The CALCULEMUS Research Training Network — A short Overview*

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1 Introduction

This paper sketches the structure and scientific contributions of the CALCULEMUS Research Training Network (CALCULEMUS RTN) since its start in September 2000. It has been reproduced from the networks midterm report [22] and credit is due to all researchers of the CALCULEMUS RTN. More than 28 young visiting researchers (with a sum of approx. 150 financed person-months) have been supported by the network so far and approx. 47 senior researchers are involved in the training measures at the different partner sites. Figure 1 provides the list of the CALCULEMUS RTN partner sites. The network's homepage is `http://www.eurice.de/calculemus/`.

2 Motivation

The long-term motivation of the CALCULEMUS research initiative (see `www.calculemus.net`) is to foster the development of a new generation of assistant systems for mathematics and formal methods. Some key characteristics of the systems CALCULEMUS is aiming at are compiled in the following (incomplete) list:

- Combined support for symbolic reasoning and symbolic computation.
- Interoperability with emerging decentralised and shared mathematical knowledge bases.
- Support mechanisms for the exploration, validation, and maintenance (in particular management of change) of domain specific knowledge.
- Support for flexible integration of heterogeneous specialist reasoners as subsystems (including classical automated theorem provers, model generators, decision procedures, etc.).
- Provision of rich and expressive representation languages and communication means to the users side (probably including rather informal or even natural language based representations) in combination with human-oriented, multimodal user interfaces.

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USAAR	Saarland University, Saarbrücken, Germany (Jörg Siekmann, Christoph Benzmüller)
UED	The University of Edinburgh, Scotland (Alan Bundy)
UKA	Karlsruhe University, Germany (Jacques Calmet)
RISC	Research Institute for Symbolic Computation, Linz, Austria (Bruno Buchberger)
TUE	Eindhoven University of Technology, Netherlands (Arjeh Cohen) University of Nijmegen, Netherlands (Henk Barendregt)
ITC-IRST	Instituto per la Ricerca Scientifica e Tecnologica, Trento, Italy (Fausto Giunchiglia)
UWB	University of Bialystok, Poland (Andrzej Trybulec)
UGE	Università degli Studi di Genova (Alessandro Armando)
UBIR	The University of Birmingham, England (Manfred Kerber)

Fig. 1. The Calculemus RTN

- Support for transformations between the expressive and user-oriented representations employed in the assistant system and the usually highly specialised machine-oriented representations employed by the integrated specialist reasoners.
- Development and utilisation of open system architectures fostering interoperability and tool exchange between different assistant systems (for example, in the emerging mathematical semantic web).
- Direct support for the preparation and validation of mathematical texts and publications.
- Applications in mathematics, mathematics education, and formal methods.

These research goals are ambitious and call for the combination of resources and the mutual exchange of scientific expertise between the involved scientific communities. To tackle them, Calculemus is basically pursuing a bottom-up approach starting from single research aspects as mentioned above and from the existing and emerging tools of the involved research groups.

The current scientific focus is on the integration of symbolic computation and symbolic reasoning which has been identified as a major issue. The sociological goal of the Calculemus RTN is to combine the scientific expertise of the involved researchers in order to optimally train and develop a new generation of young researchers in consideration of the implied scientific challenges.

3 Calculemus RTN: Research Objectives and Results

A predominant research objective of the Calculemus RTN is 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 greater than on the side of CASs.

Since its start in September 2000 the CALCULEMUS RTN 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 in the CALCULEMUS RTN focuses on the modelling 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.

The researchers of the CALCULEMUS RTN and the CALCULEMUS interest group also fostered the Mathematical Knowledge Management (MKM, EU MKM-NET) research initiative; see [40, 8]. This relatively young line of research adopts a broader perspective on the future of mathematics (e.g. research and publication practice, education, and knowledge maintenance) in the 21st century. A significant amount of CALCULEMUS research is MKM relevant and is currently being taken up in this community in order to adopt and integrate it into the MKM perspective.

The extensive research activities of the CALCULEMUS Network and the CALCULEMUS Interest Group are furthermore shown inter alia by three special issues of the Journal of Symbolic Computation [101, 4, 78] and the following international events: CALCULEMUS Symposium 2000 in St. Andrews, Scotland [69, 101], CALCULEMUS Symposium 2001 in Siena, Italy [78], CALCULEMUS Symposium 2002 in Marseilles, France [45, 49], CALCULEMUS Autumn School 2002 in Pisa, Italy [23–25, 128]. The CALCULEMUS Symposium 2003[1] will be held in September in Rome, Italy, and it will join IJCAR conference in 2004.

In the following paragraphs we sketch the highlights of the CALCULEMUS RTN since its start in September 2000; for more detailed reports to all tasks we refer to [22].

Task 1.1: Mathematical Frameworks TUE and Nijmegen University investigated type theory for the purpose of formalising mathematics: Barendregt and Geuvers [21] give an overview of type theory, how it is used to represent logic and mathematics and what issues and choices come up. Type theory (encoded in OPENMATH) as a way for communicating mathematics is proposed in [20] and in [48] it is shown how a proof presentation can be generated from a formalised proof in type theory. This paper argues that 'formal contexts' in Coq can be used as a basis for interactive mathematical documents. This topic is also

[1] `http://www-calfor.lip6.fr/~rr/Calculemus03/`

treated in [99]. An in-depth discussion of the various ways to treat computations in theorem provers is given in [19] and further related work is presented in [36].

The CALCULEMUS RTN has also studied other approaches to theorem proving and their capacities to integrate computations (see also [122]). This includes proof planning, as developed and employed by the nodes USAAR and UED. In the ΩMEGA system [104], at USAAR, symbolic calculations can be integrated into proof planning in two ways: (i) to guide the proof planner and to prune the search space by computing hints with control rules and (ii) to shorten and simplify the proofs by calling a CAS within the application of a method to solve equations. As a side-effect both cases can restrict possible instantiations of meta-variables. These approaches are discussed in [52, 107, 84, 105].

An investigation into the use of deduction for the implementation of correct computations within computer algebra system was considered at UGE and is presented in [1].

The THEOREMA system, developed at RISC, aims at providing one mathematical framework encompassing all aspects of algorithmic mathematics, notably the aspects of *proving*, *computing*, and *solving*; see [39, 37, 38].

In [70, 71] it is critically argued by UBIR that aspects of mathematical concepts, including procedural knowledge, are hard to reconstruct from the formalisation in deduction systems. This work points to limitations of the flexibility of mathematical representations which apply to all our current approaches.

Task 1.2: Definition of Mathematical Service The primary goal of this Task is the enhancement of existing computer algebra systems and deductive systems by turning them into *open* systems capable of using and/or providing mathematical services. After a preliminary analysis of the state-of-the-art of reasoning systems, it was decided to tackle the problem, in parallel, by 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. This was intended not only for current systems, but also and in particular for future implementations. To this extent particular emphasis was 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 Mechanised Reasoning Systems) developed by UGE and ITC-IRST [2], LBA (Logic Broker Architecture) developed by UGE [6, 7], MathWeb-SB (MathWeb Software Bus) developed by USAAR [129], MathBroker developed by RISC [81]. These networks can themselves be coupled again as, for instance, exemplarily investigated in [127].

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) developed by UGE and MathSat [61, 11, 10, 9, 12], developed by ITC-IRST.

In Task 1.2 the CALCULEMUS network also closely cooperates with the EU project MONET. In MONET special ontologies comprising mathematical problems, queries and services have been defined and investigated.

Task 2.1: Integration of CASs and DSs via Protocols Cooperation among several software systems can be achieved with indirect, unidirectional and bidirectional communication. The goal of this task is to investigate how protocols can be defined to provide a semantics as well as soundness results for systems exchanging mathematical information. This definition hints at several other tasks in the CALCULEMUS RTN dealing with very similar problems. This is for example true when defining a context for a computation and is partly covered in Task 1. Unidirectional and bidirectional communication protocols are designed when coupling directly different modules. Although there are no direct links between the services with indirect communication, interaction is possible when systems can communicate with a common user interface, central unit, mediator or evaluator. This approach, which is partly based on a joint work with ITC-IRST on OMSCS (Open Mechanised Symbolic Computation Systems), has been investigated within the KOMET system at UKA see [44, 76, 55, 46].

A semantics can be provided by at least three approaches: (a) define a mathematical software bus, (b) define a context from which a semantic can be derived, (c) formulate the problem as a knowledge representation paradigm.

These approaches are shared by several of the partners. Indeed, they lead to introduce multi-agent systems, contexts, and ontologies to just quote a few features (see for instance the LBA and the MathWeb-SB).

Task 2.2: Enhancing the Reasoning Power of Computer Algebra Systems Enhancement of CAS with reasoning power can be attempted at different levels: (a) enhancement of CAS on the System Level, (b) enhancement of CAS on the Theory Level, and (c) enhancement of CAS on the User Level.

Direction (a) can be achieved by adding additional reasoning capabilities, i.e., logical inference systems, to algorithms built into the CAS. The Constraint Contextual Rewriting (CCR) framework developed by UGE can be used in order to integrate the evaluation mechanism of the CAS MAPLE with an appropriate decision procedure for checking side-conditions, see [1] and [5].

Direction (b) can be achieved by adding proven knowledge about CAS functions to the CAS knowledge base. The HR system, developed at UED, has been used to conjecture properties of functions available in the MAPLE algorithm library from empirical patterns detected in computational data produced by the CAS [53].

Direction (c) can be achieved by giving the CAS user the possibility to prove mathematical statements using proof techniques from logic within the CAS in addition to the computing facilities that each CAS offers. In the framework of the

Calculemus RTN, the work of RISC represents this aspect of CAS enhancement: The Theorema system, see [41], is an add-on package for the widespread and popular CAS *Mathematica* where the user formulates mathematical theorems and proves them entirely within the *Mathematica* environment.

Task 2.3: Enhancing the Computation Power of Deductions Systems UED investigated the combination of the proof-planner $\lambda Clam$ [102] with other systems for computationally costly tasks. This includes (a) an implementation of the GS flexible decision procedure system framework in (Teyjus) LambdaProlog and within the $\lambda Clam$ proof planning system [42] and (b) the integration of the $\lambda Clam$ proof-planner into the MathWeb-SB system [54].

UED also investigated the combination of systems to discover attacks to security protocols [108, 109]. This work makes use of computational power in that it generates a large number of clauses in its processing.

Further relevant work has been done in the $\lambda Clam$ proof-planner to construct very large and modular proof-plans for complicated real analysis theorems [65, 79, 80].

The Ωmega proof planner at USAAR has been coupled with different CASs via MathWeb-SB, see [107, 84, 105]. The Ωants approach to integrate CASs into mathematical assistant systems is sketched in [29, 28, 34, 35]. This work proposes an agent-based modelling of inference rules and external systems at a very basic level within theorem provers.

Finally, work done at UBIR and UGE which render techniques from automated reasoning highly efficient by using enhanced computational power are presented in [66–68] and [9, 12, 3]. Further relevant work is given in [100].

Task 3.1: Automated Support to Writing Mathematical Publications Typically, a mathematical publication contains the following ingredients: natural language text, mathematical formulae, formal text (i.e. definitions and theorems), proofs, examples (typically with computations), and graphics (tables, drawings, sketches, etc.). In the optimal case, a software system for supporting mathematical publications would support all these facets of mathematical publications. Several systems and languages have been used for case studies in this area:

(a) The MIZAR approach (at UWB) is based on two kinds of software which automate the process of writing formal mathematical papers: (i) software used to prepare an article as a formal text whose correctness is computer verified and (ii) the software for automatic (or semi-automatic) translation into natural language (particularly English); this includes also the software for translation into XML-based formats. The cooperation with other Calculemus sites includes development of the MIZAR Mathematical Library (MML) and also the above mentioned translation into XML formats. Relevant publications are [88, 60, 16–18, 94]. Recently published MIZAR articles in the Journal of Formalized Mathematics are [113, 74, 95, 63, 117, 73, 103, 15, 14, 64, 89, 97, 90, 111, 112, 98, 93, 116, 59, 114, 91, 92, 62, 115].

(b) THEOREMA is a prototypical software system designed to give computer-support to the working mathematician during all phases of mathematical activity. Several features qualify THEOREMA as a powerful system for creating mathematical publications entirely inside the system. "Classical" mathematical documents can be written that are intended mainly for printout, as for instance the thesis [125] or the conference papers [123], [124], and [126]. In the case studies, however, emphasis has been put on using the THEOREMA system for developing interactive lecture notes for university mathematics courses. Mostly since the THEOREMA language is very similar to the language used in "ordinary mathematics" the system is highly suitable for this approach, both in illustrating computation-based courses as well as in supporting proof-oriented courses.

(c) The OMDOC [72] content markup scheme which has been developed at USAAR, supports authors with writing formal mathematical documents including articles, textbooks, interactive books and courses. OMDOC allows to capture the semantics and structure of these documents. Various tools are available to transform OMDOC documents into other formats for presentation purposes (using, e.g., MathML) or to support inter-system communication (e.g., by transformation into the logic of a theorem prover).

(d) TUE has developed the MATHDOX tool supporting interactive mathematical documents. MATHDOX is based on DOCBOOK but also has similarities to OMDOC.

Task 3.2: Support to the Development of an Industrial-Strength Application of Formal Methods to Program Verification In addition to formal methods, which is undoubtedly the most important application area for our research, we have identified the education sector as another interesting application for DSs and CASs. Actually the systems THEOREMA (RISC) and ACTIVEMATH [87] (USAAR), which make use of tools and approaches developed in the CALCULEMUS RTN, are already employed in education practice. Another example is the MATHDOX tool developed at TUE since the next version of the interactive textbook *Algebra Interactive!* [51] will appear in this format.

Formal method applications currently pursued in the CALCULEMUS RTN include (a) an approach to support the verification of hybrid systems with the help of mathematical services in MathWeb-SB [27, 26], (b) the investigation whether specialised reasoning tools within the MathWeb-SB can fruitfully support the formal verification of information flow properties and error detection in security protocols [12], and (c) the application of proof planning in first-order linear temporal logic (FOLTL) to feature interactions as they arise in large telephone networks [50].

Task 3.3: Support to the Solution of Undergraduate Exam in Calculus and Economics 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 analyse 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.

A task relevant case pursued at Nijmegen University compares how the problem of proving the irrationality of $\sqrt{2}$, which involves computations, can be proved in fifteen different theorem proving environments (including systems of the CALCULEMUS RTN) [122, 121, 106, 33, 105].

Among the case studies that are currently being started at USAAR are exercises from the German *Bundeswettbewerb Mathematik* and Calculus exercises being encoded and investigated in the ACTIVEMATH project. Empirical studies at USAAR investigates the phenomena of natural language dialog with mathematical assistant systems on proof exercises in naive set theory.

Task 3.4: Modelling of Existing Systems as Mathematical Services The work in this Task so far has concentrated both on developing the required infrastructure (languages, protocols, semantic specifications, architectural schemata) for making existing systems inter-operate, and on studying extensions and enhancements of the reasoning capabilities of some existing tools. The relevant contributions are: (i) MathSat framework developed at ITC-IRST [11, 10], (ii) the RDL (Rewrite and Decision procedure Laboratory), (iii) the LBA [6, 7, 127] developed by UGE, (iv) the modelling of existing systems, for instance, $\lambda Clam$ developed at UED [102], as mathematical services in MathWeb-SB developed at USAAR [54].

Further work at USAAR concentrates 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 [56, 33, 32].

Task 3.5: Challenge Mathematical Problems During the work on the above tasks some challenging mathematical problems had to be tackled already, in order to have non-trivial working examples. Some of the examples were done either by single partner nodes or in collaboration between some of the nodes. The examples include: (i) Fundamental Theorem of Algebra [58, 57], (ii) Involutive Bases [47, 43], (iii) Exploration in Finite Algebra, (iv) The Residue Class Domain [82, 85, 83, 84], (v) Proving with Invariants [86], (vi) The Jordan curve theorem for special polygons, (vii) Continuous lattices [75], (viii) Order sorted algebras [119, 110, 118], (ix) Proofs in Homological Algebra, (x) Proofs in Graph Theory, (xi) Exploration in Zariski Spaces. Further related work is given in [30, 31].

4 Discussion

Prima facie it may appear disappointing that a predominant, single and uniform solution for the integration of deduction and computation is not possible and that the network places an emphasis on integration at the systems level (which requires support for heterogeneous problem representations). However, it is the *authors opinion* that mathematical assistant systems, in particular those for theory exploration, generally have to find a good compromise between a well chosen degree of heterogeneity and flexibility of mathematical representations and the enforcement of representational uniformity. Finding *good* representations has been identified as a key issue in artificial intelligence and the author is convinced that it is important for mathematical theory exploration and mathematics education as well. Unfortunately many of todays deduction system are still strongly afflicted with the spirit of Hilbert's program: the possibility to encode mathematics in a uniform, restrictive manner (e.g. based on set theory) does not imply the usefulness of representational uniformity for theory exploration.

Heterogeneity at the representations and the related systems layer, however, requires support for the semantically validated exchange of information and for transformations of representations (probably including algorithms and proof objects based on them) in various goal directions. For instance, semantical descriptions of system capabilities and uniform information exchange facilities can be used for making heterogeneous systems interoperable in "abstract" level proof development. Transformation mechanisms (if possible and available) may then be later used to generate proof objects in a uniform goal representation format. Alternatively the employed systems may be trusted in the context of their particular usage.

In short, the author claims that a well chosen degree of representational heterogeneity and flexibility should be considered a design requirement for mathematical assistant systems instead of a drawback.

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