja deductively analyses the correctness of algorithms for homological algebra. In joint work between EUT, UBIR, and USAAR the first steps towards proving non-isomorphisms in graph theory have been made by successfully certifying solutions to permutation group problems [Cohen *et al.*, 2003b].

With respect to point 3 joint work by USAAR, UBIR, UED and young researcher Simon Colton (at UKA) led to tool support for exploration in finite algebra. They were successfully applied to exploration and classification tasks in the domain of residue classes [Meier and Sorge, 2001; Meier *et al.*, 2001a; 2002b; 2002d] as well as further developed to lead to new classification results for non-associative algebras as described in Section A.1 point 3.5 [Colton *et al.*, 2004b; Sorge *et al.*, 2004b].

4.1, 4.2, 4.3: Training

See Sections B.7 and B.8.

5.1, 5.2, 5.3, 5.4: Dissemination of Results

See Section B.6.3.

A.3 Joint Publications and Patents (4th year)

We give an overview on the Networks' list of *joint* publications (i.e. publications with authors from two different nodes of the Network) in the fourth year. We list some additional papers and explicitly justify why they should be considered as joint publications. Some other EU research training networks even categorize publications as joint publications if they have been published in a Book, Special Journal Issue or Proceedings that has been edited by a senior researcher of the network. We abstain here from this, since this would include a high percentage of articles that appeared in the Networks' proceedings listed below.

As the reader already may have noticed, the underlined neames in our citations and references refer to young researchers that have been employed by the network. We want to point to the impressive overall publication output of our young researchers as documented by the underlined names in the Overall CALCULEMUS Bibliography at the end of this document.

Books, Journal Issues, Proceedings, Proposals (Involvement of Network as a whole)

[1] C. Benzmüller, editor. *Special Issue on Mathematics Assistance Systems*. Journal of Applied Logic, Elsevier, 2005. To appear.

[2] Christoph Benzmüller and Dieter Hutter. Calculemus-II: Computer-supported mathematical knowledge evolution. Project proposal for a Marie Curie Research Training Network within the EU 6th framework, 2003.

[3] Christoph Benzmüller and Wolfgang Windsteiger, editors. *Proceedings of the IJCAR 2004 Workshop on Computer-Supported Mathematical Theory Development*, number 04-14 in RISC Report Series, RISC Institute, University of Linz, July 2004. University College Cork, Ireland. ISBN 3-902276-04-5. Available at http://www.risc.uni-linz.ac.at/about/conferences/IJCAR-WS7/.

[4] Therese Hardin and Renaud Rioboo, editors. *Proceedings of the 11th Symposium on the Integration of Symbolic Computation and Mechanized Reasoning (CALCULEMUS 2003)*, Rome, Italy, 2003. MMIII ARACNE EDITRICE S.R.L. (ISBN 88-7999-545-6).

[5] F. Wiedijk. The fifteen provers of the world. Unpublished Draft available at `http://www.cs.kun.nl/~freek/notes/index.html`.

Book Contributions

[1] Alessandro Armando, Luca Compagna, and Silvio Ranise. Rewrite and decision procedure laboratory: Combining rewriting, satisfiability checking, and lemma speculation. In D. Hutter and W. Stephan, editors, *Festschrift in Honour of Prof. Jörg Siekmann*, LNAI. Springer, 2004. To appear.

[2] Christoph Benzmüller, Andreas Meier, and Volker Sorge. Bridging theorem proving and mathematical knowledge retrieval. In Dieter Hutter and Werner Stephan, editors, *Mechanizing Mathematical Reasoning: Techniques, Tools and Applications; Festschrift in Honour of Jörg Siekmann*, volume 2605 of *LNAI*. Springer Verlag, Berlin, Germany, 2003. to appear.

[3] Manfred Kerber and Martin Pollet. On the design of mathematical concepts. Norman Foo's Festschrift, eds., Abhaya Nayak and Maurice Pagnucco, November 2003. see, `http://www.cse.unsw.edu.au/~ksg/Norman/`.

Refereed Journal Articles

[1] Serge Autexier, Christoph Benzmüller, Armin Fiedler, Helmut Horacek, and Bao Quoc Vo. Assertion-level proof representation with underspecification. *Electronic in Theoretical Computer Science*, 93:5–23, 2003. (Publication with YVR who benefitted from training at at least two nodes of the Calculemus network).

[2] Malte Hübner, Serge Autexier, Christoph Benzmüller, and Andreas Meier. Interactive theorem proving with tasks. *Electronic Notes in Theoretical Computer Science*, 2004. To appear. (Publication with YVR who benefitted from training at at least two nodes of the Calculemus network).

[3] Mateja Jamnik, Manfred Kerber, Martin Pollet, and Christoph Benzmüller. Automatic learning of proof methods in proof planning. *Logic Journal of the IGPL*, 11(6):647–673, November 2003. 2003.

[4] G. Sutcliffe, J. Zimmer, and S. Schulz. TSTP Data-Exchange Formats for Automated Theorem Proving Tools. In V. Sorge and W. Zhang, editors, *Distributed and Multi-Agent Reasoning*, Frontiers in Artificial Intelligence and Applications. IOS Press, 2004. (to appear).

Refereed Conference and Workshop Articles

[1] Alessandro Armando and Luca Compagna. An optimized intruder model for SAT-based model-checking of security protocols. In *Proceedings of the IJCAR04 Workshop on Automated Reasoning for Security Protocol Analysis (ARSPA)*, Cork, Ireland, July 4, 2004.

[2] Alessandro Armando and Luca Compagna. SATMC: a SAT-based model checker for security protocols. In *9th European Conference on Logics in Artificial Intelligence (JELIA'04)*, LNAI, Lisbon, Portugal, September 27-30, 2004. Springer-Verlag.

[3] Alessandro Armando, Luca Compagna, and Yulyia Lierler. Automatic compilation of protocol insecurity problems into logic programming. In *9th European Conference on Logics in Artificial Intelligence (JELIA'04)*, LNAI, Lisbon, Portugal, September 27-30, 2004. Springer-Verlag.

[4] Yannick Chevalier, Luca Compagna, Jorge Cuellar, Paul Hankes Drieslma, Jacopo Mantovani, Sebastian Mödersheim, and Laurent Vigneron. A High Level Protocol Specification Language for Industrial Security-Sensitive Protocols. In *Proceedings of SAPS'2004*. 2004, to appear.

[5] Alessandro Cimatti, Marco Roveri, and Daniel Sheridan. Bounded Verification of Past LTL. In *Proc. FMCAD 2004: Formal Methods in Computer-Aided Design*, Austin, Texas, 2004.

[6] Simon Colton, Andreas Meier, Volker Sorge, and Roy McCasland. Automatic generation of classification theorems for finite algebras. In David Basin and Michael Rusinowitch, editors, *Automated Reasoning — 2nd International Joint Conference, IJCAR 2004*, volume 3097 of *LNAI*, pages 400–414, Cork, Ireland, July 4–8 2004. Springer Verlag, Berlin, Germany.

[7] Hazel Duncan, Alan Bundy, John Levine, Amos Storkey, and Martin Pollet. The use of data-mining for the automatic formation of tactics. In Christoph Benzmüller and Wolfgang Windsteiger, editors, *IJCAR-Workshop: Computer Supported Mathematical Theory Development*, pages 61–71, Cork, Ireland, 2004.

[8] Helmut Horacek, Armin Fiedler, Andreas Franke, Markus Moschner, Martin Pollet, and Volker Sorge. Representation of mathematical concepts for inferencing and for presentation purposes.

[9] M. Jamnik, M. Kerber, M. Pollet, and C. Benzmüller. Automatic learning of proof methods in proof planning. In *Proceedings of the 9th Workshop on Automated Reasoning: Bridging the Gap between Theory and Practice*, pages 1–2, London, England, 2002.

[10] Martin Pollet, Volker Sorge, and Manfred Kerber. Intuitive and formal representations: The case of matrices. In Andrzej Trybulec, editor, *Mathematical Knowledge Management, Second International Conference, MKM 2004*, volume 3119 of *LNCS*, Bialowieza, Poland, September 19–21 2004. Springer Verlag, Berlin, Germany.

[11] Volker Sorge, Simon Colton, Andreas Meier, and Roy McCasland. A grid-based application of machine learning to model generation. In Susanne Biundo, Thom Frühwirth, and Günther Palm, editors, *KI 2004: Advances in artificial intelligence : Joint German/Austrian Conference on AI, Work in Progress Papers*, Ulm, Germany, September 20–24 2004. In Print.

[12] Dimitra Tsovaltzi, Helmut Horacek, and Armin Fiedler. Building hint specifications in a NL tutorial system for mathematics. In *Proceedings of the 16th International Florida AI Research Society Conference (FLAIRS-04)*, Florida, USA, 2004. (Publication with YVR who benefitted from training at at least two nodes of the Calculemus network).

[13] M. Wolska, B. Quoc Vo, D. Tsovaltzi, I. Kruijff-Korbayova, E. Karagjosova, H. Horacek, M. Gabsdil, A. Fiedler, and C. Benzmüller. An annotated corpus of tutorial dialogs on mathematical theorem proving. In *Proceedings of International Conference on Language Resources and Evaluation (LREC 2004)*, Lisbon, Potugal, 2004. ELDA. (Publication with YVR who benefitted from training at at least two nodes of the Calculemus network).

PhD thesis (jointly supervised)

[1] Serge Autexier. *Hierarchical contextual reasoning*. PhD thesis, Computer Science Department, Saarland University, Saarbrücken, Germany, December 2003. (Benefitted from collaboration with visiting young researchers of the network).

[2] Seungyeob Choi. *The Use of Pre-computed Models for the Guidance of Proof Search*. PhD thesis, The University of Birmingham, 2003.

[3] Adrian Craciun. *Program Synthesis in the Context of Systematic Theory Exploration*. PhD thesis, RISC Institute, Johannes Kepler University Linz, A-4040 Linz, Austria, 2005. Ongoing.

[4] Andreas Meier. *Proof planning with multiple strategies*. PhD thesis, Computer Science Department, Saarland University, Saarbrcken, Germany, January 2004. (Benefitted from training at at least two nodes in the Calculemus network).

Technical Reports and Others

[1] Simon Colton, Andreas Meier, Volker Sorge, and Roy McCasland. Automatic generation of classification theorems for finite algebras.

A.4 Joint Publications and Patents (all four years)

The Network has produced significant publications in different catogories and it is hard to define which are the five most significant ones. We here list five examples of significant papers and refer to the list below for further references.

Five examples of significant joint publications

[1] Jacques Calmet, Belaid Benhamou, Olga Caprotti, Laurent Henocque, and Volker Sorge, editors. *CALCULEMUS-2002: Symposium on the Integration of Symbolic Computation and Mechanized Reasoning*, volume 2385 of *LNAI*. Springer, 2002.

[2] Arjeh Cohen, Scott H. Murray, Martin Pollet, and Volker Sorge. Certifying solutions to permutation group problems. In F. Baader, editor, *Proceedings of the 19th International Conference on Automated Deduction (CADE-19)*, volume 2741 of *Lecture Notes in Artificial Intelligence*, pages 258–273, Miami, 2003. Springer-Verlag.

[3] Simon Colton, Andreas Meier, Volker Sorge, and Roy McCasland. Automatic generation of classification theorems for finite algebras. In David Basin and Michael Rusinowitch, editors, *Automated Reasoning — 2nd International Joint Conference, IJCAR 2004*, volume 3097 of *LNAI*, pages 400–414, Cork, Ireland, July 4–8 2004. Springer Verlag, Berlin, Germany.

[4] G. Sutcliffe, J. Zimmer, and S. Schulz. Communication Fomalisms for Automated Theorem Proving Tools. In V. Sorge, S. Colton, M. Fisher, and J. Gow, editors, *Proceedings of the Workshop on Agents and Automated Reasoning, 18th International Joint Conference on Artificial Intelligence*, 2003.

[5] F. Wiedijk. The fifteen provers of the world. Unpublished Draft available at `http://www.cs.kun.nl/~freek/notes/index.html`.

Notes [1] is a joint publication at the prestigious CADE conference with authors from ITC-IRST/DIT and UWB; two of the authors were young researchers in the Network; high dissemination effect.

[2] is an example for our numerous Calculemus proceedings with a very high dissemination effect. These proceedings contain several contributions from the Network and three of the editors (Calmet/UKA, Caprotti/RISC, Sorge/UBIR) are senior researchers in the Calculemus Network.

[3] is a joint publication at the prestigious CADE conference with authors from TUE, UBIR, USAAR; two of the authors were young researchers in the Network; high dissemination effect.

[4] is a joint publication at the prestigious IJCAR conference with authors from UED, UBIR, USAAR; two of the authors were young researchers (Pollet and Murray) in the Network; high dissemination effect.

[5] will appear as a book in the Springer LNAI series. This book presents a comparison between proof assistants by having a proof of the irrationality of the square root of two in sixteen different proof assistants — including the Networks systems Mizar, ΩMEGA, Theorema, and Coq. This work has been widely acknowledged also outside the Calculemus community and has a very high dissemination effect.

List of all Joint Publications

See the introductory comment in Section A.3.

Books, Journal Issues, Proceedings (Involvement of Network as a whole)

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PhD thesis (jointly supervised)

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Chapter B

Part B – Comparison with the Joint Programme of Work (Annex I of the contract)

B.1 Research Objectives (4th year)

Achieving the CALCULEMUS Network's long-term goal of developing all embracing mathematical assistance systems for application in formal methods, maths research and maths teaching is indubitably ambitious and can be realized only by a sustainable integrated research effort at an international level. The CALCULEMUS Network, as part of the CALCULEMUS initiative, has made a crucial first step in this direction. As most important result CALCULEMUS has created a very active, lively, and sustainable research community with an increasing number of joint satellite activities. It has particularly fostered the integration of systems and the consolidation of resources amongst CALCULEMUS consortium partners as well as with the wider research community.

The main scientific research objective of the CALCULEMUS Network was to foster the integration of deduction systems (DS) and computer algebra systems (CAS) both at a conceptual and at a practical level. The point of origin for this kind of research is a landscape of heterogeneous approaches and systems on both sides of the spectrum, where the diversity on the DSs side is probably greater than on the side of CASs.

Since its start in September 2000 the CALCULEMUS Network has contributed to the convergence of DSs and CASs through its research on unifying frameworks for encoding and combining computation and deduction, the identification of the architectural requirements for a new generation of reasoning systems with combined reasoning and computational power, and the prototypical implementation and application of the improved systems. However, a single predominant theoretical framework is currently not possible. Such an approach would particularly involve predominant solutions to the still rather diverging systems at both sides of the spectrum between DSs and CASs. Therefore a strong line of research has focused on the modeling and integration of CASs and DSs at the systems layer. In this research direction, significant progress has been made and several systems of project partners and other research institutes have been connected in order to form networks of cooperating mathematical service systems. The benefits and impacts of such integrations have been investigated in prototypical case studies.

In Sections A.1 and A.2 (and in the reports send to the EU before) we have given an overview on the Networks research results. There we have also given references to relevant documents that describe our research results in more detail and we have given URL's to homepages of prototype systems developed in the Network such as THEOREMA and ΩMEGA; these systems are free for download and the homepages also contain system documentations.

B.2 Research Method (4th year)

Our research methodology distinguishes between a horizontal and a vertical dimension. The challenge at the horizontal level is to overcome the technological fragmentation of the field in various approaches, systems, and tools. On the vertical axis the challenge is to support the transition from prototype developments and case studies to industrial strength systems and applications; the latter long term goal however has not been sufficiently achieved yet and requires further efforts as have been proposed for CALCULEMUS-II; see [Benzmüller and Hutter, 2003].

The overall technological approach on the horizontal level is bottom-up (see Figure B.1) from existing tools towards integrated mathematical assistance environments. Thereby the careful selection and adaptation of individual tools as well as the systematic improvement of the interoperability of these tools is at the heart of CALCULEMUS research. This bottom-up strategy has been refined and successfully pursued in the fourth year of CALCULEMUS.

This methodological approach and the break down of the work program into single tasks has

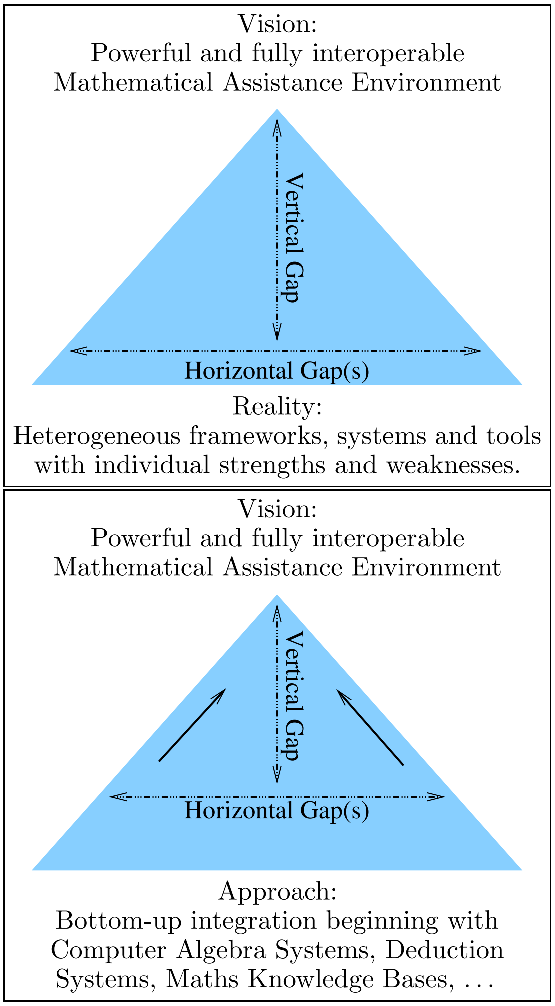

Figure B.1: Methodological approach

turned out to be successful.

B.3 Work Plan (4th year)

The early delay in scientific and young researcher employment terms which has been reported in the mid-term report has been completely resolved during the final two years of the Network. Especially in the fourth year the Network did have to face the problem that there were several highly qualified applicants for young researcher positions that could not be taken into due to the lack of funding resources.

B.4 Research Achievements (all four years)

The research and training as envisioned in Calculemus requires the combination of techniques and expertise from several areas. There is currently no single university (in Europe as well as worldwide) providing all the necessary expertise, background, and resources to ensure a full coverage of the heterogeneous spectrum of research aspects of our research. As a consequence, a high quality research training of prospective young researchers in this multidisciplinary area can only be achieved today by joining forces in computer algebra, formal methods, interactive and automated theorem proving as well as software engineering.

Standard training of students typically builds upon direct (one-to-one) student supervision as the introductory literature covering and structuring all relevant research is not yet available. Even worse, interactive and automated theorem proving, i.e. two of the important research fields addressed by the project, are currently rather diverting than consolidating in terms of scientific approaches. This is one of the reasons why the scientific background of most young researchers today is usually limited to the actual supervising group only.

A very important function of the Calculemus RTN has been to attack and avoid the potential problems of this strong focusing by (jointly) building complex and powerful mathematical assistance systems. Above all, this goal requires a good overview of the state of the art in the related research fields in order to combine and adapt the most promising individual approaches. Evidence for the impact and success of the Calculemus training is inter alia provided by the numerous joint research results and joint applications of our young researchers network. Several PhD theses that do strongly benefit from and contribute to the joint Calculemus initiative are in progress or have been already finished meanwhile.

The project objectives as laid down in the work program are

1. *outline the design of a new generation of mathematical software systems and computer-aided verification tools;*
2. *training of young researchers in the broad field of mechanical reasoning and formal methods;*
3. *dissemination of the results both in industry and in academia; and*
4. *the cross-fertilisation and amalgamation of the automated theorem proving (ATP/DS), computer algebra (CAS), term rewriting systems (TRS), interactive proof development systems (ITP) and software engineering (SE) research communities.*

We discuss the Networks' achievements w.r.t. these objectives individually:

(1) In all work packages the Network has achieved results that relate to and implement the proposed work plan. Probably the most unfortunate result of the Network is that a single predominant theoretical framework for the integration of symbolic reasoning and symbolic computation is currently not possible. Such an approach would particularly involve predominant solutions to the still rather diverging systems

at both sides of the spectrum between DSs and CASs. Therefore a strong line of research in the Network has focused on the modeling and integration of CASs and DSs at the systems layer. In this research direction, significant progress has been made and several systems of project partners and other research institutes have been connected in order to form Networks' of cooperating mathematical service systems. The Network has presented its ideas on the design of a new generation of mathematical software systems and computer-aided verification tools in various books, special journal issues and proceedings (see also Section A.4); here we especially want to point to the CALCULEMUS-II proposal [Benzmüller and Hutter, 2003] (which very precisely presents the Networks' vision for future generation of mathematical assistance systems). Furthermore, we want to point to the British Royal Society Event on the 'Notion of Mathematical Proof' that has been initiated by Alan Bundy. Not least at this meeting (Alan Bundy and Hank Barendregt gave presentations) we entered a stimulating discussing with world leading mathematicians on the prospects of mathematics assistance systems for applications in mathematics research.

(2) A new generation of young researchers has been trained that have build up a broad overview of the field and, in particular, have developed very detailed knowledge about the research of the individual CALCULEMUS training sites and much beyond. Our joint training of young researchers has fostered the creation of a very active, lively, and sustainable research community with an increasing number of joint satellite activities — especially between the young researchers. The training measures and in particular the very successful Autumn School 2002 in Pisa provided world leading teaching in the wide spectrum between symbolic computation and symbolic reasoning.

Selected young researchers have additionally gained experience in industry internships. In addition to the young researchers directly employed by the Network (see Figure B.3) many further young researchers funded by other sources at the individual Network sides have strongly benefitted from the improved collaboration, the Networks' training measures, and in particular from direct collaboration with visiting young researchers. An example is Sungyeop Choi, a young researcher at UBIR, who was not eligible in FP5; he strongly benefitted in his CALCULEMUS relevant PhD work from collaboration with the visiting young researchers Martin Pollet and Andreas Meier.

(3) Dissemination of results in academia was very high; this is reflected by the list of joint publications as reported in Section A.4 and furthermore by the list of all CALCULEMUS related publications as presented in the overall CALCULEMUS bibliography of this report in Section C. CALCULEMUS supported papers have been presented at merely all major conferences in the area including: CADE, IJCAR, ECAI, ISSAC, CALCULEMUS, MKM.

CALCULEMUS has also organized several affiliated workshops at CADE, IJCAR and IJCAI.

The Network has produced more than 100 joint publications, more than 350 Network related publications which include more than 150 publications authored or co-authored by young researchers of the Network. Several PhD theses that do strongly benefit from and contribute to the joint CALCULEMUS initiative are in progress or have been already finished meanwhile.

Dissemination of results to industry was fostered by the selected industry internships of young researchers as well as by the preparation of the CALCULEMUS-II proposal. For CALCULEMUS-II we were able to attract several additional industry partners (mainly from the formal methods area; including INTEL, NASA, and SRI International) to participate; see the expressions of interest attached [Benzmüller and Hutter, 2003].

(4) CALCULEMUS has become a leading force in the amalgamation of the automated theorem proving (ATP/DS), computer algebra (CAS), term rewriting systems (TRS), interactive proof development systems (ITP) and software engineering (SE) research communities. We particularly fostered this by collocating our yearly CALCULEMUS symposia with the main conferences in the above areas; see Section B.6.4.

B.5 Organization and Management (4th year)

Organizational and management measures such as budget shifts in the fourth year (cf. contract ammendment (3)) made it possible to better balance the recruitment situation of young researchers in the Network as a whole and to reach the impressive overall recruitment figures as reported in section B.8.

B.6 Overall Organization and Management (all four years)

B.6.1 Co-ordination, Organization, and Management

The CALCULEMUS Network has been coordinated by a team consisting of: Dr. Christoph Benzmüller and Prof. Jörg Siekmann from USAAR and Corinna Hahn from EURICE GmbH. EURICE GmbH has been responsible, e.g., for organizational and budgeting issues, and for communication with the EU. Dr. Christoph Benzmüller was responsible for the scientific and overall coordination of the Network and thereby he was supported by the experience of Prof. Jörg Siekmann. This way Dr. Benzmüller, who would have been eligible as young researcher in the Network himself, has been significantly trained in the coordination of large research networks. This construction has turned out to be effective and fruitful and can be further recommended.

B.6.2 Communication Strategy

The main communication means of the Calculemus Network are:

- E-mail lists such as `calculemus-ihp@ags.uni-sb.de`
- Common database: A Concurrent Versions System (CVS) repository maintained by the coordinator at USAAR provides access to all important Network data and documents. This CVS repository stores data such as the Network reports, the bibliography of the research teams in Bibtex format, talks, publications, figures and tables, information material, etc. The url `www.ags.uni-sb.de/~chris/calculemus-cvs/` provides a web-based access to this repository. Extending the capabilities of web-sites CVS supports the *direct* joint development of documents such as the Calculemus Network report [Benzmüller, 2003c] and this report; for this purpose it has proved far more flexible and useful than information exchange solely via e-mail or web-pages. CVS particularly provides conflict resolution tools.
- Web-sites:
  - The Networks' main web-page (`www.eurice.de/calculemus/`) provides various scientific, administrative, and internal information. It furthermore links to the locally maintained individual web-sites of the different research teams.
  - The individual web-sites of the different research teams provide an overview on their particular research tasks and their internal organizational structure.

B.6.3 Dissemination of Results

Calculemus has become a leading force in the amalgamation of the automated theorem proving (ATP/DS), computer algebra (CAS), term rewriting systems (TRS), interactive proof development systems (ITP) and software engineering (SE) research communities. We particularly fostered this by collocating our yearly Calculemus Symposia with the main conferences in the above areas; see Section B.6.4.

The Calculemus research program has been defined with the aim to subsequently increase the join of resources in the DS and CAS research communities — not only in terms of joint case studies (see also Table B.2) but in particular with respect joint system development and tool exchange (see Table B.1). This clearly fosters long-term and durable collaborations for the future which are often not easily revertible. Many examples for smaller projects that concentrate on very specific aspects of joint research and tool development have been fostered; examples are given in Table A.1.

Dissemination of results has been fostered also by an impressive list of publications at a wide range of conferences, workshops, symposia, journals and books; see Section A.4 and the overall Calculemus publications presented at the end of this document. Calculemus papers have been presented at merely all important conferences in the area including: CADE, IJCAR, ECAI, ISSAC, CALCULEMUS, MKM. In summary the Network has produced more than 100 joint publications, more than 350 Network related publications which include more than 150 publications authored or co-authored by young researchers of the Network. Several PhD theses that do strongly benefit from and contribute to the joint CALCULEMUS initiative are in progress or have been already finished meanwhile.

The very successful Autumn School 2002 in Pisa provided world leading teaching in the wide spectrum between symbolic computation and symbolic reasoning and was open and did attract further attendees (studenst as well as researchers) from outside the community.

Similarly the symposia and workshops listed in Section B6.4 were open events (except for the internal Network meetings) and they were typically collocated with other major international conferences to foster interaction and dissemination.

B.6.4 Conferences, Workshops, and Network Meetings

The Calculemus Network organized or participated in the scientific events listed below. These events were particularly used for frequent scientific discussions and the training of young researchers.

- Calculemus **Symposium in St. Andrews**, Scotland, August 6th-7th, 2000. The Calculemus Symposium 2000 was collocated with the International Symposium on Symbolic and Algebraic Computation, ISSAC 2000.

  Highlight of the event was the invited talk by Gaston Gonnet, Institute for Scientific Computation, ETH Zürich, Switzerland, and the joint invited talk by Prof. Henk Barendregt, Nijmegen University and Prof. Arjeh Cohen, TUE.

  Contributions of the event were published as a book by A.K.Peters [Kerber and Kohlhase, 2001] and selected papers did appear in a Special issue of the Journal of Symbolic Computation [Recio and Kerber, 2001].

- CALCULEMUS **Symposium in Siena**, Italy, June 21st-22nd, 2001. The CALCULEMUS Symposium 2001 was held in conjunction with the International Joint Conference on Automated Reasoning (IJCAR). This event particularly fostered the interaction of the CALCULEMUS community with the deduction systems community. As a result CALCULEMUS became a full member of the IJCAR conference 2004 in Cork, Ireland.

  Highlight of the CALCULEMUS Symposium 2001 was the invited talk of Prof. Doron Zeilberger, Department of Mathematics, Temple University , Philadelphia, USA.

  Selected papers of the proceedings were published in a special issue of the Journal of Symbolic Computation [Linton and Sebastiani, 2002b].

  Participants: approx. 70

- CALCULEMUS **Network Meeting in Genova**, Italy, February 14th-15th, 2002:
  This internal meeting was used to identify and discuss the Networks' main bottlenecks. The two days meeting was split into a scientific part and an organizational part. The scientific part was used to discuss the current state of all work packages. The emphasis, however, was on the work packages 1 and 2. In the organizational part measures were discussed and decided to improve the internal communication strategy and to force better young researcher hiring strategies; see also Section B.10. Furthermore, the organization of the CALCULEMUS Autumn School was addressed.

  Participants: 31
  Network Participants: 31

- CALCULEMUS **Symposium in Marseille**, France, July 3rd-5th, 2002: The CALCULEMUS Symposium 2002 (`www.ags.uni-sb.de/~calculemus2002`) was held in conjunction with the AISC 2002 Conference: Artificial Intelligence and Symbolic Computation – Theory, Implementations, and Applications. The joint event (with joint proceedings in the Springer LNAI series; see [Calmet *et al.*, 2002] in publication list) fostered the interaction of the CALCULEMUS interest group and the symbolic computation community. Highlights of the event were the invited talks of Prof. Claude Kirchner, INRIA Paris, France, and Prof. Thomas Sturm, University Regensburg, Germany, and the CologNet Panel Discussion on *Challenge Mathematical Problems* chaired by Prof. Jacques Calmet with Prof. Alain Colmerauer, Prof. James Davenport, Prof. Claude Kirchner, Prof. Jörg Siekmann, and Prof. Thomas Sturm as panelists.

  Work in progress papers, including contributions of young researchers from the CALCULEMUS Network, are published in [Caprotti and Sorge, 2002].

  Participants: approx. 45
  Network Participants: approx. 18

- MONET-CALCULEMUS Workshop, Hagenberg Castle, Linz, Austria, November 2002; see `poseidon.risc.uni-linz.ac.at:8080/results/seminars/mathbrokerWS.html`. This workshop has been organized by O. Caprotti to foster the collaboration between CALCULEMUS and the EU project MONET (project number IST-2001-34145). In MONET special ontologies comprising mathematical problems, queries and services have been defined and investigated.

  Participants: 9
  Network Participants: 4

- CALCULEMUS **Autumn School**, Pisa, Italy, September 23th - October 4th, 2002. More details on this central training event of the Network will be given in Section B.8.2; see also `www.eurice.de/calculemus/autumn-school/`. The course notes of the event are published in [Benzmüller and Endsuleit, 2002a; 2002b; 2002c] and the student poster abstracts in [Zimmer and (eds.), 2002].

  Participants: $\geq$ 75
  Network Participants: approx. 30

- CALCULEMUS **Midterm Review Meeting**, Saarbrücken, Germany, 2003. The official midterm report is published in [Benzmüller, 2003c] and [Benzmüller and Hahn, 2003]. The program of the midterm review meeting is available via the Networks' CVS repository `http://www.ags.uni-sb.de/~chris/calculemus-cvs/mtr-meeting/mtr-meeting.html`. There were 18 senior researchers from the Network and 13 young researchers present. Each head of node and seven young researchers gave presentations. Further young researchers presented their work in a poster session.

  Participants: 32
  Network Participants: 31

- **Theorema-ΩMEGA Workshop at RISC Hagenberg Castle**, Austria, May, 2003 (`http://www.ags.uni-sb.de/~omega/workshops/TheoremaOmega03/`) In this training meeting two of the Networks' mathematical assistance systems were presented and discussed in detail: the THEOREMA system and the ΩMEGA system. Senior researchers of the Network and further affiliated researchers gave tutorial talks and young researchers of the Network presented their ongoing research projects.

  Participants: 27
  Network Participants: 16

- **International Joint Workshop "Mathematics on the Semantic Web"**, Eindhoven, The Netherlands, May 12-14, 2003; see (`http://www.openmath.org/meetings/eindhoven2003/`). This workshop with participants from the following networks / research initiatives: MONET, CALCULEMUS, MKM, Types, OpenMath, and MoWGLI was jointly organized by MONET and CALCULEMUS. It has been used to disseminate results, stimulate collaborations between related research initiatives and to train young researchers. Each particpating group did organize a special track were their particular research goals and achievements were presented and discussed.
- CALCULEMUS **Symposium in Rome**, Italy, September 2003 (`http://www-calfor.lip6.fr/~rr/Calculemus03/`) The Symposium was held in conjunction with Theorem Proving and Higher Order Logics (TPHOL 2003) and Automated Reasoning with Analytic Tableaux and Related Methods (TABLEAUX 2003). The proceedings of this CALCULEMUS meeting are published in [?]. The invited speakers where Thierry Coquand and James Davenport. Selected papers of the event will be published also in a special issue of the Journal of Symbolic Computation [Hardin and Rioboo, 2004].

  Participants: approx. 60
  Network Participants: approx. 25
- **IJCAR Conference** and CALCULEMUS **Workshop 'Computer-Supported Mathematical Theory Development'** in Cork, Ireland, July 2004. In 2004 the CALCULEMUS Symposium joined the International joint Conference on Automated Reasoning (IJCAR; see `http://4c.ucc.ie/ijcar/index.html`) as a constituent meeting; C. Benzmüller was a member of the IJCAR Steering Committee. The IJCAR proceedings are published as [Basin and Rusinowitch, 2004].

  In order to also provide a platform for the discussion of less polished and ongoing work the additional Workshop on *Computer-Supported Mathematical Theory Development* was organized by the Network; see `http://www.risc.uni-linz.ac.at/about/conferences/IJCAR-WS7/`. The proceedings of this workshop are published in [Benzmüller and Windsteiger, 2004a]. The highlight of this workshop was the invited talk by Prof. Lawrence Paulson from Cambridge University and the panel discussion CALCULEMUS *Quo Vadis?* organized by Jörg Siekmann, Jacques Calmet, Christoph Benzmüller, and Wolfgang Windsteiger. This Workshop was the last event in which the complete Network did meet before the end of the project in August 2004.

  Participants at Workshop: approx. 35
  Network Participants: approx. 20
- **Several Task Force Meetings**. Special task force meetings were held in conjunction with CALCULEMUS Network meetings in
  - CALCULEMUS Network Meeting in Siena, Italy, June 2001
  - CALCULEMUS Symposium in Marseilles, France, July 2002
  - CALCULEMUS Autumn School in Pisa, September/October Italy 2002
  - CALCULEMUS Midterm Review Preparation Meeting in Saarbrücken, Germany, March 30 2003
  - CALCULEMUS Network Meeting in Saarbrücken, Germany, April 1 2003
  - CALCULEMUS Network Meeting in Eindhoven, The Netherlands, May 12-14, 2003.
  - CALCULEMUS Network Meeting in Rome, Italy, September, 2003
  - CALCULEMUS Network Meeting at the MKM Symposium in Edinburgh, Scotland, November 2003, 2003
  - CALCULEMUS Network Meeting at IJCAR 2004 in Cork, Ireland, July 2004
  - CALCULEMUS Network Meeting at MKM 2004 in Bialystok, Poland, September 2004

  Participants: approx. 5-20
  Network Participants: 5-20
- **Further Conferences, Workshops and Tutorials** Senior researchers and young researchers of the CALCULEMUS Network did organize or actively participate in several other conferences, workshops and tutorials. Among them are the events as listed in Figure A.1 but also several smaller tutorials organized at the individual Network nodes in which the young researchers got introduced to the local mathematical assistance systems and tools.

B.6.5 Joint System Development and Joint Applications

CALCULEMUS aims at the integration of DS and CAS. As a consequence joint efforts of the Network were spent in the development and enhancement of existing computer algebra systems and deduction systems by turning them into open systems capable of using and providing mathematical services. CALCULEMUS investigated both, the enhancement of Computer Algebra Systems by

System, Language, Software	Developed/used at the following nodes
OMDoc	USAAR,UBIR,UED,UWB
MathWeb	USAAR,UBIR,UGE,UED
ΩMEGA	USAAR,UBIR
MIZAR	UWB,TUE
MathSat	ITC-IRST/DIT,UWB
TSAT++	UGE
Coq	TUE(Eindhoven + Nijmegen)

Table B.1: Joint system development and application in Calculemus

reasoning power as well as the enhancement of Deductive Systems by computation power.

Table B.1 illustrates the joint system developments of the Calculemus partners. It illustrates the impact of the research training network in joining forces. Especially the decision to jointly develop and employ systems and tools stimulates lasting and durable collaborations.

These systems are evaluated and tested with the help of application scenarios given in Table B.2. Some of these examples were done either by single partner nodes or in collaboration between different nodes.

B.7 Training (4th year)

In the fourth year recruitment and training of young researchers was further intensified. Several young researchers have visited a second or even third node in the Network. This is reflected in particular by the increased amount of joint publications with at least one, often even several, young researchers as co-authors. The success of training is also reflected in the career steps and employment situations of our young researchers after their appointment in Calculemus; see Table B.4.

Worth to mention is that for some young researchers (see the list of ogoing PhD projects in Section A.3) the end of Calculemus was very abrupt and scientifically as well as sociologically unfortunate. Our intention when proposing Calculemus-II with a start state as close as possible after the end to Calculemus-I was also to secure much needed support for the ongoing work of some young researcher. Unfortunately, Calculemus-II did not get funded in the call we entered.

B.8 Training Overview (all four years)

B.8.1 Recruitment

The Network as a whole was very successful in the recruitment of young researchers and has delivered more than 40 person months more of training effort than specified as deliverable. Our young researchers were hired from 15 states which demonstrates (in addition to our impressive recruitment figures) the success of our broad recruitment effort. The states are: *Austria Belgium, Bulgaria, Czech Republic, Finland, France, Germany, Hungary, Italy, Netherlands, Poland, Romania, Spain, Sweden, and United Kingdom (England and Scotland)*

The EU wants to foster in particular the training of young researchers in their very early career stages (this position is fully shared by our consortium) and therefore we have put an emphasis on the recruitment of pre-doc researchers (217,25 actual person months versus 167 as deliverable) while at the same time trying to reach the specified overall post-doc person months deliverable (105,3 person months versus 109 deliverable). The Network has been advised at the midterm review meeting that the proposed person training months is a crucial minimal deliverable and we were encouraged to deliver more (ideally on the side of pre-docs) if possible with the available funds. Further details on our recruitment/employment figures are given in Table B.3.

Note that the Networks' actual post-doc figure actually becomes higher than the 105,3 and definitely reaches our deliverable of 109 person months when looking into the very details of individual young researcher employments: while some young researchers did finish their PhD during their employment in the Network they were nevertheless fully calculated as pre-docs; a precise burocratic calculation would consider them as post-docs from the date of their viva. An example is Markus Moschner who received his PhD during his employment at USAAR.

The recruitment figures of the individual nodes however vary according to national academic specifics, problems, and cultures. By overall Network coordination measures (including the budget shifts) we were able to partially counter this problems at the overall Network management level and to achieve the successful overall recruitment figures. With respect to the variations of some individual nodes from the proposed figures we particularly want to point to the contract amendment (3) (see Page 6).

Many of the young researchers trained in the Network are opting for an academic career. A smaller number went to industry or semi-industrial institutions. In Table B.4 we list information on the young researchers training in the Network; e.g. at which sites they have been

Application	performed by the following nodes
Irrationality of $\sqrt{2}$	TUE,USAAR,UWB,RISC
Exploration of Residue Classes	USAAR,UBIR,UED
Permutation Groups	USAAR,UBIR,TUE
Zariski Spaces	UBIR,UED
Hybrid Systems	USAAR,UGE,UED, ITC-IRST/DIT
Correct Functions in MAPLE	UKA,UED,UGE
Formal Analysis of Security Protocols	UED,UGE,ITC-IRST/DIT
Model Checking for Real-Time Systems	ITC-IRST/DIT,UWB,UGE
Temporal Reasoning	ITC-IRST/DIT,UGE

Table B.2: Joint applications and case studies in CALCULEMUS

Participant	Contract Deliverable of Young Researchers to be financed by the contract (person-months)			Young Researchers financed by the contract (person-months)		
	PreDoc (a)	PostDoc (b)	Total (a+b)	PreDoc (c)	PostDoc (d)	Total (c+d)
USAAR	18	15	33	34	9	43
UEDIN	26	16	42	33	3	36
UKA	24	15	39	27,5	9,5	37
RISC	18	13	31	54	10	64
EUT	24	14	38	0	31,8	31,8
ITC-IRST/DIT	26	17	43	22,75	29	51,75
UWB	12	3	15	15	3	18
UNIGE	11	8	19	17	10	27
UBIR	8	8	16	20	0	20
TOTAL	167	109	276	223,25	105,3	328,55

Table B.3: Training/Recruitment Figures after the 4th Year

trained, whether they have done an industry internship and where they are employed now.

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". The report suggests that "Therefore, the total number of graduates in mathematics, science and technology in the European Union should increase by at least 15% by 2010 while at the same time the level of gender imbalance should decrease".

The Network has succesfully contributed to this EU objective and our training measures have been targeting exactly the area of mathematics, science and technology.

B.8.2 CALCULEMUS Autumn School

The CALCULEMUS Autumn School 2002 (see `www.eurice.de/calculemus/autumn-school/`) was held September 23rd — October 4th in Pisa. It was organized in a cooperation between USAAR (Christoph Benzmüller and Jörg Siekmann), UKA (Regine Endsuleit and Jacques Calmet), Eurice GmbH (Corinna Hahn), and University of Pisa (Carlo Traverso).

Two further events were co-located with the event: (i) an OPENMATH workshop and (ii) an MKM Network kick off meeting.

CALCULEMUS Autumn School had more than 75 participants (including the lecturers; some of them did attend all courses as well). The participants split into undergraduates, postgraduates, postdocs, and experienced researches. All young researchers of the Network employed at that time were present. In order to support participation of students from outside the Network 26 student grants were additionally made available in the EU IST program. Due to these grants several students, for instance, from eastern European countries were able to attend the school which could not have attended without support. Since all participants, including the lecturers, were accommodated at the former monestary Santa Croce in Fossabanda, many discussions and interactions were fostered aside from the main program.

The participants were trained both theoretically and experimentally on selected topics and tools. They were given the opportunity to experiment with the main tools of this area and to interact with the researchers developing them.

In addition to representatives from all CAL-

Student	Nationality	Training at	Internship	Current Position
Adams, A.	UK	USAAR		Lecturer (U. of Reading, UK)
Aransay Az., J. M.	ES	UKA, AS		Research Assistant (U. La Rioja)
Audemard, G.	FR	ITC-IRST/DIT		Assistant Professor (Lens)
Carlstrom, J.	SWE	TUE		
Colton, S.	UK	UED, UKA, USAAR, UBIR		Lecturer (Imperial College L., UK)
Compagna, L.	IT	UKA, UGE, UED	Siemens	PhD Student (UGE)
Craciun A.	ROM	RISC, UED, AS		Marie-Curie Fellow (Project e-Austria, Linz, Austria)
De Lucia, P.	IT	USAAR, AS		Industry
De Cabezn, I	ESP	UKA		PhD student (Spain)
Duncan, H.	UK	UED, UWB, USAAR, AS		PhD student (UED)
Fiedler, A,	DE	UED, USAAR		Researcher (USAAR)
Franke, A.	DE	USAAR, UBIR, AS		Research Assistant (USAAR)
Ganty, P.	BE	UGE		
Geleijnse, G.	NL	UWB		
Giero, M.	PL	TUE(KUN)		pre-doc teaching assistant professor (UWB)
Giromini, C.	IT	UGE, USAAR, UED, AS	Motorola, (DFKI)	Industry (Project Manager, Excelsa S.p.A., IT)
Jibetean, D.	ROM	TUE		Post-doc (TUE)
Junttila, T.	FIN	ITC-IRST/DIT		Researcher (Helsinki U., FIN)
Keighren, G.	UK	ITC-IRST/DIT		Researcher (ITC-IRST/DIT)
Kirov, V.	BG	ITC-IRST/DIT,		Industry (Australia)
Kocsis, C.	ROM	RISC		PhD student (RISC)
Kornilowicz, A.	PL	ITC-IRST/DIT		
Researcher (UWB) Lefevre, V.	FR	UKA		Tenured Researcher (LORIA, Nancy, France)
Lesourd, H.	FR	USAAR		Researcher (USAAR)
McNeill, F.	UK	UED, USAAR		PhD student (UED)
Meier, A.	DE	USAAR, UBIR, AS	Bosch	Researcher (DFKI, DE)
Moschner, M.	AUT	USAAR, UWB		Researcher (Vienna U., Austria)
Murray, S	FR	TUE		Marie Curie Postdoc (TUE)
Musset, J.	FR	UKA, UED		Junior Partner (JP Morgan, London, UK)
Pollet, M.	DE	USAAR, UBIR, TUE, UED, AS		Researcher (USAAR)
Ranise, S.	IT	USAAR		Researcher (LORIA, Nancy, France)
Revol, N.	FR	UKA		Tenured Researcher (ENS Lyons, FR)
Rossum, P.v.	NL	ITC-IRST/DIT		Researcher (ITC-IRST/DIT)
Schulz, S.	DE	ITC-IRST/DIT, RISC, UED		Researcher (University of Verona)
Sheridan, D.	UK	ITC-IRST/DIT		Industry (`www.adelard.com/`, UK)
Steel, G.	UK	UED, UKA, UGE		Research Associate (UED)
Stratulat, S.	ROM	UGE		Researcher (U. of Metz, France)
Tsovaltzi, D.	GRE	USAAR		PhD student (USAAR)
Urban, Josef	CZE	UWB		Researcher
Vajda, Robert	HUN	RISC		PhD student (RISC)
Wagner, A	AUT	UKA		Researcher (ETH Zurich, SUI)
Winterstein, D.	UK	UED, RISC		Research Associate (UED)
Zimmer, J.	DE	USAAR, UGE, UED, AS	NAG	PhD student (USAAR)

Table B.4: Examples of PhD projects that contributed to and benefitted from CALCULEMUS; the CALCULEMUS Autumn School in Pisa is abbreviated with AS culemus Network nodes further experts from the field were invited, such as Prof. James Davenport (University of Bath, England), Prof. Tobias Nipkow (TU Munich, Germany) and Prof. Christoph Kreitz (Cornell University, Ithaca, USA). The other lecturers were: Alessandro Armando (UGE), Christoph Benzmüller (USAAR), Bruno Buchberger (RISC), Alan Bundy (UED), Jacques Calmet (UKA), Arjeh Cohen (TUE), Herman Geuvers (Nijmegen University, Netherlands), Fausto Giunchiglia (ITC-IRST/DIT), Dieter Hutter (DFKI, Germany), Manfred Kerber (UBIR), Michael Kohlhase (Carnegie Mellon University, USA), Ursula Martin (University of St. Andrews, Scotland), Andreas Meier (USAAR), Erica Melis (DFKI, Germany), Marco Pistore (ITC-IRST/DIT), Marco Roveri (ITC-IRST/DIT), Jörg Siekmann (USAAR), Volker Sorge (UBIR), Werner Stephan (DFKI, Germany), Czeslaw Bylinski (UWB), Wolfgang Windsteiger (RISC), Tom Kelsey (University of St.Andrews, Scotland), Olga Caprotti (RISC)

We briefly discuss the impact and success of the Autumn School which was in fact the first major international display of *all* major system developers in this interdisciplinary area.

1. Training: The success of the Calculemus Autumn School as a training measure for students has been evaluated by a questionnaire. The evaluation of this questionnaire shows that the overall concept of the school which had many short lectures of max. 3 hours was highly appreciated by the participants. The idea of the school was to provide a complete overview of Calculemus relevant topics instead of picking out just a few single aspects and presenting them in full detail; see also the Course Notes of the Autumn School published in [Benzmüller and Endsuleit, 2002a; 2002b; 2002c].

   This way the participants particularly had the opportunity to get into contact with the research topics and senior researchers from all partner nodes of the Calculemus Network. The questionnaire also shows that Autumn School indeed optimally targeted students at the postgraduate level, since their overall ratings of the School were the best; but also the ratings given by undergraduates and postdocs are highly satisfying.

2. Student Posters: The students (including young researchers from the Network) were asked to give poster presentations on their current research projects; see also the student poster abstracts in [Zimmer and (eds.), 2002]. This particularly supported an important flow of information from Network and non-Network students to the lecturers and the senior scientists of the Network. Many discussion and new research ideas were fostered.

3. Networking and External Research Contacts: Networking was strongly supported by the Autumn School at various levels (i) amongst young visiting researchers, (ii) between students and lecturers, (iii) between lecturers, and (iv) between the Calculemus Network and related interest groups due to the co-located OpenMath workshop and MKM kick off meeting. The informal atmosphere particularly fostered new social contacts.

4. Dissemination of Results: Due to the high number of participants and the wide announcement of the school, the event website, the preparation of notes, etc., the event strongly contributed to a dissemination of the Networks' research results.

5. Recruitment of young researchers: The event provided an excellent opportunity for the recruitment of new young researchers. From the recruitment perspective it seems to be a valuable suggestion for research training networks to organize such an event approximately at the beginning of the second year; i.e. several months earlier as we did in the Calculemus Network.

B.8.3 Training Methodology

Training and transfer of knowledge in the Network is organized along a horizontal and a vertical axis. While the horizontal axis enumerates the various domains of research activities, the vertical axis reflects the various stages in the transfer from basic research to applications.

The Horizontal Training Axis. Concerning the horizontal axis Calculemus provides an infrastructure to train young researchers in heterogeneous approaches, various systems, and tools pursued and developed at the individual partner sides. The goal thereby has been to build up a new generation of researchers that will have a much broader scientific and technological background as it would be possible at an individual site only. Scientists trained in Calculemus are expected to foster and guarantee a lasting impact of the Networks' vision to the involved and highly fragmented research fields (like, for instance, deduction systems) and to further promote the research and systems. Calculemus has set an important first step to overcome the situation in which PhD students often reach only a very deep specialization highly depending on their particular research environment. This positive impact of Calculemus is already visible, for instance, in the deduction community.

The joint work on the *Certification of solutions to permutation group problems* [Cohen *et* *al.*, 2003b] by Arjeh Cohen (TUE), Scott Murray (TUE), Martin Pollet (USAAR), and Volker Sorge (UBIR) is a good and illustrating example on how the CALCULEMUS Network has exploited its complementarity along the horizontal training axis. Being a result of two early-stage researchers trained by USAAR, UBIR and TUE, USAAR provided the expertise in proof planning and the use of the ΩMEGA system, UBIR contributed the expertise in integrating computer algebra systems into proof planning, and UWB accounted for the expert knowledge on the mathematical domain and on the computer algebra side. None of the involved partners exhibited sufficient experience at its side to pursue this research on its own.

The main instruments for the training at the horizontal level have been:

- Secondments of young researchers at individual nodes of the Network and at industrial and academic collaborators; this included local training measures at the nodes such as lectures, tutorials, seminars, group meetings, and other activities.
- The CALCULEMUS Autumn School 2002 in Pisa.
- CALCULEMUS Symposia organized by the CALCULEMUS interest group; see Section B.6.4.
- The CALCULEMUS workshops and Network Meetings; see Section B.6.4.
- Further tutorials and workshops organized by subsets of the consortium and events organized by collaborating research initiatives such as listed in Table A.1.

The Vertical Training Axis On the vertical axis the training was concerned with the systematic personal development of young researchers towards their intended career goals. The two main options for young researchers are to aim either at a career in industry or at a career in academia. Specialization to foundations, system and tool development, integration aspects, applications were further options on an orthogonal scale. Depending on the options different training instruments are appropriate. The vertical training did also address the training of complementary skills.

The training instruments on the vertical axis included:

- Industry internships and application oriented case studies.
- Active involvement of experienced young researchers in the Networks' training events, e.g. by giving courses and tutorials or as technical organizers.
- Involvement of experienced young researchers in research management, for instance, as CALCULEMUS node manager.
- Involvement of young researchers at the local nodes in Network independent management tasks or technical challenges.
- Participation in courses addressing complementary skills

The training of Corrado Giromini (Italy) from UGE illustrates the various stages on the vertical axis. At UGE he started his career in the area of integrating heterogeneous systems, broadened his background at USAAR and worked on techniques and case studies for the verification of hybrid systems at the semi-industrial DFKI. Next he was further trained at UED pursuing an industrial case study at Motorola, i.e., one of the CALCULEMUS industry partners. Afterwards he returned to USAAR to be trained as technical organizer of the CALCULEMUS Midterm Review meeting. Finally, Mr. Giromini was hired by industry.

Experienced Researcher The training of more experienced young researchers — usually they are aiming at an academic career — at different sites of the Network has addressed the following aspects: (i) they gained a broader picture of the Networks' research, (ii) they typically strengthened their focus in one direction, (iii) they have improved their overall academic and research management skills, (vi) they have contributed to the dissemination of results and the international recognition of the Network, e.g. by contributions to international journals and conferences, (v) they have contributed to the knowledge transfer within the Network by giving local courses at the single host nodes. Some of the experienced researchers employed by the Network have brought in a very specific and relevant expertise that was not optimally represented in the Network so far. This fostered a bidirectional enhancement of expertise between the Network and the recruited experienced researchers. A good example is the recruitment of Stephan Schulz, the developer of the theorem prover E, which is a world leading system for first-order logic with equality. During his stay at UED, RISC, and ITC-IRST/DIT, he added to the Network expertise in traditional first-order theorem proving and he was himself trained by the broader perspective the Network takes on the deduction area in which systems such as E obtain the role of important tools employed within mathematical assistance environments.

B.9 Difficulties (4th year)

We did not encounter major difficulties in the fourth year. Worth to mention is that for some young researchers the end of CALCULEMUS-I was very abrupt and scientifically as well as sociologically unfortunate; see the list of ongoing PhD projects in Section A.3. Our intention when proposing CALCULEMUS-II with a start state as close as possible after the end to Calculemus-I, as encouraged by our previous EU officer at the midterm review, was also to secure much needed support for the ongoing work of some young researchers. Interaction and communication with the EU was less cooperative and effective as at the beginning of the Network and before the change of officer.

B.10 Difficulties (all four years)

It has turned out to be a challenge in the first year to get the Network started and to quickly reach the proposed recruitment figures. One reason is that highly qualified young researchers are typically not immediately available from the day when the burocratic set-up of such a training Network has been achieved.

The situation before the Network meeting in Genova in 2001 was therefore unsatisfactory and most nodes were still far behind the proposed employment figures; a few nodes however had already successfully hired young researchers. The scientific results were in most cases also slightly behind the proposed work plan. A main measure to improve the situation was the coordinator's proposal to initiate a respective redistribution of young researcher person months from underspending nodes to nodes with overspending capacities in case the situation would not have been improved by July at the Calculemus Symposium in Marseilles. As a consequence the employment situation improved since the beginning of 2002.

The initial recruitment and collaboration problems have been fully resolved during the third and fourth year of the Network. Calculemus has become an effective, attractive and highly needed scientific training environment and that has built-up functioning and lasting research and training structures.

B.11 Industry Connections (all four years)

At the midterm review meeting the deliverable of the Network in terms of industry internships has been modified as follows: *The young researchers should accomplish an industry internship if this internship (a) is reconsilible with the duration of their employement as young researcher in the* Calculemus *Network and (b) does at least loosely fit their own research interests or the work program of the host node. If an internship is however directly beneficial to the young researcher we propose that the stay in industry may be extended in time.*

The industry internship figures did unfortunately not match our initial expectations. There are several reasons for this:

- Some young researchers, typically those involved in ongoing PhD thesis projects, were not interested to spent some months in industry because of the danger that they would simply loose important time within their typically time-limited PhD projects. Note that, for example, in the UK universities are even charged penalties when their PhD students do not finish in time — this is of course contra productive to the idea of industry internship (at least if the internship is not part of a very strongly organised ongoing research collaboration).
- Some young researchers were employed in the Network for short time only (typically because of personal constraints) so that there was not sufficient time for an additional industry internship. Example: Simon Colton's stay at UKA and Silvio Ranise's stay at USAAR.
- Some young researchers were working on topics that were thematically not compatible with an industry internship. Example: Martin Pollet's work at UBIR.
- The individual nodes interests in spending their young researchers person months in industry internships was subdominant to their interest in spending them in their Calculemus research interests.

B.12 Recommendations

- For further training networks we suggest that a small central budget is maintained for the organisation of joint training measures such as the Calculemus Autumn School. A distribution of such funds over the partner nodes only produces avoidable hassle and work for the coordinator and the event organisers.
- The hiring of HiWi's for supporting the organization of the summer school resulted in troubles during a financial audit at UKA. These expenses were not accepted at this audit.
- We propose to avoid changing the responsible EU officer of a network; at least transfer of knowledge on the specifics of a network from one officer to the next one should be better organized.
- The financing scheme should be changed into an advance payments scheme; some universities had serious problems to accept the current scheme and this in turn may negatively influence the recruitment figures in a network.

B.13 Financing

The financing details and a respective statement will be attached to this document.

Name	Nationality	Age at App	Start of App.	End of App.	Category	Speciality	Place of Work	Country of Work	Previous Exp. in Network
Adams, Andrew	British	31	01.07.01	30.09.01	Post-doc	Theorem proving with the real numbers: PVS system	USAAR, Saarbrücken	Germany	none
Aransay Azofra, Jesus Maria	Spanish	24	01.06.01	30.11.01	Pre-doc; PhD student	Verification of computer algebra systems with theorem powers	UKA, Karlsruhe	Germany	none
Audemard, Gilles	French	29	01.11.01	31.08.02	Post-doc	Decision Procedures, Satisfiability	IRST, Trento	Italy	none
Carlstrom, J.	Swedish	30	01.03.04	30.05.04	Post-doc		EUT, Eindhoven	Netherlands	none
Colton, Simon	British	29	01.10.01	31.12.01	Post-doc	Theory Formation / Exploration and Mathematical Reasoning	UKA, Karlsruhe	Germany	
Compagna Luca	Italian	29	15.06.04	15.08.04	Post-doc	Verification of security protocols	UKA, Karlsruhe	Germany	UED, 10.07.01 – 10.10.01
Craciun, Adrian	Romanian	24	01.09.01	31.08.03	Pre-doc;	Automatic Reasoning	RISC, Linz	Austria	
De Lucia, Pasquale	Italian	26	01.08.02	30.09.02	Pre-doc, PhD student	Security Protocols	USAAR, Saarbrücken	Germany	
De Cabezn Irigaray, Eduardo Senz	Spanish	31	01.07.04	31.08.04	Pre-doc; PhD student		UKA, Karlsruhe	Germany	UKA, 14.07.03-31.01.04
Duncan, Hazel	British	21	01.09.03	30.11.03	Pre-doc; PhD student	Data Mining for the Automatic Formation of Tactics	USAAR, Saarbrücken	Germany	UWB, 02.10.02-21.12.02
Fiedler, Armin	German	38	01.09.03	30.11.03	Post-doc	Human-oriented Interaction with Mathematical Assistance Systems	UED, Edinburgh	UK	none
Franke, A.	German	30	01.12.03	30.05.04	Pre-doc; PhD student	Integration of Mathematical Reasoners at the Systems Level; MathWeb-SB	UBIR, Birmingham	UK	none
Ganty, Pierre	Belgian	24	14.05.03	30.09.03	Pre-doc; PhD student	Verification of Security Protocols	UNIGE, Genoa	Italy	UNIGE, 01.10.02-31.03.03
Geleijnse, Gijs	Dutch	25	01.10.03	31.11.03	Pre-doc		UWB, Bialystok	Poland	none
Giero, Mariusz	Polish	30	21.01.03	31.12.03	Post-doc	MMode, A Mizar Mode for the proof assistant Coq	EUT(KUN) Eindhoven	Netherlands	
Giromini, Corrado	Italian	27	01.03.03	31.05.03	Pre-doc; PhD student	Formal methods and knowledge management	USAAR, Saarbrücken	Germany	UED, 01.12.2002–28.02.03
Jibetean, D.	Romanian	30	01.05.04	31.08.04	Post-doc		EUT, Eindhoven	Netherlands	EUT, 16.06.03-31.08.03
Junttila, Tommi Antero	Finish	31	15.01.04	31.08.04	Post-doc; PhD student	Decision Procedures, Satisfiability, Model Checking	IRST, Trento	Italy	none
Keighren, Gavin	Scottish	22	25.02.04	31.08.04	Pre-doc; PhD student	Satisfiability, Model Checking	IRST, Trento	Italy	none
Kirov, Veselin	Bulgarian	26	01.03.04	30.04.04	Pre-doc; PhD student	Satisfiability, Model Checking	IRST, Trento	Italy	IRST, 01.06.03-31.10.03
Kocsis, Camelia	Romanian	23	01.08.03	31.08.04	Pre-doc; PhD student		RISC, Linz	Austria	none
Kornilowicz, Artur	Polish	32	16.07.01	30.06.02	Post-doc	Computer Science	IRST, Trento	Italy	none
Lefevre, Vincent	French	31	01.08.04	31.08.04	Post-doc		UKA, Karlsruhe	Germany	UKA, 14.07.03-30.09.03
Lesourd, Henri	French	33	01.07.04	31.08.04	Post-doc	Publication-oriented Tools for Mathematics Assistance Systems	USAAR, Saarbrücken	Germany	none
McNeill, Fiona	British	28	15.09.03	15.11.03	Pre-doc; PhD student	Ontology Evolution	USAAR, Saarbrücken	Germany	none
Meier, A.	German	30	01.05.03	31.08.03	Pre-doc; PhD student	Proof Planning supported by Specialist Reasoners	UBIR, Birmingham	UK	none
Moschner, Markus	Austrian	35	07.10.02	07.01.03	Post-doc	Mathematical knowledge bases; protocols for the exchange of mathematical knowledge	UWB, Bialystok	Poland	USAAR, 01.06.2001 – 31.05.2002
Murray, Scott	English	30	01.08.02	31.07.03	Post-doc	Mathematics and Deductions Systems	EUT, Eindhoven	Netherlands	EUT, 01.08.01-31.08.2001
Musset, Julien	French	27	24.03.03	31.08.03	Pre-doc; PhD student	Verification of infinite states system	UKA,Karlsruhe	Germany	UED, 01.10.02-31.12.02
Pollet, Martin	German	33	01.03.04	31.05.04	Pre-doc;	Knowledge representation, proof planning	UED, Edinburgh	UK	UBIR, 01.10.01–28.02.02
Ranise, Silvio	Italian	30	01.10.01	30.11.01	Post-doc	Integration of Decision Procedures, Rewriting and Theorem Proving	USAAR, Saarbrücken	Germany	none
Revol, Nathalie	French	35	01.11.03	30.11.03	Post-doc		UKA, Karlsruhe	Germany	none
Rossum, Peter van	Dutch	31	15.01.04	31.08.04	Post-doc	Mathematics, Computer Science	IRST, Trento	Italy	none

Schulz, Stephan	German	35	06.2003	08.2003	Post-doc	Automated First-Order Theorem Proving	RISC, Linz	Austria	none
Sheridan, Daniel James	British	25	13.02.03	06.04.03	Pre-doc; PhD student	Model Checking, Satisfiability, Formal Methods	IRST, Trento	Italy	none
Steel, Graham	British	27	01.04.04	31.08.04	Post-doc	Finding Attacks on Security Protocols	UNIGE, Genoa	Italy	UKA, 25.09.03-31.03.04
Stratulat, Sorin	Romanian	29	01.05.01	30.09.01	Post-doc	Automated reasoning	UNIGE, Genoa	Italy	none
Tsovaltzi, Dimitra	Greek	30	01.04.03	30.09.03	Pre-doc, PhD student	Mathematical Assistance Systems and Mechanized Maths Tutoring	USAAR, Saarbrücken	Germany	none
Urban, Josef	Czech	31	01.03.04	31.07.04	Pre-doc;	Mathematics, computer science	UWB, Bialystok	Poland	UWB, 15.02.02-18.08.02
Vajda, Robert	Hungarian	30	01.07.04	31.08.04	Pre-doc; PhD student		RISC, Linz	Austria	none
Wagner, Arno	Austrian	35	01.07.04	31.07.04	Pre-doc,PhD student		UKA, Karlsruhe	Germany	UKA, 01.09.03-30.09.03
Winterstein, Daniel	British	26	02.10.03	11.12.03	Pre-doc,PhD student	Diagrammatic Reasoning	RISC, Linz	Austria	none
Zimmer, Jürgen	German	32	01.04.03	31.03.04	Pre-doc;	Networks of reasoning services, inductive proof planning and computer algebra computations	UED, Edinburgh	UK	UNIGE, 01.01.01–07.07.01

Table B.5: Factual Information on the Young Researchers

Chapter C

Overall Calculemus Bibliography

Calculemus Related Publications

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