Proposal for an ESF Research Networking Programme – Call 2009

Section I: *(1 A4 single page)*

Programme title:

Applied and Computational Algebraic Topology

Programme acronym:

ACAT

Name and full coordinates of principal applicant(s) (*up to three including the contact person*):

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Indication of which of the principal applicants is the contact person:

Martin Raussen

Keywords relating to the topic of the proposal (*up to five; one "keyword" can be a string of not more than three words*): Persistent Homology, Shape Analysis, Topological Robotics, Statistical Topology, Directed Topology & Concurrency

Abstract of the proposal (*max. 300 words*):

The revolutionary growth of experimental data in the sciences and the availability of unprecedented computing power pose many challenges to contemporary mathematics. The ESF Research Network on ''Applied and Computational Algebraic Topology" will combine efforts of researchers from thirteen European countries to develop mathematical tools for the following broad research themes:

(a) The topological and statistical analysis of shapes, images, and large multi-dimensional data sets;

(b) Algorithms for motion planning and the study of configuration spaces of mechanical systems;

(c) Statistical topology and the study of large growing systems;

(d) The theory of concurrent computation and computer networks.

Research on these themes is currently carried out in small groups spread over several European countries. The Network will facilitate intensified interactions and cross-fertilization, which we predict will lead to new results and entire new research directions as well as to commercial applications in industry. The Network will organize summer schools and conferences to support the formation of an integrated research community in "Applied and Computational Algebraic Topology" and to attract an increasing number of students to the field. The Network will actively collaborate with experts outside Europe.

Previous or concurrent applications to the ESF for any of the ESF instruments:

None.

Section II: *(not more than 8 A4 single pages / max. length 3000 words)*

Status of the relevant research field; scientific context, objectives and envisaged achievements of the proposed Programme:

Several areas of application oriented mathematical research have the theoretical mathematical discipline *Algebraic Topology* as their background. Their aim is to develop new theoretical instruments and algorithms making topological methods suitable for application purposes. This gives rise to the field of *Applied and Computational Algebraic Topology*, which may be divided into the following areas:

- Computational Algebraic Topology
- Topological Robotics
- Statistical Topology
- Directed Algebraic Topology and Concurrency
- Combinatorial Algebraic Topology

As evident from the description below, there are strong connections between these areas. Collaboration between researchers in different areas needs to grow in the near future.

Computational Algebraic Topology

Persistent Homology (PH)

The homology groups of a topological space describe its hole structure. Their classifying power is weaker than that of homeomorphisms, but they are still sensitive to small changes in the space. In other words, the groups provide an incomplete as well as an instable measurement of the topology. While the incompleteness is often an advantage, the instability diminishes the usefulness of homology groups in practice dramatically. The purpose of *persistence* is to remedy this deficiency (see Edelsbrunner, Letscher, Zomorodian (2002) and Zomorodian, Carlsson (2005)). It is based on a filtration that represents the space across scale levels, from fine to coarse, and measures for each class its interval of activity along the filtration. Drawing the intervals as points in the extended plane, we get the persistence diagram, a combinatorial representation of the homological information contained in the filtration. In contrast to the ranks of the homology groups, this diagram is *stable* (see Cohen-Steiner, Edelsbrunner, Harer (2005)). This paves the way for the use of homology in a wide range of applications in mathematics and computing but also in the sciences and engineering (for an introduction, see the new book by Edelsbrunner, Harer (2009)). This gives motivation to further develop our understanding of the foundations as well as to overcome obstacles that prevent an even wider range of applications. We list a few questions we will investigate.

- Is there additional structure that can be added to the persistence diagram without sacrificing its stability? An example would be the *containment* relation among the components of the spaces in the filtration.

- *Well modules* have recently been introduced to measure the robustness of intersections and to prove the stability of contours of mappings. At this time, we have no algorithms other than for a few special cases. Is there a connection to persistence that can be used to get a general algorithm?

- The well module can be used to formulate a notion of robustness for fixed points of mappings. Can these ideas be further developed to get a notion of persistence for *dynamical systems*?

- Filtrations are generated by real-valued functions on the space. Replacing the functions by vector-valued mappings gives *multi-parameter* filtrations. These are much more difficult to understand already for vectors of length two (see Carlsson and Zomorodian (2008)). A deeper understanding of the rank invariant of these multi-parameter filtrations is important for a variety of applications in *image processing*.

Homology Computation (HC)

The task of computing homology can be reduced to finding the Smith diagonalization of the boundary matrices. However, this direct approach becomes impractical for large data. We need specialized fast homology algorithms. This demand appeared some twenty years ago in different fields, including image analysis, dynamical systems, robotics, electromagnetic engineering, and material science, with input data sets of a few million elements or more. The problem is complicated by the range of required output, which varies from Betti numbers, to homology generators, to matrices of homology maps. Of particular interest are of course persistent variants of all these.

- The papers of Delfinado, Edelsbrunner (1995), Erickson, Whittlesey (2005) and Mrozek, Batko (2009) indicate that in some special situations homology may be computed in *almost linear* time. The scope to which the existing algorithms apply is not well known. Furthermore, our understanding of what ingredients of homology, under what assumptions, and by what method can be computed fast remains limited.

- It would be useful to extend the available reduction algorithms from simplicial complexes to more general *CW-complexes*. This is particularly important for spaces with non-uniform fractal structure for which the CW-complexes offer a dramatically more compact representation.

- The homology algorithms can be extended to computing *cohomology*, which is particularly important in electromagenetic engineering. The running time characteristics of the cohomology variants are likely to be different from the homology algorithms, and this difference needs to be explored.

- Matrix reduction algorithms lend themselves to implementations on *parallel* computer architectures, which promise a further increase in efficiency. We need to understand which reduction algorithms are best suited for this effort.

- The work on applications of homology and persistence is predicated on the existence of a suite of sophisticated *software*. Starting with Plex and Dyonysos (software packages developed at Stanford), we would like to build a software environment that will allow us and others to attack important application questions without reinventing the wheel.

Shape Analysis (SA)

Two broad questions in shape analysis are the classification of shapes and their retrieval when organized in a database. Both questions are based on a *measure of dissimilarity*. To this aim, a shape is seen not just as a geometric object, but as a mapping that expresses what we deem important about the shape. This provides a high degree of flexibility and the possibility to express human subjectivity. Measures of dissimilarity are then defined based on these mappings, such as for example the natural pseudodistance introduced by Ferri and Frosini. Its computation is hard and applications are carried out through bounds obtained by persistent homology (cf. PH). That algebraic topology is well suited for shape analysis is not particular surprising since it is by its very nature a formal way of capturing qualitative features. We state a few concrete questions in our algebraic approach to shape:

- Persistent homology based on mappings representing shapes has been used for *shape classification* and *image retrieval*. It is now important to explore the space of mappings. A deeper understanding of this space will be key to reaching a higher and more stable level of image analysis, which is essential for *automatic learning*.

- In practice, we necessarily work with *approximations* of real shapes. We therefore need to understand the relationship between the invariants of the shapes and those we compute for their approximations. For the case in which the shape and its approximation give close real-valued functions, the stability of persistence implies that the two diagrams are close. Can similar results be obtained for other invariants, such as Reeb graphs?

- How does *occlusion* in an image affect the invariants of persistent homology? In other words, can we find partial agreement in the diagrams, can such partial matches be efficiently detected, and what can we prove about the shapes when we detect partial matches?

Topological Robotics (TR)

The *motion planning problem* plays a prominent role in modern robotics. An autonomous mechanical system must be able to select a specific motion once the current and the desired states are given; such a selection is accomplished by a motion planning algorithm. Mathematically, a motion planning algorithm is a section of a path-space fibration. Using methods of algebraic topology it is easy to see that continuous motion planning algorithms exist relatively rarely (if and only if the configuration space of the system is contractible). This explains why decisions are often discontinuous as functions of the input data.

To measure these discontinuities numerically, one may use the notion of *topological complexity TC(X)* of topological spaces which was introduced by M. Farber in 2003. Many properties of *TC(X)* were discovered, however its computation in general is quite difficult, the situation is similar to its classical "relative" *cat(X)*, the Lusternik – Schnirelman category. One of the surprises came with a theorem (Farber, Tabachnikov, Yuzvinsky) stating the equivalence between the problem of computing the topological complexity of real projective spaces and the immersion problem; the latter is one of the classical well-researched problem of differential topology. Another theorem of this type was proven by J. Gonzalez and P. Landweber (2009); it shows equivalence between the embedding problem for real projective spaces and the problem of computing their symmetric topological complexity.

We plan to combine the scientific expertise of various researchers in the network to further develop the concept of *TC(X)* and its variations. In particular we plan to apply the theory of motion planning algorithms in the context of *directed* topological spaces (cf. DAT) allowing only directed paths between the source and the target. Results would be applicable to problems of concurrent computation theory. Besides, we plan to start collaboration between partners with the goal to create appropriate cohomological tools for estimating the sectional category of fibrations; this will involve strengthening and generalising the technique of category weights of cohomology classes using cohomology operations; as was originally suggested by Fadell and Husseini in the context of *cat(X)*.

Statistical Topology (ST)

Quite often, standard mathematical notions become inadequate in modern applications to problems arising in areas of engineering, biology and statistics. One such notion is the concept of a *configuration space* or a phase space, which plays a prominent role in physics. For a mechanical system of great complexity it is unrealistic to assume that its configuration space can be fully known or completely described; it is more reasonable to believe that the space of all possible states of such a system can be understood only approximately, with some unavoidable error, or using *probabilistic techniques*. Similar problems arise in modelling of large financial, biological or ecological system. This

motivates the need to study *random* manifolds and random simplicial complexes as models of large systems. Typical properties of such models are: (a) growing dimension; (b) their asymptotic character; (c) key metric parameters are random with partly known statistical properties.
Recent results (Farber, Kappeler, Mazza and others) show that despite limited information one may predict the outcome topology (say, the Betti numbers) with surprising precision. We plan to study various models producing *random complexes* (generalizing the well-developed theory of random graphs) and investigate their possible applications in engineering and computer science. This approach will also be useful for pure mathematics since random mathematical objects are often simpler than their non-random analogues.
A very interesting model of random complexes was suggested recently by Linial and Meshulam; its properties were investigated further by Kozlov and others.
A recent dynamic branch of combinatorial algebraic topology also brings probability aspects into play. There have been several developments studying various probability spaces arising naturally in topology, and establishing thresholds for the non-triviality of various algebraic invariants. The idea is to incorporate not just the final data sample, but the sampling process itself into the computational model. Our methods can produce global *quality assessment* invariants for specific computations in terms of tools of probability theory.

Directed Algebraic Topology and Concurrency

Directed Algebraic Topology (DAT)

Directed Algebraic Topology is a recent subject which arose in the 1990s, theoretically in abstract settings for homotopy theory and, application driven, in investigations of geometric models in the theory of concurrent computation (with HDA; cf. ATC). Its general aim is to model non-reversible phenomena.
The point of departure is most often a d-space (d=directed): a (reasonable) topological space with a distinguished set of (d-)paths that is closed under reparametrization and concatenation, but usually *not* under reversal. The overall aim is an understanding of the interplay between the properties of the topological space in question and of spaces of d-paths within that space. Methods and invariants of classical algebraic topology do not tell very much or are not applicable, at least not without several twists. First of all, homotopy of paths has to be replaced by d-homotopy of d-paths. The fundamental group of a (classical) space has to be replaced by a fundamental *category*: its morphisms depend very much on the chosen end points.
Current research deals in particular with the following topics and questions:
- Modern category theory can serve as a language and as a looking glass to organize the study of d-spaces and to provide a setting for invariants; the recent book *Directed Algebraic Topology* (CUP 2009) by Marco Grandis collects already an impressive material in this direction. Connections to the theory of 2-categories and *n*-categories are visible and deserve a closer investigation; likewise relations to model categories.
- How exactly does the topology of the spaces of d-paths depend on the chosen end points? For applications (cf. ATC), it is desirable to split a given d-space into *components* such that the homotopy types of path spaces only depend on the components of start and end point. If finitely (or countably) many such components suffice, it is possible to describe coarser models that can be used by a machine. It is important to devise inductive algorithms deriving models for (co)-limits of d-spaces.
- For geometric models of computation, abstract homotopy theory tools yield models for associated spaces of d-paths in a combinatorial form, i.e., by (prod)-simplicial complexes. It is desirable to develop this theoretical method into algorithms for applications allowing machine calculations of their homology groups (cf. ATC, HC).
- d-maps between d-spaces are not only continuous, they also preserve d-paths. d-maps have to be investigated up to d-homotopy. Prominent d-maps are *dicoverings*

(cf. ATC); these are characterized by unique lifting of d-paths and of d-homotopies between such.
- It is still not entirely clear what to use as the directed replacement for the notion homotopy equivalence.
- An exploration of *equivariant* directed algebraic topology for d-spaces with symmetry seems promising.
- Motion planning algorithms (cf. TR) have so far been investigated for reversible motions using methods of classical algebraic topology. Methods and results that apply to a directed irreversible setting are needed, as well.

Algebraic Topology and Concurrency (ATC)

Concurrency Theory is an area of theoretical Computer Science investigating the challenges represented by parallel architectures within an individual computer and within computer networks; in particular for the assessment of the correctness and/or safety of non-sequential distributed algorithms. To achieve this, computer scientists tend to use process algebras or Petri nets. A less well-known alternative was described under the name *Higher Dimensional Automata* (HDA) by Vaughan Pratt around 1990 and developed by Goubault and co-authors since. Van Glabbeek (2005) has shown that these HDA are at least as expressive as their competitors.
HDA are modelled combinatorially as pre-cubical sets. Their geometric realization comes with a built-in set of directed (d)-paths (cf. DAT); d-homotopic d-paths correspond to *equivalent* execution paths. For static analysis purposes, it is important to determine the homotopy type of spaces of d-paths with given end points - or at least the fundamental category (cf. DAT) of such a d-space. For HDAs, the spaces of execution paths (and thus their algebraic invariants) "jump" (alter homotopy type) only when the end points pass certain subcomplexes; often, this allows slicing the underlying space into components (cf. DAT).
Current research deals in particular with the following topics and questions:
- The definition of components of d-spaces has been developed for simple d-spaces, in particular for spaces corresponding to HDAs without directed loops. Several ways defining and describing coarser categories (cf. DAT) with these components as objects have been devised. Both for theoretical and practical reasons, methods should be further developed in more general and realistic settings. Algorithmic methods to determine those components have been developed and implemented on real-time platforms in simple cases. Generalizations are needed.
- The (prod)-simplicial models for spaces of execution paths from DAT have to be implemented algorithmically so that at least calculations of their Betti numbers (cf. HC) can be performed.
- Given a platform for such calculations, it makes sense to investigate (both theoretically and practically) the "bar codes" for (persistent) homology classes (cf. PH) under variation of end points or components. This is particularly interesting for the investigation of distributed algorithms performed in rounds.
- Relations with the impossibility results for algorithms in a *distributed* environment that were obtained using methods from combinatorial Algebraic Topology (which earned Herlihy, Saks, Shavit and Zaharoglou the Gödel Prize in 2004) need to be explored.
- Dicoverings (cf. DAT) correspond to bismulation equivalences of HDAs and shed further light on this notion.
- Relations with/ applications to the homological results in the area of *Rewriting Systems* (in particular the results of Squier), to weak *n*-categories and also to *logics* need to be better understood.

Combinatorial methods in applied algebraic topology

Many constructions representing sampled data combine *geometric* features of the object with *combinatorial* features of the model. Combinatorial algebraic topology exploits particular combinatorial properties of the model to compute algebraic *invariants* of such spaces. It interacts and delivers tools to all the above mentioned areas;

moreover, it sheds light on many other problems, particularly within discrete mathematics (cf. the recent book Kozlov (2008)).
The crucial feature used in combinatorial computations is the presence of *symmetry* – via the action of the symmetric group or of a group composed out of subgroups of symmetric or related groups. To combine the use of symmetry with effective computations of algebraic invariants will very likely be the next challenge in the field.
Classically, methods of combinatorial algebraic topology were designed for computing regular Betti numbers - global invariants of combinatorial topological spaces. In applied algebraic topology, the focus is on recognizing global and *stable* invariants, i.e., persistent homology (cf. PH). The latter is the homology dependent on a filtration, and its computation is related to, but quite different from the corresponding spectral sequence computation. There has already been some work exploiting tools from the combinatorial context, such as *discrete Morse theory*, to the calculation of persistent homology, as well as of some related invariants. Possibilities for further connections in this direction are much greater than has been explored until now.
Equivariant methods applied to problems in *discrete mathematics* have played an important role in combinatorial algebraic topology in the past. Similar methods were useful in applications to computer science; more specifically to the theory of feasibility of *distributed computing* (cf. ATC). These connections need to be investigated more closely in view of a better understanding of hard algorithmic problems and of new results in computational feasibility.

Facilities and expertise which would be accessible by the Programme:

During the first year of the programme, a website will be established in order to collect information about ongoing and planned research activities and the participants.
We intend to attract many graduate students to summer schools. After having followed course activities throughout a week, many of the students should be able to profit from participating in the subsequent conference. It is planned to establish Lecture Notes in connection with the summer schools; likewise proceedings for the conferences. Lecture Notes and proceedings may be made available on the web site.

Expected benefit from European collaboration in this area:

The existing small European research groups within Applied and Computational AT will profit from the synergy that arises from increased collaboration and cross-fertilization. Applied and Computational AT is still an emerging research field that should attract more research students forming the next generation of researchers. The area is attractive for students with a theoretical topological background because of a wealth of applications and of unsolved problems; but also for students with a background in applications (mathematics, CS, engineering) who wish to develop their practical expertise on hard theoretical problems. A series of summer schools is designed in order to pave the way to research in the area.
The programme wishes to act as a catalyst for enhanced cooperation between mathematicians and experts in Computer Science and Engineering throughout Europe.
Applied and Computational AT is a field that already flourishes in the USA; an example is the SToMP (Sensor Topology & Minimal Planning) network based on a 8M$ DARPA grant aiming at industrial applications; moreover note the DARPA funded project TDA (Topological Data Analysis) and the Stanford based network TMSCSCS (Topological Methods in Scientific Computing, Statistics and Computer Science).
European researchers need to learn from and interact with the American schools in order to build up a level of competition.

European context

(list of relevant R&D networking activities at the European level directly related to the proposal, and already existing or envisaged collaboration activities, in particular, networks or activities under the EC Framework Programme, COST or under any other international programmes or organisations. State how the Programme would complement these and any applications on this or a similar topic to these organisations):

In recent years, several international conferences on topics within the area have been held in Europe; among them
- the Oberwolfach workshop *Computational Algebraic Topology* (2008);
- two minisymposia *Applied Algebraic Topology* and *Discrete Structures in Geometry and Topology* during the 5th European Congress of Mathematics, Amsterdam (2008);
- the international conference *Algebraic Topological Methods in Computer Science III,* Paris (2008); a satellite conference to the 5th ECM;
- the international conference Dynamics, Topology and Computations, Bedlewo (2009).
In January 2010, a workshop *Geometric and Topological Methods in Computer Science* (the 10th in a series of such workshops) will be held at Aalborg, Denmark.
Prof. Edelsbrunner (one of the principal applicants) aims at building up a European center for Computational Algebraic Topology at the newly established Institute of Science and Technology Austria during the next years.

Proposed activities, key targets and milestones:

Workshops, Conferences and Summer Schools

2011: Summer school followed by Workshop/Conference on Computational Algebraic Topology, 1 week each.
2012: Summer school followed by Workshop/Conference on Topological Robotics, 1 week each.
2013: Summer School on Image and Scene Analysis, 1 week.
Large Scale International Conference on Algebraic Topological Methods in Computer Science and Engineering, 1 week.
2014: Summer School followed by Workshop/Conference on Directed Algebraic Topology and Concurrency, 1 week each.
2015: Large Scale International Conference: Status on Applied and Computational Algebraic Topology, 1 week.
Summer schools (with top experts as lecturers, some of them from outside Europe) and associated workshops/conferences will focus on a particular aspect of the research field; researchers from all over applied and computational AT will be encouraged to participate. The combination of a summer school and a conference should make it easier for research students to get access to current research themes in the area.
The hosting institutions for the conferences will apply for additional funds, in particular for the large scale conferences.

Short scientific visits between members of the scientific teams

An average of 2-3 visits per group (13 groups) and year; with a duration of 1-2 weeks. One visit has a budget of around 1.5k€ on average. We expect that an increasing number of such visit grants will go to young researchers (PhD students and postdocs); this is why the amount foreseen for visit grants is expected to grow during the network period.

Publicity, Websites and Publications

A web site will collect information about the research field at large: introductions to various topics, bibliographies, collaborators, events etc. We aim at producing lecture notes in connection with the programme's summer school; moreover proceedings for (at least some of) the workshops and conferences.

Duration (48 or 60 months)**:**
60 months

Budget estimate (in €) by type of activities and per year of the Programme
(Please use the headings listed in the section "*Level and use of a Programme budget*" of the Call, as appropriate. Do **not** include the ESF administration fee in the annual budget. This is calculated and included by the ESF office before submission for funding to MOs)**:**

Activity/Year	**2011**	**2012**	**2013**	**2014**	**2015**	**Total**
Steering Committee	6.5	6.5	6.5	6.5	6.5	32.5
Science Meetings	40	40	60	40	40	220
Grants for Visits	39	45	51	57	63	255
Website/Publications	12	12	12	12	8	56
External Administration	7.5	7.5	7.5	7.5	7.5	37.5
Total	105	110	135	120	121	**591**

External administration covers essentially part-time secretarial assistance to the chair. All amounts are in k€. Yearly average: **118.2k€**.

Section III: *(not more than 3 A4 single pages+ 1 single page for global dimension if applicable)*

List of names and full coordinates of the **envisaged Steering Committee members listed by country** in alphabetical order (One member per collaborating country; this can be a provisional list and names can be added to it later)**:**

Austria: Prof. Herbert Edelsbrunner, Institute of Science and Technology Austria, Am Campus 1, A-3400 Klosterneuburg.
Denmark: Assoc. Prof. Martin Raussen, Dept. Mathematical Sciences, Aalborg University, DK-9220 Aalborg Øst.
France: Prof. Eric Goubault, CEA & Ecole Polytechnique, CEA/Saclay & Ecole Polytechnique, F-91191 Gif-sur-Yvette.
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Israel: Prof. Roy Meshulam, Technion, Haifa 32000.
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UK: Prof. Michael Farber, Dept. Mathematical Sciences, Univ. Durham, Durham DJ1 3LE, UK.

Programme Collaborations: names and affiliations (including department, institute, university) of the **researchers/research groups** that are foreseen to participate in the Programme's activities **listed by country:**

Austria: Prof. Herbert Edelsbrunner, Institute of Science and Technology Austria, Am Campus 1, A-3400 Klosterneuburg.
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Assist. Prof. Krzysztof Worytkiewicz, Dept. Computer Science, AGH Univeristy of Science and Technology, Mickiewicza 30, PL-30-059 Kraków.
Portugal: Assoc. Profs. Lucile Vandembroucq, Thomas Kahl, Lucía Fernández Suárez, Dr. Pawel Pilarczyk, Centro de Matemática, Universidade do Minho, Campus de Gualtar, P-4710-057 Braga.
Slovenia: Dr. Gregor Jerse, Prof. Neza Mramor Kosta, Dept. Mathematics, Faculty of mathematics and physics, Jadranska ulica 19, SI-1000 Ljubljana.
Spain: Ass. Prof. Ainhoa Berciano Alcaraz, Dr. Rocio Gonzalez Diaz, Ass. Prof. Belen Medrano Garfia, Prof. Pedro Real Jurado, Ass. Prof. Daniel Diaz Pernil, Ass. Prof. Maria José Jiménez Rodriguez, Dr. José Andrés Armario Sampalo, Dr. Victor Alvarez Solano, Prof. José Antonio Vilches, Dpto. de Matemática Aplicada I, Universidad de Sevilla, Avda. Reina Mercedes, s/n. E-41012 Sevilla;
Prof. Juan Alfonso Crespo, Departamento de Economía, Universidad Carlos III de Madrid, E- 28903 Getafe;
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Prof. Thomas Kappeler, Inst. für Mathematik, Universität Zürich, Winterthurerstr. 190, CH-8057 Zürich;
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Lecturer Mark Grant, School of Mathematics, Univ. Edinburgh, James Clerk Maxwell Building, Mayfield Road, Edinburgh DH9 3JZ, UK.

Global dimension

Proposals with a global dimension should include one additional page outlining the key persons in the global network(s), the scientific benefits expected from the collaboration and the status of the non-ESF request for funds**:**

The network will actively seek collaboration with researchers outside Europe, in particular by inviting them as speakers to the proposed summer schools and conferences. Specific related networks in the USA (StOMP, TDA, TMSCSCS) have already been mentioned in the Section on expected benefit. The (incomplete) list below consists of researchers with natural ties to the network.

Canada:

Prof. John Frederick Jardine, London, WO
Prof. Tomasz Kaczynski, Sherbrooke, QU

Mexico:

Prof. Sergio Rajsbaum, UNAM, D.F. 04510

USA:

Prof. John Baez, UCLA, CA
Ass. Prof. Peter Bubenik, Cleveland, OH
Prof. Gunnar Carlsson, Stanford, CA
Prof. Fred Cohen, Rochester, NY
Prof. Robin Forman, Rice, Houston, TX
Prof. Eli Gafni, UCLA, CA
Prof. Robert Ghrist, University Pennsylvania, PA
Prof. John Harer, Duke, Durham, NC
Prof. Maurice Herlihy, Brown, RI
Prof. Vijay Kumar, UPenn, PA
Prof. Konstantin Mischaikow, Rutgers, NJ
Prof. Partha Niyogi, Univ. Chicago, ILL
Ass. Prof. Vin de Silva, Pomona College, CA
Prof. Stephen Smale, City University of Hong Kong
Prof. Shmuel Weinberger, U. Chicago, ILL
Ass. Prof. Afra Zomorodian, Dartmouth College, NH

Section IV: *(not more than 3 A4 single pages in total)*

CVs
(Full coordinates and short *curriculum vitae* of the applicant(s) including 'contact person'. The list of the five most recent relevant publications of each applicant)**:**

Curriculum Vitae Herbert Edelsbrunner

Austrian citizen, born March 14, 1958.

Academic degrees

1980: Dipl.-Ing. in Technical Mathematics from the Graz University of Technology, Austria.
1982: Ph.D. in Technical Mathematics from the Graz University of Technology, Austria.

Academic positions

1982-1985: Assistant Professor in the Department of Information Processing at the Graz University of Technology, Austria.
1985-1987: Assistant Professor in the Department of Computer Science at the University of Illinois at Urbana-Champaign, USA.
1987-1990: Associate Professor in the Department of Computer Science at the University of Illinois at Urbana-Champaign, USA.
1990-1999: Full Professor in the Department of Computer Science at the University of Illinois at Urbana-Champaign, USA.
1999-present: Arts and Sciences Professor of Computer Science at Duke University, USA.
2009-present: Professor at the Institute of Science and Technology Austria.

Visiting positions

IBM Yorktown Heights, Free University of Berlin, Hong Kong University of Science and Technology, Lawrence Livermore National Laboratory, California Institute of Technology, Berlin Mathematical School.

Awards

2008: Member of the German Academy of Sciences (Leopoldina).
2006: Honorary doctorate (Dr. h.c.) from the Graz University of Technology.
2005: Member of the American Academy of Arts and Sciences.
1991: Alan T. Waterman Award by the National Science Foundation, USA.

Recent plenary talks

Persistent homology, diagrams, and vineyards. AMS invited address, Annual Joint AMS-MAA Mathematics Meeting, San Antonio, Texas, January 14, 2006.
A primer in topological persistence. Eurographics, Vienna, Austria, September 6, 2006.
An introduction to persistent homology. ICIAM 2007, 6th International Congress on Industrial and Applied Mathematics, Zürich, Switzerland, July 17, 2007.
Measuring scale before simplification. BMS Friday Colloquium, Berlin Mathematical School, Berlin, Germany, October 26, 2007.
Messen mit Algebra und Hartnäckigkeit. Deutsch-Österreichischer Mathematiker Kongress, Graz, Austria, September 24, 2009.

Recent relevant publications

1. Ban, Y.-H. A., Edelsbrunner, H. and Rudolph, J., *Interface surfaces for protein-protein complexes*. J. Assoc. Comput. Mach. **53** (2006), 361-378.
2. Agarwal, P. K., Edelsbrunner, H., Harer, J. and Wang, Y., *Extreme elevation on a*

2-manifold. Discrete Comput. Geom. **36** (2006), 553-572.
3. Cohen-Steiner, D., Edelsbrunner, H. and Harer, J. *Stability of persistence diagrams*. Discrete Comput. Geom. **37** (2007), 103-120.
4. Cohen-Steiner, D., Edelsbrunner, H. and Harer, J., *Extending persistence using Poincare and Lefschetz duality*. Found. Comput. Math. **9** (2009), 79-103.
5. Edelsbrunner, H. and Harer, J., Computational Topology. An Introduction. American Mathematical Society, Providence, RI.

Curriculum Vitae Michael Farber

British and Israeli citizen, born August 31, 1951 in Vladivistok, USSR.

Academic degrees

1973 MSC in Mathematics and Mechanics, University of Baku, USSR
1976 PhD in Geometry and Topology, University of Baku, USSR
1986 DSc in Geometry and Topology, University of Georia, USSR

Academic positions

1974 – 1987: Researcher, Institute of Cybernetics, Academy of Sciences, USSR
1987 – 1991: Associate Professor, School of Mathematics, Tel Aviv University, Israel.
1991 – 2003: Professor, School of Mathematics, Tel Aviv University, Israel
2003 – Chair of Pure Mathematics, University of Durham, UK.

Visiting positions

IHES (Paris), ETH (Zurich), Max-Planck Institute for Mathematics (Bonn), MSRI (Berkeley) and others.

Awards

2004 Royal Society Wolfson Research Merit Award

Recent Grants

2010 – 2014: EPSRC grant "Tools of Applied Algebraic Topology", PI.
2004 – 2009: EPSRC grant "Applications of Algebraic Topology", PI.

Recent Conferences Organized

Conference "Topology and Robotics" ETH, Zurich, Switzerland (2003, 2006)
Conference "Topology of Closed 1-forms", ETH, Zurich, Switzerland (2004)
Siegen Topology Symposium, Siegen, Germany (2005)
Minisymposium "Topological Robotics", ICIAM07, Switzerland (2007)
Minisymposium "Applied algebraic Topology", ECM, Amsterdam (2008)

Most Recent Invited Talks

"Configuration spaces and robot motion planning algorithms" Invited series of lectures at conf. "Braids, Knots and Applications", University of Montpellier, 2008; "Topology of Motion Planning Algorithms", Invited Plenary talk at conf. "Algebraic Topology Methods in Computer Science", Satellite conference to 5ECM, Paris, 2008; "Topology of random manifolds", Ulam Centennial Conference, University of Florida, Gainesville Florida, USA, 2009.

Most Recent Relevant Publications

1. M. Farber, J.-Cl. Hausmann, D. Schuetz, *On the conjecture of Kevin Walker*, Journal of Topology and Analysis **1** (2009), 65 - 86.
2. M. Farber, M. Grant, *Topological complexity of configuration spaces*, Proc. AMS **137** (2009), 1841-1847.
3. M. Farber, *Topology of random linkages*, Alg. Geometric Topology **8** (2008), 155 - 171.
4. M. Farber and T. Kappeler, *Betti numbers of random manifolds*, Homology, Homotopy and Applications **10** (2008), No. 1, 205 - 222.

5. M. Farber, M. Grant, *Robot motion planning, weights of cohomology classes, and cohomology operations*, Proc. AMS **136** (2008), 3339-3349.

Curriculum Vitae Martin Raussen

German citizien. Born May 25, 1954 at Trier (Germany). Married. Three daughters.

Academic degrees

1975: Dipl. Math. (MSC, Mathematics and Computer Science), Universität des Saarlandes, Saarbrücken, Germany.
1981: Dr. rer.nat. (PhD) Georg-Wilhelms-Universität, Göttingen, Germany

Academic positions

1977 – 1984: Assistant and post.doc positions at Univ. Göttingen, Technical Univ. Lyngby, Univ. Aarhus (Denmark)
1984 – : Associate Professor, Univ. Aalborg (Denmark)

Visiting positions

Paris XI, Orsay, France; UNAM, Mexico; Univ. Göttingen; Institut Mittag-Leffler, Djursholm, Sweden; Brown University, Providence, RI, USA; Ecole Polytechnique, Paris

Conferences (organization; participation as invited speaker)

One of the main organizers of workshop series “Geometric and Topological Methods in Concurrency Theory”, 1999-. Member of organizing committee of "Algebraic Topological Methods in Computer Science III", Paris 2008.
Recent Invited Talks: MSRI, Berkeley, 2006. Neuchatel, 2007. DMV-GDM Berlin, 2007. AMS-PTM Warsaw, 2007. Göttingen, 2007. Oberwolfach, 2008, Paris, 2008, Baia Mare, Romania, 2008. UA Madrid, 2008. Bremen, 2008. Trondheim, 2009.

Editorial and board responsibilities

Matilde, Newsletter of Danish Mathematical Society, 1999 – 2003 (editor-in-chief: 2002 – 2003)
Newsletter of the European Mathematical Society, 2003 – (editor-in-chief 2003 – 2008)
J. Homotopy Relat. Struct. (2005 –)
Proceedings of “Geometric and Topological Methods in Concurrency Theory”, Electr. Notes TCS
Study board Aalborg (1985 – 88, 1990 – 91, 1995 – 2001), department board (1992 – 96, 2005 –)
Member of the executive committee of the European Mathematical Society, 2009 –

Research Education

Ph.D. students Rafael Wisniewski (2005), Ulrich Fahrenberg (2005), John Leth (2007)
Frequent PhD courses at the faculties of engineering, science and medicine, Aalborg University

Most recent relevant publications

1. Fajstrup, Goubault, Haucourt, Raussen, *Components of the Fundamental Group,* Appl. Categ. Structures **12**, 81-108 (2004)
2. Fajstrup, Goubault, Raussen, *Algebraic Topology and Concurrency,* Theor. Comput. Sci. **357**, 241-278 (2006)
3. Fahrenberg, Raussen, *Reparametrizations of continuous paths*, J. Homotopy Relat. Struct. **2** (2), 93-117 (2007)
4. Raussen, *Invariants of directed spaces,* Appl. Categ. Structures **15**, 355-386 (2007)
5. Raussen, *Trace spaces in a pre-cubical complex,* Topology Appl. **156**, 1718-1728 (2009)